The effect of rainfall and contaminants on road pavement skid resistance

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An important note for the reader

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Contents

Executive summary

It has been well proven that as the skid resistance of a road surfacing decreases, the number of loss-of-control type crashes increases, causing road death and injuries. However, the management of the skid resistance of road surfacings continues to be difficult, due to the inherent and sometimes random variation in skid resistance levels over time.

This research was an investigation and analysis of seasonal and short-term variation of measured skid resistance, undertaken between 2003 and 2006 in two phases:

- **Phase 1:** Regular field monitoring was undertaken using the GripTester and the Dynamic Friction Tester measurement devices on seven sites in the Auckland and Northland regions of New Zealand over a period of 2.5+ years. The effects of temperature, rainfall, contaminants, new surfacings, geometric elements and aggregate properties were analysed to investigate factors that initiate changes in the measured skid resistance of pavement surfacings.

- **Phase 2:** Laboratory-prepared samples were constructed for accelerated polishing and skid resistance testing of four different aggregates (two greywackes, a basalt and an artificial iron-making melter slag aggregate). The samples were polished in an accelerated polishing machine to an 'equilibrium skid resistance' level (stage 1 polishing). Contaminants were then added to the accelerated polishing process to determine the effect of varying additives, particle sizes and hardness in an attempt to simulate seasonal and/or short-term variations that occur in the field.

The results demonstrated that significant and previously unpredictable variations (greater than 30%) in measured skid resistance could occur over short time periods. These variations could not be explained by any one factor. They were the result of a number of interrelated factors, including the geological properties of the aggregates and the contaminants themselves, the previous rainfall history, the road geometry, the calendar month of the year and (depending upon the measurement device), the temperature during testing. The laboratory tests demonstrated that accelerated polishing tests of aggregate samples could be prepared for testing by the Dynamic Friction Tester, and that significant variations in measured skid resistance could be simulated on various aggregates in the laboratory by the addition of contaminants. The results of the testing and addition of contaminants on various aggregates resulted in significant behavioural differences that were related to the geological properties of the aggregates themselves, as well as the contaminants used in the accelerated polishing process.

The findings of the research have specific relevance to the following three areas of industry:

- road controlling authorities, who are primarily interested in skid resistance policy, standards and management

- road asset managers, who operate, maintain and manage the condition level and safety aspects of the road network

- crash investigators, who collect and analyse crash data primarily for legal proceedings.

All three of these industry organisations need to clearly understand the inherent variability of skid resistance, the factors involved and the effects that geological and environmental variations have on skid resistance measurement.

Further research is required to investigate a greater sample of geological and artificial aggregates, and 'mix designs' that may lessen the variation in measured skid resistance and subsequently improve the prediction and safety performance of surfacing aggregates in the long term.

Abstract

This research project, which was undertaken between 2003 and 2006, aimed to improve the understanding of the effect that environmental factors (eg rainfall and detritus) have on the variation of measured skid resistance, both in the short and longer term. Phase 1 of the research was a field study of seven sites in the Auckland and Northland regions over 2.5+ years, with regular skid resistance measurements primarily utilising the GripTester. Phase 2 involved developing a new laboratory-based accelerated polishing device and methodology for testing large (600 x 600mm) chipseal surfaces with the Dynamic Friction Tester.

Phase 1 results demonstrated that significant and previously unpredictable variations (greater than 30%) in measured skid resistance could occur over short time periods. These variations were the result of a number of interrelated factors, including the geological properties of the aggregates and the contaminants themselves.

Phase 2 results demonstrated that large aggregate samples could be prepared for accelerated polishing tests in the laboratory and that significant variations in measured skid resistance could be achieved by the addition of contaminants and simulated traffic action. Significant behavioural differences were related to the geological properties of the aggregates, as well as the contaminants used in the accelerated polishing process.

Further research is proposed to investigate a greater sample of geological and artificial aggregates, and 'mix designs' that may lessen the variation in measured skid resistance during the surface asset life and subsequently improve the prediction and safety performance of surfacings in the long term.

1 Introduction

This research project, which was undertaken between 2003 and 2006, was concerned with developing a better understanding of the effect that road contaminants and rainfall have on the seasonal variations of skid resistance of the road pavement surfacing. Seasonal variations in skid resistance begin to occur after the initial surface aggregate ‘polishing’ phase has been completed. The time up to the point that seasonal variations begin to occur depends upon a number of factors, including the amount of heavy commercial vehicle (HCV) traffic and the geological source properties of the aggregate itself.

The research project arose from a need to be able to more reliably predict the future skid resistance levels of road surfaces and thereby efficiently select road sections for remediation. It is expected that this research is relevant to the management of the state highway network by the NZ Transport Agency (NZTA), territorial Road Controlling Authorities (RCAs) and their local network managers.

1.1 Background

Unlike other road pavement distress modes, skid resistance measurement is not highly repeatable, as it varies by a number of significant factors over relatively short time periods. This variability means that it is difficult for both RCAs and their assigned network managers to understand how their asset is performing and subsequently how to make good asset management decisions based on this information. It is thought that one of the most significant factors on measured skid resistance variability is the effect of contaminants building up and the ‘cleaning’ effect of rainfall/traffic interaction. This research project investigated this phenomenon, known as the ‘seasonal variation effect’, and quantified a sample of collected contaminants on the pavement surface with the aim of determining the contaminants’ effect on skid resistance measurement.

1.2 The need for research

The research project sought to develop a prediction methodology whereby RCAs and asset managers could better predict skid resistance levels (year by year). RCAs and their road network managers have found that on a network level, and in many cases also at a project level, it is very difficult to predict the minimum skid resistance levels that will be attained over the short- to medium-term future. For this reason, the New Zealand dTIMS system (Deigton’s Total Infrastructure Management System) currently does not have predictive deterioration models for skid resistance.

The objectives of this research project are directly relevant to the NZTA (formerly Land Transport NZ and Transit NZ) because they relate to the key topic areas of asset management, safety and environmental effects.

In particular, the asset management outcomes from this work sought to improve the performance of the land transport asset by:

- developing a better understanding of pavement surface performance/deterioration, including regional variations
- improving data-capture technology and analysis/utilisation

- improving asset management systems.

Furthermore, in terms of road safety outcomes, the findings of this research will improve public safety through improvements in the land transport environment/architecture decision-making process by:

- ensuring that those areas of the network in most need of an improvement in skid resistance are properly identified
- improving the safety performance of the land transport architecture in terms of the asset management decision making that is required.

An additional value or benefit in undertaking research directly related to the environmental effects of transport systems has been the development of systems to mitigate the adverse impacts of land transport. Road-based contamination samples were collected and the pollutant loads generated under different road usage conditions (vehicle density, road age, etc) were determined. Associations were explored between the different pollutants – metals, petroleum hydrocarbons and sediments – found on road surfaces. The results led to a better understanding of the impact on the environment of land transport, infrastructure and construction, and understanding the generation of road runoff and reducing its impact.

1.3 Research objectives

The primary goal of the research was to provide a more reliable means of quantifying the seasonal variation in the skid resistance effect, with the aim of enabling the better prioritisation and treatment of road sections. This would provide better pavement surface characteristic management, thereby preventing future loss of control in the wet-type road crashes that currently form approximately 25% of fatal and serious-injury crashes across New Zealand.

The specific objectives of the research programme were to:

- effectively quantify the rainfall/contaminants phenomenon by developing a better understanding of the combined effect that contaminants and rainfall have on measured skid resistance in terms of the GripTester, the Dynamic Friction Tester (DF Tester) and SCRIM
- develop statistical methods to be able to quantify confidence limits from one or more skid resistance measurements given certain environmental information (eg rainfall data)
- objectively quantify the contaminant materials and source obtained from road surfacing samples in the Northland region of New Zealand, and propose ways of mitigating their effects in terms of skid resistance and the receiving environment.

The research outcomes would allow improved programming of physical resources, to enable intervention at the appropriate time to ensure skid resistance levels did not fall to a level whereby crash risk increased to unacceptable levels. The methodology used both a time-based regular skid-testing programme over three years (2003–2005) on various state highway sites in the Northland region, and laboratory methods to ascertain the effect of various skid resistance parameters by holding other parameters constant.

1.4 Scope of the report

This report presents the results of a study on the seasonal variation of skid resistance, by analysing the effect of rainfall and contaminants on the measured coefficient of friction.

- Section 2 discusses the rainfall and contaminants effect and previous research in the literature, both in New Zealand and internationally.
- Section 3 describes the experimental design methodology used in phase 1 – the field testing.
- Section 4 describes the methodology used in phase 2 – the preparation of sealing chip samples and the development of a laboratory methodology to 'polish the samples' under accelerated conditions, and a surface friction test throughout the simulated life of the surfacing.
- Section 5 summarises the skid resistance testing results from the field and subsequent data analysis.
- Section 6 discusses the analysis of the seasonal and short-term variation of skid resistance field results.
- Section 7 describes the environmental analysis methods used and the results of the contaminant materials collected off the road surface.
- Section 8 discusses the analysis and results of the laboratory-based accelerated polishing method for a prepared sample of road aggregates used in the Northland region of New Zealand.
- Section 9 provides a summary of the research project.
- Conclusions from the research are given in section 10, and recommendations in section 11.

2 Skid resistance and seasonal variations

2.1 Overview

The road surface friction that is available at any particular time, either to the road user or as tested dynamically by a friction tester, depends upon many variables. These variables can be grouped together under four main surface friction factors, as shown in table 2.1.

Table 2.1 Factors affecting the skid properties of a road

Pavement surface aggregate factors	Load factors	Environmental factors	Vehicle factors
Geological properties of the surfacing aggregate	Age of the surface	Water film thickness and drainage conditions	Vehicle speed
Surface texture (microtexture and macrotexture)	Traffic intensity and composition – equivalent vehicle loadings	Surface contamination	Angle of the tyre to the direction of the moving vehicle
Chip size and shape	Road geometry	Temperature	The wheel-slip ratio
Type of surfacing (concrete, asphalt mix and mix design, chipseal surface and design method)	Traffic flow conditions – congested or free-flowing	**The combined 'seasonal effects' and short-term variations**	Tyre characteristics (structural type, hardness and wear)
		Rainfall	Tyre tread depth and pattern

This report only discusses the literature regarding the combined seasonal variation effects and its relationship to rainfall (highlighted in table 2.1). Other effects are discussed in detail in Wilson (2006). It is recognised that the seasonal effect to some degree is also related to surface contamination, temperature and water film thickness. However, as most field skid testers (including the one primarily used in this research – the GripTester) control the water depth beneath the tyre and the road surface, water film thickness and drainage conditions are largely controlled. Temporary surface contamination can also affect skid resistance measurements, as shown as far back as Bird and Scott's research in 1936. However, this is thought to also be related to the period since the last rainfall and is therefore captured to some degree in the 'seasonal effect'.

The temperatures of the road surface and the water have also been shown to affect the hysteretic friction component of skid resistance, as rubber tyres and bitumen are visco-elastic materials. Depending upon the skid-testing device used and the standard correction procedures, some devices modify measurements based on a temperature correction factor to standard testing temperatures. The SCRIM device does include a temperature correction but the GripTester does not. The developers of the GripTester (Findlay Irvine Ltd) state that their research has shown that once the testing tyre has been conditioned and reaches operating temperatures, the temperature effects are minimal in normal-temperature operating conditions.

2.2 Variation of skid resistance through surface life

The level of measured skidding resistance of a road surfacing has been shown to vary throughout the life of the surfacing and also with the seasons of the year (after the initial phase of traffic polishing and wearing has been completed), as shown in figure 2.1.

Figure 2.1 Simplified general pavement polishing model (Prowell et al 2003)

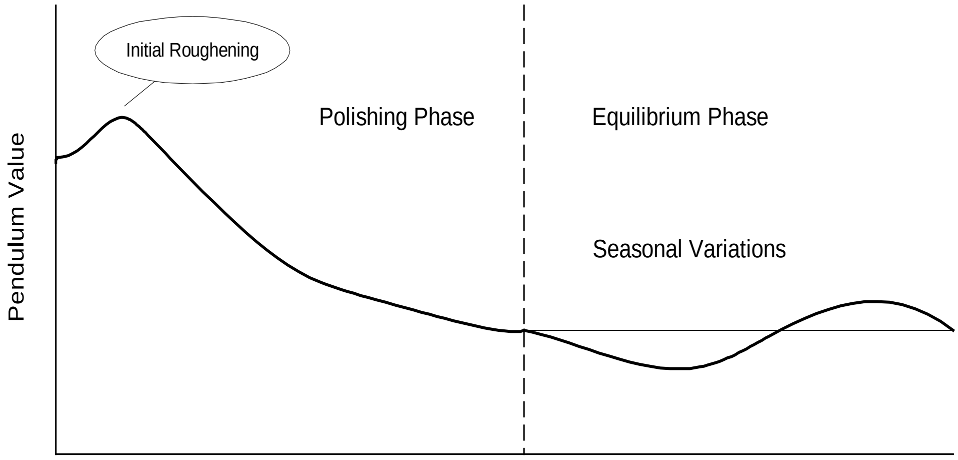


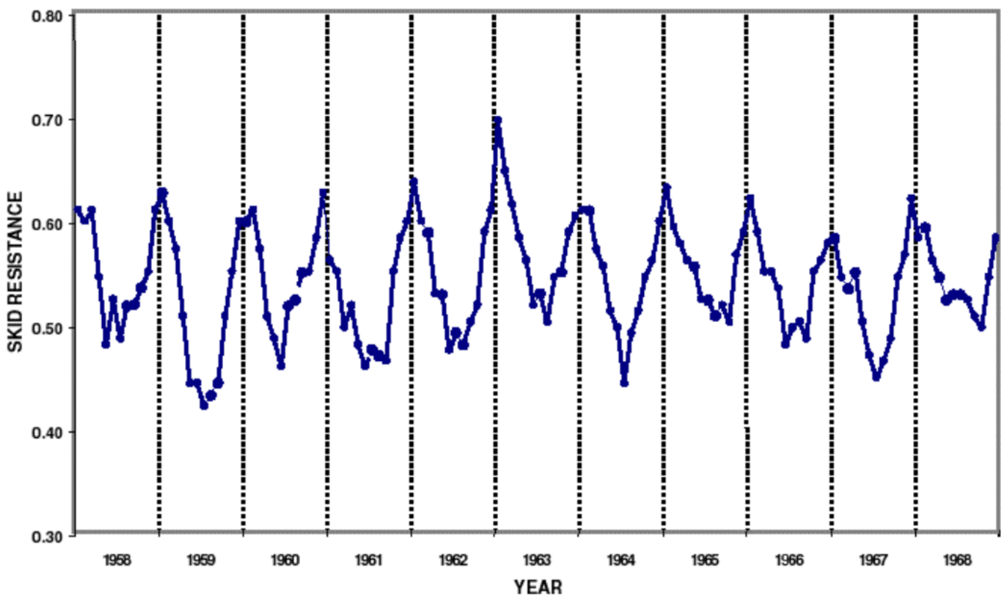
Figure 2.1 is a generalised model of how skid resistance has been traditionally considered to decline with time (Prowell et al 2003). After construction of the surface, there can be an initial rise in skid resistance if the surface aggregate has been contaminated by a film of bitumen (more common in asphalt mixes but can also occur on chipseal surfaces). As the film of bitumen is worn away, the aggregate microtexture is exposed and therefore skid resistance increases. The degree of change and rate of change of skid resistance will depend upon the type of surfacing material (Jellie 2003) – for example, for well-constructed chipseal surfaces, this initial effect is not really evident. However, with stone mastic asphalt (SMA) there may be a greater time lag due to the thicker coating of binder on the aggregate.

Woodward et al (2002, 2005) demonstrated the significance of this 'initial' effect on binder-rich SMA surfaces that largely dominated the whole-of-life skid resistance performance. They reported on a polymer-modified surfacing that, after four years of wearing, still had no exposed aggregate and therefore the measured skid resistance remained low. This showed that the trafficking and climatic conditions were not severe enough to remove the bitumen from the surface. In this case, the polymer-modified binder was 'too good' in its elastic and cohesive properties. The measured wet skid resistance would therefore remain low, due to the excess bitumen coating the aggregate, and could pose a significant 'early life' road safety risk and could also be susceptible to dry skidding events. This effect was reported by Bullas (2005) on SMA surfaces, but is less evident on well-constructed positive-textured surfaces such as the chipseal surfaces primarily used in New Zealand.

2.3 Seasonal variation effect

The seasonal variation has been shown to be highest in the winter and lowest in the summer for most northern hemisphere climates. This effect has been attributed to the combined effect of traffic and weather on the surface aggregate. When roads are dry, the polishing effect of traffic tends to dominate, but when they are wet for prolonged periods, they recover some of their former harshness (Rogers and Gargett 1991). The scale of the seasonal and traffic effects depends largely upon the geological history and petrography of the aggregates. Hosking (1976) reported this seasonal effect in a study undertaken for the UK Highways Agency, where the coefficient of friction was measured by the SCRIM device at a group of highway sites (that had polished to an 'equilibrium' or long-term skid resistance level), monthly over an 11-year period from 1958 to 1968. The results of this study are shown in figure 2.2 and clearly show an annual cyclical effect with a significant seasonal variation.

Figure 2.2 Measured coefficient of friction (SCRIM) in the UK over 11 years (Hosking 1976)



Other researchers in the UK (Hosking 1976, 1992; Rogers and Gargett 1991; Salt 1977) and in the US (Dahir and Henry 1979; Henry and Saito 1983; Jayawickrama and Thomas 1998; Rice 1977) also indicate a seasonal variation that is approximately sinusoidal with seasons of the year. This variation has been found to be as high as 0.15–0.20SFC (sideway force coefficient) as measured by the SCRIM device between winter and summer months.

In New Zealand, Cenek et al (1999) reported on a study of the long-term variation of measured skid resistance undertaken in Northland over a 10-year period (1988–1998) on a series of seven newly surfaced chipseal surfaces south of Whangarei. The chipseal surfaces were constructed in 1988 on a geometrically straight and flat grade, using different sources of greywacke aggregate with similar polished stone values (PSVs). The skid resistance measurements were undertaken with a British Pendulum Tester (BPT) approximately every three months. The results of this study are shown in figure 2.3.

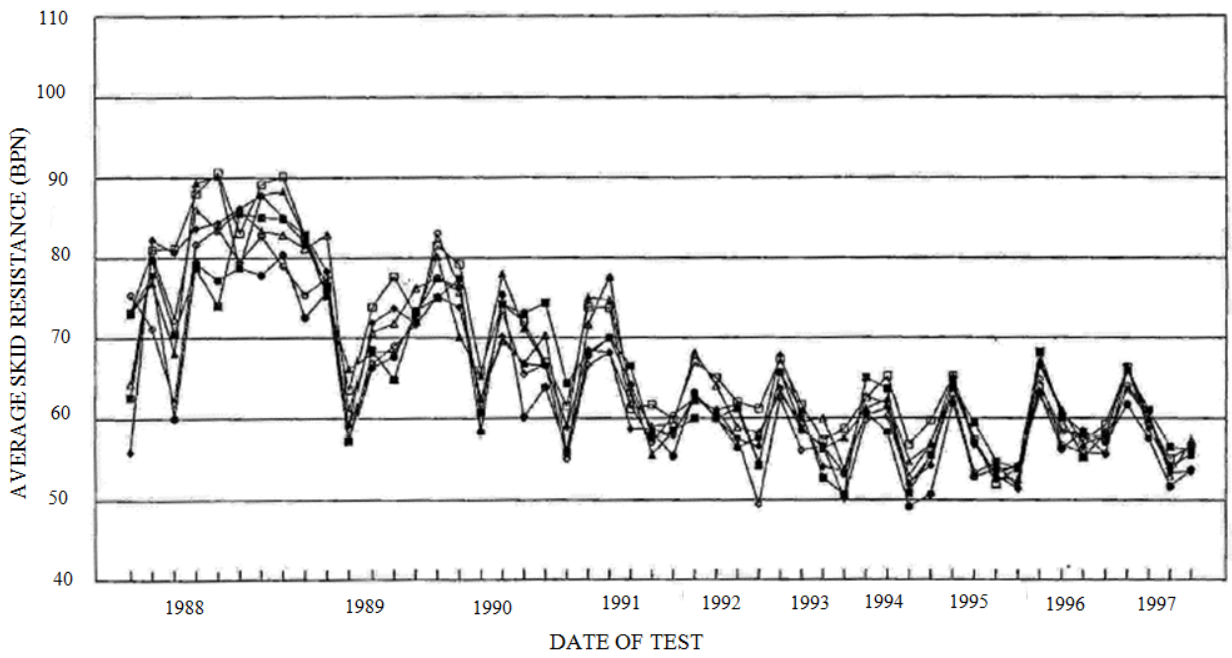
The study results clearly demonstrated the three stages of variation in skid resistance as suggested by Prowell et al (2003) and as shown in figure 2.1. The three phases were described for the New3Zealand research study, as follows:

Phase 1 – Initial roughening phase: Initial values of measured coefficient of friction are low, most likely due to bitumen coating the aggregate and/or the stone microtexture being roughened by trafficking. The bitumen is subsequently worn away, which exposes and roughens the natural aggregate surface, thereby providing increased surface friction. This initial roughening phase can last up to one year depending upon traffic levels.

Phase 2 – Polishing phase: The vehicle trafficking polishes the microtexture of the aggregate, reducing the harshness of stone texture, thereby reducing the measured coefficient of friction. The general shape of this polishing (after smoothing out yearly cyclical seasonal variations) follows a negative exponential shape and takes some four or five years to complete.

Phase 3 – Equilibrium phase: The polishing phase has reached a stable or near-equilibrium phase for the level of traffic action, and the variation of measured coefficient of friction follows a roughly annual cyclical seasonal pattern, with low skid resistance in the summer months and high skid resistance over winter months.

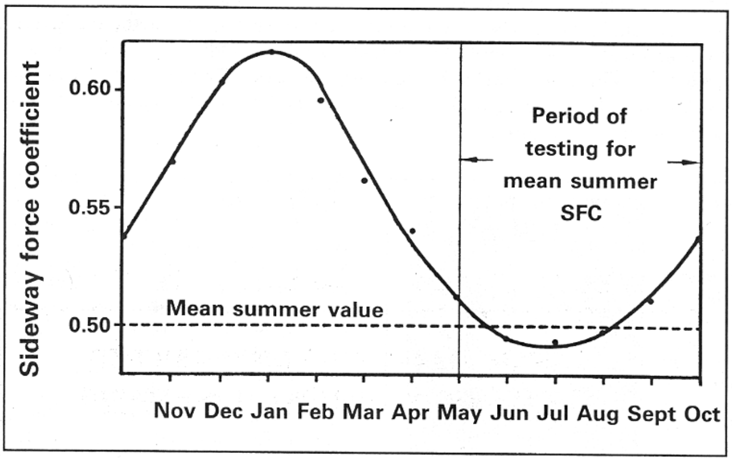
Figure 2.3 Long-term skid resistance monitoring in Whangarei, using the BPT (Cenek et al 1999)



The third seasonal variation phase (the 'equilibrium phase') has been idealised in the UK and forms the basis for measuring skid resistance surveys in the summer months in the UK and New Zealand. Network surveys are adjusted for a mean summer coefficient of friction, to determine the lowest level of measured skid resistance in any one year (being the worst condition for the road user). This variation in wet skidding resistance in the UK (northern hemisphere) throughout a year is shown in figure 2.4 for a mean summer value of 0.50SFC as measured by SCRIM, and is characterised by a clear 'sinusoidal' pattern. The degree of variation of this effect (0.15–0.20SFC) demonstrates the degree of unpredictability that could be encountered unless some form of correction factor is applied.

For this reason, controlling authorities such as the UK Highways Agency (2004) and Transit NZ (2002) have put in place a methodology to determine network- and project-level skid resistance performance based on the mean summer SCRIM coefficient (MSSC). The MSSC is based upon collecting at least three samples across the summer period for each region on carefully chosen 'seasonal skid resistance sites', being sections that should be in an 'equilibrium polished state'. The mean of the three measurements is then used to factor the network surveys up or down, based upon the network measurement on the seasonal sites. This is then expected to give the worst-case skid resistance values over the summer period. The New Zealand policy has recently been extended (Transit NZ 2002) to include a term called the 'equilibrium SCRIM coefficient' (ESC), which factors yearly network surveys by a rolling four-year average of the seasonal sites. The procedure is meant to take account of annual fluctuations in climatic patterns by region, where some summers are much wetter or dryer than others.

Figure 2.4 Estimate of the seasonal variation of SFC with the reported MSSC for the UK (Rogers and Gargett 1991)



Whilst the shape in figure 2.4 is idealised and needs to be shifted by six months for the southern hemisphere, it has been recognised that the minimum values and the shape of the sine curve of this seasonal variation vary from year to year and at different times of the year, depending upon the predominant weather patterns (Hosking 1992). These differences were also evident in the New Zealand study by Cenek et al (1999), which demonstrated that whilst most summers from 1992 onwards (refer to figure 2.3) reached a similar minimum summer value, one summer (1996) did not reach the same level of polishing. Furthermore, a comparison of the highest winter levels of skid resistance from year to year show that the winter prior to the 1996 higher summer values were also higher. This could perhaps suggest that the lower summer values in 1996 were linked to weather patterns in the winter period that caused greater rejuvenation of skid resistance some six months prior to the summer values being recorded. A close examination shows the amplitude of the sine wave length for the year of 1996 was very similar to previous years – it just moved slightly upwards. Similar examples can also be seen in Hosking's 1976 UK study (refer to figure 2.2) between winter in 1962/1963 and summer in 1963.

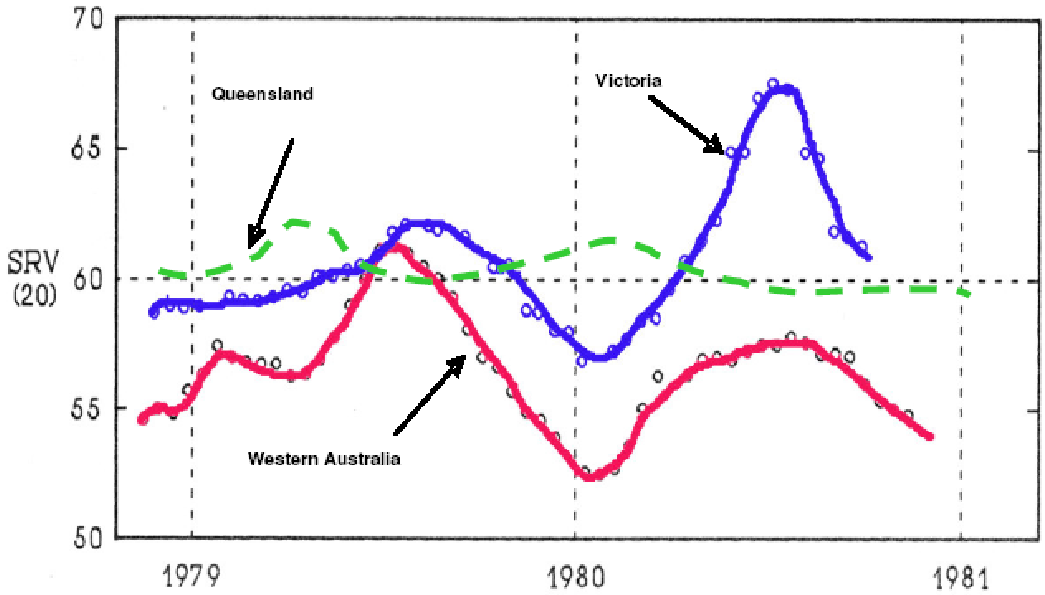
As discussed by Jayawickrama and Thomas (1998), there is general consensus among researchers regarding the following mechanism causing seasonal variation:

> *Prolonged periods of dry weather in the summer allow the accumulation of fine particles that assist in polishing of the pavement surface. The combination of polishing and particle accumulation, together with the contamination from vehicles such as oil drippings and grease, results in a loss of microtexture and macrotexture during the summer months. In winter, the aggregate surface is rejuvenated with chemical reactions from the rainwater exposing new particles. The increased rain flushes out the finer particles responsible for polishing and other debris increasing macrotexture. The coarser aggregate surface and the increased macrotexture in turn lead to an increased skid resistance of the pavement.*

Some researchers also suggest that the water film covering the pavement for longer periods in winter acts as a lubricant and reduces the polishing effect of vehicles on the surface aggregate.

However, not all climates or regions have been shown to act in this same relatively predictable and cyclical pattern after an equilibrium level of polishing has been attained. In Australia, Oliver et al (1988) indicated different seasonal patterns and variations. Regular testing (almost weekly) was carried out with a BPT on a group of sites in the capital cities of each of the six states in Australia, and examples of the results are shown in figure 2.5. The measured BPT coefficient of friction values have been normalised to 20°C to eliminate seasonal temperature effects, and the resultant values shown represent the mean of six sites (three sprayed seal and three asphalt surfaces) in each state of Australia. The results show the seasonal variation is not only substantial and varies from state to state, but is largely unpredictable. The variation for Queensland (a subtropical climate) is unique in that it shows very little variation in amplitude and no real dependency on seasonal variation, in comparison with Victoria and Western Australia.

Figure 2.5 Seasonal variation of skid resistance in Western Australia, Victoria and Queensland (Oliver et al 1988)



2.4 Short-term variations

Bird and Scott (1936) took measurements on the UK Transport and Road Research Laboratory (TRRL) test track in Crowthorne, UK, using a side-ways force method tester (an early version of the SCRIM device). They found that skid resistance levels varied significantly with changing weather conditions, from prior to a rainfall event, to an immediate drop in skid resistance as rain fell, and then increasing skid resistance as contaminants were washed away and as the pavement dried out.

Hill and Henry (1981) discussed the results of a three-year research programme that undertook regular skid resistance measurements with the locked wheel ASTM[1] test method E 274 on public highways in Pennsylvania and other US states. This demonstrated that there were both long-term cyclical seasonal (a primary effect) and short-term skid resistance variations (a secondary effect). They recognised that the combination of the two variations makes the establishment of a surfacing maintenance programme a

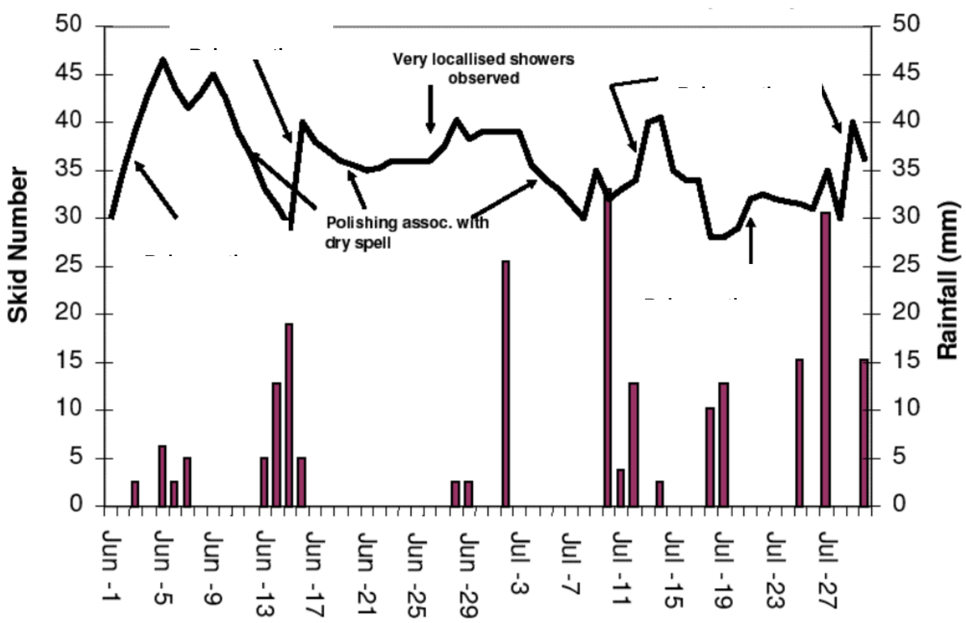
1 American Society for Testing and Materials.

difficult task. Henry (2000) discussed the secondary effect that is not limited to typical annual seasonal variations, such as seen in northern climates, but is a short-term variation caused by the combined effect of rainfall and contaminants on the road surface. During dry periods, dust and oil accumulate on the pavement surfacing. When a skid resistance test is made during the dry period, the water that is applied mixes with dust and oil, which reduces the measured friction. When the measurements are made shortly after periods of rain, the pavements are less contaminated and this effect is reduced.

Hill and Henry (1981) stated that the variations from day to day (short term), seemingly due to rainfall pattern and local weather conditions, are superimposed on the seasonal annual cycle. Frequent tests during the summer periods indicated that pavement skid resistance could vary as much as 25% during a single week, and they and others (eg Hegmon 1978) concluded that these variations were real skid resistance changes related to changing conditions.

As part of the same research, Dahir and Henry (1979) reported this effect with regular testing only days apart for a period of two summer months – this resulted in low skid numbers (coefficient of friction as measured by the ASTM E 274 locked wheel tester) after a dry period and rejuvenated high skid numbers after a rainy period (refer to figure 2.6).

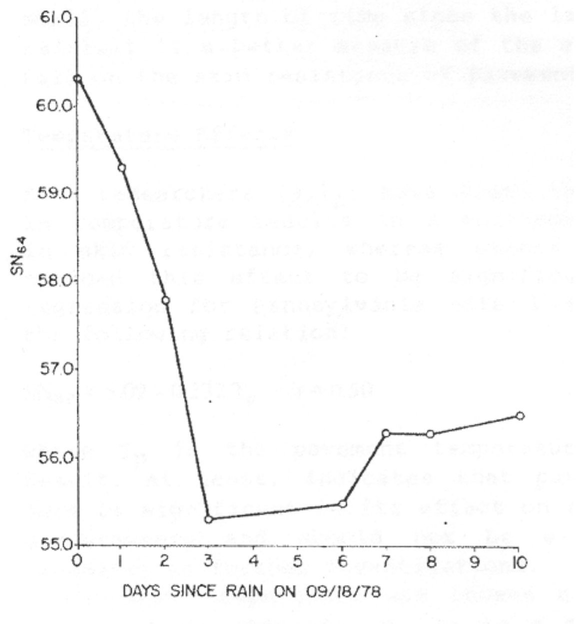
Figure 2.6 Influence of rainfall on skid resistance (Haydon 2005, reproduced from Hill and Henry 1981)



The effect of rainfall on measured skid resistance, in terms of reducing the coefficient of friction from dry conditions to wet conditions, has been discussed previously. However, there is a further combined effect of contaminants and periods of prolonged dry periods that also reduces measured wet skid resistance. Cenek et al (2003a, 2003b) described this effect, which occurs during periods of prolonged dry weather, where 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 and dust and other detritus. The contamination is usually washed off by regular rain. However, after prolonged dry periods, a shower or rainfall can create a very slippery road surface (often described as 'summer ice'). Vehicle drivers often say the road is most slippery when it first gets wet. If the rainfall continues some 'washing and cleaning' occurs, which increases surface friction.

This short-term influence of pollutants at the beginning of precipitation, causing lower measured wet skid resistance that then recovers to a 'cleaner' wet-surface friction, was also confirmed by Bennis and De Wit (2003). The short-term pollutants effect was measured by Hill and Henry (1981) as a reduction in measured wet skid resistance (as measured by the E274 Locked Wheel Tester) over a period of 10 days, and is shown in figure 2.7 for one site in Pennsylvania, US. Hill and Henry did not quantify the nature of the pollutants. Nevertheless, they reported similar relationships for a number of sites, and generally the decrease in measured skid resistance reached a maximum after approximately seven days of no rainfall. It was observed that this lower value of measured skid resistance then remained at that low level until the next significant rain.

Figure 2.7 Effects of pollutants and days since last rain on measured skid resistance (Hill and Henry 1981)



Hill and Henry (1981) assumed that the long-term variations in skid resistance (after an equilibrium polishing level is reached) are a function of pavement aggregate properties and traffic density, whereas the short-term residuals are a result of:

- rainfall effects
- temperature effects
- errors in the measurement of skid resistance by the testing equipment or vehicle.

Hill and Henry (ibid) reported on the work of Dahir et al (1979), who attempted to predict the measured skid resistance from rainfall records and suggested using the following weighted rain function (WRF) over the five days prior to a skid test as a measure of the effect of rain and pollutants on skid resistance:

$$WRF = \sum_{i=1}^{5}\left(\frac{R_i}{i}\right)$$

(Equation 2.1)

where: WRF = weighted rain function

R_i = rainfall in mm on the i^{th} day prior to the test

i = number of days prior to the test, ranging from 0 to 5 days.

In a study in Australia, Dickinson (1989) also 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 the rainfall. However, when using the WRF function with data collected from a number of Pennsylvania sites, Hill and Henry (1981) found that the correlation coefficients (r) were consistently low (0.08–0.13) and concluded that if a correlation exists between precipitation and skid resistance, a parameter other than WRF must be used. They subsequently proposed the following dry-spell factor (DSF) in place of the WRF function:

$$DSF = \ln(t_R + 1)$$

(Equation 2.2)

where: DSF = dry-spell factor

t_R = the number of days since the last rainfall of 2.5mm or more (up to a maximum of 7 days, hence $0<t_R<7$).

The DSF rainfall relationship was then tested on the same data that was used to test the WRF and significant improvements were obtained for the correlation coefficients (r) over the five sites, ranging from 0.16 to 0.56, with an average value of 0.38. Hill and Henry (1981) concluded that although (r) was still small, the length of time since the last significant rainfall (DSF) was a better measure of the effect of rainfall on the skid resistance of pavements when compared with a weighted rain function (WRF).

Cenek et al (1999) reported that although the occurrence of rainfall is generally accepted as the reason for short variations in skid resistance, the mechanism by which the variations were produced was not yet sufficiently well understood to permit reliable modelling. This view regarding rainfall as a contributory cause of short-term variations in skid resistance is not universally agreed in the research literature. Research undertaken by the Australian Road Research Board, reported by Oliver et al (1988), indicated that contamination of surfaces by vehicle oil droppings and tyre detritus could be eliminated as a cause of the variation observed in skid resistance.

2.5 Summary

A review of the literature indicated that environmental effects such as temperature and rainfall have a significant effect on the short-term variation of skid resistance and the longer-term seasonal fluctuations. Whilst the occurrence of rainfall is generally accepted as a 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 modeling.

Skid resistance functions related to rainfall were developed in the US (Hill and Henry 1981) for a specific climatic zone where the climate and general topography is significantly different from New Zealand. The relationships that were developed in the US were predominantly on asphalt mixes or Portland cement concrete surfaces, and not on the thin chipsealed surfaces that are predominant in New Zealand. The causal relationships that were developed are not well understood and therefore have not been incorporated into current road asset management practices. As yet, road asset managers have great difficulty in being able to manage currently specified standards of skid resistance with naturally sourced aggregates. This is especially so on roads with relatively high traffic volumes and especially high volumes of HCV, as well as on road sections with high demand for braking and cornering (eg Transit NZ T/10 (2002) site categories 1 or 2).

The effects of temperature variation and the length of time since rain, combined with the effect of the accumulation of surface contaminants on various aggregate types, is therefore not well understood at this point. Furthermore, current prediction methods of an aggregate's ability to resist polishing (primarily the PSV test) have been shown to not adequately predict the long-term skid resistance level that is obtained in the field (Cenek et al 2003b; Roe and Hartshorne 1998; Woodward et al 2004).

This research sought to quantify these effects on various surfaces in the Northland and Auckland regions. The following section will describe the methodology used for the field skid resistance measurements.

3 Experimental methodology

3.1 Introduction

The literature review in the previous chapter summarised research that has shown that in some climates an annual seasonal variation occurs after initial polishing of the aggregate surface has been completed. In other climatic zones this effect has been recorded as being less obvious. Furthermore, there have been observations of short-term effects on skid resistance measurements that relate to the amount of rain and/or time since the last significant rainfall and the contaminants on the road surface. The issues and variables are many and complex.

There is, however, an established and proven relationship between the level of skid resistance and loss-of-control crashes on the road network. The effect of not managing skid resistance on the road network to the appropriate level is significant in terms of loss of life and serious injury to road users. During the last 20–30 years, the implementation of better skid resistance standards has led to significant road safety benefits. These standards have raised road surface skid resistance levels by targeting polish-resistant aggregates on the areas of the road network that have a higher risk or demand for braking and cornering (an attempt to 'equalise risk'). However, the models and asset management procedures currently in use are not adequately predicting the variability of skid resistance as measured on real surfaces. Further research is needed to better understand and model the variability of skid resistance over time.

3.2 The hypothesis

This research sought to better understand the seasonal variation of skid resistance by regularly measuring the surface friction on various controlled sites in the Auckland/Northland regions over a period of 2.5 years and collecting data on the main variables thought to have an effect on skid resistance variation (eg rainfall prior to the test, temperature, and where possible, the amount of contaminants and type of deposited material).

To meet the objectives of this research project (described in section 1.3), the specific research aims were to quantify:

1. confidence limits of measured skid resistance variation, which includes 'seasonal' and 'short-term' variability of skid resistance on various road surfaces
2. variability between measurement devices (SCRIM, GripTester and the DF Tester) on various surfaces
3. concentration and particle size distribution of the types of contaminants that accumulate on the road surface, and how they vary with time and rainfall
4. effects of various washing treatments on the pavement surfacing, to determine whether the presence of detritus in itself reduces measured skid resistance
5. effects of wet and dry accelerated polishing on prepared laboratory specimens
6. effects of various contaminants on skid resistance due to accelerated polishing on prepared laboratory specimens.

The specific hypotheses that were tested for statistical significance were as follows:

1 That skid resistance fluctuates in a band about an 'equilibrium level', once initial aggregate polishing has been completed.

2 That the relative confidence limits of the band about the 'equilibrium level' are approximately 0.1SFC units or 0.15GN[2] units from upper to lower limits.

3 That the time period since the last rain has a significant effect on the short-term deterioration of measured skid resistance; ie that the slope of the short-term deterioration line is significantly different from zero and approximately 0.01SFC units (or equivalent GN) per day.

4 That the type and classification of the contaminants that accumulate on the road surface are significant in determining the magnitude of the short-term variation of measured skid resistance.

A better understanding of the relationship between measured skid resistance, contaminants on the road surface and rainfall will help RCAs to better refine skid resistance investigatory and threshold levels and to to develop their road management systems to better reflect the changing nature of skid resistance. This research is a key component in the development of a skid resistance decision-making system that is based upon crash risk, and essentially aids better management of the natural and physical resources available in New Zealand while at the same time providing a 'safe and efficient' roading network.

3.3 Research methodology

The field research methodology was designed and developed in two stages:

Stage 1 – Field tests: Regular skid resistance testing was carried out at a number of carefully chosen locations, using a continuous-friction measurement device with the aim of quantifying the extent of the skid resistance measurement and, where possible, controlling and/or collecting the dependent variable information at each site location.

Stage 2 – Laboratory-based polishing tests: Chipseal surfaces were constructed and underwent accelerated polishing of the surfaces, with periodical measurement of the coefficient of friction to determine the effects of the variation in measured skid resistance due to aggregate polishing to an 'equilibrium level'. Subsequently, the effects of the addition of contaminants and polishing under controlled laboratory conditions were quantified.

3.4 Testing methods and models

As shown earlier in table 2.1, there are many factors affecting the measured surface friction of a road surfacing.

The factors that are related to a vehicle that is being used by a road user, or to a vehicle for the purposes of measuring the surface friction of a surfacing, are the same and can be summarised under the following categories:

- vehicle speed

2 GripNumber (GN) is the coefficient of friction as measured by the GripTester.

- the tyre angle to the direction of the moving vehicle
- the wheel-slip ratio
- tyre characteristics
- tyre contact area and stress.

A number of skid-testing equipment/methods available for skid resistance measurement have been developed by different countries over the last 50 or more years. However, all of the commercially available test equipment developed essentially uses the same principle, ie to measure the resistance of a rubber slider or tyre being forced to slide across a wetted road surface, under an applied load (Austroads 2005). The horizontal friction, traction or force resisting the sliding of the tyre or slider is measured, and the vertical load is either measured or assumed to be constant.

The frictional force measured depends upon the load that is applied, and therefore the coefficient of surface friction (f or μ) is the ratio of the frictional force resisting motion divided by the applied vertical load.

The range of wet skid resistance measuring techniques available are categorised into either:

- in-situ road-surface-based devices
- laboratory-based predictive devices.

The in-situ road surface (on-site) devices can be further divided into two basic categories: those that are capable of measuring continuously over a long stretch of pavement surfacing (continuous friction measurement equipment, CFME devices); and those that measure skid resistance at specific sites (static devices). The continuous techniques can also be categorised as either 'angled test wheel methods' or the 'braked wheel' method. The braked wheel method can be further subdivided into locked wheel, variable slip and fixed slip methods. The most common static devices can either be used at a specific point on a road surface or in the laboratory. These techniques all measure friction, although with different weightings on the variables that surface friction depends upon. Figure 3.1 shows a classification of the different skid resistance measurement methods and subsequent examples of commonly used measurement devices that all use some form of contact between rubber and the road surface.

Due to their significant differences, a direct comparison between the different device results is not generally possible. Measured friction is dependent upon variable parameters such as slip ratio, testing speed, vertical load, tyre-rubber composition, tyre tread and inflation pressure, and the amount of surface water present. Some of the systems detect the peak friction and some vary the slip in an attempt to operate around the peak friction level. Henry (2000) stated that each method of measuring friction has advantages. The direct use of the values produced by one type of measurement relates to a different testing scenario. The locked wheel method simulates emergency braking without anti-lock (ABS) brakes; the sideway force method measures the ability to maintain control in curves; and the fixed slip and variable slip methods relate to braking with anti-lock brakes. The variation of friction with slip speed is shown in figure 3.2.

Figure 3.1 Classification of skid resistance measuring contact methods, with common examples

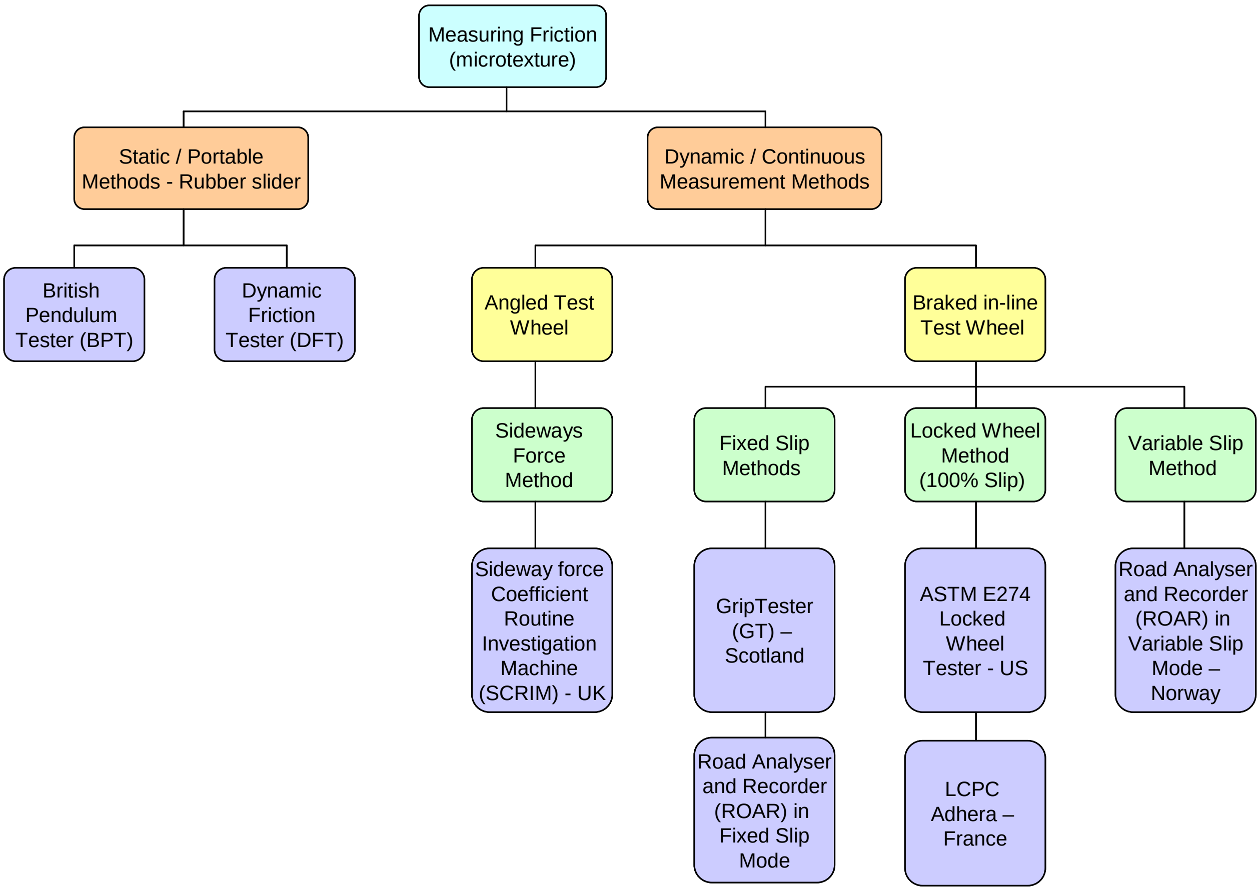
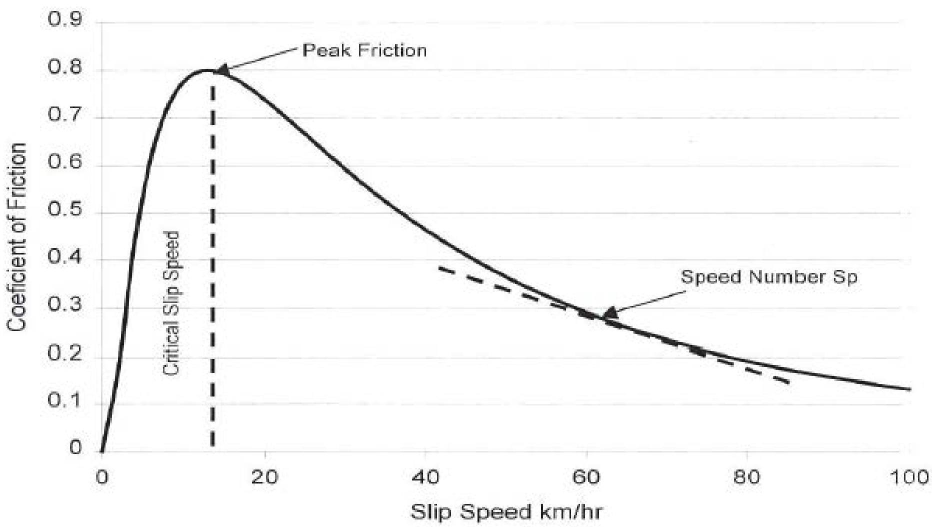


Figure 3.2 Relationship of slip speed to friction on a road surface (Austroads 2005)



The PIARC World Road Association International Harmonisation study (Wambold et al 1995) tested 51 various skid-testing and texture devices (37 friction measurement and 14 texture measurement devices).

Commonly known devices used in New Zealand and Australia to measure surface friction that can be correlated to microtexture measurements are SCRIM, GripTester, ROAR, DF Tester and the BPT. Continuous macrotexture measurements are now predominantly undertaken by laser texture measurements usually described as the mean profile depth (MPD); alternatively, the volumetric sand patch test method can be used to determine macrotexture at a specific location. These devices, the methods and the harmonisation models are well described in various literature including Wilson (2006), and will therefore not be discussed in detail in this report. However, as the testing devices vary considerably by the factors listed above, combined with the variation in environmental factors that affect skid resistance (such as rainfall history, contaminants and seasonal factors), the harmonisation attempts have yet to produce correlation equations that are reliable from one device to another.

This research project primarily used the GripTester for regular surface friction measurements in the field and the DF Tester for field correlation exercises and for laboratory surface friction testing. Annual SCRIM+ survey data was available for both microtexture and macrotexture (MPD) measurements and on the Transit NZ seasonal site, data was available for most years, three times in the summer season. Macrotexture measurements (MPD) are more repeatable with time (as compared with microtexture measurements), as long as the seal surface is stable and chip loss or bitumen flushing is not occurring. Therefore, the annual SCRIM+ MPD measurements were primarily used for this research, although some spot measurements were measured using the volumetric sand patch test method. The GripTester, DF Tester and the SCRIM devices are described in more detail in appendix A.

3.5 Field test site characteristics

Particular attention was given to the selection of test sites. A field testing site matrix was designed to incorporate a range of the most significant surface friction variables that are common in Auckland and Northland conditions and that were thought would show variation in skid resistance measurements with time. The number of test sites and the frequency of testing for the data collection programme were designed, with statistical significance in mind. However, because of the significant practical constraints of the research programme, the desirable number of tests needed to be limited to a feasible level. Factors involved in the decision making for the test sites were as follows:

- Skid resistance testing in a 'live traffic' environment requires the appropriate management of a significant number of non-technical skid resistance considerations, especially Health and Safety requirements for temporary traffic control.
- High-capacity highways (ie most state highways close to the Auckland CBD) require a pilot vehicle in front of the skid resistance testing device, due to their high traffic volumes, and therefore were not considered as feasible seasonal monitoring sites.
- The sites chosen for regular testing needed to be reasonably close to the University of Auckland (UoA) City campus and available for regular skid-testing measurement.

The field testing site matrix required careful planning to ensure safe testing procedures whilst still including sites with a range of the following road classifications, surface and loading characteristics (refer to table 3.1):

- road classification and function (private road, heavy industrial and state highway)
- surface types (chipseal and asphaltic mix)

- aggregate geological type (sedimentary, igneous and artificial)
- traffic volumes and traffic loads (light to high traffic volumes and the rate of equivalent standard axle loads per day)
- polishing action (predominant direction of traffic loading, longitudinal, transverse and radial)
- operating speeds (30km/h to 100km/h posted speed limits).

Table 3.1 Field-testing sites – location and general details

Site no.	Site name	Road class	Surface type	Geological group & properties	Traffic vols	Predominant polishing action	HCV %	Operating speed (km/h)
1	UoA Tamaki Campus loop road	Urban private	Asphalt mix	Igneous basalt	Light	Longitudinal	NA	20
2	Ports of Auckland (POAL)	Container-loading area	Asphalt mix	Igneous basalt	Heavy	Transverse	Container forklifts/ straddlers	30
3	Kaiwaka Northland	SH[a]1	Chipseal	Artificial	8650	Longitudinal and radial	9.6%	100
4	Brynderwyn Northland	SH1	Chipseal	Sedimentary greywacke	8650	Longitudinal and radial	9.6%	80–100
5	Hikurangi Northland	SH1	Chipseal	Sedimentary greywacke	9700	Longitudinal	9.7%	100
6	Kara Road Northland	SH14	Chipseal	Sedimentary greywacke	5500	Longitudinal and radial	5.5%	90–100
7	Snooks–Tatton Northland	SH14	Chipseal	Sedimentary greywacke	5500	Longitudinal and radial	5.5%	90–100

a) State Highway

The field testing site matrix shown in table 3.1 was then further categorised and sectioned by road geometry, section length, surface treatment, the age and source of the aggregate and its resistance to polishing including (refer to table 3.2):

- horizontal and vertical geometry (straight and curved, flat and sloped)
- a range of surface treatments and age (from newly surfaced to a polished ‘equilibrium state’ and various types of surface treatments that had no planned periodic maintenance treatments for the duration of the data collection period)
- macrotexture levels (ranging from low to high)
- microtexture levels – the aggregate source and susceptibility to polishing as measured by the PSV (reasonably low to reasonably high).

Further requirements of the test sites were that:

- *section lengths* should be at least 150m long

- sections should be *homogeneous* in terms of texture, with no major defects such as cracks, flushing and potholes
- they should allow for *safe and easy turn-around* near both ends, to enable repeated skid-testing measurement runs over the same section
- *an open, safe area* was available in the vicinity of the site for the assembly of the test equipment, and where possible, access to water supply and storage of a trailer with associated equipment whilst testing
- they would allow for measurements to be carried out in *conditions of maximum safety* – ie have either low traffic volumes, or traffic control and good sight distance visibility along the test sections.

The research programme had other considerations that required managing, including the following:

- *Availability of testing equipment* to undertake the research: As this was a 'new' area of research for the university department, little equipment existed at the outset of the research. All equipment that was needed for the research required successful research funding applications to be prepared and approved, then ordered, shipped and/or designed and fabricated prior to proceeding with the data collection programme. Some internal funding for equipment required supplementing from external industry partners to enable the purchase of the new equipment.
- *Training*: Once the equipment arrived, initial training, calibration and familiarity with the testing equipment and procedures was required prior to the programmed research.
- *Temporary traffic control*: Stationary tests required a reliance on industry partners for temporary traffic control and lane closures (due to the New Zealand Department of Labour and Transit NZ Health and Safety legislation requirements for working in a 'live traffic' environment.
- *Support technical staff* for skid testing: A minimum of two people were required for field tests.
- *Weather conditions*: Field testing could not be undertaken in adverse weather conditions where rain water was physically flowing or ponding on the surface, or where the macrotexture was full of water, thereby changing the tyre–surface contact area and pressure of the measuring wheel.

Table 3.2 Field-testing sites – surface material characteristics, properties and loads

Site no.	Site name	Geometry & topography	Section length	Curve radii	TNZ T/10 site cat.	Surface treatment	Seal date	Macro-texture TD (mm)	Aggregate source	Approx PSV
1a	UoA Tamaki Flat	Straight, level	200m	NA	NA	AM Mix 10	2002	0.5	FH Reliable Way Quarry	Approx 58
1b	UoA Tamaki Sloped	Straight, 7.2%	200m	NA	NA	AM Mix 10	2002	0.5	FH Reliable Way Quarry	Approx 58
2	POAL	Straight, level	750m	NA	NA	AM Mix 20	1996	0.40	Lunn Ave Quarry	Approx 55
3	Kaiwaka Northland	Curved, rolling	550m	200m	2	Chipseal 2 Coat 3/5	7/05/ 2003	1.7	Melter slag Glenbrook Steel Mill	58
4a	Brynderwyn 2003 Northland	Curved, rolling	170m	160m	2	Chipseal 2 Coat G4	24/03 /2003	2.5	Bellingham Larmers Rd Quarry	58

Site no.	Site name	Geometry & topography	Section length	Curve radii	TNZ T/10 site cat.	Surface treatment	Seal date	Macro-texture TD (mm)	Aggregate source	Approx PSV
4b	Brynderwyn 2004 Northland	Curved, rolling	170m	160m	2	Chipseal Racked in G2/4	16/03 /2004	2.5	Otaika Quarry	51/52
5	Hikurangi Northland	Straight, level	600m	NA	4	Chipseal Single Coat G2	20/04 /1999	2.3	Otaika Quarry	51/52
6	Kara Road Northland	Curved, rolling	660m	150m 160m	2	Chipseal Racked in G3/5	28/01 /2003	2.3	Otaika Quarry	51/52
7a	Snooks-Tatton Section 1	Curved, level	1740m	140m	2	Chipseal 2 Coat G 3/5	28/01 /2003	2.3	Otaika Quarry	51/52
7b	Snooks-Tatton Section 2	Straight level	1740m	NA	4	Chipseal 2 Coat G 3/5	24/02 /2000	1.9	Otaika Quarry	51/52
7c	Snooks-Tatton Section 3	Curved, level	1740m	160m	2	Chipseal 2 Coat G 3/5	28/01 /2003	2.0	Otaika Quarry	51/52

3.6 Field test frequency

To accurately measure and thereby predict the full range of short-term variations in skid resistance would require almost daily readings of skid resistance measurements. A research programme designed for skid-testing measurement at *daily* intervals, for a number of different physical location and sites, and for a duration of a minimum of two years for yearly seasonal variation, was seen to be both practically unfeasible as well as unrealistic, due to the high costs in terms of resources (human, capital, equipment and time). A pragmatic approach was therefore adopted to collect minimum *monthly* field results (and more often when possible) at the selected sites. It was expected that this approach would, over an almost three-year data collection period, obtain results that were close to the minimum and maximum levels measured, but would miss much of the short-term daily variation. However, the relationship of the short-term variations in measured skid resistance with variables such as temperature, contaminant levels and rainfall could reasonably be investigated with daily records of rainfall patterns.

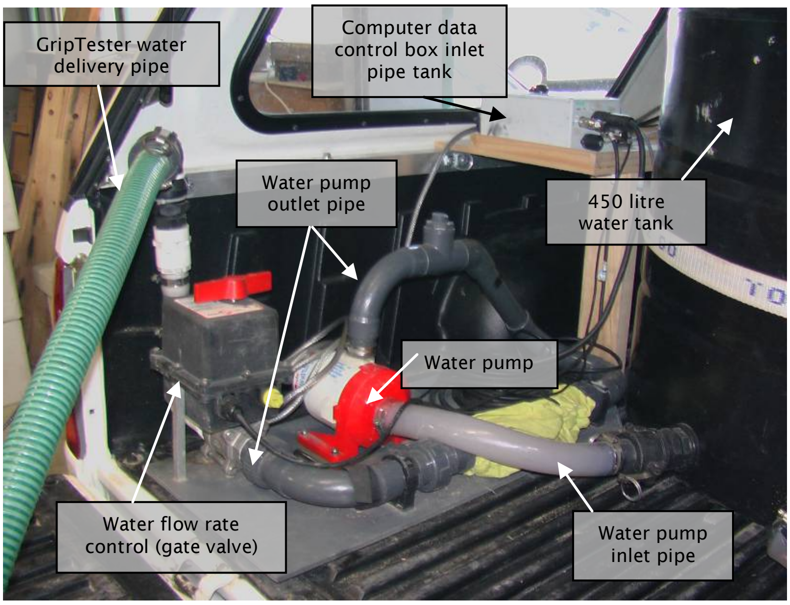
3.7 Field test equipment and standard surface friction tests

3.7.1 Continuous skid resistance (microtexture) measurements

Continuous friction measurement testing was undertaken using a Type-D GripTester. The GripTester is a 15% fixed slippage braked in-line wheel tester (refer to appendix A.2). The GripTester is towed behind a test vehicle (see figure 3.3) that houses a water bag/container and associated automatic pump control equipment (see figure 3.4). The pump delivers a computer-set water depth (usually 0.25mm) beneath the measuring tyre by varying the water pump delivery rate according to the vehicle speed.

Figure 3.3 University of Auckland GripTester and 4WD tow vehicle

Figure 3.4 GripTester automatic watering system and water storage tank in back of testing vehicle



3.7.2 Standard skid resistance field test procedures

Each test site was tested in both directions, classified as 'Increasing' or 'decreasing' directions based on the Transit NZ linear route position (RP) referencing system or by direction (north, east, south, west) for private internal pavement-testing sites. The extents of the test sections were marked on the pavement and these points were recorded with markers by the computer operator and recorded in the GripTester computer software at the commencement of each test run. Clear change points, such as a change of seal, were also marked during surveys, which allowed confidence in the locational referencing from one test date to another and for the multiple test runs. The following outlines the standard GripTester test parameters used for monitoring of the test sections:

- **Target test speed:** A standard test speed of 50km/h was used for all sites except for the Tamaki site, where it was not possible to travel at this speed, and a test speed of 30km/h was therefore utilised. A 50km/h test speed is the same target speed as adopted for the Transit NZ national skid-resistance surveys using the SCRIM device. Variable speeds were also undertaken on some sites to investigate the relationship of speed, texture and skid resistance.
- **Water film depth:** A standard 0.25mm depth of water under the measuring tyre was set for GripTester surveys. This corresponded to a pump rate of approximately 10.5 litres per minute at a test speed of 50km/h.
- **Wheel path tested:** The left-hand wheel path (LWP) was tested for all standard test sites (however, a defined longitudinal wheel track was not applicable at the Ports of Auckland site, as most traffic was transverse in direction at this site). The New Zealand SCRIM survey vehicle tests both the left and the right wheel paths in one survey. The results from historical SCRIM surveys generally show the left-hand wheel path to have lower skid resistance than the right-hand wheel path. Areas of deficiency have often been identified by the annual SCRIM device surveys, where the left-hand wheel path is well below the Transit NZ T/10 Investigatory Level (2002), whilst the right-hand wheel path remains compliant.
- **Number of test passes per lane:** Five test runs per test site were undertaken. The methodology of multiple runs over each site was adopted in order to evaluate the run-to-run variability and repeatability of the GripTester. Furthermore, the adopted scheme allowed consideration of whether multiple runs physically changed the skid resistance in terms of any surface contaminants being washed off the surface, or whether any further aggregate polishing was taking place. Henry (1996) identified in the PIARC harmonisation study in 1992 that repeated runs on a surface were a potential source of difference between testing vehicles, as it was feared that repeat tests may polish the aggregate surface.

3.7.3 Stationary skid resistance tests

On testing sites where traffic was either very light (eg the Tamaki site) and not on public roads (the Ports of Auckland site), or where temporary traffic control and a lane closure was possible, stationary skid resistance tests were also obtained periodically at defined points using the DF Tester (refer to appendix A.3).

The DF Tester is a stationary skid resistance device that measures the frictional resistance of three rubber sliders mounted on a 284mm diameter spinning disk. The disk is usually spun up to a normal testing speed of 80km/h and then lowered onto the test surface, and the frictional resistance is progressively determined from the torque forces generated during the spindown of the disk. Initial tests showed that on high-textured surfaces, the initial test speed needed to be reduced to 60km/h, otherwise the DF Tester could catch on large aggregate chips and dynamically move during a test.

The DF Tester has been found to be very stable with time and gives highly reproducible measurements. Accordingly, it has been chosen as the standard reference in the recently revised IFI[3] ASTM International Standard for static devices (ASTM E1911-98 2002), thereby superceding historical reliance on the BPT as a static device. In this research, the DF Tester allowed seasonal and short-term variations to be considered at a specific repeatable point and a correlation between the GripTester and the DF Tester to be developed. A further advantage of the DF Tester is that it can also be used in the laboratory. A disadvantage of the DF Tester for in-field testing is that it does not test skid resistance in the line of traffic movement, due to its circular motion and the diameter of the spinning disk, and it may therefore 'average' out some of the variation that occurs in defined longitudinal wheel paths. Other continuous-friction measurement devices, such as the GripTester, ROAR and the SCRIM, have shown differences in measurement across different lines of the traffic lane (Cenek et al 1996), and the SCRIM device has shown differences in skid-testing measurement when the same wheel path was tested in the opposing direction (Hosking and Woodford 1976). This disadvantage is relevant when comparing the DF Tester results with other in-line longitudinal systems (eg GripTester, ROAR and SCRIM), but is not significant when the device is being used as a comparative device at a specific location.

3.7.4 Macrotexture measurements

Skid resistance measurement depends upon both microtexture and macrotexture texture profiles. However, if the surface has been appropriately constructed, macrotexture levels should not markedly change over time or due to seasons of the year. If the surface binder and aggregate chips have been appropriately applied, then the macrotexture levels should gradually and linearly decrease over time as the aggregate surface slowly abrades away (attrition). If there is a significant and unexpected decrease in macrotexture over a reasonably short time period (within a year and usually in the summer period), then it is most likely that the binder is 'flushing' (where excess binder rises over the chip and reduces macrotexture). 'Bleeding' (which occurs in hot weather when the binder is soft and can adhere to vehicle tyres and be tracked downstream) does not significantly reduce macrotexture but can temporarily affect microtexture both at the location and downstream. This effect is due to the soft, more viscous bitumen film being picked up by vehicle tyres and coating the asperities of the stone, thereby reducing measured skid resistance.

Macrotexture levels can change reasonably quickly (both up and down) due to loss of aggregate chip through one of the following processes (Transit NZ and Roading NZ 2005):

- stripping, which occurs generally along wheel paths, in long strips
- attrition, in which chips are worn away by friction
- scabbing, which is chip loss from patches of chipseal.

If the chip loss occurs soon after construction, it is usually related to construction deficiencies and could be due to a number of factors, including:

- low binder application rate or binder-spreading temperature
- inappropriately hard binder penetration grade

3 International Friction Index.

- lack of appropriate volume of temporary 'cutback' diluent (eg kerosene) or semi-permanent 'flux' diluent (eg Automotive Gas Oil – AGO) and/or adhesion agent that has been applied during construction
- lack of adhesion between the aggregate stone and the binder, due to the seal application being undertaken during adverse weather conditions or soon after, or a lack of chemical bonding, eg due to the presence of detritus/dust on the aggregate
- excessive traffic speeds during or soon after construction.

If the stripping occurs later in the seal life, this is more likely to be due to oxidation of the binder (embrittlement), where the binder loses its elasticity due to repeated tension/compression wheel load cycles, causing the aggregate to break away from the binder.

In summary, if seals are constructed and designed appropriately, macrotexture levels are more stable, consistent and predictable over time than microtexture levels. The field sites for this research were carefully chosen to investigate *microtexture* changes over time, and therefore the sites' macrotexture levels should not have changed markedly during the data collection period. Hence, the frequency of testing macrotexture at each of the test sites did not need to be as regular as the microtexture measurements.

Measurements of macrotexture at the sites were undertaken approximately annually to ensure the surface macrotexture was not affecting differences in the measured coefficient of surface friction. Macrotexture measurements were conducted on various occasions at defined points, using either the volumetric sand patch method to determine mean texture depth (MTD) as specified in Transit NZ T/3 Specification (1981), or by laser profilometer MPD method. The state highway test sites were tested with the MPD laser profilometer method as measured by the Transit NZ high-speed SCRIM data collection programme.

3.8 Field test sites for surface friction testing

3.8.1 Introduction

A description of each of the seven chosen test sections follows. The test locations were split into two main locations:

- **Auckland sites** (refer to figure 3.5): Two urban test sites were chosen within Auckland City. The first site had predominantly light personal-vehicle traffic, as the road was an internal private road to the University of Auckland Tamaki campus. The other site was a Ports of Auckland container-loading site that had very heavy and mostly transverse traffic movements by ship container straddlers and forklifts. Automatic rainfall gauge stations on site at the Tamaki campus, and near the Ports of Auckland (POAL) site, provided rainfall data for analysis.
- **Northland sites** (refer to figure 3.6): Five test sites were chosen on state highways, with more typical and standard traffic conditions on chipseal surfaces with varied aggregates, geometrics, polishing conditions and geographical areas. Manual rain gauges were installed on each of the five sites and these were read by Works Infrastructure[4] staff in Northland as often as possible, usually daily. The

4 Works Infrastructure has since become Downer NZ Ltd.

manual rainfall gauge station data was also correlated against the closest NIWA[5] automatic rainfall gauge stations in order to have continual daily rainfall recordings at each of the locations of the Northland sites. The NIWA rainfall gauge station locations and their proximity to the test sites are shown in figure 3.6.

Figure 3.5 Auckland field test location sites (NZMS 262 map series)

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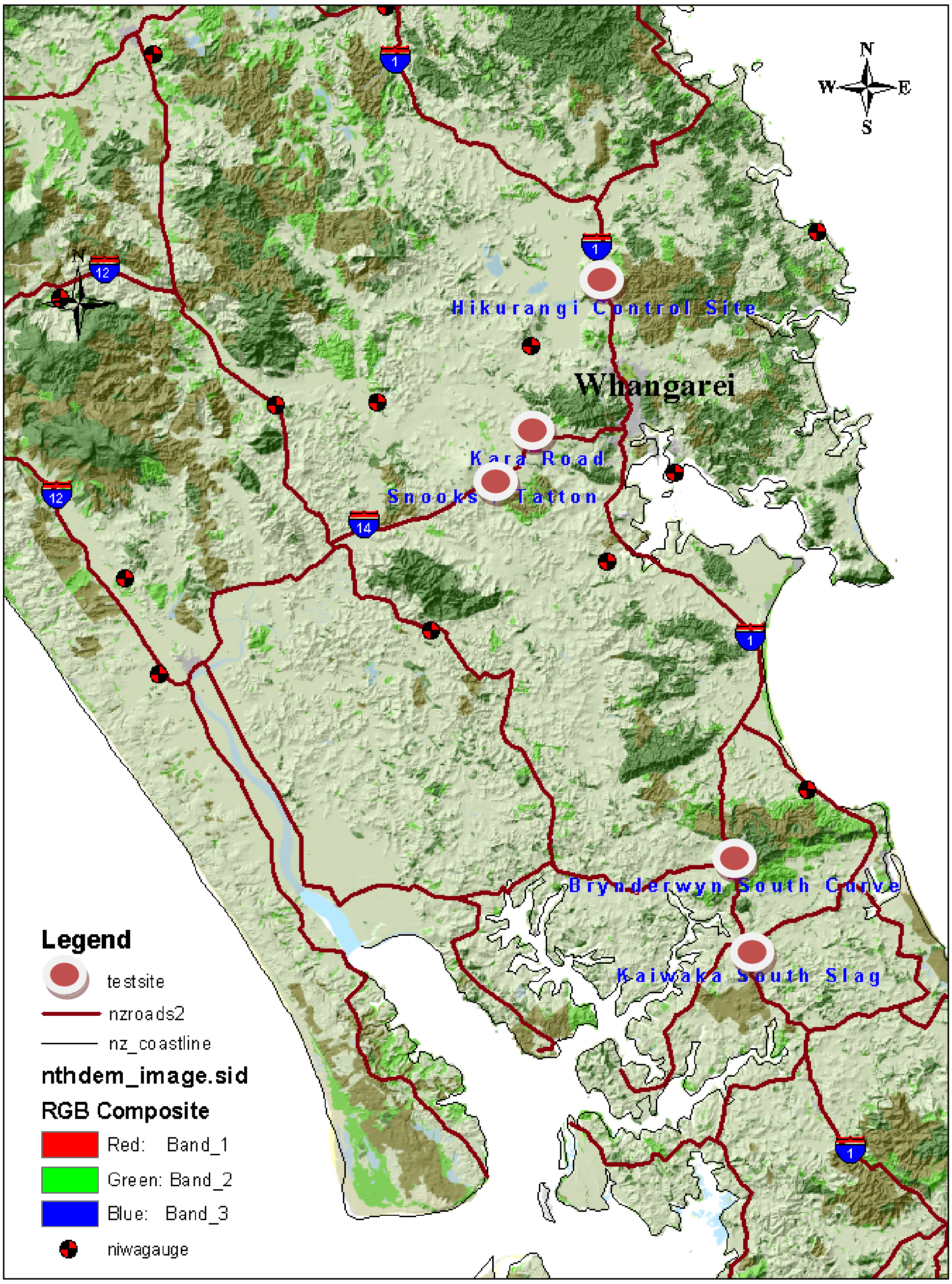
5 National Institute of Water and Atmosphere.

Figure 3.6 Northland field test location sites (ARC GIS)



3.8.2 Timeslice analysis technique

Although it was outside of the brief of the contracted research, a 'timeslice' technique was developed in order to analyse the performance of specific locations on the field test sites and their polishing mechanisms, as opposed to the overall section averages. The timeslice technique was developed as a pragmatic compromise between the inaccuracies of the linear referencing and transverse location of the GripTester measurement wheel for a single 10m average section and the total section length average that would develop variances based upon localised differences in the polishing mechanisms. As such, a timeslice is defined as the average of a 30m section calculated by the mean of the three 10m average sections reported in this case by the GripTester, one 10m average either side of the timeslice location, and including the reported location distance. For example, a timeslice at location 690m on the Kaiwaka slag site in the increasing direction (refer to figure 3.9) would report the average10m GripTester coefficient of friction (GN) for the 10m averaged results of 680m, 690m and 700m.

The choice of specific locations for the timeslices was based on the type of downstream comparative analysis that was required. Some examples of the types of geometrical element comparative analysis that the timeslice technique made possible were:

- new seal performance in comparison with adjacent older seal lengths
- horizontal curves in comparison with straight road sections
- turning intersection areas in comparison with straight non-turning traffic areas
- down-gradient sections in comparison with level-gradient sections.

The locations of the timeslices and the results of the skid resistance measurements at the position of the timeslices are recorded in subsequent sections of this report, for completeness of data collection. As this research fell outside of the brief of this research project, the analysis and discussion of the timeslices are not given; however this analysis can be found in Wilson (2006).

3.8.3 Tamaki Campus (University of Auckland) site

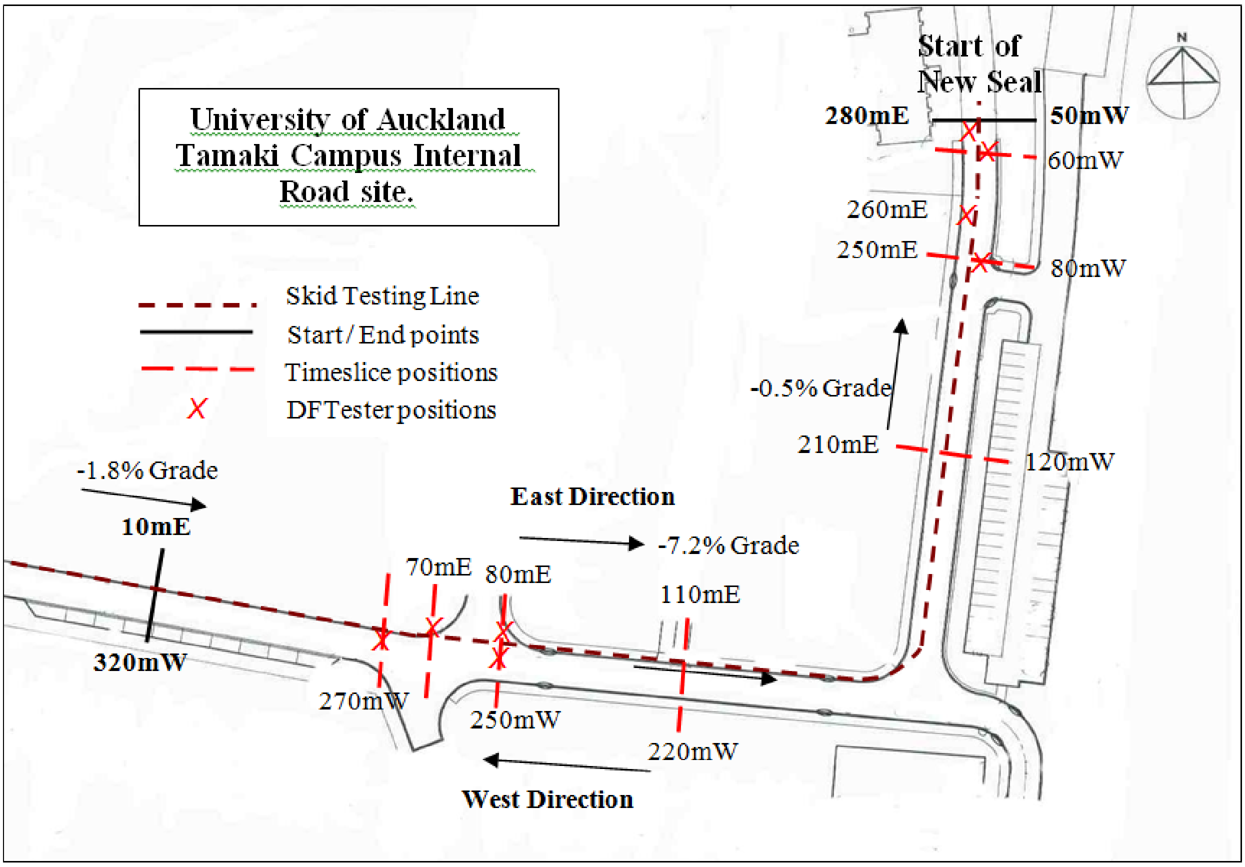
The University of Auckland Tamaki Campus test site was located on an internal 15km/h speed limit campus road. Speeds were restricted on this site due to the presence of pedestrians and other University campus and road users. However, no stopping or parking was allowed on the test section and therefore the testing was generally not affected by other users.

The road pavement and surface had been newly laid in early 2002 and comprised a 25mm thick TNZ Mix 10 asphalt mix. The aggregate was sourced from the Fulton Hogan Reliable Way Quarry and was reported as having a PSV of 58.

The test section was split into two sections approximately 150m each in length, one on level ground, the other on a grade of 7.2%. The extents of the test sections were painted on the road surface and traffic cones were placed at points of differences for the placement of software markers whilst undertaking a skid test (refer to figure 3.7).

Regular (approximately monthly) skid testing with the GripTester began on this site in July 2002.

Figure 3.7 Tamaki Campus (University of Auckland) test site



3.8.4 Ports of Auckland site

The Ports of Auckland site was located adjacent to a railway loading area at the Fergusson Container Terminal, Ports of Auckland (known to Ports of Auckland staff as 'the Rail Grid'). The testing strip was a 475m long, straight and level section of asphaltic concrete (refer to figure 3.8), with a pavement depth of 1.3m and a top surface layer of 50mm deep TNZ Mix 20.

The test site was clear of all other traffic and pedestrians during testing. This enabled a wide range of speeds to be used and static tests to be undertaken without risk or inconvenience to other road users. Skid testing at this site was restricted, due to Ports of Auckland Health and Safety regulations, to periods outside of normal Port working hours.

Testing was normally conducted from 4-6:30pm after the rail grid container loading was completed for the day, or on a Sunday. Regular (approximately monthly) skid testing with the GripTester began on this site in September 2002. Due to the time of the testing and on occasions during winter months, considerable temperature variation occurred at this site between the first and last skid resistance survey runs.

Figure 3.8 Ports of Auckland Rail Grid site (Auckland City Council aerial photo maps)

Note: The red crosses denote where stationary DFTester tests were undertaken and the red dotted line was the GripTester run line.

3.8.5 Kaiwaka site (SH1N)

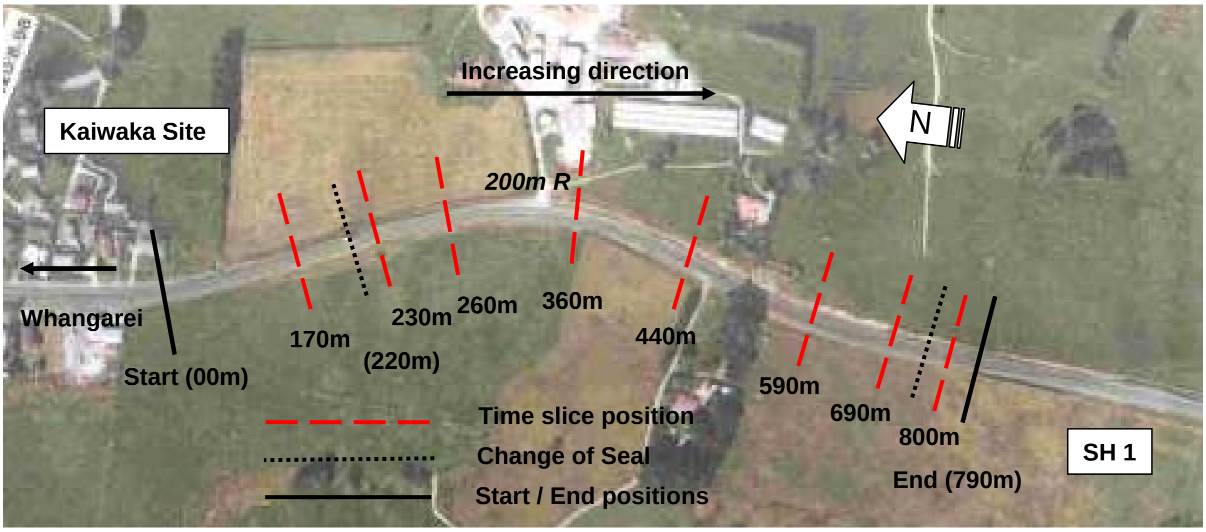
The Kaiwaka test site was a 790m section on State Highway (SH)1, some 62km south of the intersection of SH1 and SH14 in Whangarei and immediately south of Kaiwaka township (refer to figure 3.9). The horizontal geometry consisted of a series of three back-to-back reverse curves with curve radii of approximately 200m, and the vertical geometry was undulating.

The test section operated under a 100km/h open road speed limit and the average annual daily traffic (AADT) volume was approximately 8650vpd, with 9.6% HCVs. The site was characterised under Transit NZ T/10 specification (2002) as Site Category 2, as the horizontal curve radii were less than 250m.

The site had been resurfaced in April 2003, as a result of the December 2002 SCRIM survey identifying the site as being deficient due to the measured MSSC being lower than the investigatory level (IL) of 0.50, with some sections lower than the Threshold Level of 0.40. The previous seal consisted of a grade 5 voidfill with an aggregate PSV of 55. The low macrotexture that corresponded with a grade 5 void fill (approximately 0.5mm) was also demonstrated in the December 2002 SCRIM texture results and was less than the desirable minimum of 0.7mm texture for high-speed highway sections.

The site was first skid tested with the GripTester on 21 March 2003, prior to a new two-coat grade 3/5 reseal with an artificial melter slag aggregate (sourced from SteelServ, with a Transit NZ-published PSV of 58 (2004)) being placed on 7 May 2003. Regular (approximately monthly) GripTester skid measurements were undertaken at this site from March 2003 until June 2005.

Figure 3.9 Kaiwaka slag site (SH1 – Northland, RP 220/9.27–220/9.87)



3.8.6 Brynderwyn site (SH1N)

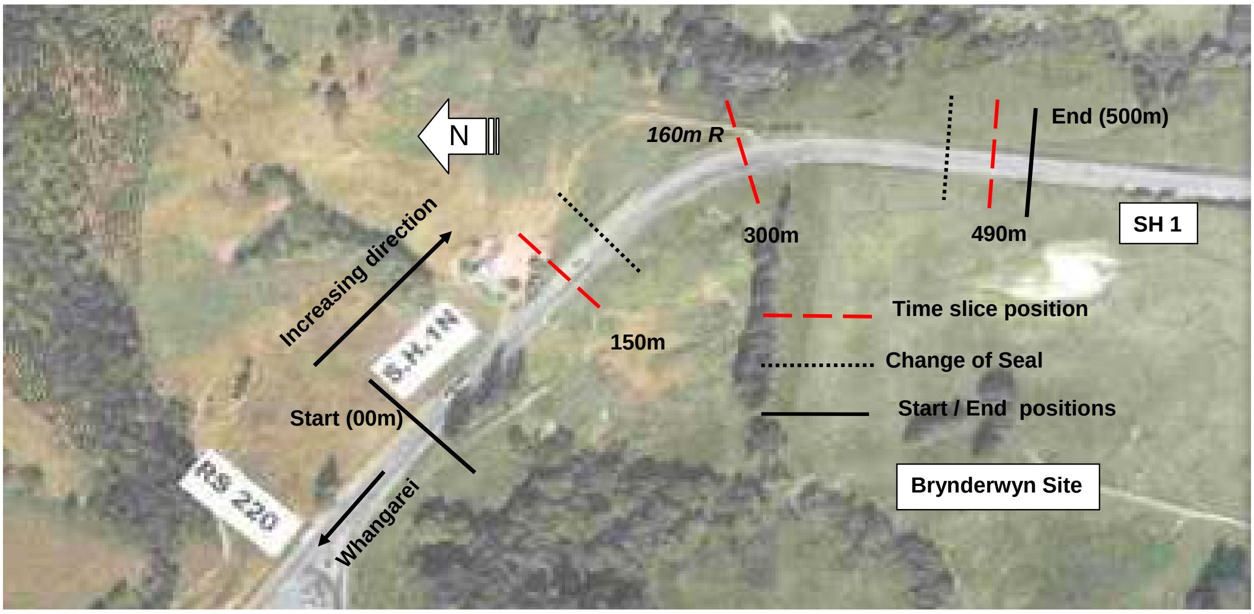
The Brynderwyn test site was a 490m section on SH1 some 53km, south of the intersection of SH1 and SH14 in Whangarei and immediately south of the intersection of SH1 and SH12 (refer to figure 3.10). It was located approximately 9km north of the Kaiwaka site.

In the northbound direction, this section was the first curve that led into a lower-speed environment and a hilly-to-mountainous climbing section of highway. This short curve operated under a 100km/h open road speed limit and the AADT was approximately 8650vpd, with 9.6% HCVs. The 85th percentile operating speed prior to this curve was assessed as being approximately 90–100km/h, the curve leading into an extended section of constrained horizontal and vertical geometry with an estimated 85th percentile speed of approximately 70km/h. The horizontal geometry in the northbound direction consisted of a sharp left-hand horizontal curve of 160m, and the vertical geometry was slightly rising. The site was classified under Transit NZ T/10 (2002) specification as Site Category 2, because the horizontal curve radius was less than 250m.

The site had a consistently poor crash history, primarily due to its less-than-desirable horizontal geometrics. Multiple layers of chipseal surfaces had been applied in an attempt to maintain high friction values, although the positive effects of a new resurfacing were shown to quickly decline, due to microtexture polishing.

The site was shown to be consistently deficient in terms of SCRIM surveys undertaken on the Northland PSMC[6] 002, and consequently the surface had been resealed twice since the beginning of the PSMC 002 contract. The previous chipseal surface had been constructed with a PSV aggregate of 58 in April 2002, and yet the site had failed the SCRIM survey some six months later. Both Transit NZ and Works Infrastructure realised that due to the relatively high approach speeds from the southern direction, the long-term solution to this site would be to reduce the demand for friction and increase the factor of safety by realignment and increasing the horizontal curve radii. This capital works improvement, which included horizontal geometric realignment to radii more appropriate to the speed environment and approach speeds from the south, has since been completed.

Figure 3.10 Brynderwyn South curve (SH1 – Northland RP 220/0.36–220/0.532)



The site was first skid tested with the GripTester on 21 March 2003, prior to a new two-coat grade 4/6 reseal, with a Bellingham aggregate having a published PSV of 56 being placed in April 2003. The results of the regular skid testing also showed that the aggregate polished very quickly, albeit combined with some bitumen flushing and loss of macrotexture to the point of becoming deficient again by the next

6 Performance-specified maintenance contract.

summer period. Works Infrastructure staff once again resurfaced this site in 2004 with a racked-in grade 2/4 reseal, with a locally sourced Otaika sedimentary aggregate that had a published PSV of 51/52 (2004).

Regular (approximately monthly) GripTester skid measurements were undertaken at this site from March 2003 until June 2005.

3.8.7 Hikurangi site (SH1N)

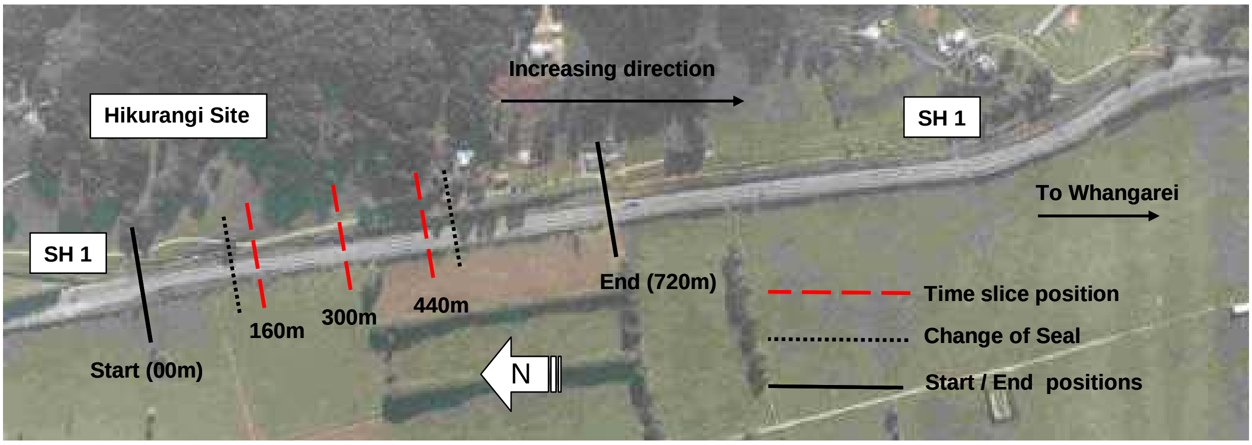
The Hikurangi test site was a 720m section on SH1 located 14.5km north of the intersection of SH1 and SH14 in Whangarei and immediately south of the Hikurangi township (refer to figure 3.11). The Hikurangi site was chosen as a control testing site because:

- the horizontal geometrics were straight and level
- the seal age was more than five years old (last reseal 20 April 1999, with a grade 2 chip from Otaika quarry and a reported PSV of 51/52)
- the macrotexture levels were stable and no flushing or other surface defects were evident.

This site was also a SCRIM seasonal site where no periodic maintenance was planned in the short-to-medium term, and where no other skid resistance variation would be expected other than seasonal environmental variations. Previous SCRIM surveys had shown a reasonably consistent level of SFC and therefore the surface aggregate could be considered as being in an 'equilibrium level' of polish.

The test section operated under a 100km/h open road speed limit and the AADT volume in 2004 was approximately 9700vpd, with 9.7% HCVs. Regular (approximately monthly) GripTester skid measurements were undertaken at this site from March 2003 until June 2005.

Figure 3.11 Hikurangi site (SH1 – Northland RP 144/6.215–144/6.766)



3.8.8 Kara Road site (SH14)

The Kara Road site was located on SH14, approximately 8.5km west of the intersection of SH1 and SH14 in Whangarei (refer to figure 3.12). It consisted of several TNZ Site Category 2 horizontal corners with curve radii ranging from 150 to160m. The site also had a previous history of SCRIM deficiency.

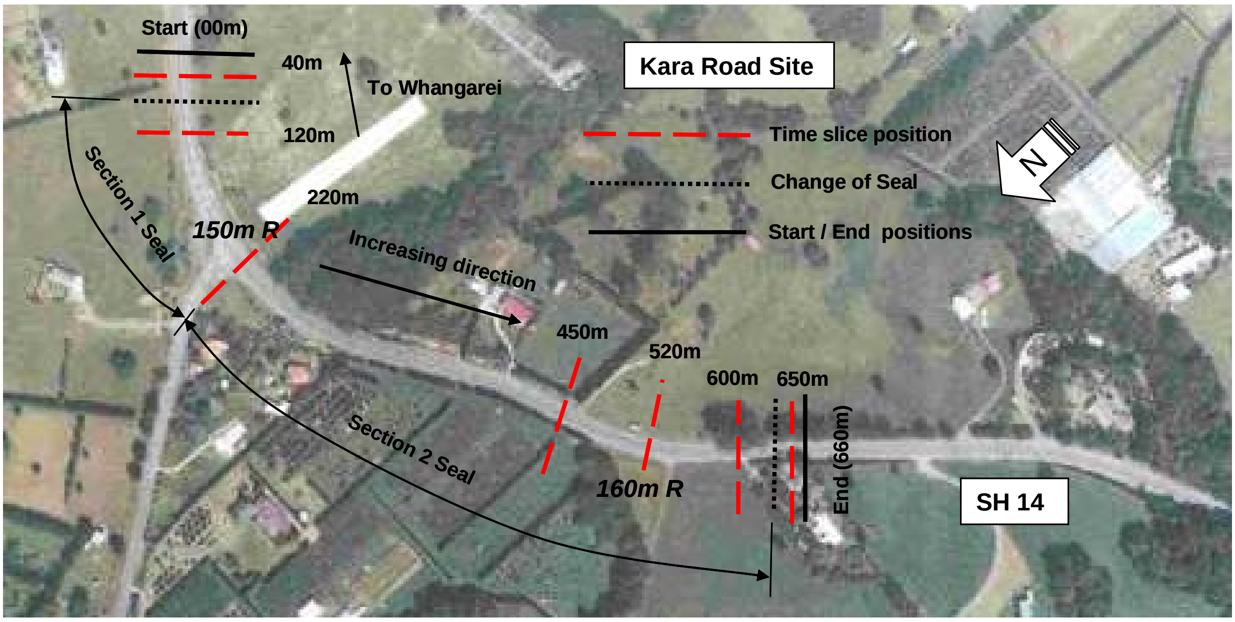
The test section included a reasonable down grade in the westerly (increasing) direction of -7%. The section also included the intersection of Kara Road, which intersects with SH14 at almost the point of intersection (PI) of the 150m radius curve.

The site had been resealed in January 2003 with a racked-in seal using a grade 3/5 Otaika quarry aggregate. The reason for the reseal was that the April 2003 SCRIM survey showed some sections of the left wheel path had deteriorated below the TNZ T/10 intervention level, although the average between the two wheel paths remained compliant with TNZ T/10.

The test section operated under a 100km/h open road speed limit, although the 85% percentile operating speed was estimated to be around 90km/h, due to the constrained horizontal and vertical geometrics. The AADT volume in 2004 on this section of SH14 was approximately 5500vpd, with 5.5% HCVs. Kara Road had very low traffic volumes.

The site was monitored (approximately monthly) with GripTester skid measurements from March 2003 until May 2005.

Figure 3.12 Kara Road site (SH14 – Northland RP 0/8.442–0/9.099)



3.8.9 Snooks-Tatton site (SH14)

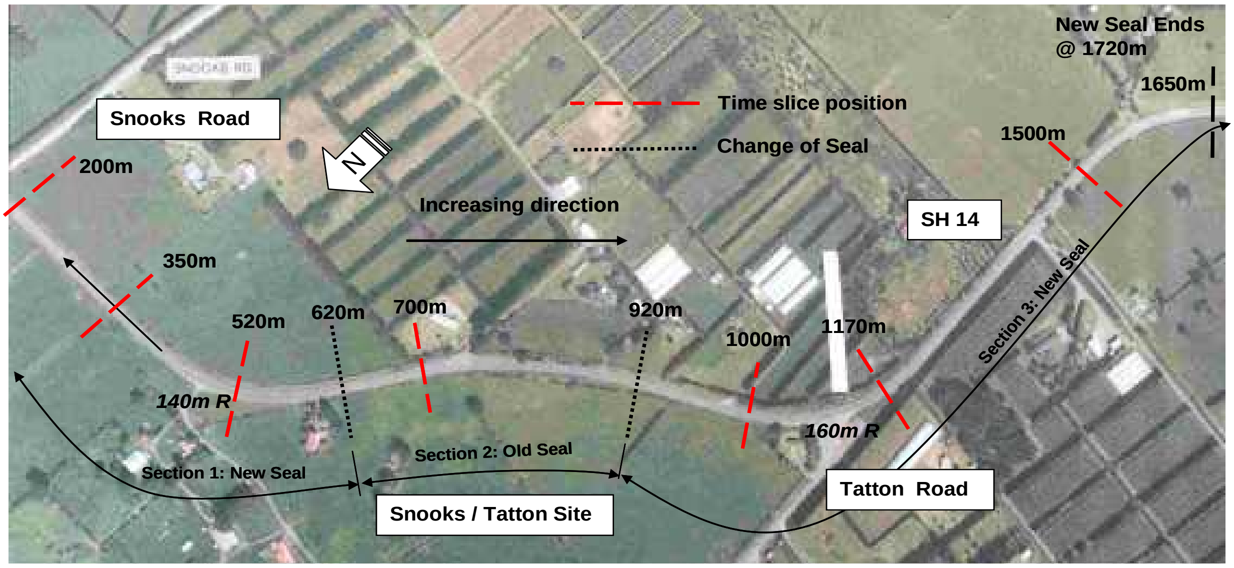
The Snooks-Tatton testing site was also located on SH14, approximately 13.9km west of the intersection of SH14 and SH1 in Whangarei and 5.5km west of the Kara Road test site (refer to figure 3.13). It was the longest test site of all of the test sections (1700m) and it contained three TNZ T10 Site Category 2 corners.

The test section was made up of two sections of new seal separated by a 300m section of older seal in between. The two newly resealed sections had been sealed with a two-coat reseal with a grade 3/5 Otaika quarry aggregate (PSV 51/52). The AADT in 2004 was recorded in the RAMM database as being the same as the Kara Road site, being approximately 5500vpd, with 5.5% HCV.

The test section operated under a 100km/h open road speed limit and had a relatively level vertical alignment; therefore the 85% percentile operating speed was estimated to be around 100km/h. The traffic volumes on both Snooks Road and Tatton Road were relatively minor.

The site was monitored (approximately monthly) with GripTester skid measurements from March 2003 until May 2005.

Figure 3.13 Snooks-Tatton site (SH14 – Northland RP 0/13.91-15/0.647)



3.9 Surface detritus analysis methodology

3.9.1 Introduction

As discussed in section 2, it has been thought that the accumulation of finer particle detritus material contributes towards the polishing of the aggregate, usually coinciding with lower-rainfall summer months. Conversely, coarse grit contributes to abrasion of the aggregate and, when the finer material has been washed away in wetter months, helps to rejuvenate skid resistance (Jayawickrama and Thomas 1998).

Road-based detritus has also been reported as being a major contributor to stormwater pollution, as the road dusts contain a variety of suspended and dissolved inorganic and organic contaminants (Sansalone and Buchberger 1997). The amount of detritus accumulation on road surfaces is dependent on the traffic, road use and local environment conditions. Local environment conditions include such factors as:

- rainfall frequency and intensity
- wind
- preceeding dry days
- total volume of runoff discharged
- drainage systems
- contributing catchment characteristics, such as the surrounding geology, areas of permeability and impermeability (Onwumere 2000; Stotz 1987).

In particular, rainfall volume appears to be the major factor in the removal of total road dust detritus, and rainfall frequency mainly affects the accumulation of particle-bound contaminants (O'Riley et al 2002). In order to substantiate or disprove the effect of detritus on the variation of measured skid resistance, procedures were developed to quantify in-field pavement surface detritus that lodges within the surface macrotexture. The main objectives of the detritus collection and laboratory analysis were the:

- quantification of the detritus that accumulates on the road surface
- classification of the detritus in terms of particle size distribution and its material characteristics ie suspended solids (sediments), heavy metals (eg copper, lead, zinc and cadmium) and organic and petroleum hydrocarbons).

A secondary objective was a consideration of the likely source of the detritus and its effects in terms of the receiving environment, in comparison to other international studies.

The expectation was that the longer the period of no rainfall, the greater the volume of detritus and therefore the greater the effect of finer material polishing the microtexture of the surface, thereby reducing measured skid resistance.

3.9.2 Detritus sample collection method

A significant constraint on the possible number of collected samples was the requirement to close the road traffic lane and provide temporary traffic control whilst obtaining samples. The detritus on the road surface was sampled by brushing of the target test areas with deionised water and collecting the liquid using a high-power vacuum. This vacuuming technique has been reported as an efficient method of collecting solid particles from the road surface whilst preserving their physical and chemical characteristics (Ng et al 2003).

The test site locations were at each of the field sites immediately over the left wheel path (LWP). The test area of each sampling site was one square metre, limited by a 1m x 1m wooden frame. The gaps between the edge of the frame and the macroxtexture of the road pavement surface were sealed with a foam sponge to prevent leakage of the sample detritus.

The following procedures were developed for the collection and storing of the surface detritus for subsequent laboratory analysis (refer to figure 3.14):

- Place a 1m x 1m wooden frame with sponge over the target surface sample area.
- Stand on the wooden frame in order to compress the foam sponge into the macrotexture of the pavement surface, and spread one litre of deionised water evenly over the target area.
- With a relatively vigorous but careful action, brush the sample area with a hard nylon scrubbing brush to mobilise the detritus within the macrotexture area.
- Collect the mobilised detritus and liquid mixture from within the timber frame by the use of a high-powered wet-and-dry vacuum cleaner, ensuring that the edges of the sponge on the bottom of the wooden frame are also vacuumed
- Use an additional 250mls of deionised water, through the vacuum cleaner hose and machine, to wash any detritus sticking to the inner surfaces of the vacuum cleaner.
- Take the sampled mixture from the vacuum cleaner and store it in a labelled plastic container.
- Store all samples in a temperature-controlled refrigerator until laboratory analysis.

Figure 3.14 Pavement surface detritus sample collection method

3.9.3 Detritus laboratory analysis methods

The detritus samples obtained were then separated into water and sediment fractions by centrifugation and air-drying. Samples were analysed for suspended solids, particle size distribution (PSD), heavy metals (eg copper, lead, zinc and cadmium), total petroleum hydrocarbons (TPH) and total organic carbon (TOC). All laboratory tests were undertaken by the Environmental Engineering Laboratory at the University of Auckland, except for the PSD analysis, which was conducted by Malvern Instruments Ltd.

Suspended solids were determined using the gravimetric method outlined in section #8158 in HACH (1997), and the heavy metals extraction by the standard nitric acid digestion method outlined in section 3030E in American Public Health Association et al (1992). The concentrations of copper, lead, zinc and cadmium were measured by a Varian SpectrAA Atomic Absorption Spectrometer equipped with an atomiser-burner. The measurement range of the instrument was 0–50ppb, and as such, the digested samples required dilution using deionised water prior to testing.

The laboratory testing for TPH was undertaken according to the methodology provided by TPH Working Group (1998). The samples were mixed with high-purity reagent grade n-pentane in a 1:1 volume ratio, vortexed for five minutes, and then the extracts were filtered through a 0.2μm nylon filter membrane (Phenomenex AFO-0501) prior to the TPH determination. The analysis instrument was a gas chromatograph (GC) using a Hewlett-Packard HP 6890 series GC system equipped with an Alltech Econo-cap EC-1000 column and a flame ionisation detector.

The total organic matter (including TPHs) in the samples was measured using TOC, calculated as the difference of the measured total carbon and total inorganic carbon values. Both dissolved and insoluble forms of TOC were analysed by a Shimadzu model TOC-VCSH Total Organic Carbon Analyser with a Solid Sample Module SSM-5000A. Specifically, the dissolved form of TOC was quantified based on units of TOC mass per unit of collected fluid (mg-TOC/L-water), whilst the insoluble form of TOC content was based on units of TOC mass per unit of associated sediment mass (mg-TOC/g-sediments).

4 Laboratory accelerated polishing methodology

4.1 Introduction

A controlled laboratory experiment was designed to attempt to simulate the in-field skid resistance performance of surfacing aggregates. The laboratory experiment required the control and simulation of the effects of the following variables:

- road pavement surfacings utilising aggregates commonly used in practice
- T = traffic action simulating heavy commercial vehicle polishing effects
- rainfall/washing cycles
- effects of the addition of contaminants
- stationary skid tester able to be used in the laboratory on prepared specimens.

4.2 Laboratory sample preparation

The experiment required laboratory testing equipment and the construction of large, hand-placed chipseal surfacing samples that were compatible with each other. The University of Auckland (in collaboration with Pavement Management Services Ltd) had in 2003 co-purchased a Dynamic Friction Tester (DF Tester – refer to figure 4.1 below and appendix A.3). This stationary device was able to measure surface friction in the laboratory on a greater surface contact area than the British Pendulum Tester, and was therefore chosen as the surface friction testing device. Subsequently, it became the critical factor that determined most of the other experiment variables.

Figure 4.1 The DF Tester

(a) The DF Tester on a prepared sample **(b) Rubber sliders and rotating disk of DF Tester**

4.3 Aggregate samples

Four aggregate sources were chosen from a range of geological types for the building of the laboratory surface samples:

- Moutohora sedimentary greywacke, being the highest reported natural PSV in the North Island (Napier)
- Holcim igneous basalt, midrange reported PSV, sourced from Auckland Region (Bombay)
- Otaika sedimentary greywacke, lowest-reported PSV acceptable for Transit NZ sufacings, locally sourced from Northland
- Melter slag, artificial by-product from Glenbrook Steel mill, through SteelServ Ltd.

Two samples of each aggregate source were constructed, one to be a control sample that was not polished, and the other sample polished by the accelerated polishing machine (AAPD). The methodology included preparing large surfacing samples (approx 600mm x 600mm) with aggregate chips that were sieved through a 9.5mm sieve, and with all flaky aggregate chips removed by the use of a slotted sieve and/or rejected by hand. Figure 4.2a shows a sample being prepared by hand (upside down), with the placing of the aggregate chips with their average least dimension (ALD) flat on a sheet of glass in a mixture of sand and oil. Figure 4.2b shows the sample immediately prior to being fixed in a sand/cement mortar mix. Figure 4.2c shows a completed sample after it had been set and cured by the sand/mortar mix and was ready for accelerated polishing and skid resistance testing.

A full description of the controlled experiment methodology for the required accelerated polishing and skid testing is given in Wilson and Dunn (2005) and Wilson (2006).

Figure 4.2 Preparation of the laboratory surface samples

(a) Placing the aggregate chips by hand **b) Sample ready for setting with sand/cement mortar** **c) A completed sample mounted in a wooden frame and ready for testing**

4.4 Accelerated polishing of samples

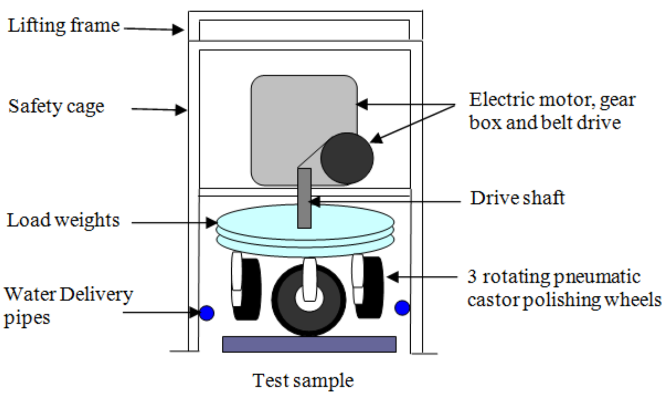
An accelerated polishing machine (Auckland Accelerated Polishing Device – AAPD) was developed to polish the prepared surface samples in the same circular motion and track as the DF Tester. This was seen to be of benefit as it would simulate the in-field traffic action that occurs in the wheel paths.

The main features of the AAPD (see figure 4.3) are:

- three castor wheels with rubber tyres, filled with rubber to a constant tyre pressure of 20psi and rotating on a diameter of approximately 284mm
- a loaded wheel assembly weight of approximately 57kg over the three wheels
- a variable-drive electric motor and gearing to enable a maximum speed of 47rpm at a motor speed of 50Hz.

Figure 4.3 The Auckland accelerated polishing device (AAPD)

(a) Schematic of UoA AAPD



(b) The AAPD wheel assembly unit in operation

4.5 Polishing to equilibrium skid resistance (ESR) levels

To examine and simulate the variation of measured skid resistance over the expected life of a surfacing, a two-stage accelerated polishing methodology was developed. The initial stage of accelerated polishing (stage 1 polishing) was without the use of contaminants (detritus) and used only the accelerated polishing of rubber tyres with water. The duration of accelerated polishing was not arbitrarily set (cf the 6-hour end-of-life PSV test that has set 2 x 3-hour cycles of polishing of corn emery and subsequent emery powder), but continued until a steady-state level of polishing was observed (nominally called an equilibrium skid resistance (ESR) level).

A procedure was developed to polish and test the skid resistance of the samples, using the following steps:

1. Lightly clean the prepared samples with water.
2. Test the paired samples for the coefficient of friction of both the unpolished and the ‘to-be-polished’ sample three times, each utilising the DF Tester at an initial slip speed of 60km/h.
3. Polish the sample marked ‘polished’ for 15mins with continual watering and no addition of contaminants.
4. Repeat step 2 and test both samples with the DF Tester.
5. Repeat step 3 for another 15mins and once again repeat step 2.

6 Continue polishing the polished sample at the following time intervals, or until ESR is reached (0, 15mins, 30mins, 45mins, 60mins, 90mins, 120mins, 3hrs, 4hrs, 5hrs, 6hrs and 7hrs if required).

4.6 Polishing with contaminants

Once each of the 'polished' surface samples had clearly reached an 'equilibrium level' for that specific aggregate, load and polishing action, the samples were ready for the stage 2 polishing phase. The stage 2 polishing phase was designed to determine the effect on the variation of the coefficient of friction when certain specific additives were placed upon the surface with the addition of polishing. This was designed to simulate, in the laboratory, the effect of traffic, environmental effects and surface detritus on the coefficient of friction on a surface that had polished to an 'equilibrium level'. The polishing action and the method of wetting and drying of the surface, and all other known variables (where possible) were held constant to isolate the effect of the specific additive.

The theory of the Stage 2 variation in measured skid resistance (known as the 'seasonal variation') as described by Jayawickrama and Thomas (1998) has been that the accumulation of finer particle detritus material contributes towards the polishing of the aggregates (reducing skid resistance), whereas the coarse grit contributes to abrasion of the aggregate, which helps to rejuvenate skid resistance. Cycles of rainfall wash away finer material, therefore allowing the grit to rejuvenate skid resistance during wetter periods. During drier periods, the finer material accumulates, polishing the aggregate and reducing skid resistance.

To test this theory, a number of additives were considered for addition to the laboratory surface samples, combined with accelerated polishing to measure the effect on measured skid resistance. The additives that were chosen were similar to the detritus particle-size distribution expected to accumulate in the field and were as follows:

- Oedometer clay – a soft but well-graded material with particle-size distribution ranging from approximately *d(0.1)*[7] = 2*μm* to *d(0.9)*[8] of 1190*μm* and a mean size *d(0.5)*[9] of 550*μm*. Oedometer clay is predominantly a soft material (kaolinite) and is strongly anistropic in terms of its properties, with a Mohs hardness of 2–2.5.

- Emery powder – a fine but very hard material with particle-size distribution ranging from approximately *d(0.1)* = 2.5*μm* to *d(0.9)* of 100*μm* and a mean size *d(0.5)* of 8.0*μm*. Emery powder is derived predominantly from corundum minerals (Al203), which have a Mohs hardness of 9. Emery powder is used in the PSV test machine as a polishing medium.

- Leighton Buzzard sand – a coarse and hard material with particle-size distribution ranging from approximately *d(0.1)* = 600*μm* to *d(0.9)* of 1265*μm* and a mean size *d(0.5)* of 860*μm*. Leighton Buzzard sand is predominantly from quartz minerals, which have a Mohs hardness of 7.

7 *d(0.1)* denotes the 10 percentile diameter of the sample particle-size distribution.

8 *d(0.9)* denotes the 90 percentile diameter of the sample particle-size distribution.

9 *d(0.5)* denotes the 50 percentile diameter or mean of the sample particle-size distribution.

The stage 2 polishing consisted of measuring the effect of the following variations, in turn, on the phase 1 wet-polishing phase:

- dry polishing with the addition of oedometer clay (10 grams)
- dry polishing with the addition of sieved oedometer clay (10 grams) with particle sizes of <0.15mm
- dry polishing with the addition of sieved oedometer clay (10 grams) with particle sizes of >1.15mm
- dry polishing with the addition of emery powder (10 grams)
- dry polishing with the addition of Leighton Buzzard sand (20 grams)
- wetted surface (damp) polishing with the addition of oedometer clay (10 grams).

After each polishing variation had been tested, the surface sample was then polished, wet but with no additives, to try to restore the sample to its ‘equilibrium skid resistance level’.

5 Field-testing results

5.1 Introduction

This section provides summary results of the seven field test sites. Appendix B provides a summary figure and discussion for each field site, displaying the field-testing results of the average section GripTester coefficient of friction measurement (GN on y1 axis) and surface temperature (y2 axis) in both traffic directions compared over time (x axis). Where applicable the figures also display the average DF Tester coefficients of friction (μ) obtained at the specified test locations along the section length. Appendix B also provides a summary table following each figure, displaying descriptive section statistics for each field site.

Unfortunately, due to a series of problems with the GripTester skid-testing device (which included the need for a new signal-processing unit and a new measuring axle with horizontal and vertical force transducers, and issues with a slowly seizing measuring-wheel bearing unit) the results over the 2003/2004 summer season on all of the sites cannot be regarded as credible, and have subsequently been removed from the analysis as 'data outliers'. However, for completeness of presentation of the data, these measurement values have been included and the problem period identified on the figures. These problems with the GripTester over the 2003/2004 summer season meant that, in essence, from March 2004 the GripTester skid-testing device was almost a completely new device (except for the chassis, suspension and driving wheels) – an undesirable but uncontrollable external factor.

During this same period (summer 2003/2004), all of the field test sites skid resistance measurements increased to a higher level (from 'before' the device problems to 'after'). It is unknown whether this change was due to the changes in the device (which is possible, and if so, the amount is significant) or whether the coefficient of friction increase was 'real' and due to environmental changes external to the device. It was fortunate that the DF Tester became available during this period, allowing a retrospective analysis that clearly demonstrated that the GripTester device was having problems with its measurement during this period. However, because the DF Tester was not available to the research programme in 2003, a direct comparison cannot be made with the previous year.

A skid resistance measurement device correlation trial was undertaken in Christchurch subsequent to the 1st International Surface Friction Conference in May of 2005. The correlation trials were undertaken north of Christchurch on 5 and 6 May 2005 between five GripTesters (including the University of Auckland device), the WDM SCRIM device, the Pavement Management Services' (now Fugro) ROAR device, University of Auckland's Dynamic Friction Tester, and a Portable British Pendulum Tester (PBPT). The trials were undertaken on specially prepared surfaces with a range of low to high coefficients of friction (0.43GN to 0.94GN).

The results of this correlation exercise demonstrated that the University of Auckland GripTester performed as expected, with the Findlay Irvine Ltd 'gold' GripTester device within the range provided ($R^2 > 0.95$). It also correlated very well with the DF Tester ($R^2 > 0.98$) and with the PBPT when the grooved asphalt mix surface section was removed from the analysis ($R^2 > 0.98$). It is worth noting that the DF Tester (refer to appendix A.3) is now the preferred ASTM calibration device for various continuous friction measurement devices, as it has been shown to produce stable and highly repeatable measurements over time (Wambold et al 1995).

This gave the researchers confidence that after fixing the problems that were experienced in 2003/2004 summer period, the University of Auckland GripTester was measuring as designed. This was, however, not the case for one of the five GripTesters, which was measuring significantly higher than the other four devices. A full discussion of the correlation trials is given in Wilson (2006) and the Austroads Report AP – T72 06 (2006).

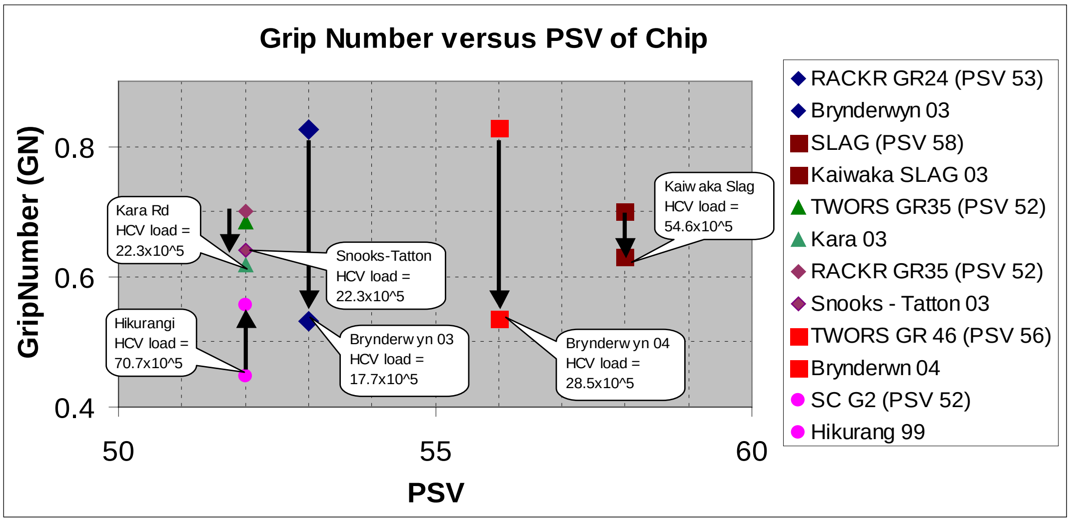
5.2 Aggregate PSV and measured skid resistance

The skid resistance field sites in the Northland region were selected for differing purposes and/or characteristics. One of the characteristics that varied for each of the sites was the actual surface treatment that had been utilised after a surface treatment was required (refer to table 3.2).

Figure 5.1 shows the initial skid resistance measured after each of the surfaces were treated, and how skid resistance performed over repeated traffic loads as a function of the Transit NZ-published PSV. The figure demonstrates the following important points:

- A higher published PSV aggregate does not necessarily lead to a high initial skid resistance value as measured by the GripTester.
- The published PSV of the aggregate does not necessarily determine the level of equilibrium skid resistance (however, the sites did have varying loading and geometric elements that would have affected the final level). This result tends to corroborate with research by Cenek et al (2003b), which states there is very little relationship between the PSV of the aggregate and the in-field skid resistance as measured by SCRIM network surveys (even on straight and level sections of road).
- The highest initial grip number (GN) was recorded at the Brynderwyn Curve. This was the only site of the five that was treated during the monitoring period with grade 2 and grade 4 chip. The other sites were treated with grade 3 and grade 5 chip. This result was not unexpected, as the larger chips with higher macrotexture and the same microtexture were expected to produce the highest initial skid resistance.
- For similar traffic loadings and curvature (eg Kara Road and Snooks–Tatton), approximately the same range of skid resistance was lost over the same trafficking period.
- The above losses in skid resistance for each of the sites must be placed within the context of the control site, which over the same two-year period increased by approximately 0.1GN for the highest traffic loading.
- Whilst the iron-making melter slag from the Glenbrook Steel Mill had the highest published PSV of 58, compared with a PSV of 52 and 53 for the other sites, its initial grip number of 0.7 was the second-lowest of the results. However, when one looks at the skid resistance performance of the slag over time in comparison with the other aggregates and sites, even with much higher loading its performance was significantly better.

Figure 5.1 Measured skid resistance over time in comparison with published PSV for Northland sites



The above analysis indicates that the Transit NZ-published PSV of the aggregate in itself, without taking other factors into consideration, cannot be reliably used as a predictor of the initial skid resistance of the aggregate and/or the level of equilibrium skid resistance after polishing. Other methods of predicting how aggregates will perform over time and under specific traffic, geometric and braking stresses are required for road asset managers to make good decisions.

5.3 Field-testing summary discussion

Seven field sites were regularly tested (approximately monthly) with the GripTester device for over two years, and three of the sites were tested with the DF Tester for up to 14 months. Table 5.1 summarises the results from the two skid resistance devices and the seven field sites over approximately two years of data collection.

Whilst it was originally thought that the extent of the variation in the GripTester results would be less for surfaces that had reached an equilibrium level of polishing (experiencing only seasonal and/or short-term variations) in comparison with sites that were still in the initial polishing phase from a new surface level, it was surprising that the results did not show this. In fact, the results showed that in terms of the coefficient of variation (CoV), the reverse occurred, and greater variation occured on the sites that were supposedly at a stable equilibrium level of polishing. Closer examination of the table 5.1 results revealed that the CoV increased on these sites because the mean skid resistance coefficient of friction value was lower; however, the standard deviations of the results remained reasonably consistent between the sites (although ranging from 0.043 on the roads with lower HCV volumes (SH14) to 0.069 on roads with approximately three times the volume of HCVs (SH1)).

Table 5.1 Summary coefficient of friction statistics of the field sites

Field-test site ave. of both directions[a]	No. of data points	CoF mean range	Ave. standard deviation	95% conf. interval	Variance	Coeff. of variation	Comments on polished state
Tamaki Campus GT30[b]	31–32	0.76–0.80	0.057	±0.020	0.003	7.4%	Nearly new seal
Tamaki Campus DFT20[c]	11	0.67–0.73	0.034	±0.019	0.001	4.8%	Nearly new seal
Ports of Auckland GT50	23–24	0.61–0.63	0.067	±0.028	0.004	10.9%	Equilibrium
Ports of Auckland DFT20	14	0.49–0.55	0.050	±0.027	0.003	9.5%	Equilibrium
Kaiwaka Slag Site GT50	28	0.70–0.72	0.056	±0.021	0.003	7.9%	New seal layers
Brynderwyn South GT50	29	0.63–0.57	0.070	±0.026	0.005	11.7%	New seal layers
Hikurangi GT50	32	0.53–0.56	0.068	±0.024	0.005	12.4%	Equilibrium
Hikurangi DFT20	8	0.62	0.069	±0.048	0.005	11%	Equilibrium
Kara Road S1 GT50	26	0.67–0.64	0.043	±0.016	0.002	6.5%	New seal layers
Kara Road S2 GT50	26	0.67–0.63	0.045	±0.018	0.002	6.9%	New seal layers
Snooks–Tatton S1 GT50	24	0.69–0.67	0.047	±0.019	0.003	6.9%	New seal layers
Snooks–Tatton S2 GT50 Increasing direction	24	0.57	0.046	±0.019	0.002	8.2%	Equilibrium
Snooks–Tatton S3 GT50	24	0.70–0.69	0.046	±0.018	0.002	6.5%	New seal layers

a) All sites are summarised for both directions of travel unless otherwise specified.

b) GT30 denotes GripTester CoF tested at 30km/h.

c) DFT20 denotes DF Tester CoF at a slip speed of 20km/h.

The asphalt mix surfaces in the Auckland region (Tamaki Campus site with light traffic conditions, and the Ports of Auckland site with heavy traffic conditions) had a CoV of GripTester results of 7.4% and 10.9%, and a 95th percentile confidence interval of ±0.020GN and ±0.028GN respectively. It should be noted that there was also a difference between the sites in terms of testing speed, which could account for some of the additional variation on the Ports of Auckland site, which was tested at the higher speed.

The CoV reported from the GripTester results of the chipseal sites in the Northland region also seemed to follow the HCV loadings at the site more than the polishing phase of the aggregate. For instance, the CoV of the Kaiwaka, Brynderwyn and Hikurangi sites (all on SH1) were 7.9%, 11.7% and 12.4% respectively, with approximately three times higher HCV volumes than the Kara Road and Snooks–Tatton sites (on SH14) which had a range of 6.5–8.2%CoV. The Kaiwaka site CoV results were lower than the other two SH1 results and it is surmised that this is a result of being surfaced with an artificial melter slag aggregate that was more resistant to polishing (and therefore with variation in measured results) than the natural aggregates used on the other sites.

The 95th percentile confidence values of the site means generally followed the same trend of CoV results for the Northland sites, with higher ranges for the three SH1 results (±0.021GN, ±0.026GN and ±0.024GN for the Kaiwaka, Brynderwyn and Hikurangi sites), compared with the SH14 results, which ranged from ±0.016–±0.019GN.

Also of significance, was the relatively narrow range and consistency between all of the sites of the standard deviation, 95th percentile confidence interval and the variance of the mean data values over the data collection period.

It was difficult to establish any significant trends for the coefficient of friction results utilising the DF Tester, as only three sites were tested, they were less regular, and there were fewer data points. However, it is pleasing to see that the DF Tester results demonstrated the same relativity between sites, in terms of the CoV, as the GripTester for the Tamaki, Ports of Auckland and Hikurangi sites (eg DFT20 CoV=4.8% cf GT50 CoV=7.4% for the Tamaki site, DFT20 CoV=9.5% cf GT50 CoV=10.9% for the Ports of Auckland site, and DFT20 CoV=11.0% cf GT50 CoV=12.4% for the Hikurangi site). This gives some confidence that the two skid resistance devices were independently measuring the same effects at each site.

6 Seasonal and short-term variation analysis

6.1 Introduction

A number of researchers have shown that after initial phases of aggregate polishing, skid resistance varies throughout the year in a seasonal or cyclical annual pattern, with generally low skid resistance in the summer and high skid resistance in wetter winter periods (Cenek et al 1999; Hill and Henry 1981; Hosking 1976; Oliver et al 1988; Rogers and Gargett 1991). The way in which skid resistance varies over time has been idealised in model form by Prowell et al (2003). It was shown earlier in an idealised form in figure 2.1 and discussed in section 2. This predictable effect has not been universally agreed upon. As Oliver et al (1988) reported, in some climates (eg Queensland, Australia) the seasonal effect is not evident. They also showed that the results from year to year in other states of Australia could vary considerably and were not predictable.

Rogers and Gargett (1991) concluded from research in the UK that the seasonal variation was due to the combined effects of traffic and weather. When roads are dry, the polishing effect of traffic tends to dominate, but when they are wet for prolonged periods, they recover some of their former harshness. The scale of the seasonal effects depends largely upon the geological history and petrography of the aggregates.

A secondary and additional short-term effect was reported by Bird and Scott (1936) in the UK, who found that skid resistance levels varied significantly with changing weather conditions. They reported that as rain began to fall there was an immediate drop in skid resistance from that prior to a rainfall event. As more rain fell, the skid resistance level increased as contaminants were washed away, and then it increased again as the pavement dried out. This effect was also shown by Bennis and De Witt (2003).

Hill and Henry (1981) stated that large variations in skid resistance, from day to day or week to week, seemingly occur due to the rainfall pattern and local weather conditions that are superimposed on an annual cycle. They demonstrated that models could be developed in the US to adjust significant seasonal and short-term skid resistance-related variations and explain up to 57% of the measured variation. They also found that a major cause of apparent skid resistance variation is measurement error, particularly the lateral placement of the test tyre.

This section presents an analysis of the field test site results for seasonal, aggregate weathering and/or polishing[10] effects due to variances in geometric elements, and the short-term environmental-based variation of skid resistance measurements that were collected at the field test sites with the GripTester over an approximately 2.5-year period.

10 The word ‘polishing’ is used loosely in this chapter to describe the process of aggregate grinding under traffic with contaminants. It is not used specifically to mean polishing that results in a reduction of surface friction, as in some cases (depending upon the contaminants) an increase in skid resistance will result.

6.2 Seasonal variation results

6.2.1 Introduction

Standardised field test procedures were developed to ensure a consistency of test methodology and experimental approach. The sites used in this analysis were sites that had a 'weathered' surface, meaning that the surface should be acting within the 'equilibrium skid resistance' phase. The sites were also geometrically benign in that they were reasonably straight and almost level in grade. Therefore, any changes in skid resistance were expected to be due only to the seasonal and/or short-term effect. This analysis investigated these effects in the field by:

- measuring the extent or range of seasonal variation of the measured skid resistance by minimum monthly skid resistance testing at sites or timeslice locations where it was thought that an equilibrium level of skid resistance existed (specifically the Tamaki Campus site, the Ports of Auckland site, the Hikurangi site, section 2 of the Snooks–Tatoon site, and timeslices taken prior to new seals at the Brynderwyn site, Kara Road site and the Kaiwaka slag site)
- recording manual rainfall pluviometer records, preferably daily but often less regularly, at each of the five sites in the Northland region
- obtaining automatic NIWA rainfall records as close to all of the sites as possible (including the Ports of Auckland and the Tamaki Campus sites) and, where applicable, correlating these against the manual rainfall gauge data to enable interpolation for days that manual rainfall information was not available
- collecting on-site data such as air and surface temperature during skid resistance testing
- whenever possible, collecting surface detritis samples for subsequent environmental laboratory analysis.

The variation at each of the field sites is described in section 5 and in detail in appendix B. However, for a comparative analysis, a greater number of data points was desirable in order to determine whether there were common trends occurring across similar field sites and across the data collection period. To enable this analysis, a 'normalisation' of the individual field section GripTester coefficient of friction results to a common level (eg 1.0GN) was initially required to remove the differences in terms of the polished state of the aggregate.

It is recognised that differences in the geological makeup of the surface aggregate may affect the extent of variation demonstrated for the respective aggregates. However, the normalisation process was expected to help reveal these effects. The 'normalisation' process allows a combination of similar field sites, providing a greater number of data points, thereby ensuring greater confidence in any statistical relationships observed in the measured skid resistance data.

The normalisation process consisted of modifying each field-recorded mean test section result (GN_j) for each test date (u) to a common 'normalised' GripTester result (NGN_u), based upon the sample mean result ($\bar{\bar{X}}$) for the field site being shifted linearly to a normalised mean section result for the data collection period of 1.0:

$$NGN_u = \left(1 - \bar{\bar{x}}\right) + GN_j$$

(Equation 6.1)

where:

NGN_u = the normalised GripNumber test result for test date *u*

$\bar{\bar{x}}$ = the surface section mean GripNumber result for the sample test period where:

$$\bar{\bar{x}} = \frac{\sum_i \sum_j \sum_u x_{iju}}{nmk}$$

i: where *i* = 1 to 5 reported GripNumber (GN) test runs for a specific 10m section

j: where *j* =1 to *m* reported GripNumber (GN_i) test runs for the section distance

u: where *u* = 1 to *k* reported GripNumber (GN_j) for the number of test dates

GN_j = the mean section GripNumber for test date *u*

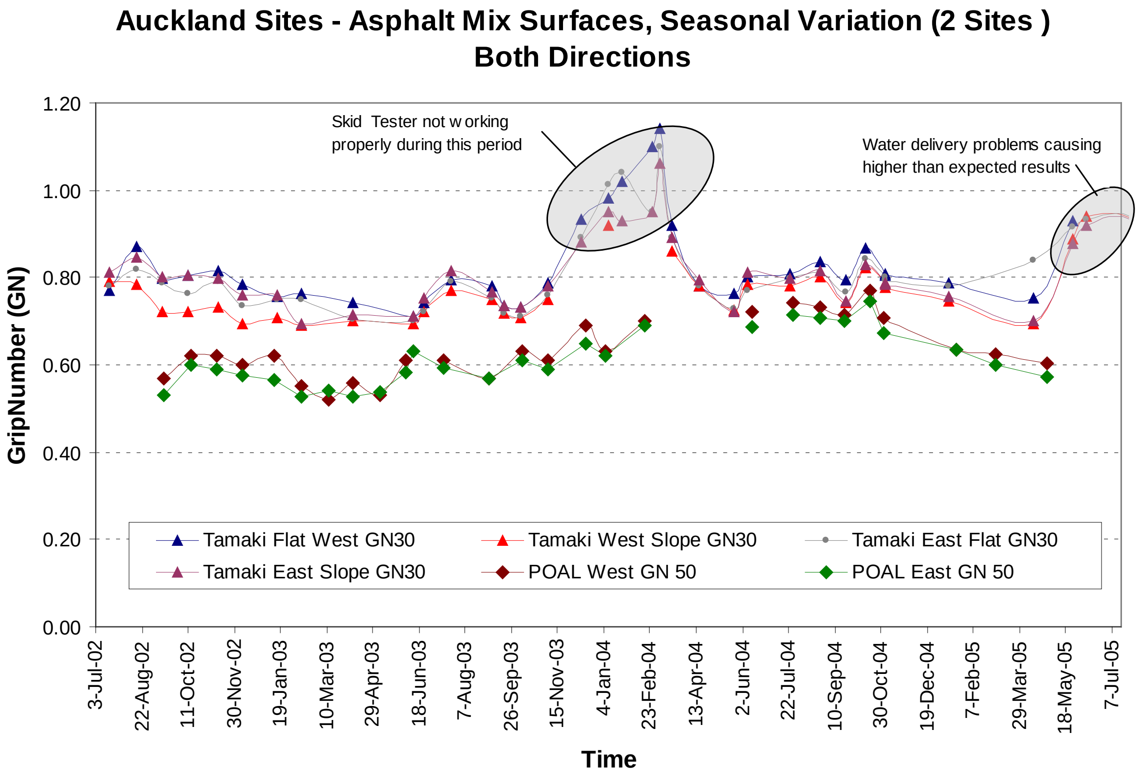
Each data point from each field site section was modified by this process. The following sections provide an analysis of these combined normalised results.

6.2.2 Auckland asphalt mix sites

A descriptive statistical analysis of the Tamaki Campus site is given in appendix B.1 and shown in figures B.1 and B.2 for the flat and sloped sections respectively. Similarly, the Ports of Auckland site is discussed in appendix B2 and the results are shown in figures B.3 and B.4 for the increasing and decreasing directions respectively. As both the Tamaki Campus and Ports of Auckland surfaces were of similar asphalt mix-type surfaces and had been shown to be both acting in an ‘equilibrium phase’, the various site section results from the two similar field sites have been ‘normalised’ by the process explained above.

Figure 6.1 shows the GripTester results (GN) of the two Auckland asphalt mix sites over the three-year data collection period. The asphalt mix surface had polished to different average section levels, due primarily to the significantly higher traffic loads at the Ports of Auckland site compared with the relatively low traffic loads at the Tamaki Campus site. It should also be noted that the Tamaki Campus site skid resistance testing was undertaken at a vehicle-testing speed of 30km/h, but the Ports of Auckland site testing speed was 50km/h. It is apparent in figure 6.1 that in the majority of cases where one site is reading high or low, the other site is similarly high or low.

Figure 6.1 Seasonal variation of Auckland asphalt mix surfaces over 3-year period



When the GripTester results (GN) for each section of the two asphalt mix surfaces in Auckland were normalised (NGN), and the known and identified outliers removed, a comparison could be made, by seasonal calendar months, to determine whether significant monthly trends were visually apparent from the data. Figure 6.2 is a plot of this relationship and table 6.1 gives the statistical data by calendar month.

The average monthly results for the asphalt mix surfaces were not conclusive – the data for each month was scattered. However, it was apparent that higher results occurred in the winter months than in the summer months. The lowest normalised average monthly result was February, with a reported NGN value of 0.94, a coefficient of variation of 2.5%, and a 95th percentile confidence interval of ±0.019.

The descriptive statistical analysis therefore demonstrated that there was a 95% probability that the normalised GN value in the month of February would fall between the values of 0.92 and 0.96. Conversely, for the month of August, an NGN value of 1.05 was calculated (the highest normalised average monthly result) with a coefficient of variation of 2.9%. The 95th percentile confidence interval was also ±0.019, which means that there was a 95% probability that the normalised GN value in the month of August would fall between the values of 1.03 and 1.07. These two months were separated by a six-month time period, indicating that possibly seasonal variations did exist, but these were offset with the effects of the polishing occurring late in summer, and vice versa in winter when the rejuvenation was greatest in late winter.

The results either side of these calendar months were significantly more variable, with no distinct patterns and coefficients of variation increasing in the months of March, May and June to 8.4%, 9.3% and 8.0%, respectively. In these months, the 95th percentile confidence intervals ranged between ±0.036 and

±0.060, which means that there was no confidence at the 95% level that the result would be either higher or lower than the normalised average monthly data.

It should be noted that the number of data points varied for each month and ranged from 6 to 22, the lowest month being February. It should also be taken into account that the Ports of Auckland site was not a typical longitudinal wheel path polishing site, and whilst the loads were significant, they were mostly transverse in nature. Furthermore, the Tamaki Campus site was a very lightly trafficked internal campus road and therefore would not be expected to demonstrate typical urban or state highway polishing mechanisms. This may explain the more random nature of the results, which displayed little predictable pattern by month of the year. It could also explain the greater variation between the reported results. The Northland state highway results (discussed in the next section) were expected to give more predictable patterns.

Figure 6.2 NGN for the Auckland asphalt mix sites, by month

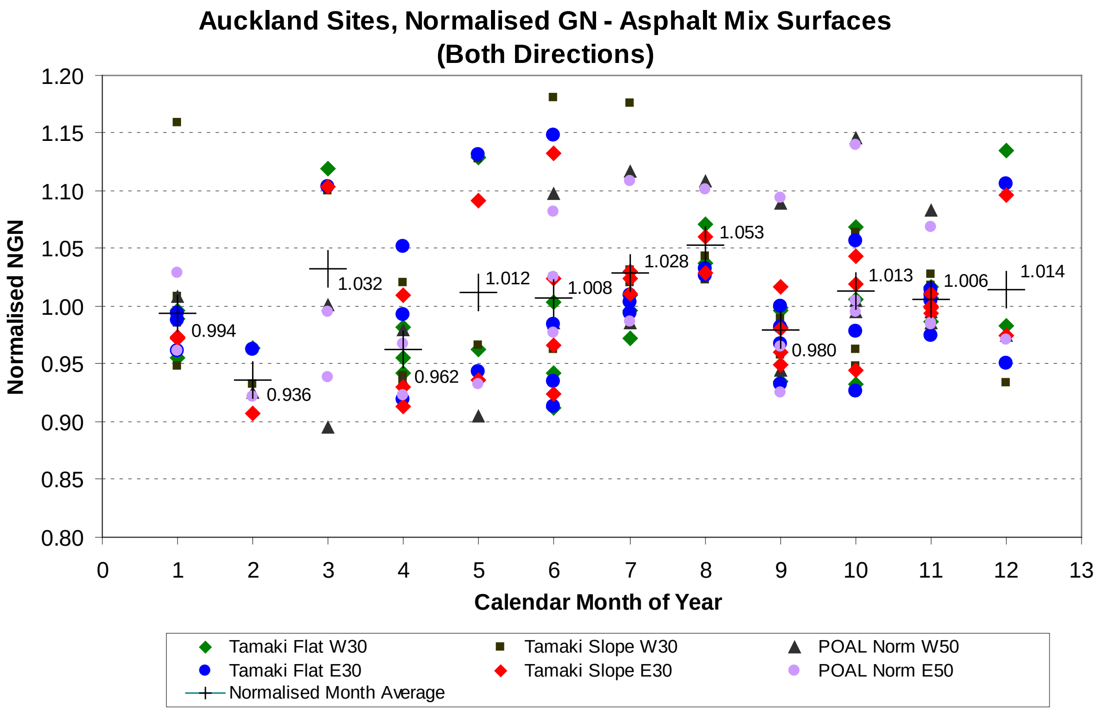


Table 6.1 Normalised GripTester results for Auckland sites, by calendar month

All Auckland Sites (Both directions) Normalised NGN results by Months of the Year

Sample Section Descriptive Statistics	Jan Month 1	Feb Month 2	Mar Month 3	April Month 4	May Month 5	June Month 6	July Month 7	August Month 8	Sept Month 9	Oct Month 10	Nov Month 11	Dec Month 12
Sample Count	17	6	8	16	10	20	17	10	22	18	22	9
Mean	0.99	0.94	1.03	0.96	1.01	1.01	1.03	1.05	0.98	1.01	1.01	1.01
Maximum	1.16	0.96	1.12	1.05	1.13	1.18	1.18	1.11	1.09	1.15	1.08	1.14
Minimum	0.95	0.91	0.89	0.91	0.90	0.91	0.97	1.02	0.92	0.93	0.97	0.93
Range	0.21	0.06	0.22	0.14	0.23	0.27	0.20	0.08	0.17	0.22	0.11	0.20
Standard Deviation	0.047	0.023	0.087	0.041	0.094	0.080	0.054	0.031	0.043	0.064	0.027	0.076
95% Confidence Interval	0.023	0.019	0.060	0.020	0.059	0.036	0.026	0.019	0.018	0.030	0.011	0.050
Variance	0.002	0.001	0.007	0.002	0.009	0.007	0.003	0.001	0.002	0.004	0.001	0.006
Coefficient of Variation (CoV)	0.048	0.025	0.084	0.042	0.093	0.080	0.053	0.029	0.044	0.063	0.027	0.075

6.2.3 Northland state highway field sites

A descriptive statistical analysis is reported for each of the Northland state highway field sites in appendices B.3–7 for the Kaiwaka Slag site, Brynderwyn South curve, Hikurangi site, Kara Road site and the Snooks–Tatton Roads site, respectively. The time-averaged results for these sites are also shown in figures B.5–9 respectively. All of these sites were of similar chipseal type surfaces (although the Kaiwaka site utilised an artificial aggregate). Furthermore, each of the sites had sections that had been tested over the two-year data collection period, that should have been acting in an equilibrium skid resistance phase and that could be appropriately analysed for seasonal variations. Some of the sections chosen for this analysis were averages for a reasonable section length, and others were averages of 30m timeslices as identified below:

- Kaiwaka Slag site (adjacent old seal) – 30m timeslices at T/S location, 800m in increasing direction and T/S location 100m in decreasing direction
- Brynderwyn South curve site (adjacent old seal) – 30m timeslices at T/S location 490m in increasing direction and T/S location 110m in increasing direction
- Hikurangi site – full section averages for both increasing and decreasing directions
- Kara Road site (adjacent old seal) – 30m timeslice at T/S location, 40m in increasing direction
- Snooks–Tatton section 2 – middle old-seal section between two adjacent new seals in increasing direction.

Figures 6.3 and 6.4 show the GripTester results (GN) for the Northland chipseal surfaces for those increasing and decreasing directions over the two-year data collection period selected for the seasonal analysis. An examination of figures 6.2 and 6.3 shows that all of the sites were acting in an ‘equilibrium polished phase’, as the variation is relatively random about the section average from the start, and through to the end periods of data collection. There were no obvious areas of deterioration due to polishing other than normal seasonal-type variations. It is also apparent that some regional seasonal-pattern effects occurred between the sites, because similar patterns of high and low recorded results mostly coincided between the sites. It is also apparent that there were localised differences between the sites, meaning that localised factors were affecting the measured skid resistance.

Figure 6.3 Seasonal variation of Northland chipseal surfaces over 2-year period (increasing direction)

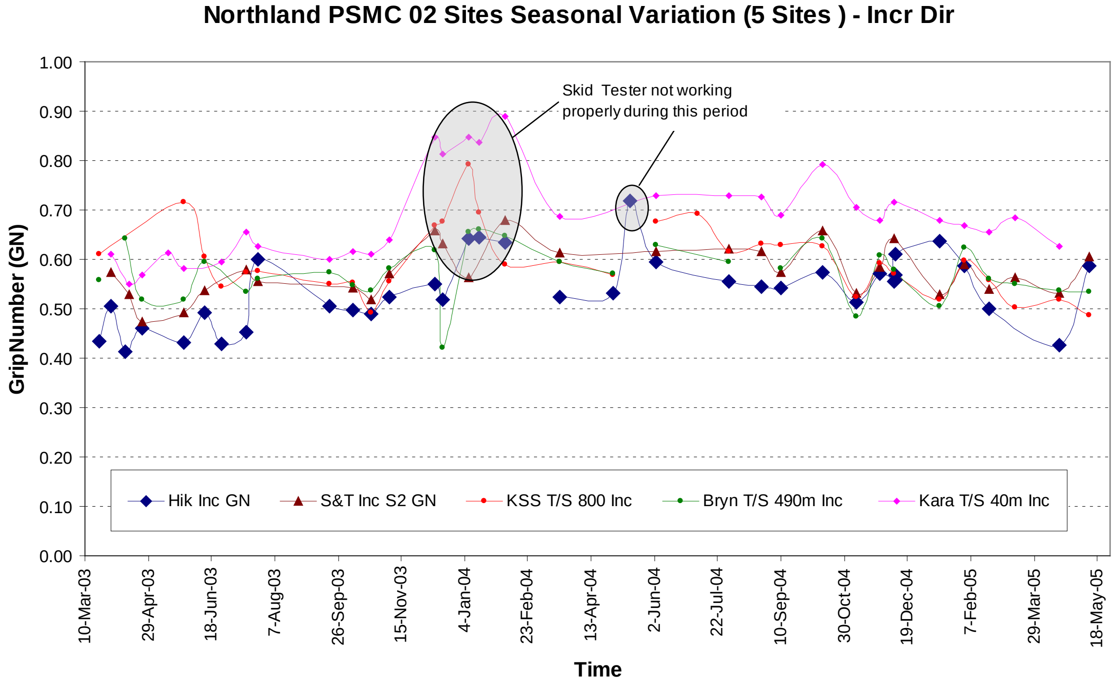
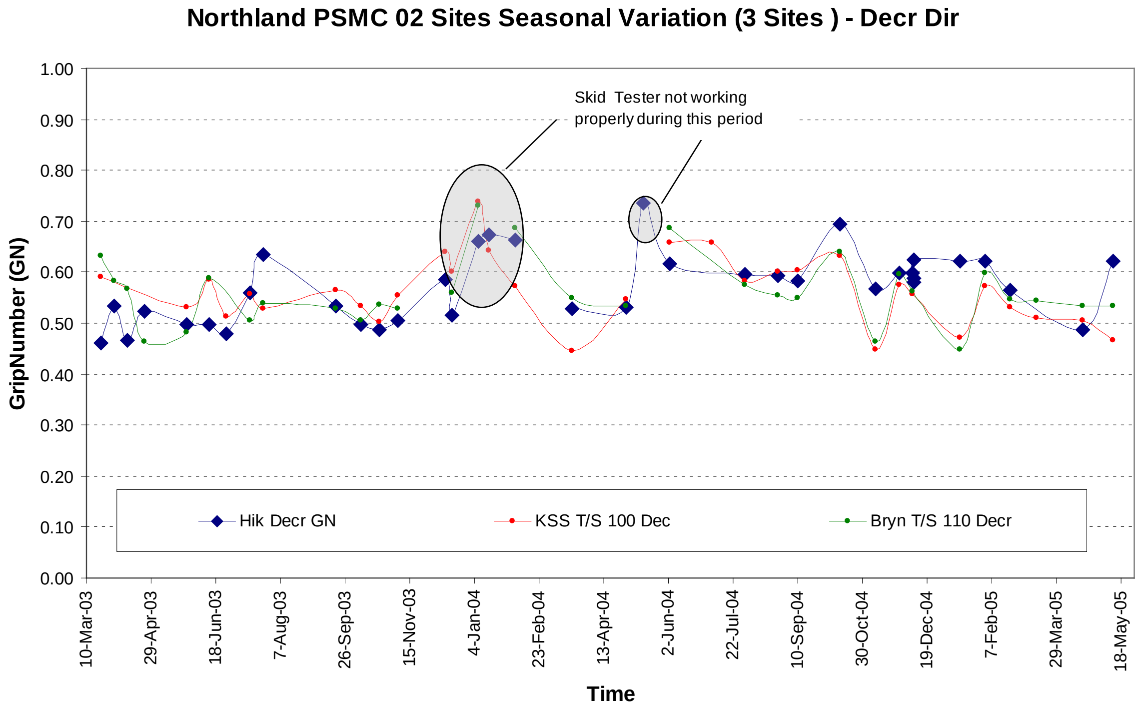


Figure 6.4 Seasonal variation of Northland chipseal surfaces over 2-year period (decreasing direction)



As with the Auckland sites, the GripTester results for the Northland chipseal sites were normalised. The known and identified outliers were removed and a comparison made by seasonal calendar months of the year to determine whether significant monthly trends were apparent from the data. Figure 6.4 is a plot of this relationship with the average normalised NGN. Table 6.2 gives the statistical data by calendar month.

Whilst the data still demonstrated a significant range and variation of normalised GripNumber results (NGN), especially for some calendar months (eg May, June and July), there did seem to be a more distinct pattern in terms of low normalised skid resistance values in late summer (eg April and May) and high normalised skid resistance for mid- to late winter (July and August).

The lowest normalised average monthly result for the Northland sites was April, with a reported NGN value of 0.96, a coefficient of variation of 4.7%, and a 95th percentile confidence interval of ±0.017. The descriptive statistical analysis therefore demonstrated that there was a 95% probability that the NGN value in the month of April would fall between the values of 0.94 and 0.98. By comparison, for the month of August, a reported NGN value of 1.04 was calculated (the highest normalised average monthly result), with a reported coefficient of variation of 2.2%. The 95th percentile confidence interval was also ±0.017, which means that there was a 95% probability that the NGN value in the month of August would fall between the values of 1.02 and 1.06. The 95th percentile confidence limits are plotted on figure 6.4, which shows that significant data fell outside this range.

These results were consistent with some of the normalised indicators for the Auckland asphalt mix surfaces (discussed earlier), whereby low measured skid resistance results were reported late in the summer (March, April) and higher measured skid resistance was apparent in July and August.

The results either side of these calendar months were more variable (eg January, May, June and October), with coefficients of variation increasing to 7.5%, 8.7% and 6.7% and 6.7% respectively. In these months, the 95th percentile confidence intervals ranged between ±0.027 and ±0.051, which means that there was no confidence at the 95% level that the result would be either higher or lower than the normalised average monthly data. It should be noted that the number of data points varied for each month, ranging from 8 to 27, the lowest month being January.

Figure 6.5 NGN for the Northland chipseal sites, by month

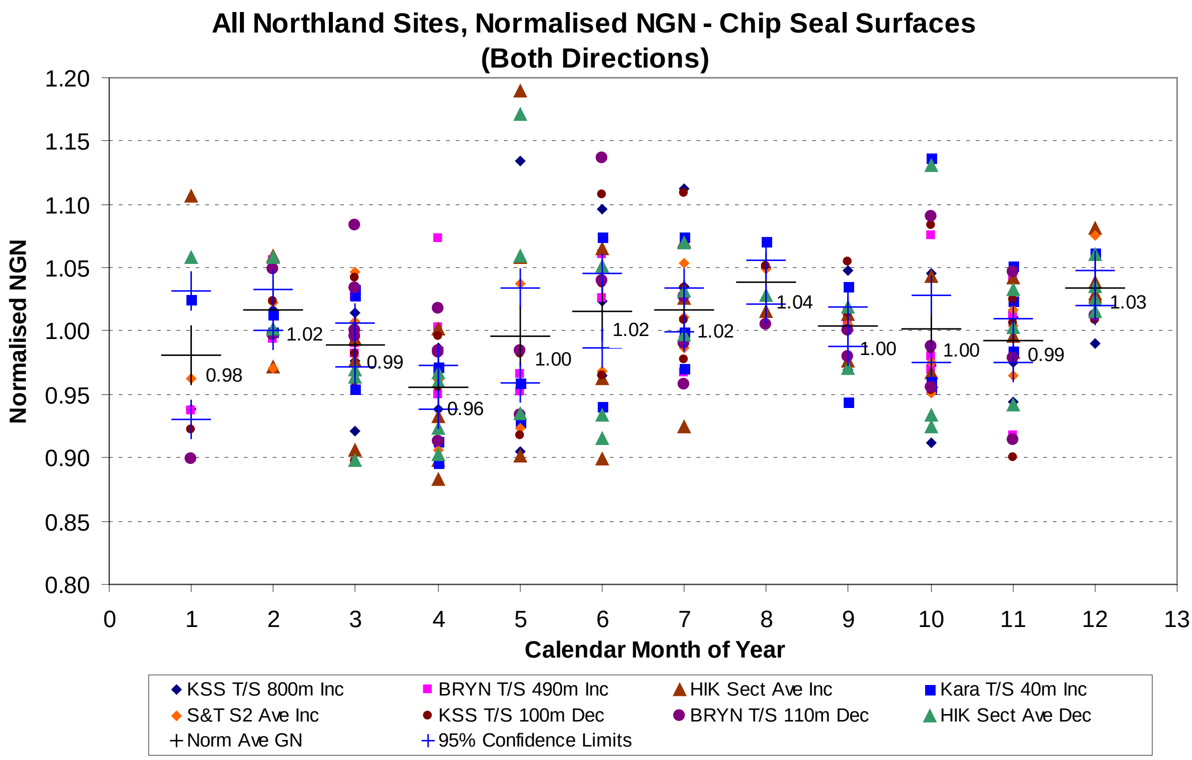


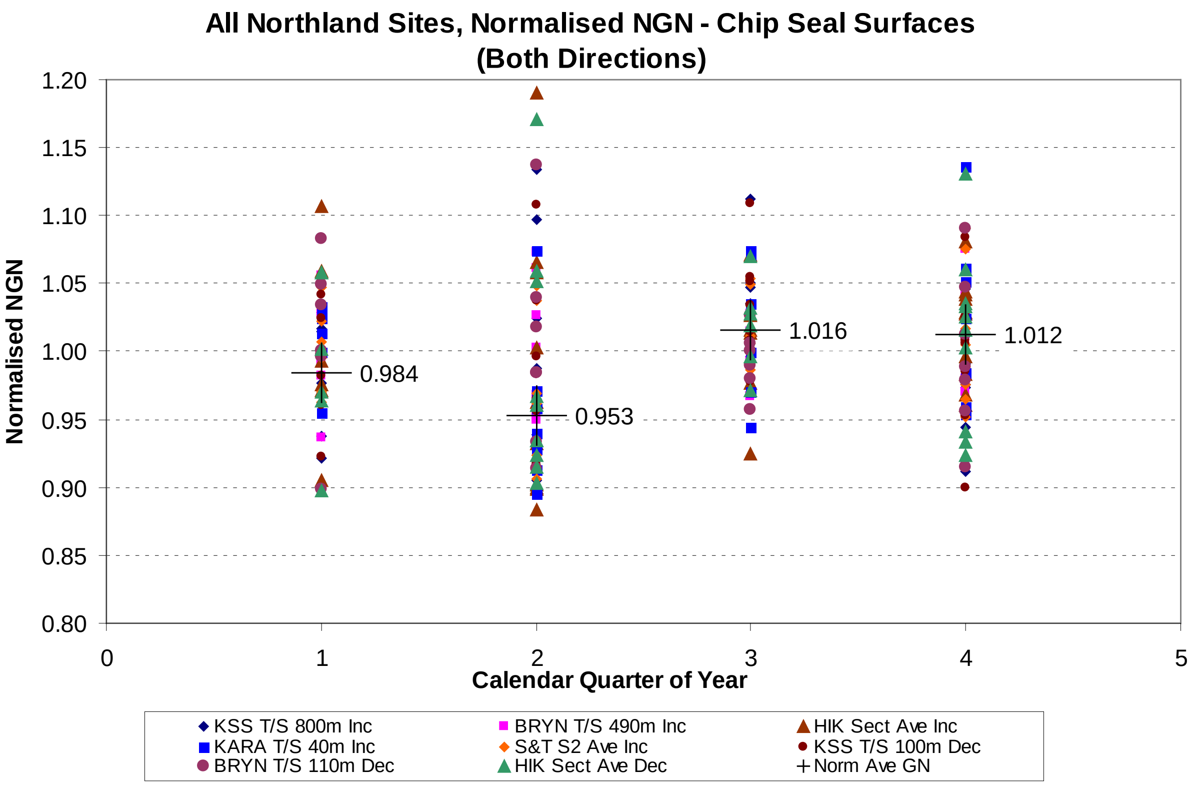
Table 6.2 Normalised GripTester results for Northland sites, by calendar month

All Northland Sites (Both directions) Normalised NGN results by Months of the Year

Sample Section Descriptive Statistics	Jan Month 1	Feb Month 2	Mar Month 3	April Month 4	May Month 5	June Month 6	July Month 7	August Month 8	Sept Month 9	Oct Month 10	Nov Month 11	Dec Month 12
Sample Count	8	14	27	26	21	20	26	7	15	24	24	14
Mean	0.98	1.02	0.99	0.96	1.00	1.02	1.02	1.04	1.00	1.00	0.99	1.03
Maximum	1.11	1.06	1.08	1.07	1.19	1.14	1.11	1.07	1.05	1.14	1.05	1.08
Minimum	0.90	0.97	0.90	0.88	0.90	0.90	0.92	1.01	0.94	0.91	0.90	0.99
Range	0.21	0.09	0.19	0.19	0.29	0.24	0.19	0.07	0.11	0.23	0.15	0.09
Standard Deviation	0.074	0.030	0.047	0.045	0.087	0.068	0.045	0.023	0.031	0.067	0.043	0.027
95% Confidence Interval	0.051	0.016	0.018	0.017	0.037	0.030	0.017	0.017	0.015	0.027	0.017	0.014
Variance	0.005	0.001	0.002	0.002	0.009	0.005	0.002	0.001	0.001	0.004	0.002	0.001
Coefficient of Variation (CoV)	0.075	0.030	0.047	0.047	0.087	0.067	0.045	0.022	0.031	0.067	0.044	0.026

Further analysis was undertaken to test the hypothesis that sorting the dates into the four quarters of the year would confirm the seasonal effect across quarters, thereby demonstrating lower NGN results in the summer quarters and higher results in the winter quarters. The results of this analysis are shown in figure 6.6, which suggests that lower normalised skid resistance results occurred in the first two quarters (0.98 and 0.95NGN respectively) and higher values occurred in the third and fourth quarters (1.02 and 1.0NGN).

Figure 6.6 NGN for the Northland chipseal sites, by quarter



6.2.4 Seasonal variation summary discussion

The analysis described above determined the average section normalised GripNumber (NGN) results for a number of field test sections, including the comparison of these results for calendar months and quarters of the year. It suggested that a seasonal polishing/rejuvenation cyclical effect does exist. However, the scatter of the results and the variation within the months or quarters of the year also demonstrated that other factors are involved and need to be accounted for in future prediction methods. These factors (eg rainfall and surface contaminants) can cause significant short-term variations in the measured coefficient of friction, and are considered in the next section.

6.3 Short-term variations

6.3.1 Introduction

As noted earlier, Hill and Henry (1981) stated that large variations in skid resistance, from day to day or week to week, seemingly occur due to rainfall patterns and local weather conditions, these being superimposed on an annual cycle. They developed a model that expresses the value of skid resistance at any time (SN_O) as a function of the short-term residual variation in measured skid resistance (SN_{0R}), the long-term residual variation in measured skid resistance (SN_{OL}), and the measure of (SN_O) that is independent of short- and long-term variations. They also found differences between surface types for the value of long-term variations in skid resistance; eg a negative exponential relationship for asphalt surfaces and a linear increase in skid resistance with time for Portland Cement Concrete (PCC) surfaces. From this, they demonstrated that models could be developed in the US to adjust for significant seasonal and short-term skid resistance-related variations, explaining up to 57% of the measured variation.

Cenek et al (2003a) confirmed the rainfall/skid resistance relationship from skid-testing results in the Wellington region of New Zealand. The results demonstrated that the time lapse since the last rainfall can have a significant short-term negative effect on skid resistance. The measured variation (using a GripTester, ie GN), apparently due to the combined effects of pollutants and rainfall, demonstrated a reduction in measured skid resistance of at least 10% over 8–11 days since the last rainfall (refer to figure 6.7). The four data points shown were each the average result of six different sites on separate days, and indicate the trend. Wilson et al (2003) and Wilson and Dunn (2004) tentatively indicated a similar trend from measurements at the Hikurangi site,[11] with both the GripTester and the SCRIM device, at different times.

An observation in the Cenek et al (2003a) research study was as follows:

> *Experience and common sense indicates that [skid resistance] cannot continue to decrease at the same rate indefinitely if there is a prolonged period without rain. It is likely that the rate of reduction … is greatest within the first 2 weeks after rain. The data in* [figure 6.7] *supports this view with some indication that the rate of reduction … decreases as time goes on … a reasonable hypothesis might be that the rate of reduction … 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 … 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.*

The corresponding increase in measured skid resistance, apparently due to washing and traffic action during a rainfall event, was also reported by Cenek et al (2003a, 2004) from eight successive runs using

11 Which has since proven to have the highest range of skid resistance variation of the Northland sites – refer to table 5.1.

the GripTester (refer to figure 6.8). The overall measured increase (approx 10%) is, as would be expected, in the same order of variation as the decrease in measured skid resistance due to the combined effect of pollutants and time lapse since the last rainfall. These measured short-term variations indicate that skid resistance does change over very short time intervals. Such effects are reported in the following sections.

Figure 6.7 Measured decline in skid resistance due to environmental effects (Cenek and Davies 2004)

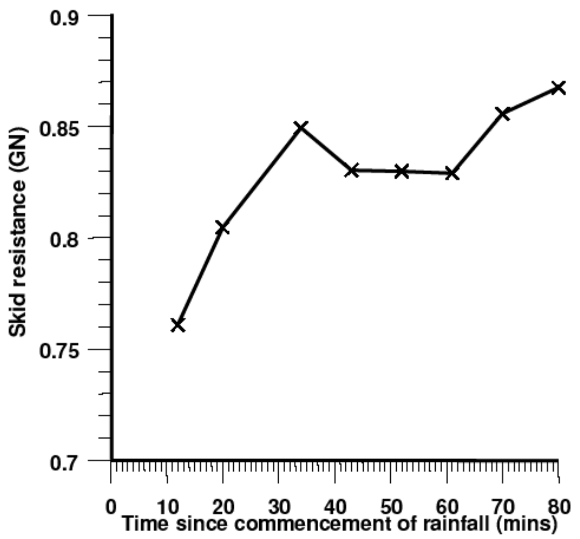
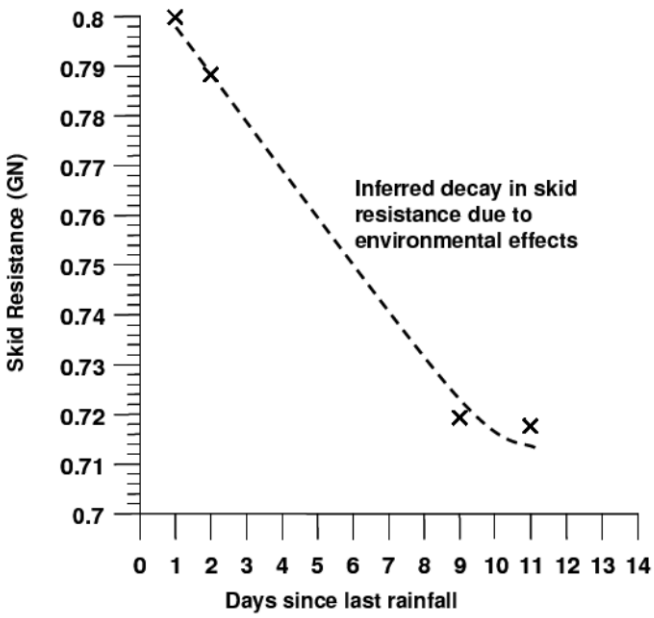


Figure 6.8 Measured increase in skid resistance during rainfall event (Cenek et al 2004)



6.3.2 Rainfall data

Rainfall data was collected for this research at the chosen field sites by a combination of two methods:

- by the recording (where possible) of daily rainfall records by Works Infrastructure staff in Northland from manual pluviometers installed in a protected position adjacent to the field sites

- from the closest NIWA automatic rainfall gauge, or Auckland City Council-operated automatic rainfall gauge stations.

For the Tamaki Campus and the Ports of Auckland sites, rainfall data from the closest automatic rainfall gauge stations were used. The Tamaki Campus site had a full automatic weather station on site. For the Ports of Auckland site, data from the Auckland City Council-operated Albert Park rainfall gauge station was used.

Due to the distance between the Northland field sites and to the closest NIWA rainfall gauge stations, manually recorded pluviometer data was used to correlate automatically recorded NIWA data with the on-site rainfall data at the Northland sites. The closest NIWA rain-gauge stations used for the Northland sites, and their associated proximity to the five field sites, are shown in figure 3.6. A correlation analysis of the manually recorded data from 1 January 2003 to 10 November 2003 was used for each of the five Northland sites to determine which NIWA rainfall-gauge stations best represented the on-site rainfall conditions. In some cases this was not the closest gauge station. It was found that in some cases, using the recorded data from two rain-gauge stations gave a better correlation than using just one rain-gauge station. The best-correlated results obtained by this analysis were then used to modify the NIWA rainfall recorded data to the on-site rainfall data used in subsequent analysis. The results of this analysis, and the chosen gauges for the rainfall analysis with measured skid resistance, are shown in table 6.3 for the five Northland sites.

Table 6.3 Correlation of NIWA rainfall gauges with manually recorded data

Northland field site	NIWA gauges and weighting for site	NIWA gauge name	Distance to site	Coefficient of determ(R^2)	Respective linear modification factor[a]
Kaiwaka Slag	A54821	Mangapai	39.2kms	0.90	0.8044
Brynderwyn South	A54821	Mangapai	39.2kms	Not available[b]	0.8044
Hikurangi	A54623 (48%) & A54737 (52%)	Ruatangata & Whangarei Aero	8.6kms & 18.4kms	0.81 & 0.87	1.2034 & 1.4541
Kara Road	A54623 (52%) & A54821 (48%)	Ruatangata & Mangapai	9.0kms & 13.0kms	0.82 & 0.75	1.0817 & 1.2723
Snooks–Tatton	A54623 (50%) & A54821 (50%)	Ruatangata & Mangapai	9.0kms & 13.0kms	0.80 & 0.81	0.9855 & 1.2734

a) The linear modification factors are used respectively to multiply the rainfall-gauge station data that gave the highest correlation with the manual rainfall data recorded at the site.

b) A problem with the manual rainfall gauge at this site meant that it was decided to use the adjacent Kaiwaka data, which was 10kms south of the Brynderwyn South site.

The rainfall data for all sites was recorded as the total depth in millimetres (mm) of rainfall per day. Therefore the intensity of rain could not be taken into account, although this was expected to have some effect on measured skid resistance. There were also some significant differences in the methods of recording the rainfall data that could affect the subsequent analysis. The NIWA rainfall-gauge stations use a 24-hour clock that sums the rainfall for the previous day until 6:00am the next morning. The manual rain gauges could only determine the total depth of rain since the last reading (at best, over a 24-hour period). The time of this reading was not always consistent, although most readings were undertaken early to midmorning. The timing of the recorded rainfall data and the timing of the skid resistance test becomes important when analysing the previous rainfall history, and when deciding whether rain occurred prior to a test at the site or after a period of rain. At times this was difficult to determine, as rainfall patterns in

Northland are often irregular and, on many occasions, the data collection team would leave Auckland in fine weather, and by the time of arrival at the site (up to 2.5 hours later), a number of showers would have occurred. Furthermore, the five sites were tested during the day between approximately 9:00am and 5:00pm (when the team returned to Auckland), which could have resulted in quite different testing conditions during that day. On a few occasions when repeat tests were undertaken on the same site in the morning and then later in the afternoon, significantly different results were recorded.

The following section discusses a number of rain functions that were used to characterise the amount of rain that had occurred at the field sites over a certain previous length of time. This was required to determine what effect the previous rainfall history had in terms of affecting measured skid resistance.

6.3.3 Rainfall functions

Various rain functions were used to compare the effect of the rainfall history prior to a measured coefficient of friction. Hill and Henry (1981) used a dry-spell factor (DSF) featuring a logarithmic function of the number of days plus one since the rainfall was greater than 2.5mm, for a maximum period of the previous seven days. They also compared the DSF results to a weighted rain function (WRF) that had been developed earlier by Dahir et al (1979). The WRF is a sum of the total for each day of the amount of rain on a given day divided by the number of days preceding the skid resistance test, up to a maximum of the previous five days.

However, it was not known how long an effect rain, or the lack of rain, lasts on the measured pavement skid resistance. Therefore, in this research, a range of rainfall periods was trialled. As manual rainfall pluviometers were used at the site, the effect of the intensity of rainfall was not addressed even though it is recognised that this may have a significant effect on the washing/cleaning of detritus off the road surface, thereby affecting the measured coefficient of friction. The effects of washing fine particles of detritus from the surface may be more effective with prolonged periods of light rainfall, compared with shorter periods of heavier rainfall, especially when combined with traffic action; however, this effect could not be tested with manual pluviometers with data readings only taken on a daily basis. A range of previous rainfall periods was used to compare with the measured skid resistance (most commonly 5 days, 7 days and 20 days).

The amount of rainfall to effect change in skid resistance behavior was tested by considering various thresholds of greater than 1mm, 2mm and 5mm of rainfall. This meant, for instance, if 10 days prior to a skid resistance measurement, 25mm of rainfall fell within an approximate 24-hour period and a threshold of 5mm was used, then even though three days prior to the test 3mm of rainfall fell in a 24-hour period, this would be deemed insignificant in modifying the behavior of skid resistance for the 10-day period. (Hill and Henry (1981) used a threshold of 2.5mm.) The rain function that produced the highest correlation was then used for further analysis. The rain functions that were trialled, and the periods of rainfall history, prior to a skid resistance test, that were analysed, were:

- **Days since last rainfall (DSLR)** > *x*mm of rainfall: This simple rain-function measure records the number of days prior to the skid resistance test until >*x*mm of rainfall occurred. It is a relatively crude measure that does not take into account how much total rainfall has occurred over previous periods prior to the test. Rainfall thresholds of greater than 1mm, 2mm and 5mm were analysed.

- **Dry-spell factor (DSF)**, where *x* was trialled for thresholds of rain of >1mm, 2mm and 5mm of rainfall.

$$DSF = \ln(t_R + 1) \qquad \text{(Equation 6.2)}$$

where:

DSF = dry-spell factor

t_R = the number of days since the last rainfall of *x*mm or more (up to a maximum of 7 days, hence $0<t_R<7$)

- **Weighted Rain Function (WRF)**, where the period of previous rainfall in days (*n*) was trialled for 5, 7 and 20 days.

$$WRF = \sum_{i=1}^{n}\left(\frac{R_i}{i}\right)$$ (Equation 6.3)

where:

WRF = weighted rain function

R_i = rainfall in mm on the *i*th day prior to the test

I = number of days prior to the test, ranging from n = 5, 7 or 20 days respectively.

The following sections discuss the results of the analysis using the above rain functions, firstly with the GripTester device and secondly, with the SCRIM device for the Hikurangi site in Northland. The Hikurangi site had an old but stable seal surface, and it was expected to be in an 'equilibrium state', other than exhibiting short-term and seasonal variations. For this reason, it was used to trial differing rain functions against the measured values of skid resistance, to determine whether rainfall can be correlated against the measured coefficient of friction. The Hikurangi site had also been shown to have the greatest variation of all the Northland sites. This variation was hypothesised to be related to the amount of detritus/ contaminant that builds up on the road surface, thereby helping to polish/abrade the surface, which either reduces or rejuvenates the microtexture.

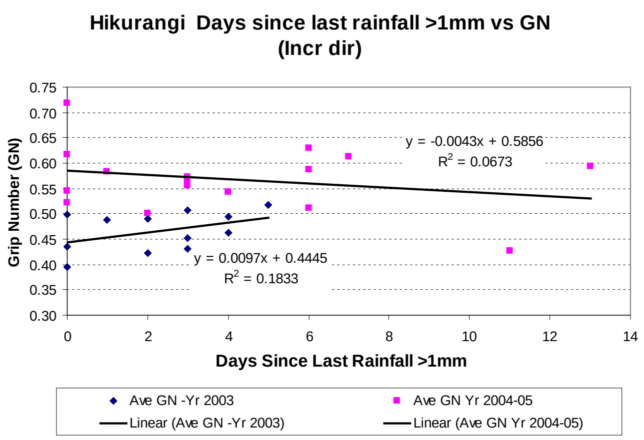
6.3.4 Effects of rainfall on GripTester device measurements

The effect of the previous rainfall history was examined in relation to the variation in measured skid resistance as measured by the GripTester device. Previous research had shown that the greater the fine and dry period prior to a skid resistance measurement, the lower the measured coefficient of friction.

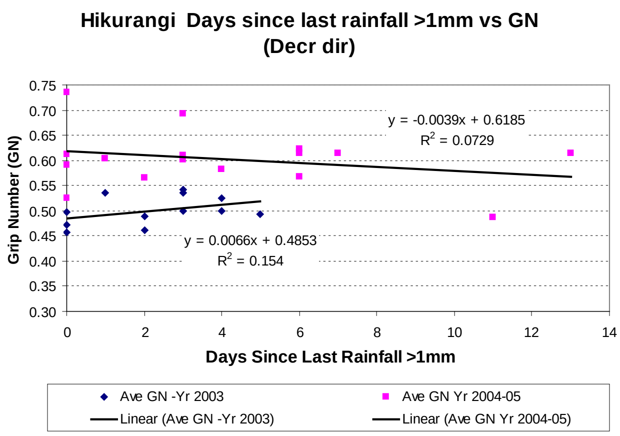
Figure 6.9a–f shows the analysis of the measured coefficient of friction by the GripTester at the Hikurangi site for the increasing and decreasing directions, respectively, in relation to the number of days since the last rainfall greater than 1mm, 2mm or 5mm (refer to the explanation of these thresholds in section 6.3.3). The analysis of the first year of results is shown separately from the second year, because the two respective years had significantly different results (as seen in the figures). As discussed earlier, it is unknown whether the differences from the first year of results (2003) are real recorded differences, in comparison with the 2004/2005 data, because of the problems with the GripTester that occurred during the summer of 2003/2004 (the device was rebuilt during this period). However, if measured skid resistance does depend upon the length of the period of no rain, then a decreasing (negative) trend of skid resistance with increase in the number of days since last rainfall would be expected within both years' data.

Figure 6.9 Days since last rainfall and GN (Hikurangi site) for various depths of rainfall

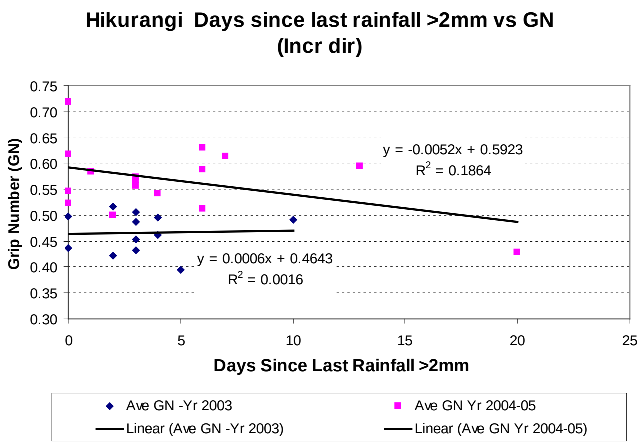
(a) Hikurangi DSLR > 1mm vs GN (increasing direction)



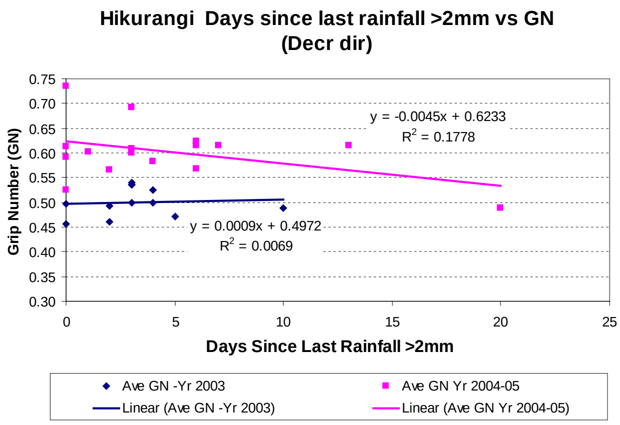
(b) Hikurangi DSLR > 1mm vs GN (decreasing direction)



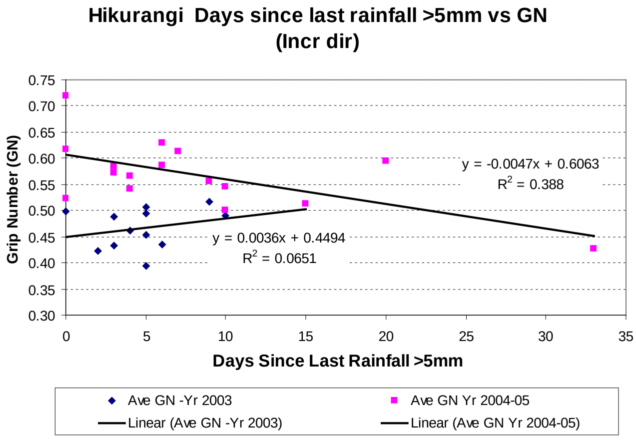
(c) Hikurangi DSLR > 2mm vs GN (increasing direction)



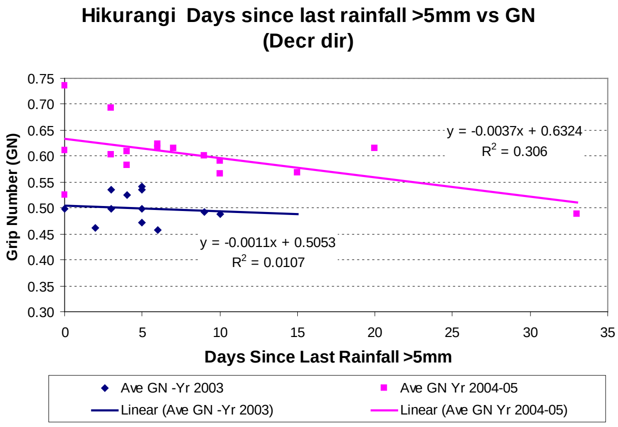
(d) Hikurangi DSLR > 2mm vs GN (decreasing direction)



(e) Hikurangi DSLR > 5mm vs GN (increasing direction)



(f) Hikurangi DSLR > 5mm vs GN (decreasing direction)



Whilst all of the figures showed a decreasing trend for the 2004/2005 years, it was not a highly correlated trend, with the coefficient of determination (R^2) ranging from 0.07 to 0.39. The outliers at both ends of the data had a significantly greater effect on the coefficient of determination than data points in the middle. This effect affected the trends in all graphs. The highest correlations were derived when the days since last rainfall greater than 5mm was used, with the coefficient of determination (R^2) recorded as 0.39 and 0.31 (for the 2004/2005 data), respectively, for the increasing and decreasing directions. The rate of decrease in measured coefficient of friction between all of the graphs (ie for the DSLR >1, 2 and 5mm) was relatively consistent for the 2004/2005 year, which had a value of approximately -0.004GN per day.

It is surprising that a possible effect exists up to 35 days for the >5mm depth of rain. If there were a lot more data points between 5 and 25 days since last rainfall, then as suggested by Cenek et al (2003b, 2004), it could become apparent that the relationship is not linear, but logarithmic, and that little real change occurs after approximately 15 to 20 days. Using a much smaller data set, Cenek et al (2003b, 2004) have suggested that a 10% loss of skid resistance can occur within the first two weeks of no rainfall.

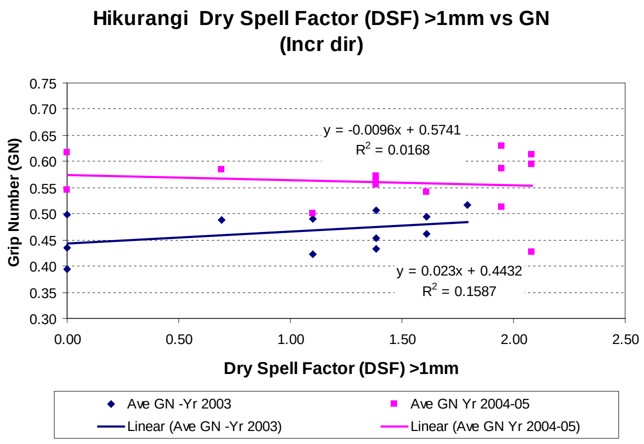
An analysis similar to that using the DSLR rain function was undertaken on the Hikurangi site and raw rainfall data, using the logarithmic DSF rain function described in section 6.3.3. The results of this analysis are shown in figure 6.10a–f. These graphs show the measured coefficient of friction as recorded by the GripTester, in both directions at the Hikurangi site, in relation to the natural logarithm of the time (in days) prior to a measured skid resistance test where the rainfall was greater than 1mm, 2mm and 5mm of rain, respectively.

As discussed above, it was expected that a logarithmic rainfall function would be a better fit to the data. However this was not so for the data for the 2004/2005 year, as the range of coefficients of determination (R^2) was significantly lower (0.02–0.14) using the DSF, compared with the DSLR rain function. Again, the 2003 year data showed either random results with no gradient, or slightly positive results, which was contrary to what was expected and shown by others.

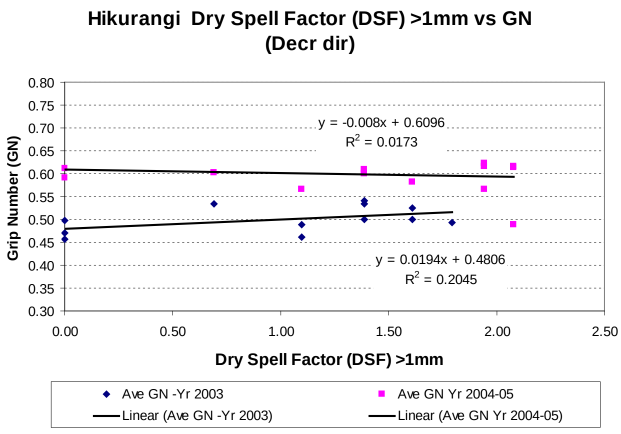
The DSF developed by Hill and Henry (1981) was limited to a maximum of only the previous seven days' rainfall history. As shown in the DSLR analysis, the rainfall history further back than seven days could continue to affect the skid resistance result. Subsequently, periods of 15 days and 20 days were analysed for depths of rainfall greater than 5mm (the highest correlated result). However, the coefficient of determination (R^2) in the increasing direction increased only marginally, by approximately 0.03–0.17, but in the decreasing direction reduced by approximately 0.045–0.048. Therefore, it can be concluded that for this data set, the DSF rain function explains very little of the measured variation of surface friction.

Figure 6.10 Dry-spell factor (DSF) and GN (Hikurangi site) for various depths of rainfall

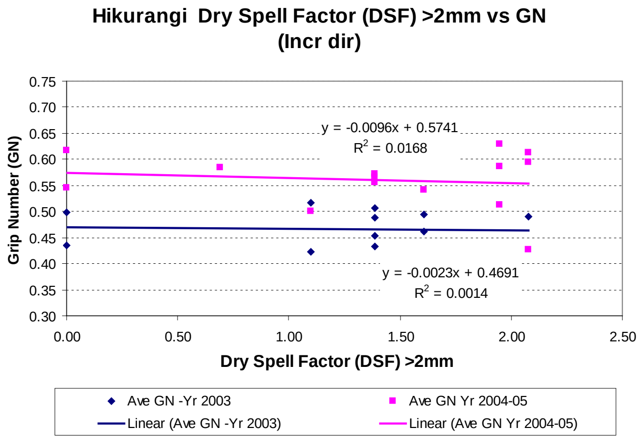
(a) Hikurangi DSF > 1mm vs GN (increasing direction)



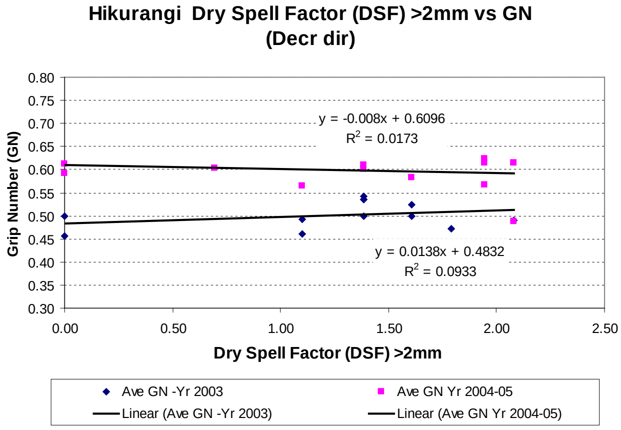
(b) Hikurangi DSF > 1mm vs GN (decreasing direction)



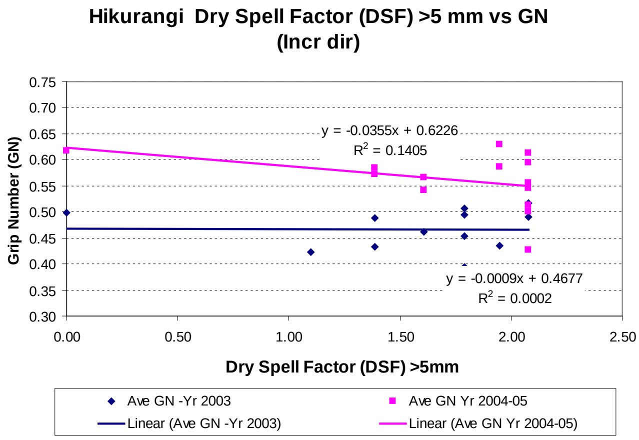
(c) Hikurangi DSF > 2mm vs GN (increasing direction)



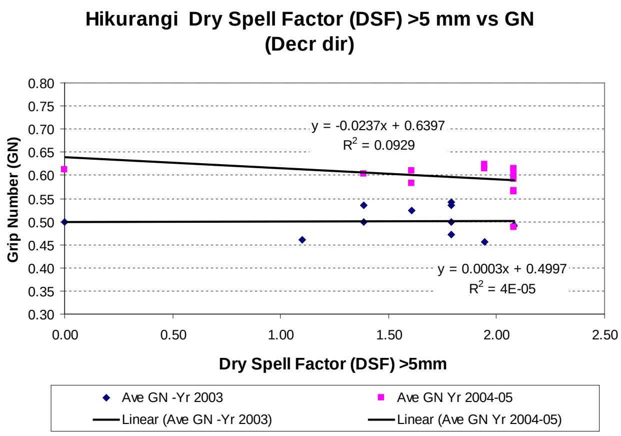
(d) Hikurangi DSF > 2mm vs GN (decreasing direction)



(e) Hikurangi DSF > 5mm vs GN (increasing direction)



(f) Hikurangi DSF > 5mm vs GN (decreasing direction)

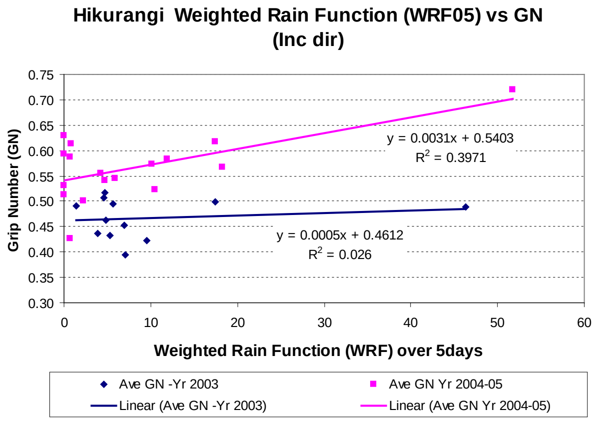


An analysis similar to that using the DSLR and DSF rain functions was undertaken on the Hikurangi site and raw rainfall data, using the linear WRF described in section 6.3.3. The results of this analysis are shown in figure 6.11g–h for the increasing and decreasing directions respectively, and for rainfall periods of 5 days, 7 days, 10 days and 20 days. These graphs show the measured coefficient of friction as recorded by the GripTester, in both directions at the Hikurangi site, in relation to the sum of each day's rainfall divided by the number of days prior to the measured skid resistance test. The rainfall period scenarios analysed were for 5 days, 7 days, 10 days and 20 days prior to a skid resistance test. For this rain function, it was expected that a positive trend would occur, meaning that the greater amount of rainfall that had occurred prior to the test, the higher the measured skid resistance value.

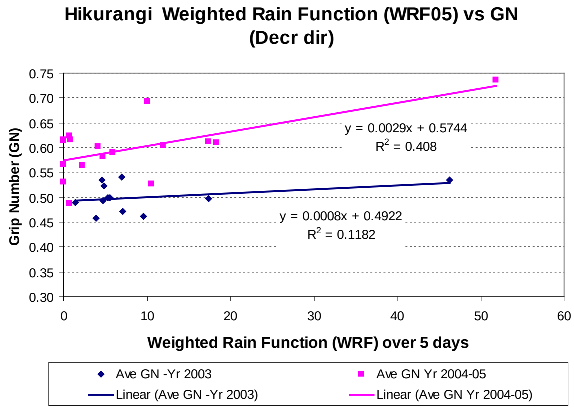
The WRF in this research had significantly higher coefficients of determination (R^2) than the 2004/2005 skid resistance data results obtained with the GripTester and analysed using the DSLR or DSF rain functions. The WRF coefficient of determination (R^2) ranged from 0.40 to 0.61. However, the correlation was still poor for the 2003 year, explaining only up to 15% of the variation. The scatter of data points, and especially the sensitivity to change in the outliers, would significantly affect the resultant coefficient of determination. This result was contrary to the research with a locked wheel tester device, undertaken by Hill and Henry (1981). They determined that the DSF better explained the variation in skid resistance results than the WRF developed by Dahir et al (1979).

Figure 6.11 Weighted rain function (WRF) and GN (Hikurangi site) for various rainfall periods

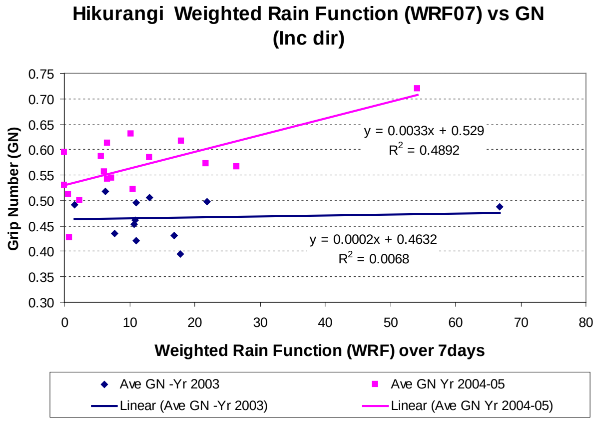
(a) Hikurangi WRF for 5 days vs GN (inc. direction)



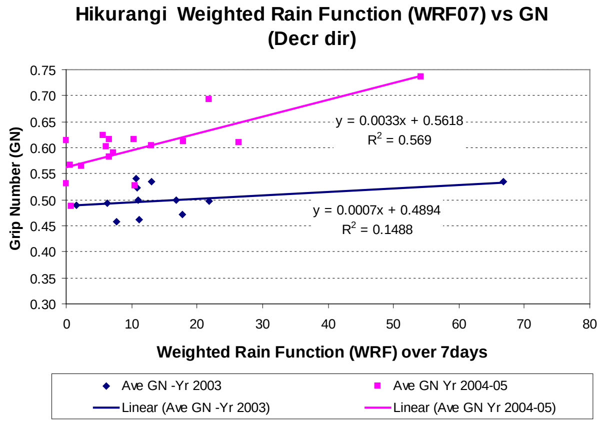
(b) Hikurangi WRF for 5 days vs GN (dec. direction)



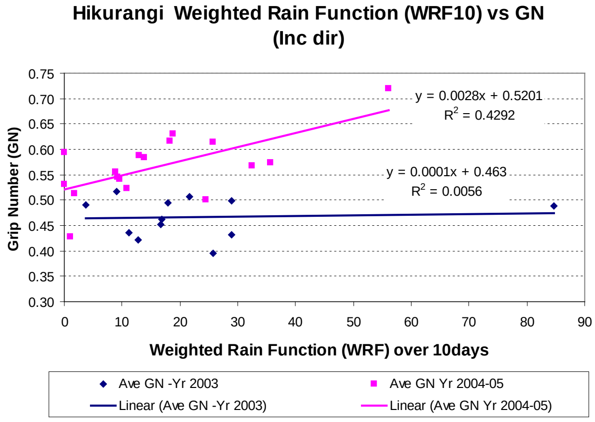
(c) Hikurangi WRF for 7 days vs GN (inc. direction)



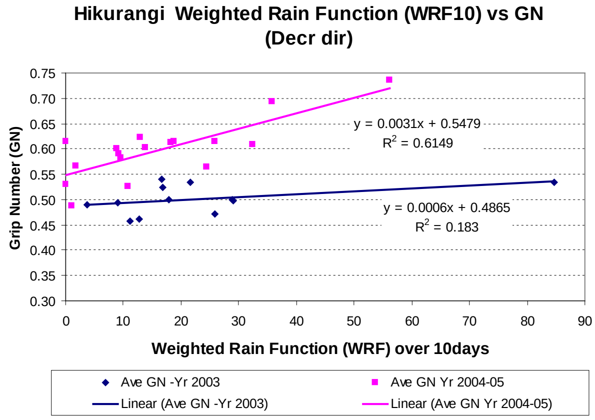
(d) Hikurangi WRF for 7 days vs GN (dec. direction)



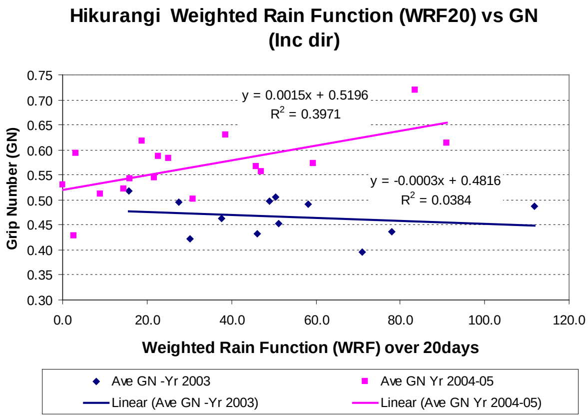
(e) Hikurangi WRF for 10 days vs GN (inc. direction)



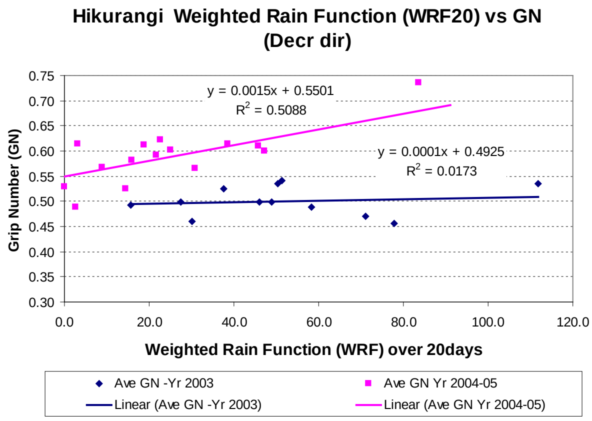
(f) Hikurangi WRF for10 days vs GN (dec. direction)



(g) Hikurangi WRF for 20 days vs GN (inc. direction)



(h) Hikurangi WRF for20 days vs GN (dec. direction)



The graphs in figure 6.11 also show that the WRF better explains the variation in the measured skid resistance data when either a 7-day or 10-day rainfall period is recorded and analysed in comparison to the 5-day or 20-day period. However, it should be noted that the correlation trend results (R^2) were heavily affected by one or two results at the data extreme ends, and if these were treated as outliers and removed the correlation results would not be as significant. Nevertheless, as these results were plausible (as it can be proven that the high amount of rainfall occurred) and it supports the hypothesis that the greater the amount of rain over a given period, the greater the effect of washing the pavement surface, they were retained. Therefore on this basis, it can be concluded that for this data set, site and skid resistance device (GripTester), the WRF was the best rain function to use as it explained up to 60% of the variation of measured surface friction. The DSLR and the DSF rain functions explained little of the measured variation of skid resistance as measured by the GripTester device.

The above analysis was repeated for the DSLR, DSF and WRF functions using only the GripTester Run 1 results to determine whether the GripTester could, by undertaking multiple test runs, 'clean' the surface, thereby affecting the skid resistance results. The analysis was re-run with the GripTester for all of the above cases at the Hikurangi site. Of the 10 cases in the increasing direction, six worsened and four increased very slightly. The DSF improved very slightly but remained a very poor correlation ($R^2 < 10\%$) whereas the best rainfall function that received a reasonable correlation for all durations (WRF05, WRF07, WRF10, WRF20) worsened, from at best, approximately 50% of the variation being explained, to approximately 35%. In the decreasing direction, five correlation cases worsened and five improved; however, the best rainfall function (WRF) once again in all cases worsened by a significant margin. On this basis, it was hypothesised that the averaging of multiple runs achieved a measurement result closer to the true mean than the first run, and on that basis this methodology was continued.

The next section discusses a similar rainfall analysis on the SCRIM device results.

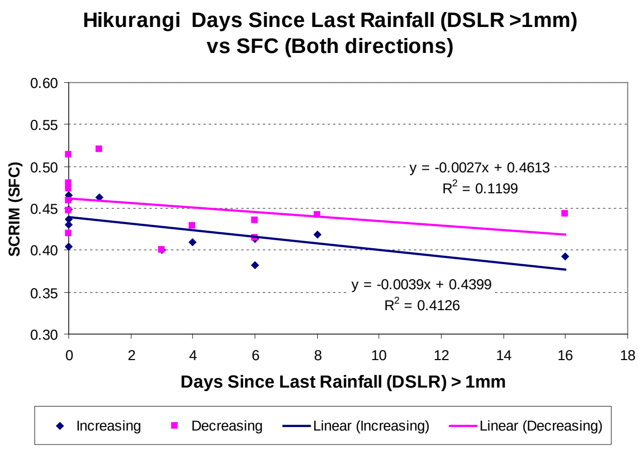
6.3.5 Effects of rainfall on SCRIM device measurements

The effect of the previous rainfall history was also examined in relation to the variation in measured skid resistance as measured by the SCRIM device. The number of data points was considerably less than the GripTester results, due to the less frequent survey measurements that were undertaken during the data collection period. WDM Ltd undertook the SCRIM skid resistance network surveys in the Northland region, both for Transit NZ and for Works Infrastructure (now Downer), who were the network managers at the time. Furthermore, the Hikurangi site was, at the outset of the research, a seasonal control section, which required a minimum of three surveys per summer period. Unfortunately, the decision was made midway through the data collection period to relocate the Transit NZ seasonal site to another location. This meant that the three seasonal SCRIM skid resistance tests per summer were not continued at this site throughout the full data collection period and only the two SCRIM network survey results could be analysed (ie for Transit NZ and Works Infrastructure PSMC 002 network surveys).

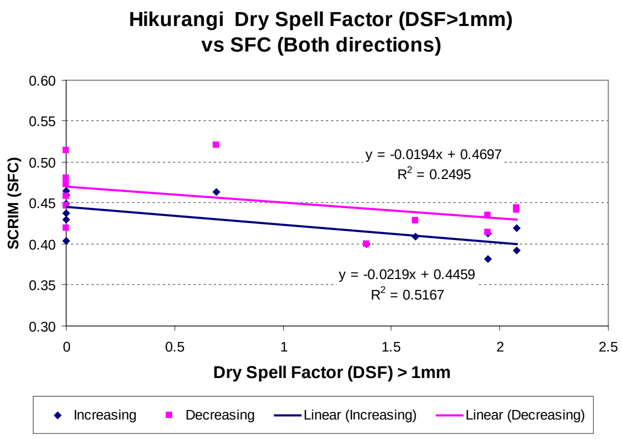
Figure 6.12a-f shows the analysis of the measured coefficient of friction by the SCRIM device at the Hikurangi site for the increasing and decreasing directions in relation to the DSLR and DSF rain functions for greater than 1mm, 2mm and 5mm of recorded rain depth. As with the GripTester analysis, if the hypothesis that the greater the period of no rain, the lower the measured skid resistance was true, then a decreasing (negative) trend of skid resistance with higher value of DSLR and DSF would be expected.

Figure 6.12 DSLR and DSF analysis with the SCRIM device (Hikurangi site)

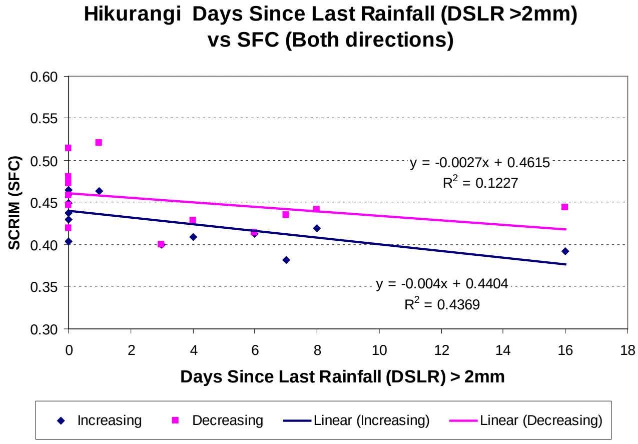
(a) Hikurangi DSLR > 1mm vs SFC (both directions)



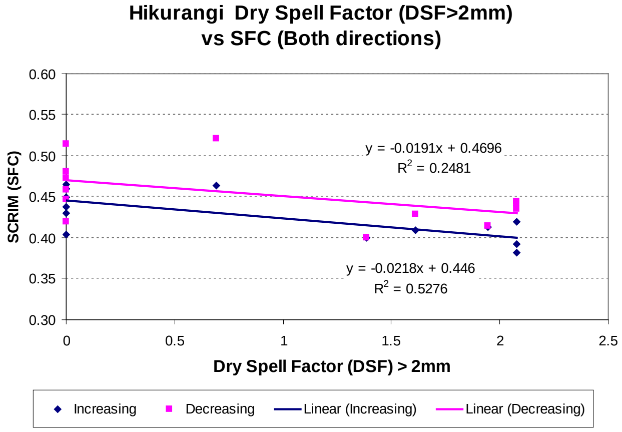
(b) Hikurangi DSF > 1mm vs SFC (both directions)



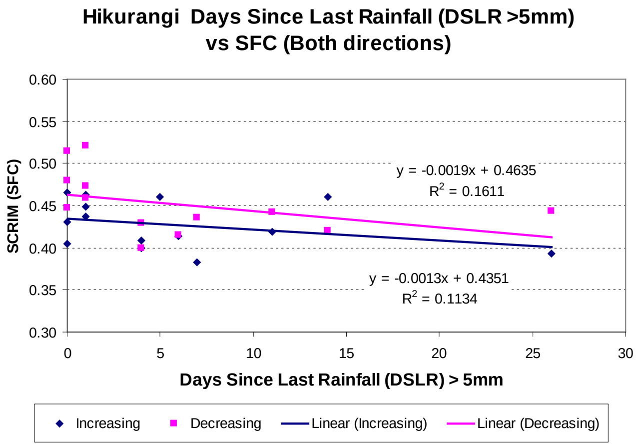
(c) Hikurangi DSLR > 2mm vs SFC (both directions)



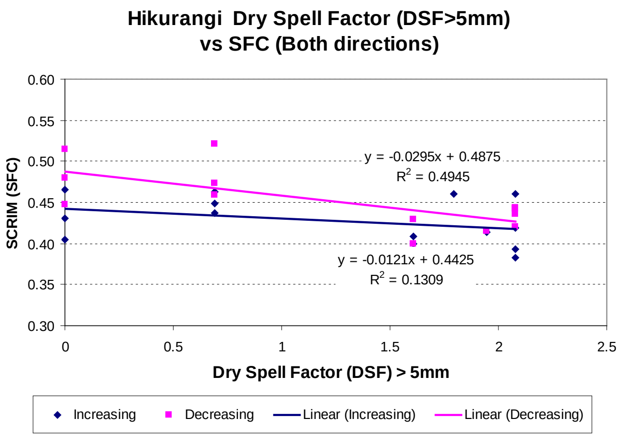
(d) Hikurangi DSF > 2mm vs SFC (both directions)



(e) Hikurangi DSLR > 5mm vs SFC (Both directions)



(f) Hikurangi DSF > 5mm vs SFC (Both directions)



As can be seen from figure 6.12a-f, both the DSLR and the DSF rain functions demonstrated the expected negative trend of decreasing measured skid resistance with increasing dry spells prior to the skid resistance test. The linear rate of decrease was approximately -0.003SFC per day of no rain. However, as discussed for the GripTester device analysis, with more data this would be expected to be closer to a negative logarithmic function, and to feature greater decrease initially. The rate was reasonably consistent among the different depths of rainfall, ranging from -0.0013 to -0.040SFC. The increasing direction gave significantly better correlation results than the decreasing direction for the >1mm and >2mm analysis results, although the opposite trend occurred for the rain depth >5mm. The coefficients of determination (R^2) ranged from 0.11 (very low) to 0.43 (reasonable) for the DSLR rain function and for the various directions of test and depths of rain, with the highest correlation obtained for the >2mm rain depth. These correlations were also higher than the results obtained using the GripTester device for the 1mm and 2mm rain depth analysis, except for the >5mm analysis, which featured similar coefficients of determination (R^2=0.38).

As expected, the results of the logarithmic DSF analysis on the SCRIM device results (unlike the GripTester device) were better than those from the DSLR rain function and demonstrated a stronger correlation between the SCRIM and the DSF rain function than the GripTester and the DSF function. The coefficients of detemination (R^2) ranged from 0.24 (reasonably low) for the decreasing direction to 0.53 (reasonable) for the increasing direction when the >2mm rain depth analysis was undertaken. This compared to a maximum (R^2) value of 0.14 with the GripTester with the >5mm rain depth. Further analysis was undertaken to determine whether increasing the previous rainfall period from 7 days to 10 and 15 days for the DSF rain function would result in an increase in the coefficient of determination (R^2) of the resultant equation. However, the analysis did not increase the observed (R^2) value and therefore it is concluded that the 7-day period was the most appropriate period for the DSF rain function based on skid resistance measurements with the SCRIM device.

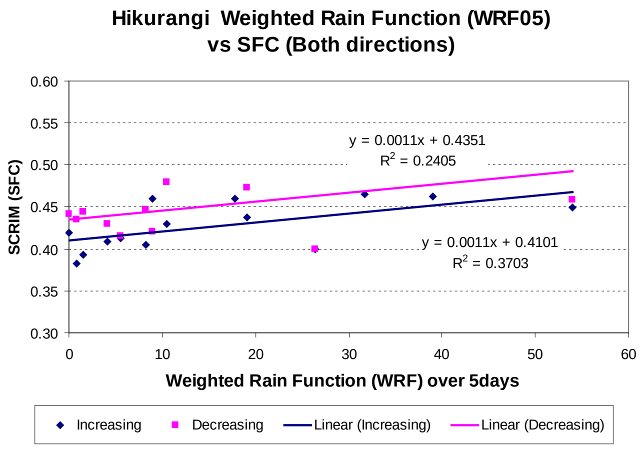
An analysis similar to both the DSLR and DSF rain functions was undertaken on the Hikurangi site and raw rainfall data, using the linear WRF described in section 6.3.3 for the SCRIM device. The results of this analysis are shown in figure 6.13a-d for rainfall period scenarios of 5 days, 7 days, 10 days and 20 days respectively. These graphs show the measured coefficient of friction as recorded by the SCRIM device in both directions at the Hikurangi site, in relation to the sum of each day's rainfall divided by the number of days prior to the measured skid resistance test. For this rain function, it was expected that a positive trend would occur, meaning that the greater amount of rainfall that had occurred prior to the test, the higher the measured skid resistance would be.

Application of the WRF to the SCRIM data (refer to figure 6.13a-d gave (R^2) values that ranged from 0.31 to 0.37 in the increasing direction and from 0.24 to 0.34 in the decreasing direction for the various rainfall period scenarios. These coefficients of determination (R^2) were lower than those for GripTester device, which showed values of approximately 0.60 for the 7-day and 10-day previous rainfall periods for the 2004/2005 data collection period. However, the results of the GripTester device with the WRF function for the 2003 year data were still poor, explaining only 15% of the variation.

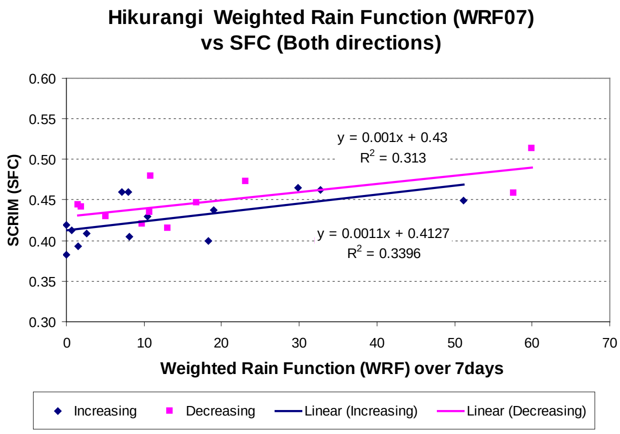
The results of the SCRIM device agreed better with the results of Hill and Henry (1981), who used a locked wheel tester device. They determined that the DSF better explained the variation in skid resistance results than the WRF developed by Dahir et al (1979), whereas the opposite trend was noted for the GripTester device.

Figure 6.13 Weighted rain function (WRF) and SCRIM SFC (Hikurangi site) for various rainfall periods

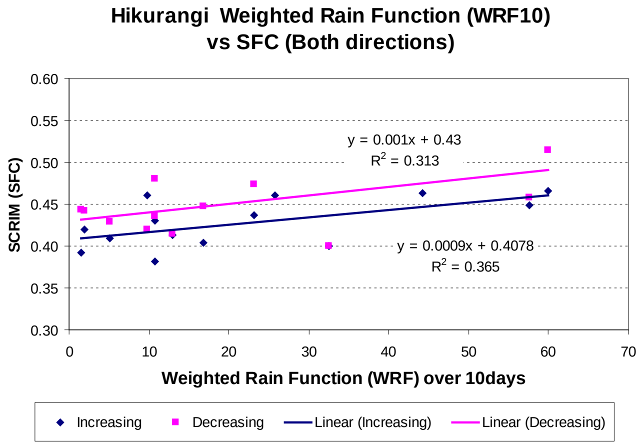
(a) Hikurangi WRF05 days vs SFC (both directions)



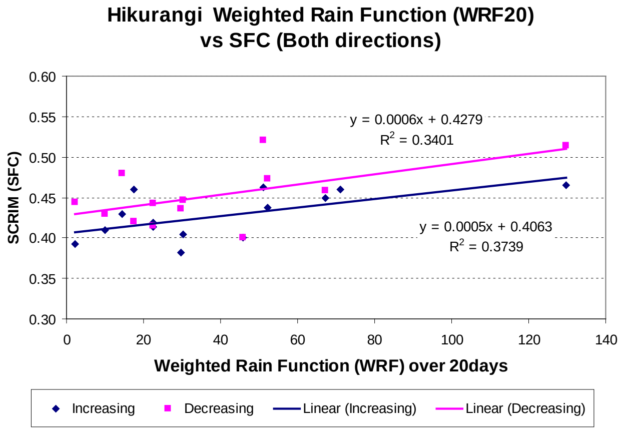
(b) Hikurangi WRF07 days vs SFC (both directions)



(c) Hikurangi WRF 10days vs SFC (both directions)



(d) Hikurangi WRF 20 days vs SFC (both directions)



These differences may be due to having had too few data points with the SCRIM device, or a possible real difference in terms of the device operating mode, and especially the differences in slip speed (GripTester = 15%, SCRIM = 34% and locked wheel tester = 100%) and the sensitivity of the device to external changes in measured surface friction. Furthermore, the devices have significant variations in their modes of operation.

6.3.6 Normalised GripTester results for Northland sites and effects of rainfall

The normalised GripTester device results obtained from field sites or timeslice locations that were predicted to be acting in a stable 'equilibrium level' of polishing and that were used as part of the seasonal analysis were also analysed against the three rain functions discussed above. The results are shown in figures 6.14, 6.15 and 6.16 for the rain depth scenario (or previous rainfall period scenario) that indicated the highest coefficient of determination (R^2).

When the results were normalised from different field sites, even when carefully chosen to be in the 'equilibrium polishing phase', the bi-variate coefficients of determination (R^2) became significantly lower than the results obtained just from the Hikurangi field site. The rain functions used (eg DSLR>*x*mm, DSF>*x*mm and WRF for *x* days) explained, at best, only 5.5% of the observed variation. It was clear from this analysis that other localised site and/or environmental factors were also affecting the measured variation. These other factors were expected to include, but not be limited to:

- temperature
- localised contaminants/detritus
- geological makeup of the aggregate
- traffic loading conditions (ie the number of HCV) – two of the field sites on SH14 (Kara Rd and Snooks-Tatton) had approximately 1/3 of the HCVs as the SH1 sites (Kaiwaka slag, Brynderwyn and Hikurangi).

Figure 6.14 Days since last rainfall (DSLR>2mm) and NGN for Northland sites

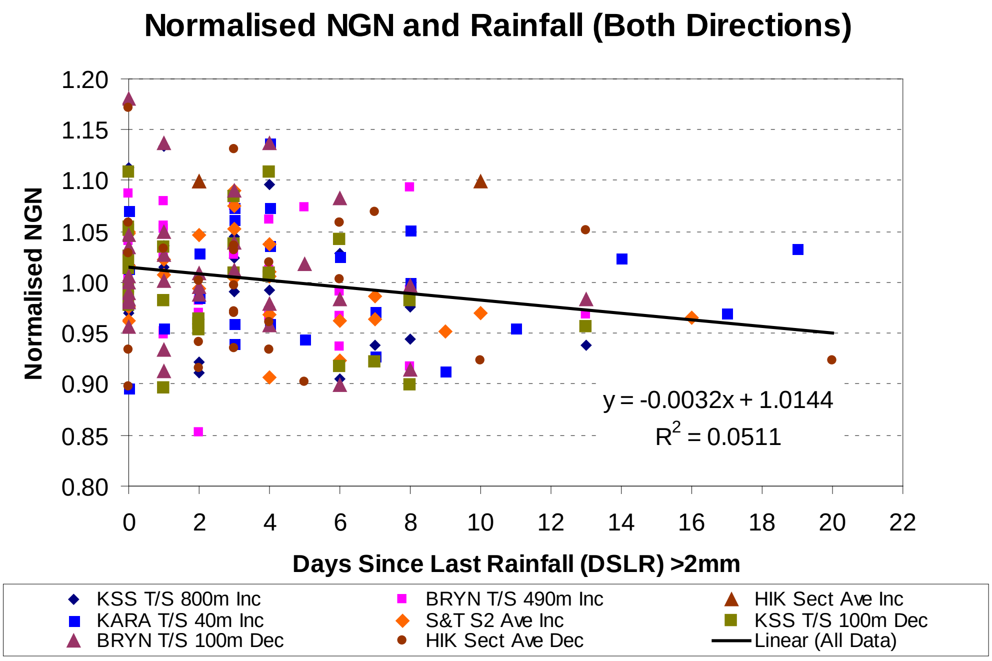


Figure 6.15 Dry-spell factor (DSF>5mm) and normalised NGN for Northland sites

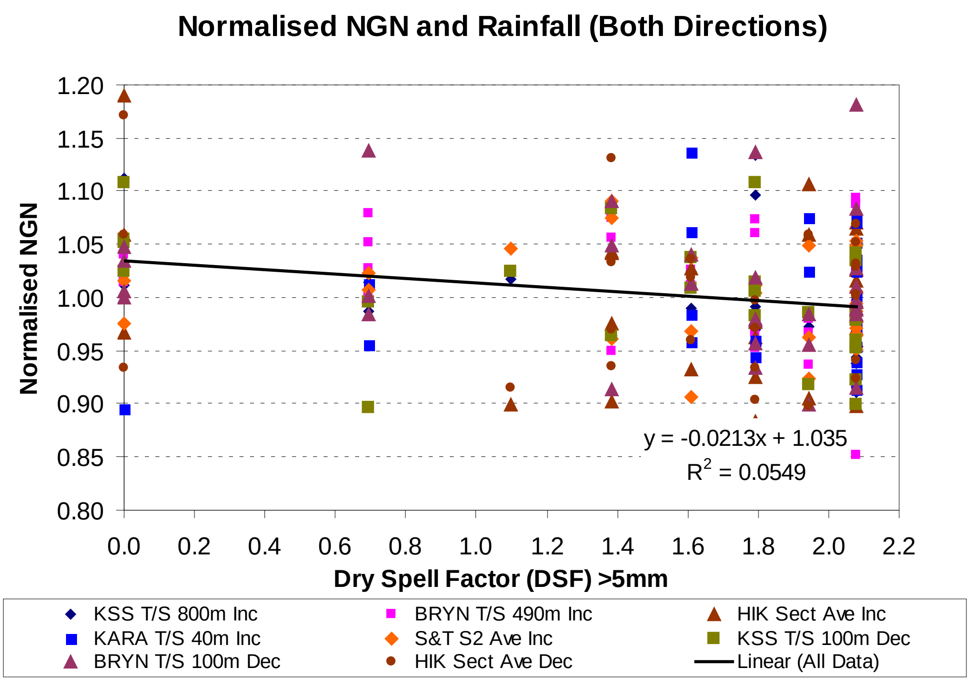
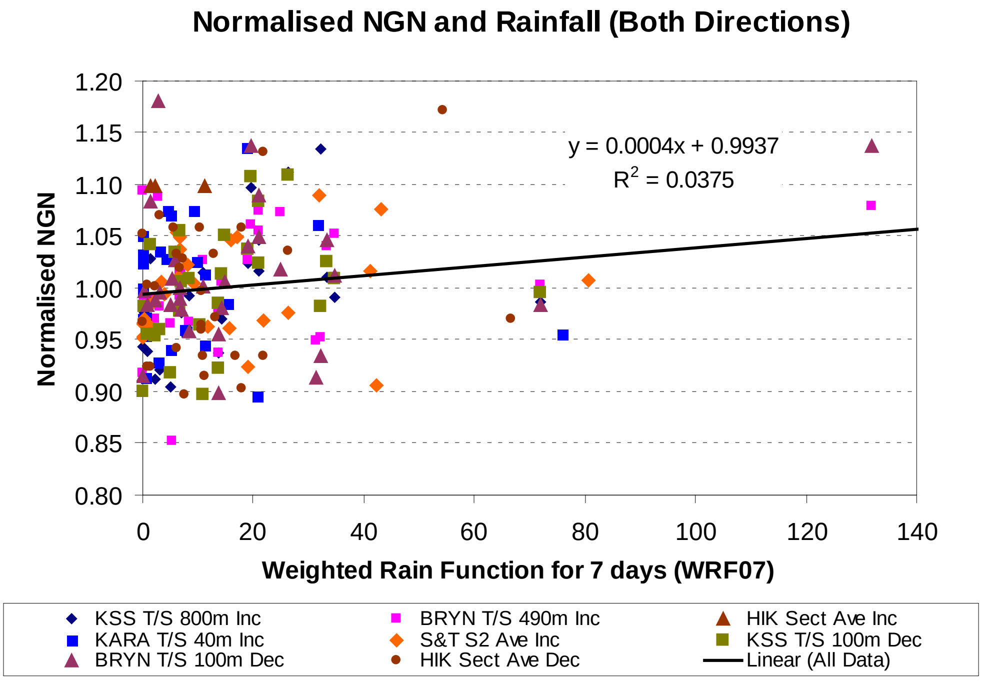


Figure 6.16 Weighted rain function (WRF07) and NGN for Northland sites



Although the coefficients of determination (R^2) of the normalised GripTester device results were poor, figures 6.14, 6.15 and 6.16 show the expected direction of the slope of the equation line and confirm the Hikurangi site trend observations. For example, for the DSLR >2mm rain depth and the DSF >5mm rain depth analysis, both equations were negative, implying that the greater the period of no rainfall, the lower the measured skid resistance would be. Alternatively, the greater the amount of weighted rain depth over a given period prior to a skid resistance measurement (as characterised by the WRF function), the higher the measured skid resistance would be. The slope of these equation lines was likely to be highly dependent upon the traffic loading, the type of surface aggregate and its susceptibility to polishing and/or abrasion, and the likely contaminant agents (detritus/contaminants) that had built up in the aggregate macrotexture of the surface. These factors varied from site to site.

6.4 Washing trials

6.4.1 Introduction

Because of the increasing evidence of the effects of contamination on measured skid resistance results, a washing trial was undertaken at the Hikurangi control site in Northland in early July 2003. The purpose of this trial was to evaluate whether the cleaning of the road surface would result in an improvement in skid resistance, and to identify whether any of the treatments applied were more effective than the others. A 300m control section was established at one end of the test section identified as section 1. Several washing test sections were established, each 150m long. These were treated using the following methods:

- section 2 – gentle washing (two passes with a water cart)
- section 3 – washing and brooming (two passes with a water cart followed by a nylon rotary broom)

- section 4 – Frimokar NZ Ltd high-pressure water-blasting process (operating at a relatively low pressure of approximately 2000psi).

Two sets of benchmarking tests were undertaken, one prior to the installation of traffic control and one after it had been installed. The treated sections were not open to traffic between treatment and testing. Testing of the site was undertaken using both the GripTester and BPT, with texture being determined by the sand circle test method. The results of the trial are discussed in the next section.

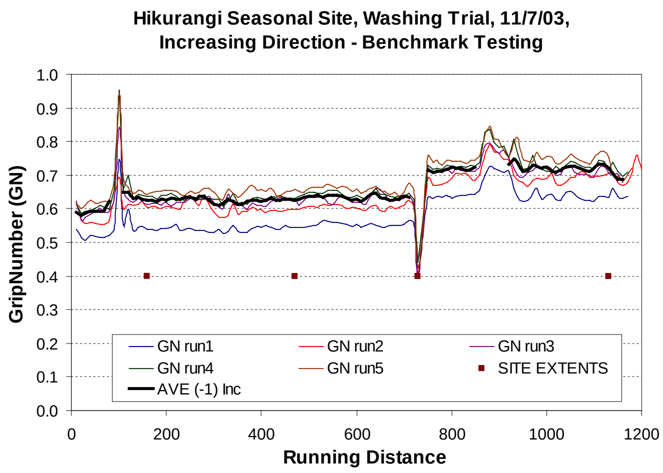
6.4.2 GripTester results

Figures 6.17a and b shows the GripTester results of the benchmarking runs in the increasing and decreasing directions, respectively. Reasonable repeatability and trending can be seen along the length of the sites, with each successive run gradually increasing. The test sections were all located along the left-hand wheel path of the decreasing direction, as shown in figure 6.16c. No treatment was undertaken in the increasing direction, and this lane was left open to carry traffic in a modified arrangement in both directions.

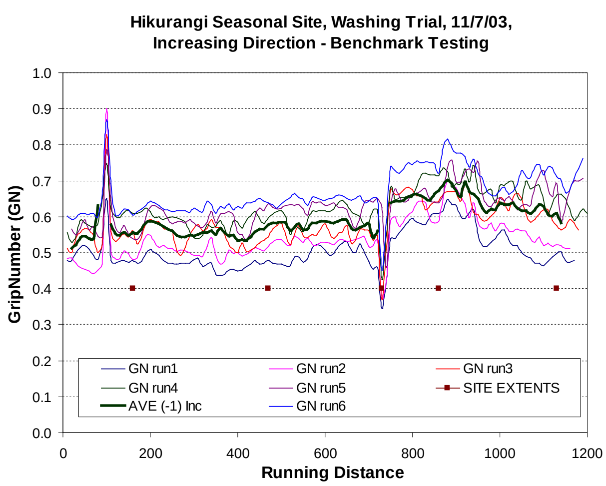
The effects of roughness on the 10m averages of skid resistance produced by the GripTester are shown in figure 6.17a by the spike seen at 100m, while the effect of flushing can also be seen by the trough located at 750m. These sections were deleted from the analysis results so as not to skew the averaging process.

Figure 6.17 Results of washing trials on Hikurangi site, Northland (before and after washing)

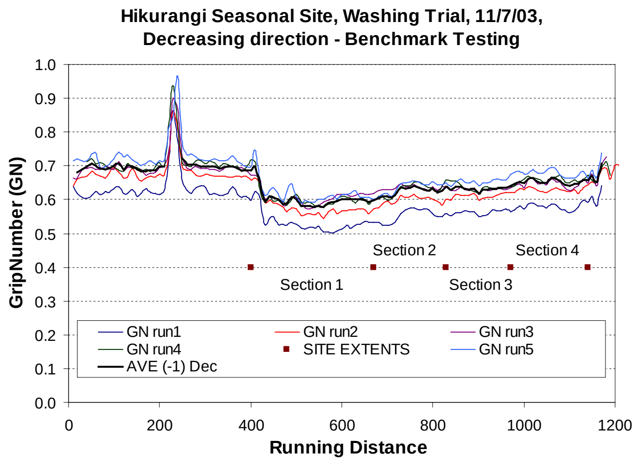
(a) Hikurangi before washing (increasing direction)



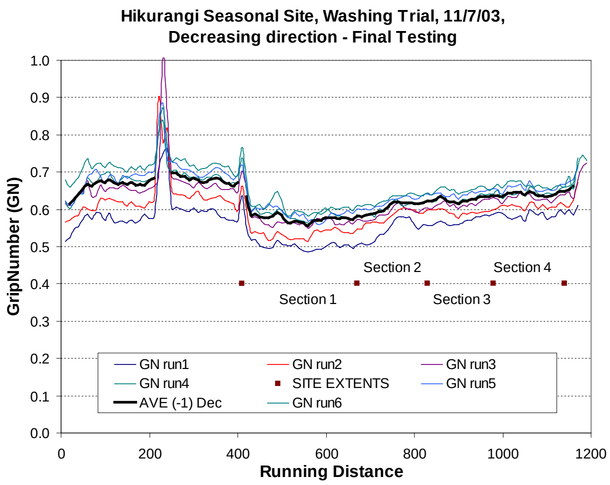
(b) Hikurangi after washing (increasing direction)



(c) Hikurangi before washing (decreasing direction)



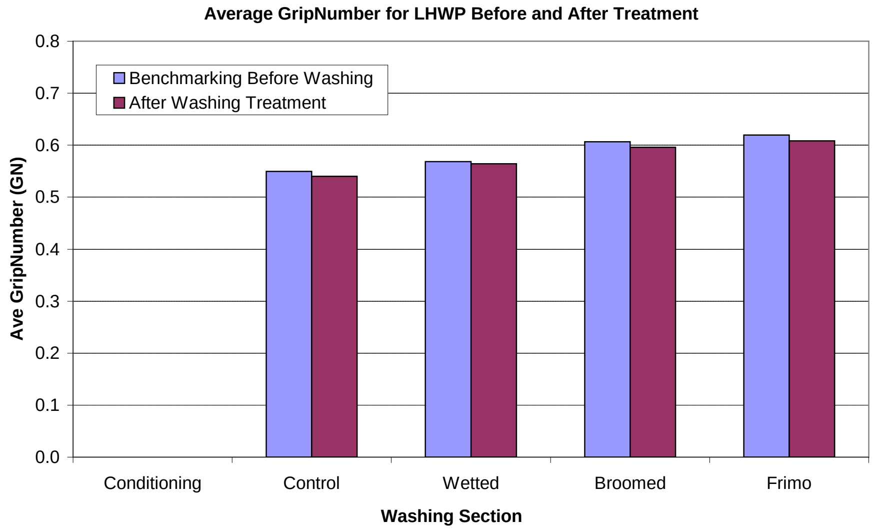
(d) Hikurangi after washing (decreasing direction)



The results shown in figure 6.17b and d represent the testing after the treatments had been applied and the traffic closures had been removed. Six test runs were undertaken in each direction. Run 1 was essentially a warm-up run of the GripTester and was not included in subsequent analysis. An average of the subsequent five runs (AVE(-1)) was the average of runs 2–6. Analysis of the results shown in figure 6.17d for the treated wheel path showed that no significant increase in friction levels measured by the GripTester was apparent due to the cleaning. This is more clearly shown in figure 6.18, where the average of the various trial sections are compared against each other, both before and after the washing treatments. It can be seen that all of the sections (including the control section where no treatment was applied) reduced slightly in the measured skid resistance as measured by the GripTester. This difference was negligible and less than the repeatability of the measurement device itself. It could therefore be concluded that none of the washing treatments had any effect on the measured skid resistance as measured by the GripTester.

The results for the increasing direction, which had no washing treatments applied and remained open to traffic, were unexpected. Figure 6.17b shows the results from the six runs that were undertaken. These show a much larger spread (standard deviation) between the consecutive GripTester runs, and poor trending along the length of the test site as well as a drop in the average coefficient of friction as measured by the GripTester. Whilst the increasing trend of results was still present, it seems that the road was not in a uniform skid resistance condition.

Figure 6.18 'Before' and 'after' results of the washing trials (decreasing direction)



These results have been interpreted as showing an extreme case of the effects of contamination of the road surface. In order to have room to treat and test the left-hand wheel path in the decreasing direction, traffic was moved closer to the shoulder. In places, it was observed that vehicles travelled onto the unsealed shoulder, resulting in mud being splashed and tracked onto the pavement surface. Normal cleaning processes, such as the effects of traffic and water interaction, did not occur, as all traffic was restricted to low speeds. The testing of this wheel path illustrated the type of results a contaminated pavement with detritus would be expected to exhibit; that is, a reduction in the measured skid resistance.

6.4.3 British Pendulum Tester (BPT) results

Before and after treatment, all of the treated sections were also tested using a BPT, including the untreated control section. Three test points were used in all sections with the exception of the Frimokar treated section, which was tested at five locations, with two repeat tests undertaken after treatment. These results were corrected for temperature as per normal device practice.

The results indicated no significant change in the measured British Pendulum Number (BPN) for the control, washed or broomed sections. The only change identified occurred in the Frimokar section, where an increase of 5BPN (approximately 0.05GN) was recorded on the first repeat test after the cleaning occurred. However, the retest revealed a smaller improvement of only 2BPN.

It was unclear whether these results suggested that the Frimokar offered an improved washing mechanism compared with the other treatments, or whether the Frimokar treatment could have been rejuvenating microtexture. As the cleaning was only undertaken at low pressure, it was considered unlikely to be the latter, although this possibility could not be totally discounted. For whatever reason, it seemed that the positive effect was temporary, as most of the positive effect was lost very quickly. A visual inspection of the sections after treatment identified that material was removed from the Frimokar section much more effectively than the other treatments, as would have been expected, particularly in the case of accumulated material at the bottom of the macrotexture. The macrotexture results (which were only available for the Frimokar section due to rainfall preventing testing on the other sections) revealed an increase of 0.4mm average MTD, obtained from the sand circle tests from this treatment.

6.4.2 Washing trial conclusions

The washing trial revealed some interesting, although inconclusive, results regarding the effectiveness of a range of washing treatments that can be applied for improving skid resistance levels. None of the washing treatments produced any improvement as measured by the GripTester device. The BPT also showed no improvement between the benchmarked levels and the post-washed treated sections on all sections except the Frimokar section. The Frimokar section results with the BPT indicated an improvement in skid resistance after the treatment was applied (5BPN), although this improvement was very temporary as a further test a short time later resulted in a reduced improvement of 2BPN.

It was suggested that the inconclusiveness of the results could partly be attributed to the 'clean' state of the pavement prior to the trial being undertaken – although observation and inspection of the water-blasted material that was collected by vacuum into the tank of the Frimokar vehicle calls into question the relativity of the word 'clean'. High rainfall was experienced (accumulative rainfall of approximately 100mm over the previous two weeks) prior to the washing trial, with 6.5mm falling over the course of the day that the trial was conducted. This is borne out by the comparison of the skid resistance levels for the normal monitoring of the site (as shown in the appendix figure B.7) and the test results either side of those for 11 July 2003. The skid resistance measurements on this washing trial date resulted in one of the highest levels of measured skid resistance. It was concluded that the initially relatively clean state of the pavement negated some of the expected increase in skid resistance due to the varying levels of pavement 'washing'.

Other spot washing trials were undertaken with the DF Tester on surfaces that were initially tested and then retested after waterblasting the surface with relatively low pressure (approximately 2000psi). The sites trialled included the Tamaki Campus, Ports of Auckland and Hikurangi sites, after significant dry periods. The results did not show marked improvements in the skid resistance results following washing of the surface. It is hypothesised that washing the surface by itself does not improve the skid resistance. However, the combined effect of the pavement surface being wet, with the 'kneading and abrasion effect' of traffic loads on the wet surface, does help to rejuvenate the surface. The controlled laboratory-based experiments discussed in section 8 investigate this effect further.

7 Detritus environmental analysis results

7.1 Introduction

As discussed in section 2, it has been thought that the accumulation of finer-particle detritus material contributes towards the polishing of the aggregate, usually coinciding with lower-rainfall summer months. Conversely, the coarse grit contributes to abrasion of the aggregate and, when the finer material has been washed away in wetter months, helps to rejuvenate skid resistance (Jayawickrama and Thomas 1998).

This section discusses the results of the environmental analysis on the surface detritus samples that were collected from 1m squared test positions at the skid-testing field test sites. The methodology used for the detritus sample collection and the detritus laboratory analysis methods is discussed in sections 3.9.2 and 3.9.3 respectively. The samples were analysed primarily in the Environmental Engineering Laboratory (Department of Civil and Environmental Engineering, The University of Auckland) for suspended solids, heavy metals (eg copper, lead, zinc and cadmium), total petroleum hydrocarbons (TPH) and total organic carbon. Particle size distribution (PSD) tests were also undertaken by Malvern Instruments Ltd.

7.2 Sampling site details

Samples were obtained primarily from four of the skid resistance test sites in 2005. The test site characteristics are discussed in section 3.8. Traffic conditions ranged from primarily light private-car usage to moderately heavy state highway traffic volume conditions. Ideally, multiple samples from the same site at varying times of the year (ie summer and winter and after various periods of previous rainfall) would have been obtained. However, as temporary traffic management and lane closures were required to obtain the samples, the available times were restricted to when lane closures were occurring due to other activities. Therefore the results were not able to demonstrate the difference between detritus samples at various times of the year, but provided a 'benchmark' or snapshot for future comparisons. The roadside vegetation alongside the field test sites varied from urban conditions to rural rolling terrain with predominantly farmland or light agricultural activities. Three of the field sites were located in rural areas in the Northland region and the fourth was at the University of Auckland Tamaki Campus site. The field site details, characteristics and the sample collection locations are shown in table 7.1.

Table 7.1 Detritus sampling details (2005)

Sampling location	Site details	Surrounding environment	Traffic speed (km/hr)	Traffic volume (ADT)	HCVs	Sample collection date
T1, T2, T3, T4	Tamaki campus, UoA	Urban, flat terrain	30	-	-	8 Mar 2005
K1, K2, K3, K4	Kara Road, SH14	Rural, rolling terrain	100	5510	5.5%	14 Mar 2005
S1, S2, S3, S4	Snook–Tatton, Titoki, SH14	Rural, flat terrain	100	5510	5.5%	14 Mar 2005
H1, H2, H3	Hikurangi, SH1	Rural, flat terrain	100	9700	9.7%	18 Apr 2005
H1', H2', H3'[a]	Same site as above	As above	As above	9700	9.7%	12 May 2005

a) Samples H1', H2' and H3' were collected at the same location as H1, H2 and H3, respectively, but on different days.

In addition, comparative analysis was undertaken on the results of a preliminary study completed in 2004 when the sampling methods were being trialled. The preliminary study included an analysis of the samples for suspended solids, PSD and heavy metals. The details of the sites are shown in table 7.2.

Table 7.2 Preliminary study detritus sampling details (2004)

Location details	Surrounding environment	Traffic speed (km/h)	Traffic volume	Sample collection date
TeAtatu, motorway off-ramp	Urban	100	Heavy	12 Jan 2004
Kaiwaka Slag site	Rural	100	Heavy	6 Jul 2004
Ports of Auckland	Urban	50	Heavy	21 Sep 2004
Tamaki Campus, UoA	Urban, flat terrain	30	Light	22 Sep 2004

In order to evaluate the effects of the previous rainfall history on the sample characteristics, particularly for the comparisons of the samples collected at the Tamaki and Hikurangi field sites that were collected on different days, the preceding 15-day rainfall depth data was determined. The rainfall data was recorded from either manual rainfall gauges installed at the site (eg for the Northland rural sites) and/or obtained from the closest NIWA automatic rainfall gauge station data. The summary rainfall data is given in table 7.3.

Table 7.3 Preceding 15-day rainfall depth (mm)

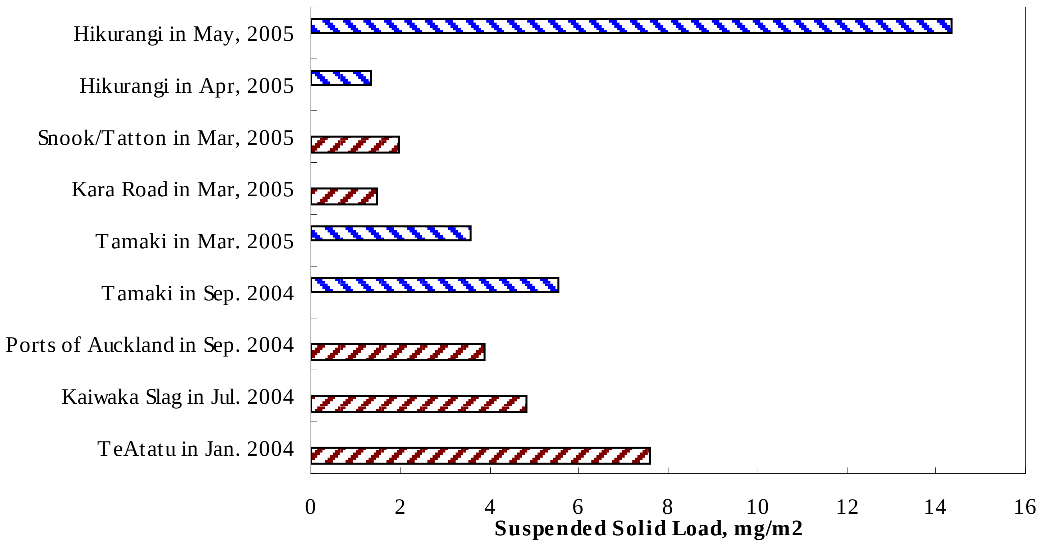
Days	Tamaki (2004)	Tamaki (2005)	Kara Road	Snook-Tatton	Hikurangi (Apr 05)	Hikurangi (May 05)
0	0.50	0	0	0	0	0.49
-1	1.51	0.56	0	0	0.74	0
-2	1.51	0.80	2.23	2.77	0	0
-3	2.52	0	2.12	0	0	0
-4	3.52	0	0	0	0	0.49
-5	0.50	0	0	3.59	0	0
-6	7.04	0	1.70	0.16	0	14.03
-7	0.50	0	2.12	0	0.49	5.66
-8	5.03	3.27	0	0	0	7.63
-9	9.55	0	0	0	0	1.97
-10	0	0	0	13.37	0.25	1.48
-11	0	0	0.21	0	1.72	0
-12	0	5.45	0.64	0	0	0
-13	0	20.71	0	0	0.74	0
-14	0	0	0	2.44	0	0.49
-15	0	0	0	2.61	0	0

7.3 Suspended solids and particle size distribution

The event mean sediment loads, calculated using the observed sediment concentration and the one-litre volume of fluid collected at each site, are presented in figure 7.1. At the Hikurangi and Tamaki sites, duplicate samples were collected on different days, which is an indication of the variation in sediment load that could be expected over time. A maximum of four samples were collected at each site, as shown in table 7.1.

During any sampling event the observed variation in the sediment load, measured as suspended solids, was less than 25%. However, it was apparent, particularly at the Hikurangi site, that local conditions, vehicle commodities and environmental changes (eg rainfall and wind speed) could significantly affect the amount of road sediment accumulating on road surfaces. On the other hand, although the number of preceding dry days was expected to be one of the significant factors in determining the sediment load, the limited data in table 7.3 meant that a correlation was unable to be determined.

Figure 7.1 Mean sediment load at each site (mg/m^2)



As with the sediment load, the PSD values for the sediments obtained during individual sampling events were surprisingly consistent, as shown in figure 7.2. Accordingly, the mean values of the particle characteristics obtained for the replicate samples were adopted for the analysis (shown in table 7.4). It is worth mentioning that the means of the particle characteristics in all sampling events were also similar. These observations suggest that the PSD did not change significantly with time of sampling and/or location. This fact is likely to be influenced by the sampling methodology and protocol. The methodology was based upon obtaining the majority of sediments at source, and that originated from the weathering of the road surface, which gave similar particle sizes from one location to another. The weathering of the aggregates was also thought to be related to the geological makeup of the aggregates themselves – yet the results have shown surprisingly little variation between samples.

Figure 7.2 Mean particle size distributions of solid samples

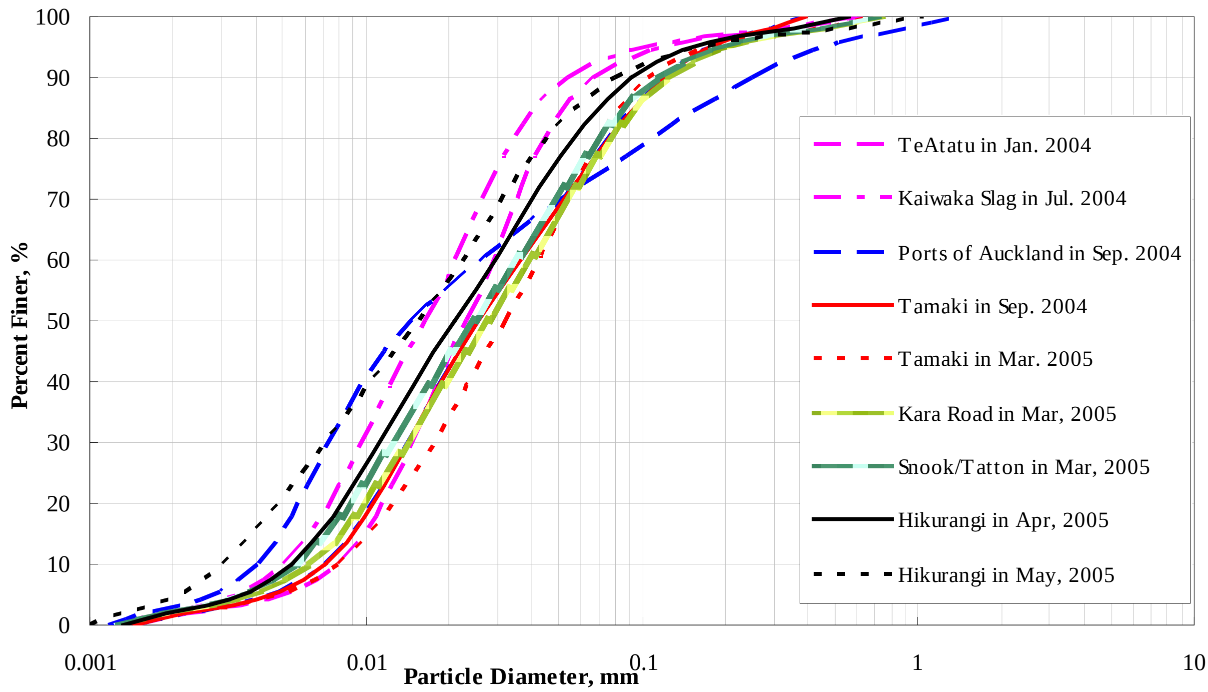
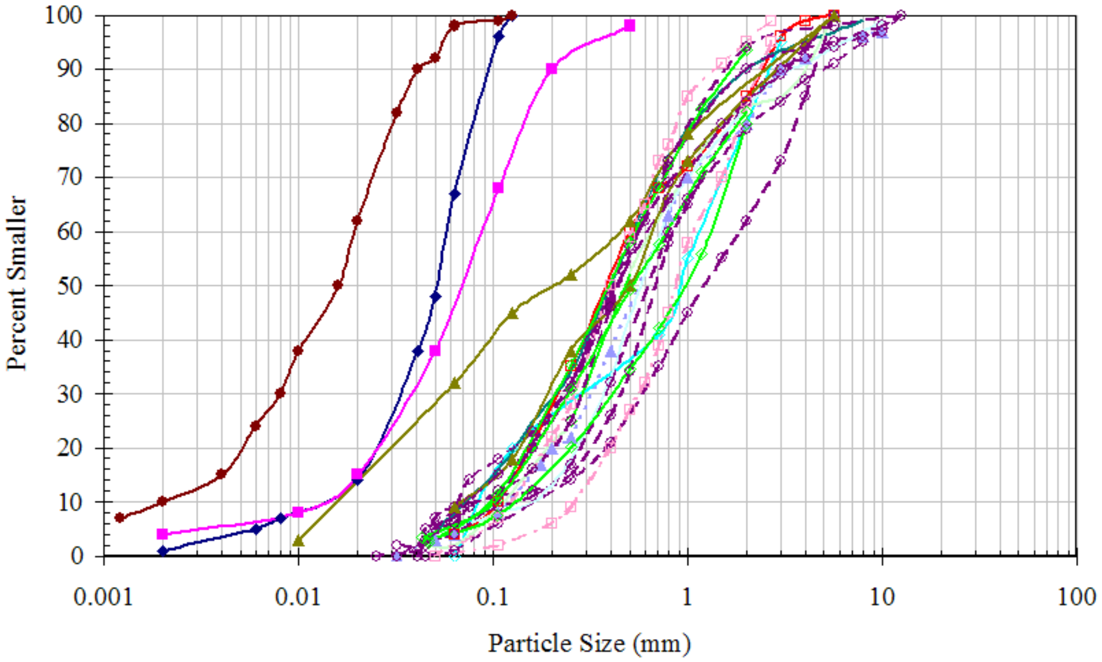


Table 7.4 Mean particle size distribution data of each site

Date	Sample location	Mean specific surface area (m^2/g)	Mean particle size (µm)		
			d(0.1)	d(0.5)	d(0.9)
Jan 04	Te Atatu site	0.371	7.968	22.976	67.341
Jul 04	Kaiwaka Slag site	0.544	5.026	16.529	54.529
Sep 04	Ports of Auckland site	0.617	4.095	14.565	250.589
Sep 04	Tamaki site	0.384	7.153	25.484	120.674
Mar 2005	Tamaki site	0.338	8.041	32.034	105.415
Mar 2005	Kara Road site	0.410	6.249	27.634	125.544
Mar 2005	Snook-Tatton site	0.443	5.578	24.752	114.131
Apr 2005	Hikurangi site	0.488	5.388	20.794	91.185
May 2005	Hikurangi site	-	3.017	15.541	79.678
Overall mean		**0.449**	**5.835**	**22.257**	**112.121**
Standard deviation		**0.164**	**1.606**	**5.587**	**54.046**

The mean PSD of sediments for the replicate samples collected at each site are presented in figure 7.2, which shows that the sediment sizes at all locations were similarly distributed. The sediment particles ranged from 0.001mm to approximately 1mm – a range that is somewhat smaller to the 0.001-10mm range that is reported for sediments from previous stormwater-based PSD research, as shown in figure 7.3.

Figure 7.3 Distributions of road runoff sediment sizes from literature (modified from Walker et al 1999 and Ng et al 2003)

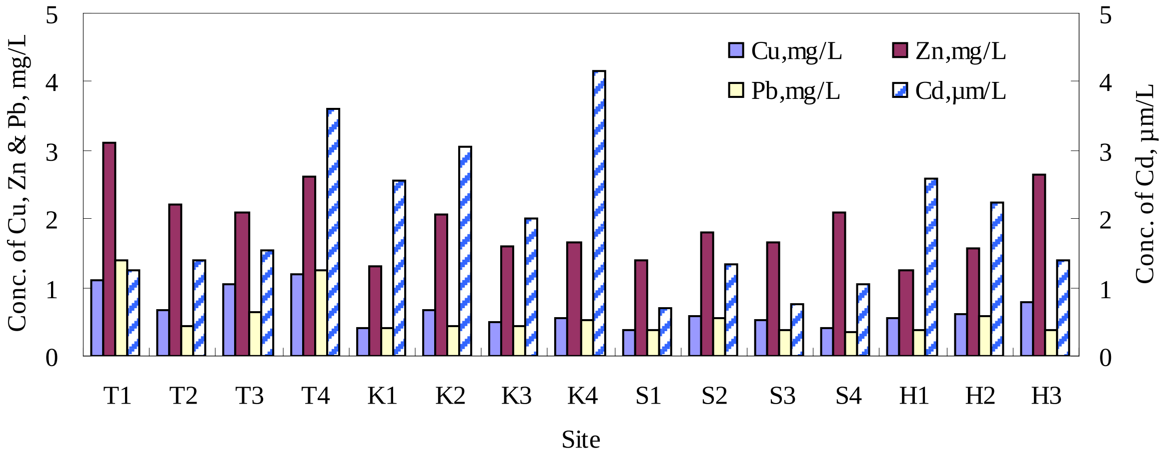


7.4 Heavy metals

The results of the analysis of heavy metal concentrations for the one-litre samples collected at various locations are presented in figure 7.4. The metal concentrations measured from the samples collected from the field test sites were relatively low compared with the literature. This was presumably due to low levels of contamination at the selected sampling locations, associated with low/moderate levels of traffic volumes and the rural surroundings. Previous research has predominantly been in more dense urban contexts, where there are large areas of heavy braking and traffic volumes are significantly higher than the sites used for skid resistance testing in this research.

The concentrations of cadmium were particularly low (below 5μg/m^2). The results of earlier samples collected in 2004 in other urban areas (given in table 7.2), which included a high traffic volume motorway off-ramp on SH16, had similar ranges of copper and zinc concentrations. As would be expected, the Ports of Auckland site, which had very heavy industrial ship container straddlers and forklift traffic that load containers onto the immediately adjacent railway grid tracks, had significantly higher concentrations of heavy metals. Concentrations at the Ports of Auckland site were significantly higher than the average values for the other sites – 17 times higher for copper and 8 times higher for lead concentrations.

Figure 7.4 Metal concentration of each sample



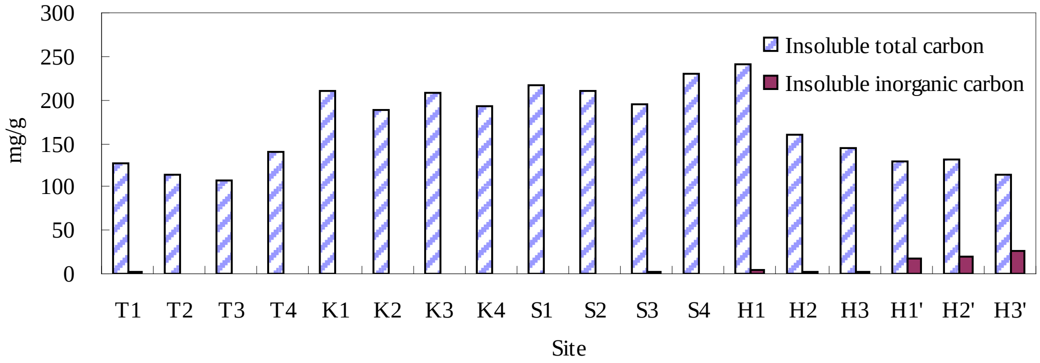
Attempts to correlate the metals to sediment concentrations showed moderate correlations (R^2 of 0.49–0.76) between copper, zinc, lead and the associated suspended solids, suggesting that the metals may have been sediment-bound. Cadmium, on the other hand, showed no correlation (R^2 below 0.04) with suspended solids or with the other metals. This trend is contrary to that reported by Yim and Nau (1987), who observed strong correlations between cadmium and copper as well as between cadmium and zinc. The weak correlation from this research is likely to be due to the negligible amounts of cadmium existing in all of the collected samples.

7.5 Petroleum hydrocarbons and organic carbon

As discussed in section 3.9.3, the detection limit for the Hewlett-Packard HP 6890 series GC system was approximately 0.001% (by volume) or 10mg/L of the 1:1 petrol–diesel mixture in n-pentane. The total petroleum hydrocarbons (TPH) amount in each of the samples was close to the method detection limit (ie below 10mg/L), indicating that little or no TPH existed in all samples.

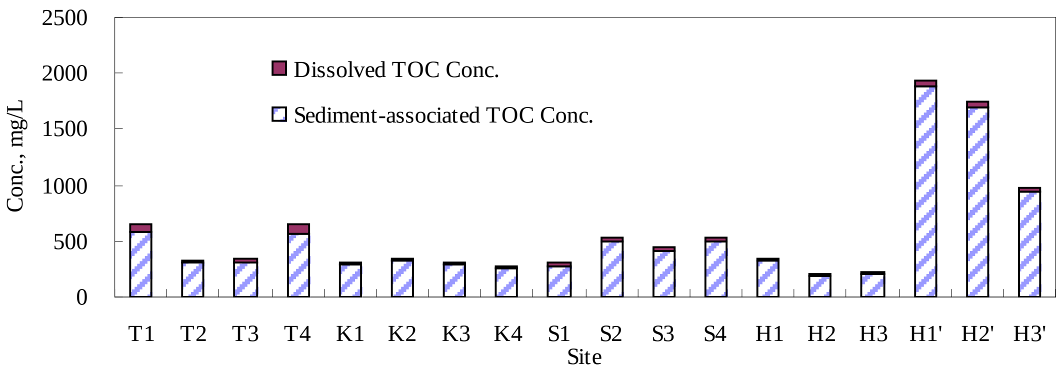
To separate the contribution of dissolved and particulate organic matter, the total organic carbon (TOC) values were quantified separately for the sediment-associated (mg-TOC/g-sediments) and dissolved (mg-TOC/L-water) fractions of the one-litre samples collected at the different sites. The sediment-associated total carbon and inorganic carbon values are presented in figure 7.5, which shows that the inorganic carbon concentration was generally negligible and the total carbon concentrations ranged from 110 to 240mg/g. The small amounts of inorganic carbon on the Hikurangi site (H1–H3′ sites) are believed to be due to calcium carbonate ($CaCO_3$) formed by the reaction between atmospheric carbon dioxide (CO_2) and lime. This is presumably spilled from trucks carrying lime on SH1, as a lime quarry is located reasonably close to and north of the Hikurangi site.

Figure 7.5 Carbon load in sediments (mg/g)



The dissolved TOC values for the sampled liquid, along with the sediment-associated TOC values converted to mg/L-water, are presented in figure 7.6. It can be clearly seen from figures 7.5 and 7.6 that the organic carbon is primarily associated with particulate matter. The two sets of samples collected from the Hikurangi site show that when TOC is expressed on the basis of the volume of sample collected, it can give a very different picture from that when the TOC is expressed on the basis of sediment mass in samples. In addition, it is interesting to note that there is a consistent trend for sediment load, insoluble inorganic carbon and sediment-associated TOC concentration at the Hikurangi site. Although it is difficult to predict the variability of these measured parameters based on limited data, it is believed that the variations were due to external sources. Furthermore, as the TPH levels measured were negligible, the organic carbon more likely resulted from roadside vegetation rather than from other sources.

Figure 7.6 TOC concentration of each sample (mg/L)



7.6 Summary of detritus analysis

In this analysis, 29 samples of detritus were collected from seven field sites between January 2004 and May 2005. The samples were analysed for sediment load and particle distribution, heavy metals, TPH and TOC. The sample results revealed that the sediment loads ranged from 1.5–14.4 mg/m^2 in response to local conditions (eg traffic volume, vehicle composition, and site setting) and environmental factors (eg rainfall and wind speed). Samples collected during the same sampling event showed little variability, whereas samples collected at the same site on different days varied significantly. Although the number of preceding dry days was expected to be one of the primary factors influencing the amount of road sediment accumulating on the road surfaces, a limited number of data points at the same sites meant that a correlation could not feasibly be considered.

The sediment size distribution remained relatively similar, with particles ranging from 0.001to 1mm at different locations and times of sampling. The mean particle size d(0.5) was 21.5 ± 5.8μm, while the average d(0.1) was 5.7 ± 1.6μm. These results give somewhat finer distributions than those reported for stormwater sediments researched elsewhere. All samples collected from all sites, excluding one exception (the Ports of Auckland site) had low metal concentrations (Cd 1–4μg/L, Cu 0.4–1mg/L, Pb 0.3–2mg/L, and Zn 1–3mg/L). The samples collected from the Ports of Auckland site reported 17-fold higher levels of zinc and 8-fold higher levels of lead than the average results observed for the other sites. This is understandable, given the nature of the very heavy industrial traffic at this site. The majority of the copper, zinc and lead measured appear to be sediment-bound, while cadmium was primarily dissolved. The TPH concentrations were close to the detection limit of the analysis (ie 10mg/L). Although little or no TPH could be detected in the samples, TOC values suggested the presence of non-TPH organic matter, primarily in the form of particulate matter.

Previous research had shown that rainfall volume appears to be the major factor in the removal of total road dust detritus, and rainfall frequency mainly affects the accumulation of particle-bound contaminants (O'Riley et al 2002). Unfortunately, due to the limitations in sampling the road surface-based detritus, insufficient samples were obtained at the same sites and for varying seasonal effects to enable a proper assessment of any relationship between road-based sediment and rainfall volume and frequency.

In summary, analysis of the detritus results demonstrated that the variations of sediment and pollutants were site-specific, and no unique differences between predominantly urban and rural settings could be detected, other than for very heavy industrial sites. The analysis also demonstrated the following:

- Samples collected at the same time and same location showed relatively little variability.
- Samples collected at the same location but at different times could vary significantly, indicating that site-specific environmental factors were significant and could be highly correlated with the variation in measured skid resistance.
- Compared with previous research, the particle size distribution of the collected samples was somewhat finer, but very consistent for all samples and sites, and provided confidence in determining particle size distributions for the controlled laboratory analysis methodology described in section 4.
- Compared with previous research, the sediment contained low concentrations of heavy metals, except for the Ports of Auckland site, where (as would be expected) significantly higher concentrations were found. These relatively low concentrations of metals at the highway indicated (from a preliminary analysis) that the heavy metal concentration does not play a significant role in the variation in measured skid resistance. However, more data is required to confirm this preliminary indication.

Section 8 discusses the results of controlled laboratory experiments developed to simulate in-field polishing of surfacing aggregates and the effect of various contaminants being placed upon prepared surface samples.

8 Laboratory accelerated polishing results

8.1 Introduction

As outlined in section 4, a primary objective of the research was a better understanding of the factors that cause the significant changes in skid resistance due to microtexture changes. Research by Hill and Henry (1981) demonstrated that significant short-term variations in skid resistance exist over relatively short periods of time. This largely unpredictable variation cannot be explained by yearly seasonal patterns, nor by the effects of temperature or rainfall changes. It therefore became clear that other factors, hitherto not accounted for, were affecting the variation in measured skid resistance.

The literature review and the initial field data collection demonstrate the difficulty in understanding the complex interrelationships of skid resistance variables at any point in time. Too many in-field variables exist that can neither be controlled nor monitored closely enough to be understood. It was apparent that controlled laboratory-based experiments were required to simulate the aggregates and road surface texture, traffic loading, and environment conditions. The experiments would need to simulate certain conditions whilst other variables were controlled to isolate their effects. This section discusses the results of the controlled laboratory-based experiments that were designed and developed to simulate cycles of polishing and rejuvenation of surface aggregates.

As discussed in detail in section 4, two surface samples for each aggregate type were constructed by hand-placing the individual aggregate chips onto a thin layer of sand on a plane of oiled glass. The aggregate chips were then bonded together in a mix of sand and cement mortar. Once hardened, the mix was turned over, the sand brushed away and the mould set into a wooden frame and cemented in place. One of each surface sample was left as a 'master sample' that remained unpolished, whilst the other sample was polished with the AAPD developed and manufactured specifically for this research. Examining and simulating the approximately seasonal and short-term variations of measured skid resistance required the following two stages of laboratory testing:

- Stage 1 – polishing the prepared surface samples to equilibrium skid resistance (ESR) level
- Stage 2 – simulating the cyclical effects of polishing/rejuvenation of the surface samples thereby decreasing and increasing measured surface friction.

In the following sections, some geological descriptions of the chosen aggregates are presented, followed by the results of the controlled laboratory experiments and the aggregate polishing that was undertaken. Some explanations of the geological mechanisms of polishing and abrasion that affect measured skid resistance are also presented.

8.2 Geological properties of the aggregates

8.2.1 Introduction

The selected samples of sealing aggregates used in the controlled laboratory experiments were chosen on the basis of the aggregates being commonly used in the Auckland and Northland regions and/or having varying geological properties. A range of low, medium and high reported PSV aggregates was also seen as being desirable for the test matrix. The following four aggregate sources were chosen from a range of geological types for the building of the laboratory surface samples:

- Moutohora sedimentary greywacke – the highest reported natural PSV in the North Island (Napier)
- Holcim igneous basalt – mid- to low-range reported PSV, sourced from Auckland region (Bombay)
- Otaika sedimentary greywacke – lowest reported PSV acceptable for Transit NZ surfacings, locally sourced from Whangarei, Northland
- Melter slag – artificial by-product from Glenbrook Steel mill, through SteelServ Ltd.

Professor Black (2005b), from the Department of Geology in the University of Auckland, supplied geological descriptions of the four sample aggregates used in the laboratory experiments, from specific tests undertaken in the University of Auckland's Geology Laboratories. These descriptions and explanations are given in the following sections.

8.2.2 Moutohora greywacke

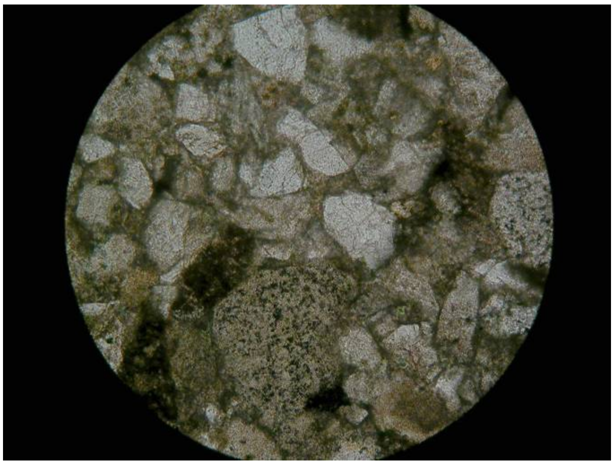
Greywacke sandstone chips from two quarries were tested in the laboratory experiment: Moutohora quarry from the Matawai District north of Gisborne, and Otaika quarry near Whangarei, Northland. These two sediments are different in age and nature. The Cretaceous Moutohora sandstone is more uniform in its properties, has a coarser grain size, and is inherently less lithified (ie it is more weakly metamorphosed) than the older, late-Triassic/Jurassic greywacke from Otaika quarry near Whangarei. The Otaika greywacke is a fine-grained sandstone that is variable in grain size (ranging through to siltstone) and strongly lithified. These differences influence the aggregates' polishing properties.

The Moutohora greywacke aggregate is part of the Raukumara Series from the Cretaceous geological period (from Matawai District in Gisborne). The sample sealing chips showed a variety of colours indicating different degrees of weathering. However, they all appeared to be coarse, well-sorted sandstones with uniform grain size, as shown in figure 8.1a.

Figure 8.1 Moutohora sandstone chips

(a) Moutohora chips (diameter field of view 3.5cm)

(b) Microphoto of typical Moutohora sandstone thinsection (diameter of field of view 2mm)



In thinsection (refer to figure 8.1b) the Moutohora chips are seen to be well-sorted medium- to coarse-grain-supported sandstones. The grains are dominantly quartz, including a variety of polygranular quartz grains and feldspar (plagioclase and k-feldspar). Lithic clasts are about 35% of the sand grain clasts and include sediment and volcaniclastic debris. Grain shapes are subangular to subrounded. Detrital mineral grains include hornblende, minor chlorite and biotite. The matrix constitutes about 10–20% of the sandstone, and X-ray diffraction showed it consisted largely of chlorite and illite. Some chips also had calcite cement. The clast-supported nature of the sandstone, the variety of grains and their angular to subangular shape are clearly seen in figure 8.1b).

8.2.3 Otaika greywacke

The Otaika greywacke aggregate is from Whangarei and is from the Jurassic geological period. The Otaika chips are dark grey in colour and massive. There is a range of grain sizes in the chips, varying from sandstone to siltstone. The grain size of the sandstones is notably finer than that of the Moutohora sandstones.

In thinsection the Otaika sandstones show angular to subangular quartz grains, albitised feldspar and abundant lithic debris (refer to figure 8.2). The feldspars and lithic debris are more highly metamorphosed, and thus the individual grains are less obvious in microphotos of the Otaika sample, compared with the Moutohoro sandstone, although the amount of matrix in the two sandstones is roughly equivalent. White veins of prehnite are evident cutting some grains, and prehnite also occurs in the matrix where it replaces grains in the rock. Many chips contain lenses or layers of siltstone.

Figure 8.2 Microphoto of typical Otaika greywacke sandstone thinsection (diameter field of view is 2mm)

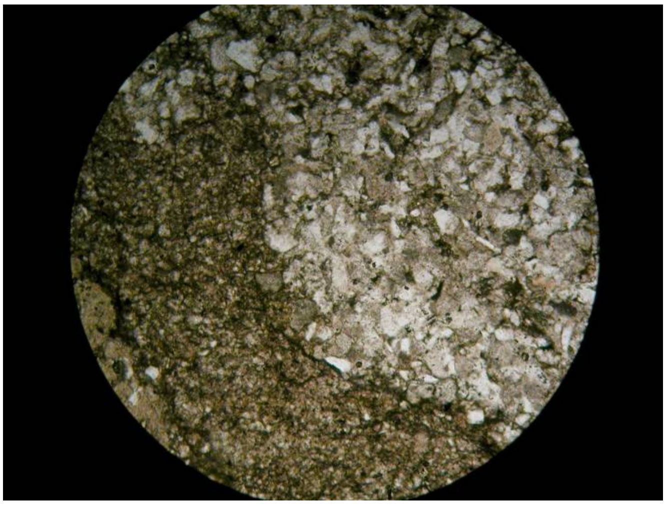
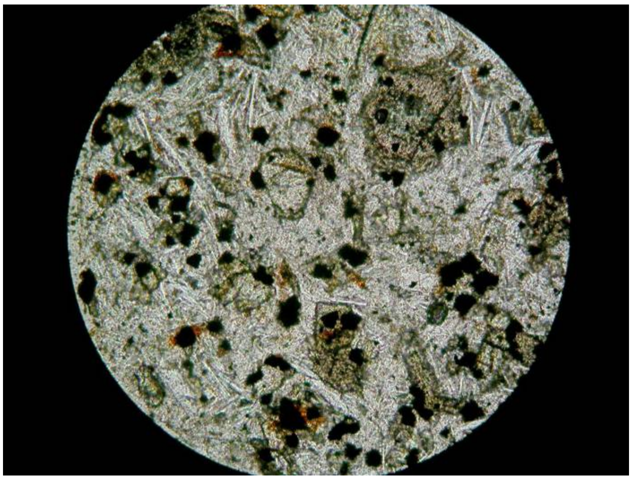


Figure 8.2 shows the angular grain-supported sandstone composed of quartz, albitised feldspar and lithic grains top and centre right, and siltstone lens bottom centre left.

8.2.4 Holcim basalt

The Holcim basalt is from a quarry near Pokeno, South Auckland and is a completely crystalline porphyritic basalt. In hand specimen, the basalt samples are grey, with brown nodular areas (phenocrysts) about 1mm in diameter, and have small vesicles. In thinsection (refer to figure 8.3), the basalt is seen to contain phenocrysts of augite, sometimes with cores clouded with iron oxides and overgrowths of augite. There is minor olivine in the rock (about 10%) as small crystals. The dominant component is plagioclase, which is always in the matrix of the rock, occurring as needles enclosing iron oxides and augite. No glass was observed.

Figure 8.3 Microphoto of typical Holcim basalt thinsection (diameter field of view is 2mm)

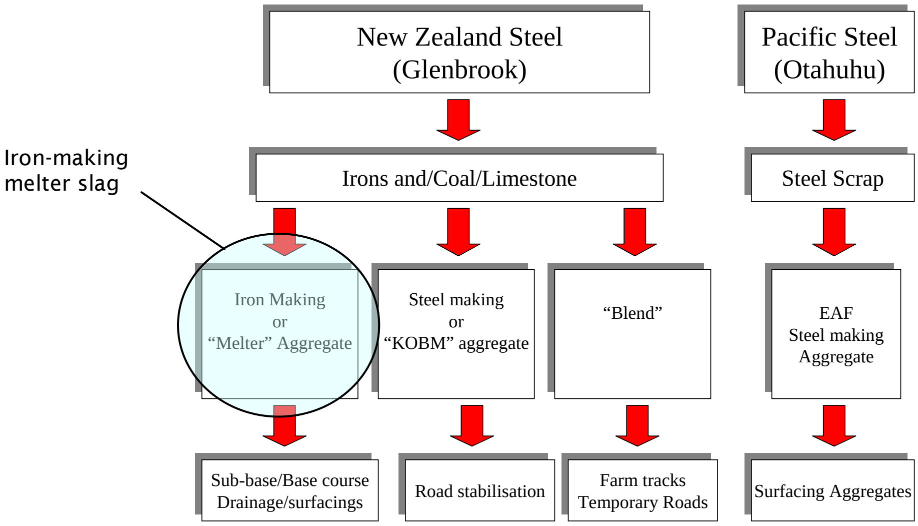


Most of the large crystals are pyroxene, with a few smaller, lighter-coloured olivines (refer to figure 8.3). Black iron oxides show minor oxidation. The colourless matrix is an interlocking matte of plagioclase feldspar.

8.2.5 Melter slag

The melter slag is an artificial aggregate that is an iron-making by-product of the New Zealand Steel Mill in Glenbrook. It is available through SteelServ Ltd and is part of a number of iron and steel by-products that form aggregates that can be used in the New Zealand roading industry (refer to figure 8.4). The Kaiwaka South field site in Northland was a trial site for this aggregate, to enable a consideration of its performance over time.

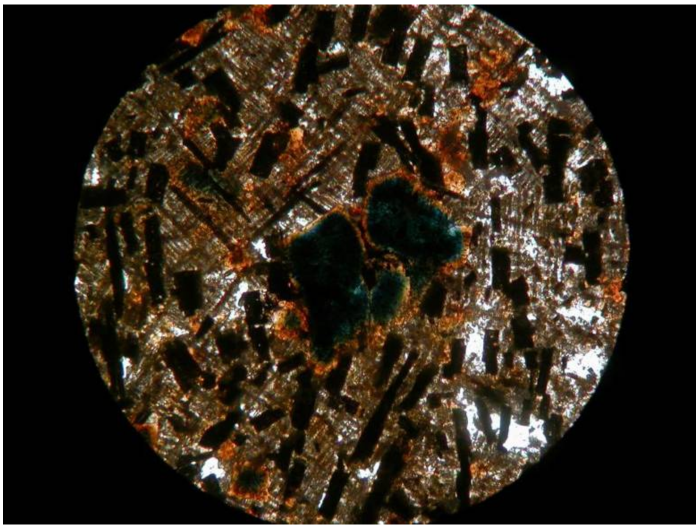
Figure 8.4 Iron- and steel-making aggregates in New Zealand[a]



a) B Bourke, SteelServe, pers comm, 2005.

The melter slag chips are black, with some reddish-brown patches. They appear metallic, but with reddish-brown patches on surfaces, and they contain many gas vesicles. Figure 8.5 shows an example of a chip thinsection that contains large cubic crystals of blue-green magnesium-rich (Mg) spinel mantled with a red-brown pseudobrookite (a Ti-rich oxide). The matrix of the slag shows a typical quench texture consisting of interlocking dendrites of extremely small grains of perovskite ($CaTiO_3$) enclosed in pyroxene (colourless material). Many chips have vesicles and show brown oxidation effects. Figure 8.5 shows large crystals (in the centrefield view) that are magnesium-spinel surrounded by pseudobrookite.

Figure 8.5 Microphoto of typical melter slag thinsection (diameter field of view is 2mm)



8.3 Polishing aggregates to equilibrium levels (stage 1)

8.3.1 Introduction

A methodological procedure was developed to polish the prepared surface samples to an 'equilibrium level' whilst periodically measuring the variation of the coefficient of friction on both the unpolished and the polished sample with the DF Tester. Table 8.1 summarises, for each of the test samples built (polished and unpolished samples), the aggregate source, the reported PSV from Transit NZ surfacing specifications, the actual laboratory-tested PSV, the geological grouping and aggregate properties, and the measured macrotexture of the surfacing sample.

All four paired aggregate samples were tested by the procedures described earlier in section 4. Table 8.2 shows the results of the mean of three test coefficients of friction (μ) for an average slip speed of between 20 and 40km/h as measured by the DF Tester for the first six hours of polishing, or until an equilibrium level had been reached.

Table 8.1 Laboratory test sample details

Sample number	Aggregate source	TNZ reported PSV	Actual[a] sample PSV	Geological grouping	Geological properties	Macro-texture TD (mm)	Comment/ description
1	Moutohora	65	63	Sedimentary	Greywacke	-	Prototype
2	Moutohora	65	63	Sedimentary	Greywacke	1.0	Polished
3	Moutohora	65	63	Sedimentary	Greywacke	1.0	Unpolished
4	Holcim	56	52	Igneous	Basalt	0.8	Polished
5	Holcim	56	52	Igneous	Basalt	0.9	Unpolished
6	Otaika	51	52	Sedimentary	Greywacke	0.9	Polished
7	Otaika	51	52	Sedimentary	Greywacke	1.0	Unpolished
8	Melter slag	58	55	NA	NA	1.1	Polished
9	Melter slag	58	55	NA	NA	1.3	Unpolished

a) These PSV results are the actual results of a PSV test taken from a sample of each of the four sealing aggregates. The tests were undertaken by TelArc-approved Works Infrastructure Testing Laboratories, Auckland to BS EN 1097-8 (2000) specification.

Table 8.2 Stage 1 wet-polishing results until 'equilibrium level' is reached

Polishing Hours	Moutohora PSV 65		Holcim PSV 56		Otaika PSV 51		Melter slag PSV 58	
	S2-Pol	S3-UnP	S4-Pol	S5-UnP	S6-Pol	S7-UnP	S8-Pol	S9-UnP
0.00	0.87	0.90	0.60	0.61	0.51	0.59	0.90	0.87
0.25			0.65	0.57	0.58	0.55	0.87	0.86
0.50			0.60	0.59	0.53	0.50	0.86	0.85
0.75			0.57	0.58	0.51	0.49		
1.00	0.77	0.87	0.53	0.58	0.50	0.48	0.82	0.83
1.50			0.50	0.58	0.47	0.45	0.81	0.82
2.00	0.68		0.46	0.56	0.45	0.44		
2.50							0.76	0.82
3.00	0.62	0.83	0.44	0.55	0.43	0.44		
3.50							0.75, 0.72	0.79, 0.80
4.00	0.54	0.81	0.41	0.54	0.42	0.43		
4.50							0.71	0.78
5.00	0.52		0.39	0.56				
6.00	0.52	0.78						

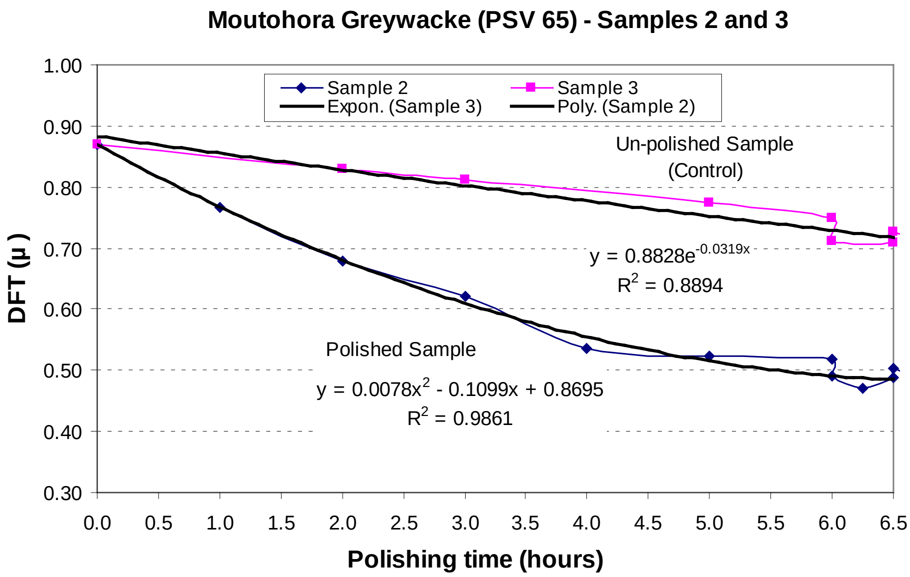
Macrophotographs were also taken through a microscope of the surface of individual chips for each of the laboratory-prepared aggregate samples used for accelerated polishing (ie samples 2, 4, 6 and 8), both before and after the accelerated polishing had been undertaken to an 'equilibrium level'. This was done to determine whether the accelerated polishing could produce microtextural changes on the aggregate surface that could be seen through a microscope and that could offer an explanation for the lower reported values of measured skid resistance as tested by the DF Tester. The following sections and figures show the results of the polishing and skid resistance testing and associated microscopic photographs for each of the four paired laboratory samples.

8.3.2 Moutohora greywacke laboratory sample

Figure 8.6 compares the coefficient of friction of the paired sample results for the polished and unpolished samples of the Moutohora greywacke aggregate with a Transit NZ-published PSV of 65. The sample that was used in this research was tested by Works Infrastructure testing laboratory and returned an actual PSV value of 63. The results of the accelerated polishing and subsequent skid resistance testing, utilising the DF Tester, showed that:

- a high initial measured coefficient of friction of approximately DFT(μ)=0.87 for both the unpolished and polished samples was achieved
- the polished sample took approximately 6.5 hours of polishing by the AAPD to level off to an ESR level
- the coefficient of friction reduced by 46% from the initial measurements to the ESR for the polished sample
- the coefficient of friction for the unpolished control sample reduced by approximately 20% with approximately 33 tests (3x11) of the DF Tester
- the polished sample ended up approximately 30% lower (DFT(μ)=0.24), in measured skid resistance, than the unpolished sample (using the AAPD)
- a highly significant coefficient of determination (R^2=0.99) polynomial prediction equation could be fitted to the polished sample data points.

Figure 8.6 Stage 1 polishing of Moutohora greywacke aggregate



Macrophotographs were taken through a microscope of a sample of the surface of a Moutohora aggregate chip before and after the accelerated polishing had been undertaken to an ‘equilibrium level’ on the polished laboratory sample (sample 2). Examples of the ‘before’ and ‘after’ photos are shown in figures 8.7a and b respectively.

Figure 8.7 Moutohora greywacke sandstone chips (unpolished and polished states)

(a) Unpolished state (approx. field of view 3.5x 2mm) **(b) Polished state (approx. field of view 3.5x 2mm)**

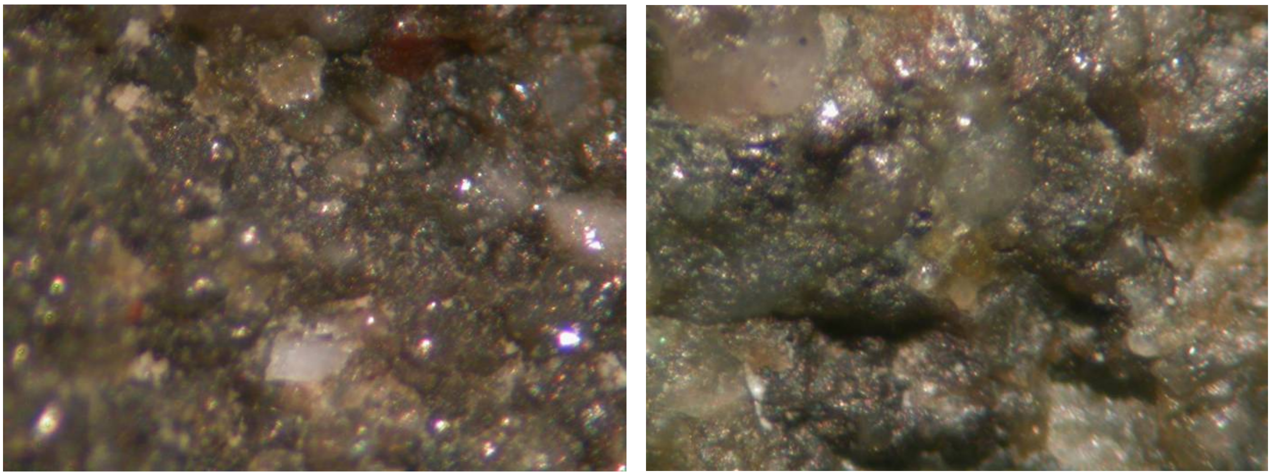


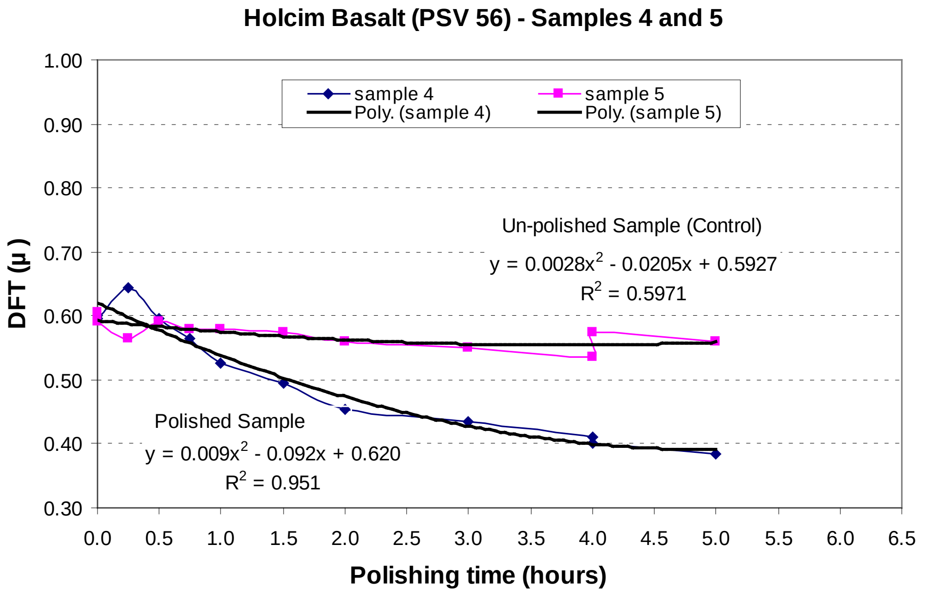
Figure 8.7a shows the angular nature of the grains in the unpolished surface and the variety of clasts in this sandstone. In the polished sample (refer to figure 8.7b) the rounded surfaces on the lithic grain surfaces and the clear quartz grains are notable compared with the more angular grains in the unpolished sample (figure 8.7a).

8.3.3 Holcim basalt laboratory sample

Figure 8.8 compares the paired sample results of the polished and unpolished samples for the Holcim basalt aggregate with a Transit NZ-published PSV of 56. The sample that was used in this research was tested by Works Infrastructure testing laboratory and returned an actual PSV value of 52. The results of the accelerated polishing and subsequent skid resistance testing utilising the DF Tester showed that:

- an initial measured coefficient of friction of approximately DFT(μ)=0.60 was achieved for both samples
- the polished sample took approximately five hours to level off to ESR
- the coefficient of friction reduced by 39% from the initial measurements to the ESR for the polished sample
- the coefficient of friction for the unpolished control sample reduced by approximately 8% with approximately 30 tests (3x10) of the DF Tester
- a significant coefficient of determination (R^2 = 0.95) polynomial prediction equation could be fitted to the polished sample data points.

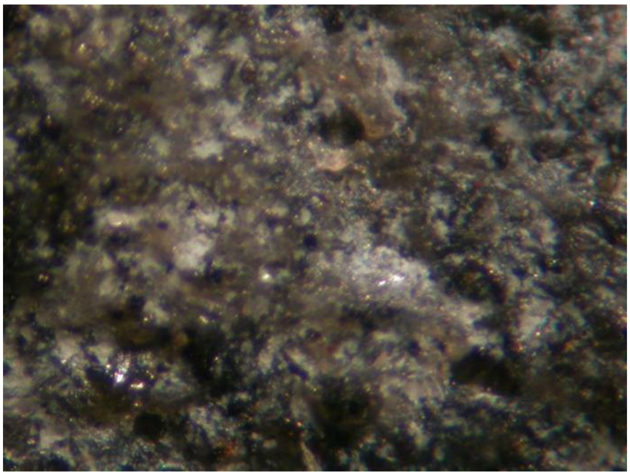
Figure 8.8 Stage 1 polishing of Holcim basalt aggregate



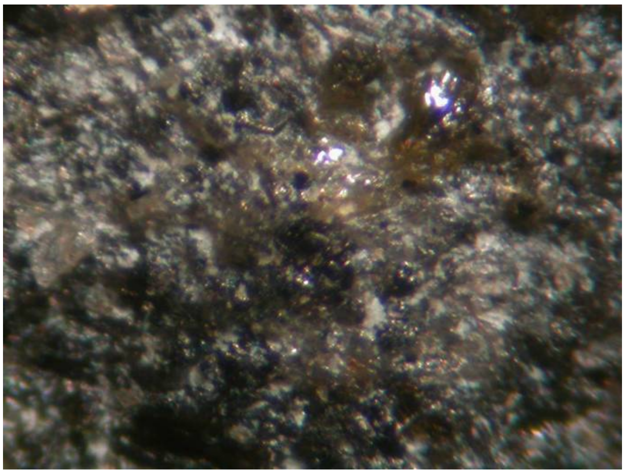
Macrophotographs were taken through a microscope of a sample of the surface of a Holcim basalt aggregate chip before and after the accelerated polishing had been undertaken to an 'equilibrium level' on the polished laboratory sample (sample 4). Examples of the 'before' and 'after' photos are shown in figures 8.9a and b, respectively.

Figure 8.9 Holcim basalt chips (unpolished and polished states)

(a) Unpolished state (approx. field of view 3.5x 2mm)



(b) Polished state (approx. field of view 3.5x 2mm)



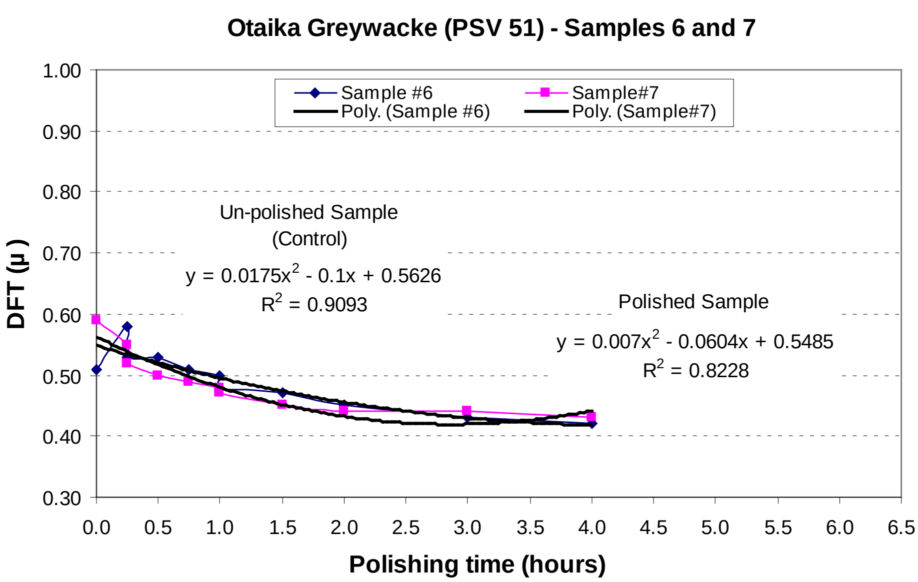
Figures 8.9a and b of the Holcim basalt chips clearly show the vesicles and the dark grains that are pyroxene and oxide crystals. The polished chip surface (figure 8.9b) retains its roughness although individual mineral grains show minor rounding.

8.3.4 Otaika greywacke laboratory sample

Figure 8.10 compares the paired sample results of the polished and unpolished samples for the Otaika greywacke aggregate (a locally sourced aggregate in the Northland region of New Zealand) with a Transit NZ-published PSV of 51. However, the sample that was used in this research was tested by Works Infrastructure testing laboratory and returned an actual PSV value of 52. It should be noted that the Otaika greywacke aggregate, in terms of PSV, is the lowest-quality aggregate specified in the Transit NZ list of suppliers of surfacing aggregates (Transit NZ 2004). The results of the accelerated polishing and subsequent skid resistance testing utilising the DF Tester showed:

- an initial average measured coefficient of friction of approximately DFT(*μ*)=0.55 for both samples, although the samples demonstrated a DFT(μ)=0.08 difference in initial measured coefficient of friction between the two samples (this, however, came together relatively quickly)
- interestingly, for this aggregate, both the polished and unpolished samples performed approximately the same in terms of the deterioration of measured coefficient of friction
- the polished sample took approximately four hours to level off to ESR
- the coefficient of friction reduced by 24% from the initial measurements to the ESR for the polished sample
- the coefficient of friction for the unpolished control sample also reduced by approximately 23% with approximately 30 tests (3x10) of the DF Tester
- the polishing action of the DF Tester (3x8=24 tests) for this lower PSV-specified aggregate was, surprisingly, more aggressive initially than the AAPD with two hours of polishing
- a significant coefficient of determination (R^2 = 0.82) polynomial prediction equation could be fitted to the polished sample data points.

Figure 8.10 Stage 1 polishing of Otaika greywacke



Macrophotographs were taken through a microscope of a sample of the surface of the Otaika greywacke sandstone aggregate chip before and after the accelerated polishing had been undertaken to an 'equilibrium level' on the polished laboratory sample (sample 6). Examples of the 'before' and 'after' photos are shown in figures 8.11a and b respectively.

Figure 8.11 Otaika greywacke sandstone chips (unpolished and polished states)

(a) Unpolished state (approx. field of view 3.5x 2mm) **(b) Polished state (approx. field of view 3.5x 2mm)**

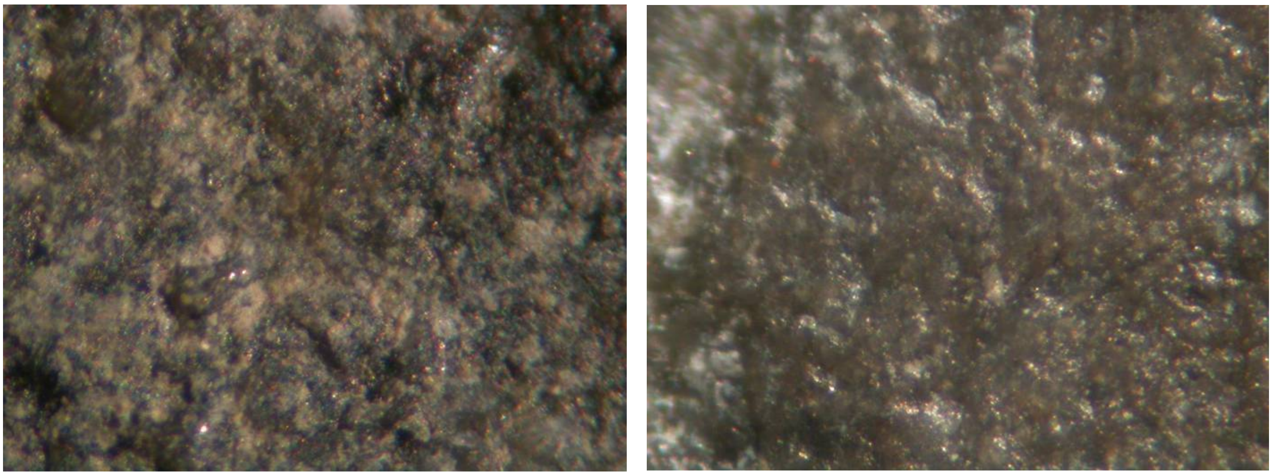


Figure 8.11a shows the unpolished Otaika greywacke sandstone surface with generally fine and uniform sized grains but an irregular surface texture. Figure 8.11b shows the same aggregate surface after accelerated polishing, showing smearing and rounding of the matrix and grains.

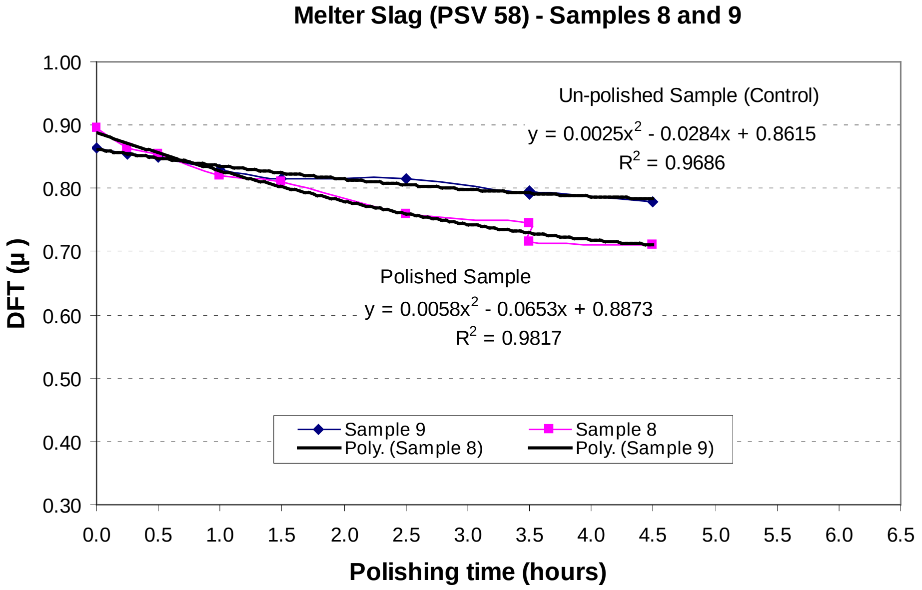
8.3.5 Melter slag laboratory sample

Figure 8.12 compares the paired sample results of the polished and unpolished samples for the melter slag artificial aggregate (a by-product from iron making at the Glenbrook New Zealand steel mill). It has a Transit NZ-published PSV of 58. However, the sample that was used in this research was tested by Works Infrastructure testing laboratory and returned an actual PSV value of 55. The results of the laboratory accelerated polishing and DF Tester friction tests on the artificial melter slag showed:

- the initial level of ESR for the slag (actual PSV 55) was similar to the Moutohora natural aggregate (actual PSV 63)
- the percentage reduction in measured skid resistance from the initial level of skid resistance was significantly less than the natural aggregates (16% cf 46% for the Moutohora greywacke; 39% for the Holcim basalt and 24% for the Otaika greywacke)
- the time to polish the slag to its equilibrium polishing level with the AAPD was approximately the same as the Holcim Basalt aggregate (4–4.5 hours)
- the melter slag significantly outperformed all of the natural aggregates in terms of resistance to polishing, including the Moutohora (actual PSV 63), which had a significantly greater PSV.

This confirmed the field-based results at the Kaiwaka slag field site (refer to appendix figure B.5 and table B.4), which was resealed with melter slag aggregate. The performance of the melter slag is discussed in appendix section B.3 and also reported in Wilson and Kirk (2005), who concluded that melter slag placed on high-stressed highway corners in Northland had a similar long-lasting performance.

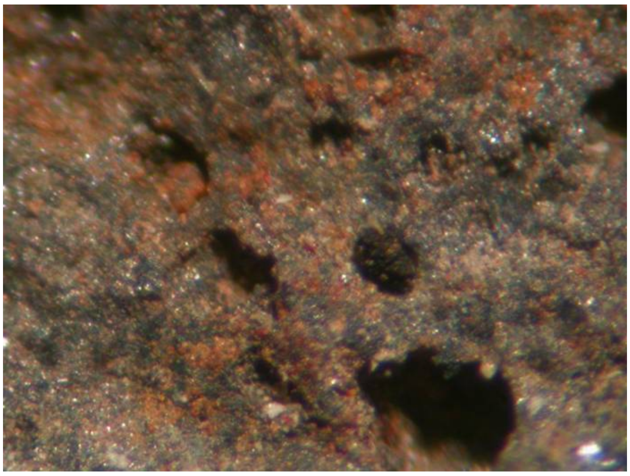
Figure 8.12 Stage 1 polishing of melter slag aggregate

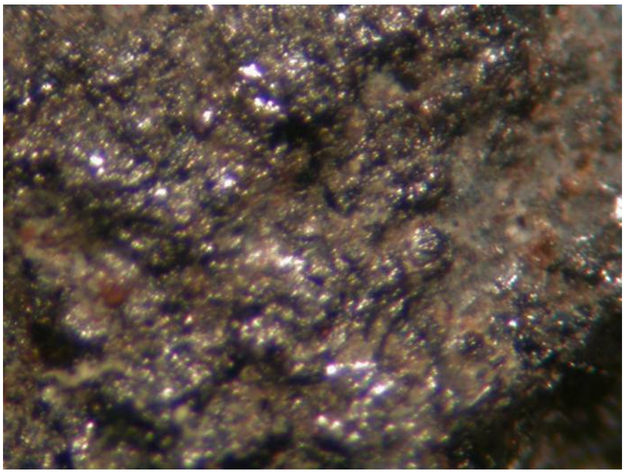


Macrophotographs were taken through a microscope of a sample of the surface of the melter slag aggregate chip before and after the accelerated polishing had been undertaken to an 'equilibrium level' on the polished laboratory sample (sample 8). Examples of the 'before' and 'after' photos are shown in figures 8.13a and b, respectively.

Figure 8.13 Melter slag chips (unpolished and polished states)

(a) Unpolished state (approx. field of view 3.5x 2mm) **(b) Polished state (approx. field of view 3.5x 2mm)**





Figures 8.13a and b show that the general surface of the melter slag was rough, with vesicles and other irregularities. In the polished state (refer to figure 8.13b) the surface retained its irregularities in terms of relief, although the metallic oxides were clearly rounded by the polishing. The brown colour was probably pseudobrookite rather than rust.

8.3.6 Summary of stage 1 accelerated polishing

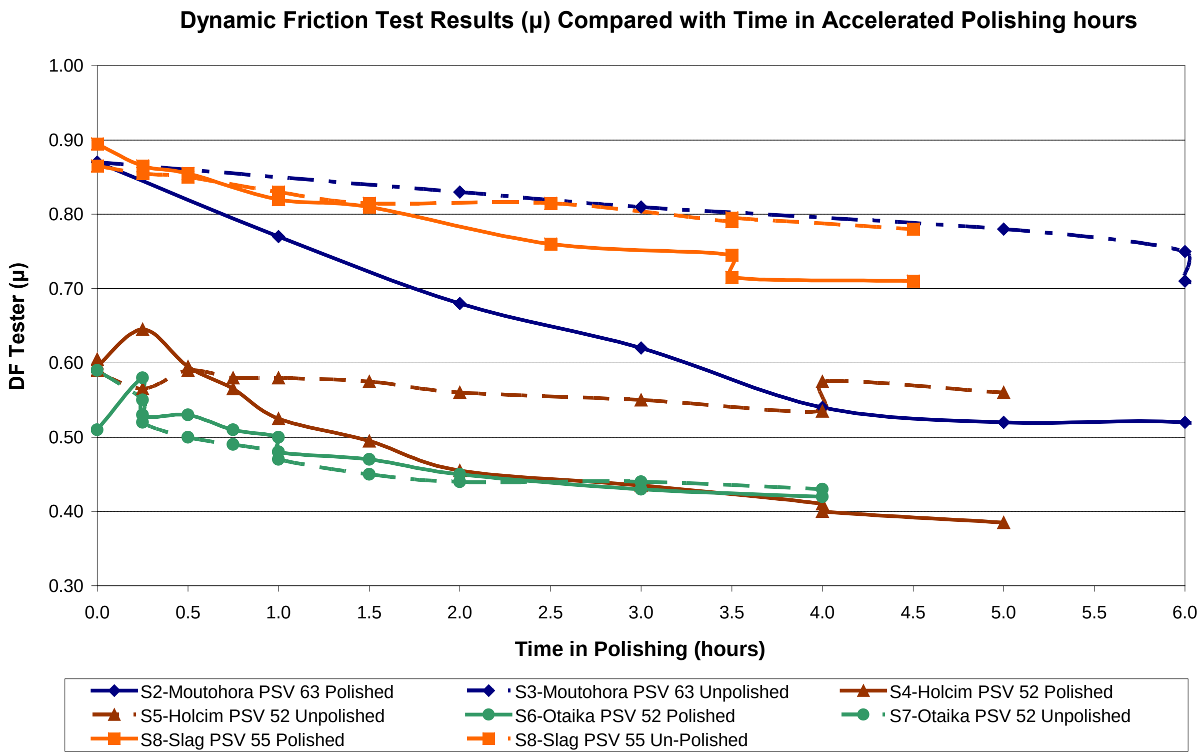
The combined summary results of the three natural aggregate samples and the melter slag artificial aggregate are shown in figure 8.14 and also reported in Wilson and Dunn (2005). All surface aggregates were polished using the AAPD developed at the University of Auckland to an ESR level (stage 1). They were regularly tested for their measured skid resistance, using the DF Tester. The results indicated some interesting comparative results, namely:

- The actual PSV of the aggregate sample generally predicted the ranking order of the initial level of skid resistance of natural aggregates prior to any accelerated polishing.
- The percentage reduction in measured skid resistance, from the initial level of skid resistance to the ESR, reduced as the aggregate PSV reduced (from 46% for the Moutohora PSV 63 to 24% for the Otaika PSV 52).
- Generally, the lower the PSV of the aggregate, the faster the aggregate polished to its ESR level (from seven hours of accelerated polishing for Moutohora PSV 63, to 2.5 hours for Otaika PSV of 52).
- There was very little difference in the final level of ESR (as measured by the DF Tester) obtained for the three natural aggregate samples (DFT(μ)=0.47 for Moutohora PSV 63, DFT(μ)=0.39 for Holcim basalt, and PSV 52 and DFT(μ)=0.43 for Otaika PSV 52).
- The greywacke sandstone and the basalt aggregates polished by different mechanisms, and therefore had different deterioration rates under the same accelerated polishing loads. Therefore the time to a polished state and the ranking order of the final level of ESR for the natural samples may not be the same as the PSV ranking. For example, the basalt sample polished to a greater extent than the Otaika greywacke, even though the actual measured PSV was the same.

The results of the stage 1 laboratory accelerated polishing and DF Tester friction tests on the artificial melter slag demonstrated some very promising results, as this material had not deteriorated at the same rate or in the same manner as the natural aggregates. The main findings were as follows:

- Whilst the actual tested PSV of the melter slag was a lot lower (PSV=0.55) than the Moutohora natural aggregate (PSV=63), the initial level of measured skid resistance DFT(μ)=0.87 was very similar.
- The percentage reduction in measured skid resistance from the initial level of skid resistance to ESR was significantly less for the melter slag than for the natural aggregates of higher or lower measured PSV (16% cf 46%, 39% and 24% for the Moutohora, Holcim and Otaika aggregates).
- The time to polish the slag to its equilibrium polishing level was approximately the same as the natural aggregate of similar PSV (4–4.5 hours).
- The melter slag significantly outperformed all of the natural aggregates in terms of being resistant to polishing, including the Moutohora (PSV 65), which had a significantly greater PSV.
- Trial tests sites with the melter slag (eg the Kaiwaka slag site in Northland) demonstrated similar measured skid resistance to polishing. The rate of decrease, even in high-stressed areas, was significantly lower over reasonably long life cycles, and outperformed highly specified natural aggregates.

Figure 8.14 Summary of accelerated polishing of all laboratory samples to ESR (stage 1)



8.4 Aggregate properties and resistance to polishing

8.4.1 Introduction

Previous studies have indicated that the nature of the minerals present and the material's microtexture play major roles in an aggregate's PSV and/or its resistance to polishing by traffic (Smith and Collis 2001). The relative hardness of individual minerals has been particularly identified as an important factor in determining the polishing properties of the material (Neville 1974).

Natural rocks (and in this case also slags) are heterogeneous materials composed of several different minerals that frequently have different grain sizes and shapes, as well as different chemical and physical properties. Further, there are differences in the nature and strength of the cement that bonds the constituent mineral grains. Volcanic rocks and slags that have crystallised and were quenched at high temperatures have the individual mineral grains welded together or cemented by glass. On the other hand, the grains in sedimentary rocks are bound together by a matrix that is usually dominated by clay, if poorly lithified, or by silica cement if strongly lithified.

Studies that have been undertaken of the grinding/polishing behaviours of various rocks and minerals (Attaway 2005; Evans et al 2003; Golini and Jacobs 1991; Lampropoulos et al 1997; Lampropoulos et al 1996; Sinkankas 1999) have clearly shown that:

- mixtures of hard and soft minerals will not polish well and thus the rock surface will retain its roughness

- the harder the mineral, the less effect abrading/grinding has on the surface of the mineral
- the depth of scratch when an abrasive medium is used correlates with the hardness difference between the abrasive and abraded material (the greater the difference, the deeper the scratch)
- finer grain sizes of abrasive material remove more material from surfaces
- the removal rate of material is influenced by the environment (ie the fluid in contact with the abrading material); water as a lubricant aids brittle fracture
- surface stress increases with decreasing grit size of abrading/polishing media
- polishing of samples with very fine but relatively harder or softer abrasive material causes surface deformation (work hardening); this occurs irrespective of whether the polishing medium is harder or softer than the material polished
- the lapping/grinding/polishing process involves both brittle fracture and ductile deformation of the surface.

Abrasive wear is the grinding/scratching (surface roughening) process that takes place when material is removed from the surface by harder abrasive grains. The abrasive grains hammer surface asperities, knocking small particles (brittle failure) out of the sample surface and causing strong local deformation in the grain that has been hammered.

Empirical studies of ground surfaces have shown that for a depth of cut less than 1μm, only material flow is observed around the cuts. As the depth of the cut increases, cracking and material flow occurs. At depths of 10μm or more, scratches are associated with fracturing in the material, and large-scale chipping and crushing have been observed, which weaken and roughen the overall surface – that is, deep scratching results in mechanical grinding of the surface. Under constant conditions the depth of the cut (scratch) will be related to the hardness difference between the cutting and cut materials. Adjacent to the cracks and fractures are areas of strained/deformed material. Thus, in all modes of grinding, there is a deformed subsurface layer caused by the buildup of stress (shear or work hardening). According to Golini and Jacobs (1991):

> *... the magnitude and depth of permanent deformation accompanying the brittle process depends on the abrasive size with smaller abrasives producing a higher overall percentage of deformation caused by plastic flow.*

Polishing of relatively larger crystals, either by fine micron-sized harder particles or by softer materials (such as clay), is a chemomechanical process that alters the surface properties of the material being polished. The grinding/polishing process induces a layer of compressive stress on the surface of the sample. The compressive stress alters the surface properties of the material, producing a surface layer along which smoothing of the surface by ductile deformation occurs.

8.4.2 Constituents of the aggregate samples

Table 8.3 shows the major mineral constituents of the four aggregates that were examined, listed in order of their Moh's hardness number (ie their order of resistance to abrasion/scratching), together with other diagnostic properties that are relevant to the minerals' polishing and failure/fracture properties. However, it should be noted that Moh's hardness scale is not linear, and its relationship to the hardness number determined by indentation methods (such as the Vickers hardness number) is log/linear.

Table 8.3 Major mineral constituents of the aggregates used in the laboratory experiments (Black 2005b)

Mineral	Formula	Moh's scale hardness	Fracture properties	Aggregate occurrence
Spinel	$MgAl_2O_4$	7.5–8	No cleavages	Slag
Quartz	SiO_2	7	Conchoidal fracture	Greywacke
Olivine	Mg_2SiO_4	7	Conchoidal fracture	Basalt
Prehnite	$Ca_2Al_2Si_3O_{10}(OH)_2$	6.5	One good cleavage	Greywacke
Plagioclase feldspar	$CaAl_2Si_2O_6$	6–6.5	Two sets of perfect-to-good cleavages	Basalt and greywacke
Pseudobrookite	$FeTiO_5$	6	No cleavage	Slag
Ilmenite	$FeTiO_3$	6	No cleavage	Slag
Magnetite	Fe_3O_4	5.5–6	No cleavage	Basalt
Perovskite	$CaTiO_3$	5.5	Poor cleavage	Slag
Pyroxene	$Ca (Fe,Mg) SiO_3$	5–6	Two sets of good cleavages	Basalt and slag

Many minerals, particularly silicates and oxides, are brittle at ambient temperatures; that is, they do not have the capacity to store energy in the form of strain, and react to stress by fracturing. Brittle minerals that are strongly anisotropic in terms of their physical properties, and which have crystal structures that contain planes of different atomic densities and bonding, will break along closely spaced planar surfaces, which reflect planes of weakness in the crystal lattice (cleavage). If the mineral has a highly uniform internal crystal structure, it will break in a random manner (fracture). Some hard minerals that lack cleavage break along randomly located fracture surfaces with curved concavities (conchoidal fractures). The nature of the fracture and the presence (or absence) of cleavages are diagnostic properties of individual mineral species, since they reflect the fundamental crystal structure.

Abrasion in the brittle mode (the case for all the samples considered) is a fracture process in which the surface is reduced by fracture and chipping (Golini and Jacobs 1991). In the abrasive grinding environment, minerals that have two sets of good-to-excellent cleavages, such as pyroxenes and feldspars, will break along those planes. The intersections of the cleavage planes provide points of weakness causing surface pitting, and the intersecting cleavage systems also allow small rectangular blocks of the crystal to be plucked out of the rock surface. In this manner, the surface of the rock is mechanically eroded, retreats and becomes smoother. Hard silicates, such as olivine and quartz, which do not have cleavage planes, tend to pluck out of the rock as entire crystals, which then scratch the surface of other minerals as continued polishing eliminates them from the surface.

The metallic oxides, on the other hand, lack cleavages and have 'polishing hardness'; that is, they retain their relief and stand proud (ie have a higher surface level) with respect to the silicate minerals. Thus, the presence of abundant metal oxides increases a material's polishing resistance.

8.4.3 A geological interpretation of the polishing of the sample aggregates

Black (2005b) states that the petrography of the aggregates that have been tested in this research, and their microtextures, allows an interpretation of the results in terms of the measured skid resistance obtained with the DF Tester.

The melter slag, which has an inherently irregular surface with many vesicles, is composed dominantly of metal oxides. Spinel, which is a substantial component of the slag, is an exceptionally hard mineral (Moh's scale 7.5–8) and the other titanium oxides (pseudobrookite and ilmenite) are also very cohesive and hard. None of these metal oxides have cleavages. The microtexture of the rock is formed by interlocking large crystals of the metal oxides, which provide cohesion to the material. Since they polish hard, these oxides effectively protect the smaller perovskite and pyroxene crystals located between them from abrasion in the polishing process, while still providing a surface relief that has rough microtexture and therefore high skid resistance. Thus it is not surprising that the slag has a reasonably high initial skid resistance and outperforms, over time, the tested natural aggregates in terms of skid resistance.

The Holcim basalt sample is composed dominantly of the silicate minerals plagioclase feldspar and augite. These minerals have similar hardness and both have two very good cleavage sets that intersect at approximately 90°, which allow the mineral grains to be physically broken down. The only hard silicate mineral present (olivine) in the Holcim basalt constitutes less than 10% of the rock and occurs as small crystals interlocked with the other silicate minerals. The magnetite also occurs as small crystals integrated in the rock matrix and has a similar hardness to the dominant silicate minerals. Thus the polishing and abrasion of the basalt surface occurs relatively evenly and there is less change between the 'before' and 'after' polishing phases. However, as there is less initial harshness in the microtexture, a low measured polished skid resistance results.

Greywacke sandstone chips from two quarries were tested: Moutohora Quarry from the Matawai District north of Gisborne, and the Otaika Quarry from Whangarei. These two greywacke sediments are different in age, degree of metamorphism (lithification) and nature.

- The **Moutohora sandstone** is from the Cretaceous period and is more uniform in its properties. It has a coarser grain size, and is inherently less lithified than the older late Triassic/Jurassic greywacke from Otaika Quarry near Whangarei. The different colours of the chips (greenish, brownish and grey, refer to figure 8.1), indicates different degrees of oxidation, together with a lack of veining, which shows the Moutohora greywacke still retains some permeability with respect to water.
- **The Otaika Greywacke** is a finer-grained sandstone, variable in grain size (ranging through to siltstone) and strongly lithified by low-grade metamorphism. Metamorphic prehnite is found in the matrix of the Otaika greywacke and in white veins cutting the rock.

The ratio of the major X-ray diffraction peaks for quartz to plagioclase in bulk Moutohora greywacke sample is 10:11, compared with 10:6 in the Otaika greywacke. It was not possible to determine the absolute amounts of quartz and feldspar present in the two greywackes (the Moutohoro sample contained minor potassium feldspar as well as plagioclase feldspar), but the relative proportions and peak heights (intensities) of the quartz and feldspar in the diffractogrammes indicated that the Moutohora sample contained approximately 40% more feldspar than the Otaika greywacke. Judging from visual estimates of quartz and feldspar in the thinsections, much of the excess quartz in the Otaika samples must have been in the recrystallised metamorphic cement/matrix of the rock.

These differences in degree of lithification, mineral content and grain size provide explanations for the different polishing and skid resistance properties of the two greywackes.

8.5 The results of polishing with contaminants (stage 2)

8.5.1 Introduction

Once each of the polished surface samples had clearly reached an 'equilibrium level' for that specific aggregate, load and polishing action (stage 1), the samples were ready for the stage 2 polishing phase. The stage 2 laboratory polishing phase required the simulation of the approximately seasonal variation of measured skid resistance. This required simulating the cyclical effects of variation of the summer and winter polishing; that is, rejuvenation of surface samples through the effects of contaminants, rainfall and vehicle trafficking. Specific procedures were developed to determine the effect on the variation of the coefficient of friction of placing specific additives upon the surface, followed by accelerated polishing to simulate traffic loads. The polishing action and the method of wetting and drying of the surface, and all other known variables, were held constant (where possible) to isolate the effect of the additive.

The theory of the phase 2 variation in measured skid resistance (known as the 'seasonal variation') as described by Jayawickrama and Thomas (1998) and discussed in section 2, has been that the accumulation of finer-particle detritus material contributes towards the polishing of the aggregates (reducing skid resistance), whereas coarse grit contributes to abrasion of the aggregate, which helps to rejuvenate skid resistance. Cycles of rainfall wash away finer material, thereby allowing the grit to rejuvenate skid resistance during wetter periods. During drier periods, the finer material accumulates, polishing the aggregate and reducing skid resistance.

The stage 2 polishing phase and procedures were developed to test this theory by adding a number of additives to the laboratory surface samples, combined with accelerated polishing, to measure the effect on measured skid resistance.

8.5.2 Contaminant additives

The sample additives that were chosen were similar to the detritus particle size distribution expected to accumulate in the field. They are summarised as:

- *Oedometer clay* – a soft but well-graded material that is predominantly kaolinite and is strongly anistropic in terms of its properties, with a Moh's hardness of 2–2.5
- *Emery powder* – a fine but very hard material derived predominantly of corundum (Al203), with a Moh's hardness of 9
- *Leighton Buzzard sand* – a coarse and hard material that is predominantly from quartz, with a Moh's hardness of 7.

The stage 2 accelerated polishing consisted of measuring the effect of the following variations to the stage 1 wet-polishing phase:

- dry polishing, with the addition of oedometer clay (10 grams)
- dry polishing, with the addition of sieved oedometer clay (10 grams) with particle size of <0.15mm
- dry polishing, with the addition of sieved oedometer clay (10 grams) with particle size of >1.15mm
- dry polishing, with the addition of emery powder (10 grams)

- dry polishing, with the addition of Leighton Buzzard sand (20 grams)
- wetted surface (damp) polishing, with the addition of oedometer clay (10 grams).

After each polishing variation had been tested, the surface sample was then polished, wet but with no additives, to try to restore the sample to its 'equilibrium skid resistance level'. Appendix C discusses the results in terms of each of the four laboratory samples.

8.5.3 Summary of stage 2 accelerated polishing with contaminants

The effect of adding various contaminants (oedometer clay, Leighton Buzzard sand and emery powder) to the four laboratory-prepared samples, consequent with accelerated polishing, was measured by the DF Tester (DFT(μ)) device. This stage was named the stage 2 polishing phase and the detailed results are in appendix C and summarised here in table 8.4.

Table 8.4 DFT(μ) and % difference in results of the stage 2 addition of contaminants and accelerated polishing

Description of contaminants and accelerated polishing	Moutohora greywacke PSV 63		Holcim basalt PSV 52		Otaika greywacke PSV 52		Melter slag PSV 55	
	DFT(μ)	%diff[a]	DFT(μ)	%diff[a]	DFT(μ)	%diff[a]	DFT(μ)	%diff[a]
Initial skid resistance DFT(μ)	0.87		0.60		0.58		0.90	
ESR polished DFT(μ) after wet polishing[b]	0.47	46.0%	0.39	35.0%	0.42	27.6%	0.71	18.4%
Oedometer clay DFT(μ) dry polishing[c]	0.58	-23.4%	0.41	-5.1%	0.43	-2.4%	0.72	-1.4%
Emery powder DFT(μ) dry polishing	0.55	5.2%	0.33	19.5%	0.36	16.3%	0.67	6.9%
Wet polishing for 30mins (no contaminants)	0.48	12.7%	0.32	3.0%	0.34	5.6%	0.63	6.0%
Leighton Buzzard sand DFT(μ) dry polishing cycle 1	0.70	-45.8%	0.66	-106.3%	0.54	-8.8%	0.71	-12.7%
Emery powder (3x10gms every 10mins) before DFT(μ)-cycle 1	0.49	30.0%	0.23	65.2%	0.26	51.9%	0.51	28.2%
Wet polishing for 30mins (no contaminants)	0.45	8.2%	0.26	-13.0%	0.26	0%	0.51	0%
Oedometer clay DFT(μ) damp polishing	0.67	-48.9%	0.41	-50.0%	0.48	-84.6%	0.58	-13.7%
Wet polishing for 45 mins (no contaminants)	0.60	10.5%	0.34	12.8%	0.43	10.4%	0.51	12.1%
Leighton Buzzard sand DFT(μ) dry polishing cycle 2	0.67	-11.7%	0.44	-29.4%	0.45	-4.7%	0.61	-19.6%
Emery powder (3x10gms every 10mins) before DFT(μ)-cycle 2	0.41	38.8%	0.22	50.0%	0.37	17.8%	0.39	36.1%

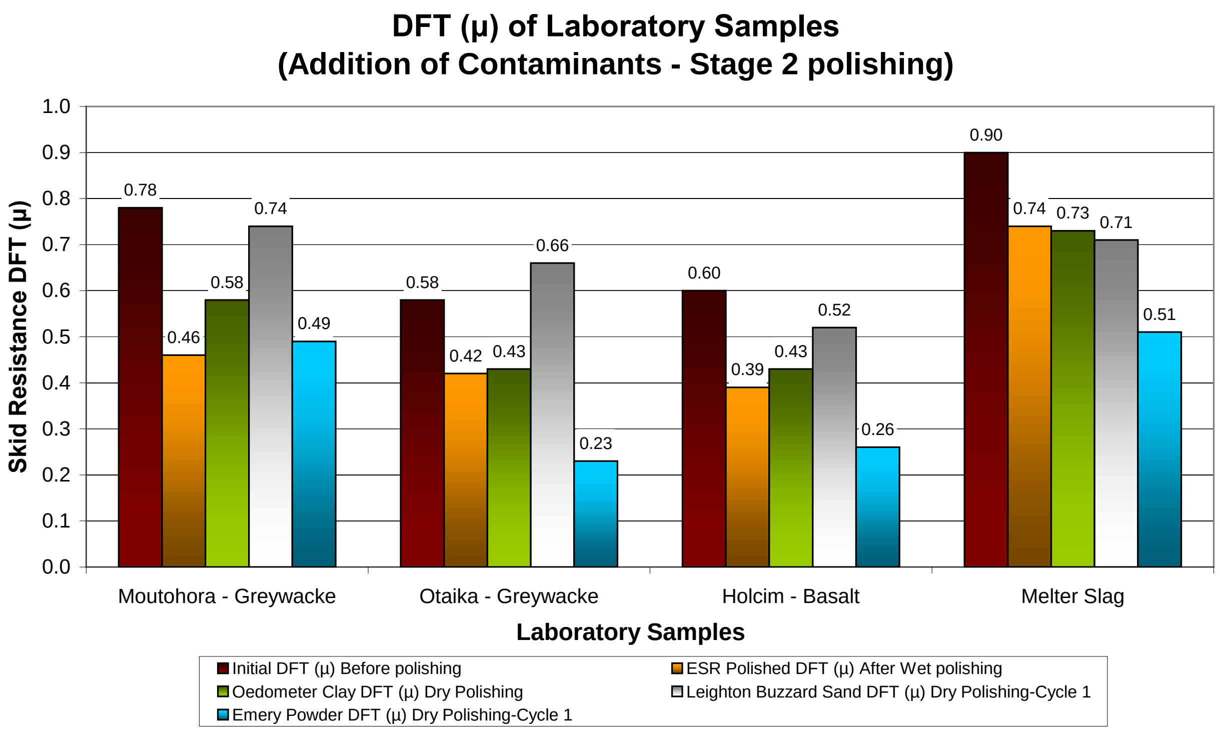
a) The values in this column are the percentage difference in the result from the prior-measured coefficient of friction condition result. This measures the change in the coefficient of friction DFT(μ) due to the addition of the contaminant under the action of the accelerated polishing.

b) End of stage 1 accelerated polishing and skid resistance measurement DFT(μ) results.

c) Beginning of stage 2 polishing and skid resistance measurement DFT(μ) results.

The DFT(μ) results of each polished laboratory sample for the value at which the DFT(μ) levelled off, and/or the polishing time was (for pragmatic reasons) stopped, are shown graphically in figure 8.15 following. Each progressive series of bar charts given in figure 8.15 shows the effects of the addition of contaminants and whether accelerated polishing was undertaken in dry, wet or damp conditions, in the order shown in the bar charts (other trials showing less effect are not shown; they have been described in detail in the previous section).

Figure 8.15 Skid resistance DFT(µ) and the effects of the addition of contaminants on the four laboratory samples

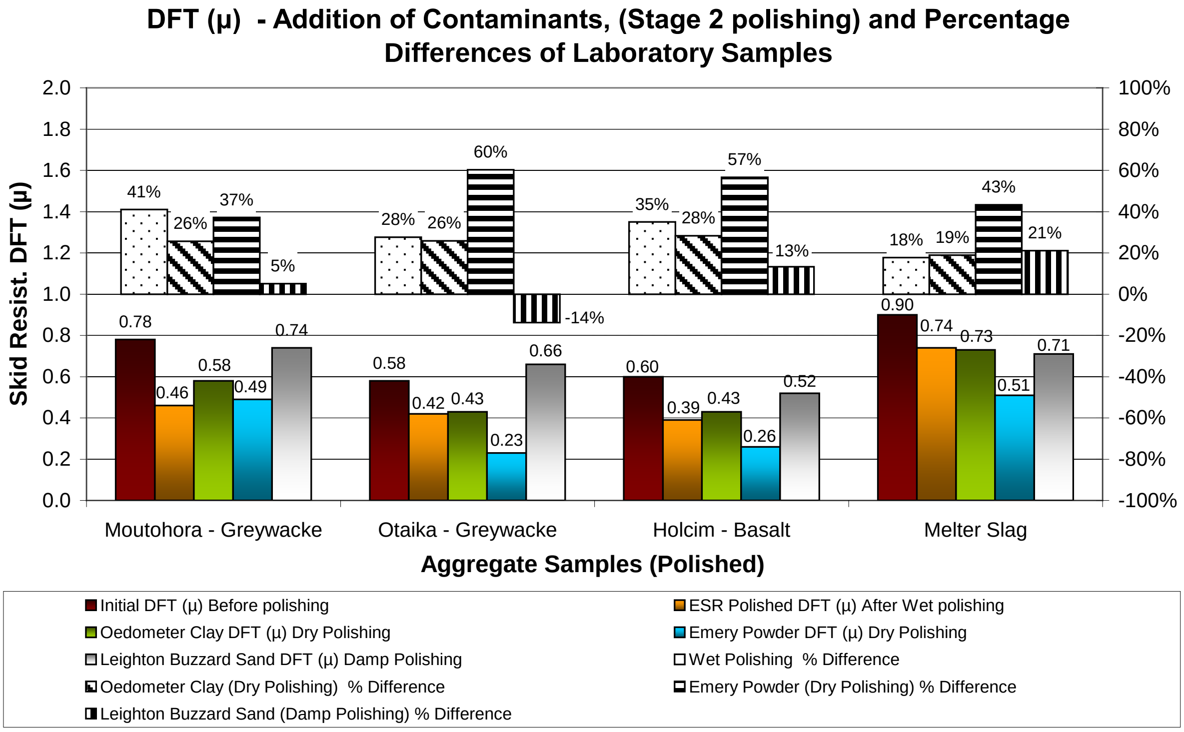


All surface aggregates were initially polished using the AAPD developed at the University of Auckland (as shown in figure 4.3) to an ESR level (stage 1). They were periodically tested throughout the polishing process for their skid resistance using the DF Tester DFT(µ). The stage 2 polishing phase also used the AAPD with the addition of contaminants and accelerated polishing, which resulted in significant changes in the measured coefficient of friction for the four laboratory-prepared samples. Figure 8.16 shows the real changes in measured skid resistance in terms of DFT(µ), and also the percentage difference in the result from that of the initially tested surface aggregate, prior to any accelerated polishing. The data analysis and figures 8.15 and 8.16 show the following results for the four laboratory samples:

- The three natural aggregates (whilst beginning at different levels) decreased in measured skid resistance to an ESR level due only to wet polishing, by 28% to 41%. Only small differences pertained in the actual DFT(µ) values at ESR (0.39–0.47) between the three natural aggregate samples, even though their initial values featured much greater differences.
- The melter slag had the highest initial position value DFT(µ)=0.90; this decreased by the smallest amount (18%) to an ESR level of DFT(µ)=0.71.

- The addition of oedometer clay (soft and well-graded, to fine and coarse PSD) with dry accelerated polishing, on the three natural aggregates, generally increased the measured skid resistance DFT(μ) to a small degree. The highest increase in DFT(μ) was recorded for the Moutohora aggregate, with an increase of DFT(μ) of 0.12. Very minor increases in DFT(μ) were recorded for the Holcim basalt and Otaika greywacke aggregates.
- The addition of oedometer clay and dry accelerated polishing on the melter slag aggregate resulted in little change (although it was slightly reduced) to the skid resistance DFT(μ) value.
- When added to the samples, the Leighton Buzzard sand (hard and coarse material), with dry polishing with the AAPD, significantly increased the measured skid resistance DFT(μ) on all three natural aggregates. Furthermore, the Leighton Buzzard sand raised the skid resistance DFT(μ) to significantly higher levels than the initially recorded value of ESR from wet polishing. The Moutohora and Holcim aggregates increased the skid resistance DFT(μ) almost back to the initial measured values prior to any polishing. When polished, the Otaika aggregate sample with the addition of Leighton Buzzard sand had an increased DFT(μ) to a value that was higher than the initially tested value.
- Accelerated dry polishing with Leighton Buzzard sand on the melter slag aggregate also increased the value of measured skid resistance DFT(μ), but to a lower level than that reached at ESR.
- The addition of emery powder (hard and fine) significantly decreased the measured skid resistance DFT(μ) on all laboratory samples from the prior level that existed after the Leighton Buzzard sand had coarsened the microtexture. The Moutohora DFT(μ) level decreased to approximately the same level as that obtained at ESR, but no further. The measured skid resistance DFT(μ) of the Otaika aggregate decreased to almost a third of its measured skid resistance when roughened by the Leighton Buzzard sand, and to a level significantly lower than the ESR level reached with wet polishing. The Holcim basalt and the melter slag aggregate DFT(μ) level also decreased significantly with the addition of emery powder, to a level significantly lower than that reached at ESR.
- Subsequent cycles of adding Leighton Buzzard sand and emery powder to the Moutohora, Holcim basalt, and the Otaika greywacke aggregates, with accelerated polishing, indicated that a historical memory of an ESR level may exist with a natural aggregate, as the measured skid resistance DFT(μ) oscillated up and down around this value, but when it was wet polished, the skid resistance DFT(μ) tended towards returning to the ESR level.
- The results of continued cycles of the addition of contaminants and accelerated polishing on the melter slag were surprising, after this aggregate had initially performed well. The results from this research indicate that once the crystalline structure is disrupted, an overall trend of decreasing measured skid resistance can occur and that the melter slag does not recover from this level. The initial benefits of the melter slag under ongoing cyclical polishing with contaminants, resulted in the melter slag DFT(μ) being reduced to a value similar to that for the Moutohora greywacke aggregate (DFT(μ)=0.39). It is currently unknown whether this would continue to decrease further, although a linear extrapolation of the stage 2 results indicate that it could.
- Polishing with emery powder produced the lowest recorded skid resistance value (DFT(μ) for all of the laboratory sample aggregates. The lowest recorded skid resistance DFT(μ) value for each of the aggregates, which included the second cycle of accelerated polishing with emery powder, were: Moutohora=0.41, Holcim=0.23, Otaika=0.26 and melter slag=0.39).

Figure 8.16 Skid resistance DFT(μ) and the effects of the addition of contaminants and the % difference from the initial SR value for the four laboratory samples



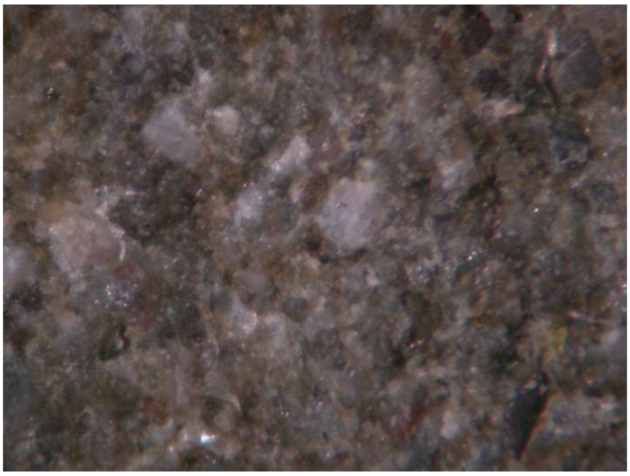
8.5.4 Macrophotographs of the effects of polishing with contaminants

Macrophotographs were taken through a microscope of the same aggregate chip and position for each of the four polished laboratory samples (or as close as was possible to the same position). Initially, a photograph was taken immediately after the addition of four doses of 20 grams of Leighton Buzzard sand and dry accelerated polishing for 10 minutes for each dose. This position (figure 8.17a) coincided with the time when the surface was rejuvenated in terms of skid resistance and measured DFT(μ) was high. The second photograph (figure 8.17b) was taken after 30 minutes of polishing with emery powder and coincided with the time when the surface was polished in terms of skid resistance and when measured DFT(μ) was low.

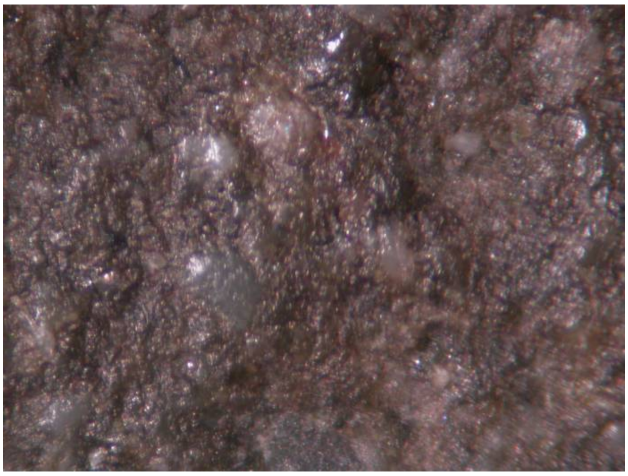
A comparison of a sample of the Moutohora greywacke aggregate after each state of polishing is shown in figures 8.17a and b. There are significant differences in the microtexture of the aggregate surface. Figure 8.17b is a lot less harsh than the rougher and uneven surface shown in figure 8.17a. As the Moutohora aggregate consists of a matrix of variable grain sizes and hardness of minerals, the coarse and hard quartz minerals of the Leighton Buzzard sand (figure 8.17a) resulted in the grinding down and the plucking out of grains from the surface, thereby producing a rough, harsh and uneven surface microtexture, leading to a relatively high measured skid resistance of DFT(μ)=0.74. The various grain sizes are much more rounded and polished in figure 8.17b after the effect of polishing with emery powder, which is very fine and comprises hard corundum minerals. It is clear that reasonable skid resistance can be attained on this polished surface (figure 8.17b), as confirmed by the skid resistance measurement of DFT(μ)=0.49.

Figure 8.17 Moutohora – after polishing with various contaminants (approx. field of view 3.5 x 2mm)

(a) After Leighton Buzzard sand polishing



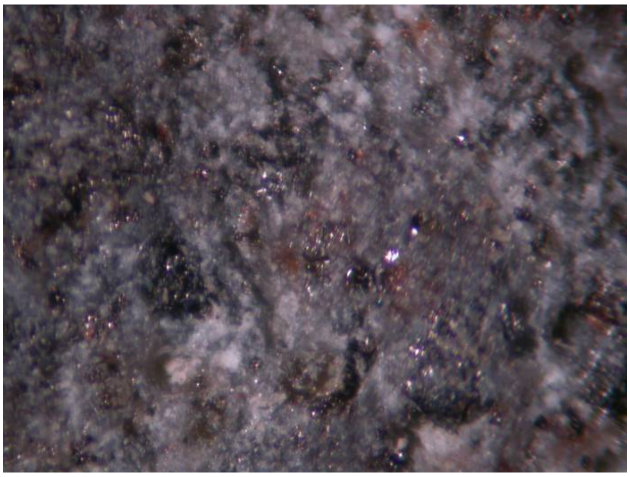
(b) After emery powder polishing



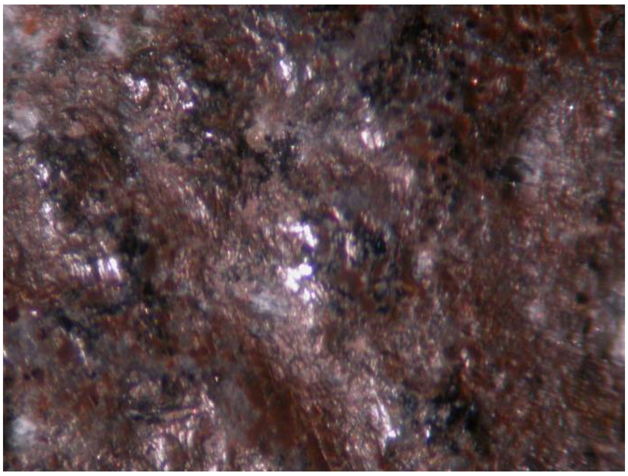
A comparison of a sample of the Holicm basalt aggregate chip photos is shown in figures 8.18a and b. It is apparent that differences exist in the microtexture of the aggregate surface. Figure 8.18b is a lot more polished on the top grain surfaces than the rougher surface in figure 8.18a. The surface in figure 8.18a has been ground and scratched with the abrasive Leighton Buzzard sand, leaving a harsher surface. However, the grain matrix has stayed reasonably intact, as both the polishing contaminants (Leighton Buzzard sand) and the basalt minerals are predominantly quartz minerals of similar hardness. The measured skid resistance after polishing with the Leighton Buzzard sand (refer to figure 8.18a is DFT(μ)=0.52. This is a lot better than that shown in figure 8.18b, but is still a lot lower than the Moutohora greywacke shown in figure 8.17a. The polishing of the basalt surface with emery powder has caused the highest-protruding surface grains to begin to flow in some cases, and therefore the measured skid resistance at this point is very low, DFT(μ)=0.26.

Figure 8.18 Holcim basalt – after polishing with various contaminants (approx. field of view 3.5 x 2mm)

(a) After Leighton Buzzard sand polishing



(b) After emery powder polishing

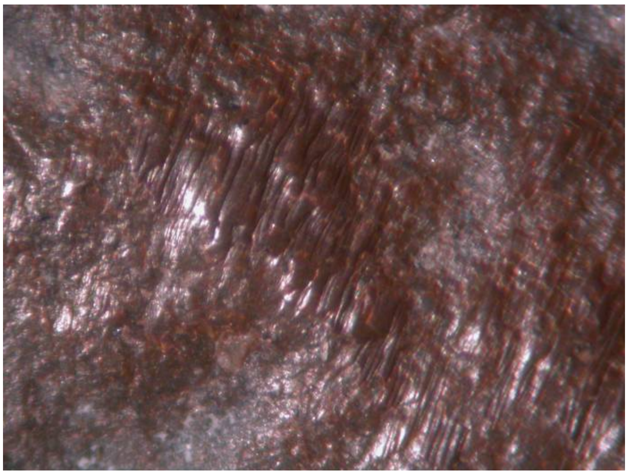


Photographs of samples of the Otaika greywacke aggregate chip are shown in figures 8.19a and b. It can be clearly seen that the Otaika grain size is much smaller and more uniform than the Moutohora aggregate shown in figure 8.17a. The two photos in figure 8.19 show the same aggregate chip surface after polishing with Leighton Buzzard sand (figure 8.19a) and polishing with emery powder (figure 8.19b). Significant differences can be seen in the microtexture of the aggregate surface – figure 8.19a shows a more harsh surface (although not very rough and uneven), and figure 8.19a demonstrates severe polishing of the grain matrix, with the surface beginning to flow. The differences in the photographs can explain the large difference in the measured skid resistance between the surfaces, although the figure 8.19a skid resistance level is still significantly lower than the Moutohora greywacke value after the same type and amount of polishing with Leighton Buzzard sand. This is due to the less rough and uneven surface of the Otaika aggregate. The measured skid resistance of figure 8.19a after Leighton Buzzard sand polishing is DFT(μ)=0.66, and for figure 8.19b, with the emery powder, is DFT(μ)=0.23.

Figure 8.19 Otaika greywacke – after polishing with various contaminants (approx. field of view 3.5 x 2mm)

(a) After Leighton Buzzard sand polishing

(b) After emery powder polishing

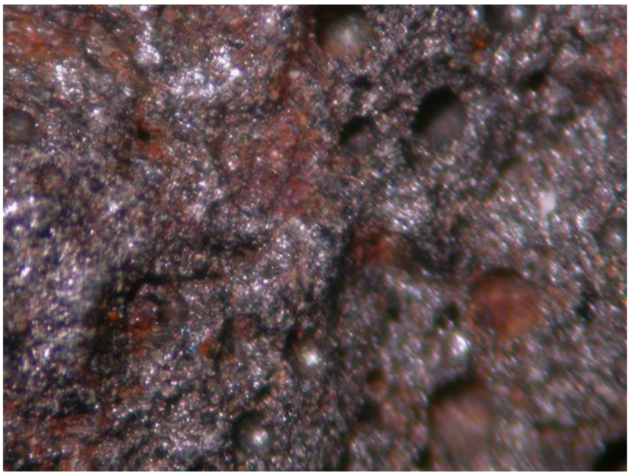


Photographs of a sample of the melter slag aggregate chip is shown in figures 8.20a and b. There is much less visual difference between the two photographs after polishing with Leighton Buzzard sand (figure 8.20a and with emery powder (figure 8.20b compared with the other aggregate samples. More polishing of the grain top surfaces in figure 8.20b is apparent, although the overall surface is still very rough and harsh. This explains why the measured skid resistance is still relatively high DFT(μ)=0.51. As would be expected from a visual inspection of figure 8.20a, the skid resistance measurement after Leighton Buzzard sand was relatively high compared with the other natural aggregate samples DFT(μ)=0.71, although this had reduced somewhat from the initial skid resistance measurement that was obtained prior to any polishing, which resulted in a DFT(μ)=0.90.

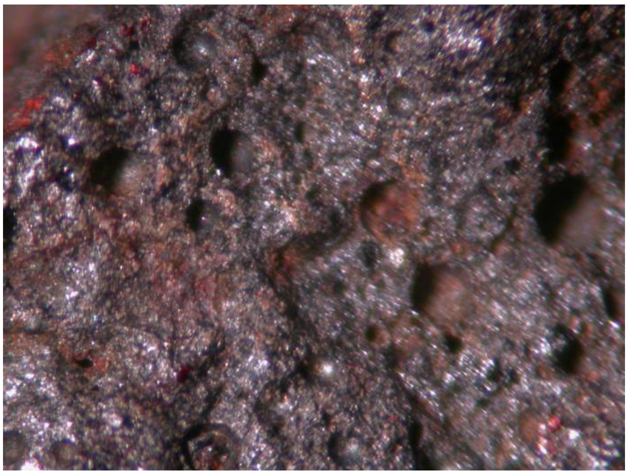
However, as discussed above, a second cycle of polishing with Leighton Buzzard sand and emery powder (after the photos above were taken) showed a trend of continuing reduction in measured skid resistance for the melter slag that was similar to that for the Moutohora greywacke aggregate (DFT(μ)= 0.39). This decreasing trend is of some concern and it is currently unknown whether this would continue to decrease further, although extrapolating results indicate that it would.

Figure 8.20 Melter slag – after polishing with various contaminants (approx. field of view 3.5 x 2mm)

(a) After Leighton Buzzard sand polishing



(b) After emery powder polishing



8.5.5 A geological explanation of the stage 2 polishing experiments

Black (2005a) considers that in simple terms, the following three processes affect change in the measured skid resistance of the laboratory samples:

1 *Polishing* surfaces with small soft material – in this case, the *oedometer clay* (kaolin with Moh's hardness (H)=2–2.5), which is softer than all the minerals in the samples and thus cannot scratch them. Clay minerals are flexible, and when damp, form cohesive masses that would be likely to fill existing depressions between asperities when polishing takes place in the damp (as distinct from wet) state. In wet polishing, however, the clay material will be washed out of depressions.

2 *Scratching* of surfaces by small hard grains – in this case with *emery powder* (H=9), which is harder than all the minerals present in the samples.

3 *Scratching* of surfaces by large hard grains – in this case by the *Leighton Buzzard sand*, which is almost pure quartz (H=7) and will scratch anything softer, forming deep scratches and removing much of the work-hardened surface produced by polishing with the emery and oedometer clay.

The scratching (mechanical) effect can be seen clearly in the behaviour of the four samples when quartz sand (Leighton Buzzard) was added to them. The greatest effect was in the Holcim basalt, which is composed dominantly of feldspar, magnetite and pyroxene, which, with a hardness range of 5–6, are all softer than quartz and thus will be scratched by quartz (H=7). The minimum effect was in the melter slag sample, which contains abundant spinel that is harder than quartz, and therefore will not be scratched by quartz. Consequently, the application of Leighton Buzzard quartz did not revive the surface, with results remaining lower than the original DFT(μ) values.

The Moutohora aggregate started with a very high DFT(μ), or PSV, and examination of the aggregate surfaces showed very good relief, with the quartz, feldspar and other grains standing out clearly on the surfaces of the rock. However, probably because of the high feldspar content and the very low level of metamorphism (and hence lithification), the measured skid resistance decreased rapidly with polishing, and the final skid resistance for the Moutohora aggregate was similar to that of the other natural aggregates.

The Otaika greywacke, because of its relatively higher level of lithification and hardness, and higher quartz content in the rock matrix, had a more uniform surface texture and a low initial measured skid resistance and consequent PSV, and showed less change with polishing.

Surface memory: The grinding/polishing process induces a layer of compressive stress on the surface of the samples, resulting in work-hardened surfaces. It is this change in the structure of the surface of the samples that creates the memory effect seen in these experiments. While the application of coarse quartz grains caused new scratching and thus rejuvenated the surface to some degree, the work-hardened surface clearly persisted in areas surrounding the new scratches, and thus the skid resistance of the chips dropped quickly to a level close to that which existed before the application of the quartz sand.

8.5.6 Summary of controlled laboratory experiments

The controlled laboratory experiments successfully demonstrated that significant variations in skid resistance could be simulated by polishing samples that were prepared in the laboratory. The results of a two-stage polishing process, which consisted of accelerated wet polishing to an 'equilibrium skid resistance level' (stage 1 polishing) and the addition of various contaminant additives to the accelerated polishing process (stage 2 polishing) demonstrated results and degrees of variation similar to those shown at field sites with normal heavy-traffic conditions.

A summary of the main findings of the controlled laboratory experiments follows, under the following categories:

Polishing to an equilibrium level:

- The accelerated wet polishing of aggregates (without any contaminant additions) can polish natural aggregates to an 'equilibrium skid resistance level' (ESR).
- The level of polish achieved at ESR does not specifically relate to the PSV results.

The addition of contaminants with accelerated polishing:

- Significant variations (both increases and decreases from ESR) in measured skid resistance can be simulated in the laboratory by the addition of various contaminants.
- The significant variation in measured skid resistance observed in the field is intrinsically related to the geological properties of the aggregates themselves and the contaminants that end up in the macrotexture of the surfacing.

Geological properties of aggregates (grain size and hardness):

- Contaminants that are fine in size (less than 10μm) and that consist of hard minerals (eg emery powder) polish the aggregate surfaces, thereby reducing the measured skid resistance.
- The amount of decrease in measured skid resistance that is achieved on a specific aggregate depends upon the difference in hardness and the geological makeup of the contaminants and the aggregate surface being polished (the greater the difference, the greater the decrease in skid resistance).
- Contaminants that are coarse (>1mm) and consist of hard minerals (eg Leighton Buzzard sand) abrade, grind and scour the aggregate surface, thereby increasing measured skid resistance.

- The amount of increase in measured skid resistance that is achieved on a specific aggregate also depends upon the difference in hardness and the geological makeup of the contaminants, as well as the aggregate surface being polished (the greater the difference the greater the increase in skid resistance).
- Contaminants that are soft in mineral content in comparison to the surfacing aggregate (eg oedometer clay), irrespective of particle size, have been shown to increase the measured skid resistance only slightly when dry. However, when polishing occurs under the action of trafficking or accelerated polishing, in damp conditions (although not so wet that the contaminants are washed away) the measured skid resistance can increase on aggregates that have a softer grain matrix and a variable particle size. This effect remains unexplained.

9 Research summary

9.1 Overview

The research reported here has highlighted that there are many independent variables that determine the skid resistance of a section of road pavement at a particular time. Not all of these have been uncovered, at this point.

Skid resistance is not a stable quantity and this research has shown that it can change markedly in just a few hours, the change depending not only on the surfacing aggregate petrology, but also on the degree of wetness, (heavy) traffic, and the properties of the contaminant/detritus. Recognition of these factors will need to be strengthened in the operational and management arena, and it may well be that skid resistance can be targeted only as a band or range of values at any location, because of its inherent variability.

9.2 Research aims and objectives

The overall objective of the research detailed in this report was the advancement of understanding of the seasonal and short-term variation of skid resistance. Better understanding would have significant implications for RCAs, who are often struggling to come to terms with which skid resistance policy to adopt or, in the case of the NZTA, how to best manage skid resistance within the context of their current TNZ T/10 skid resistance policy. The research used a combination of fieldwork and laboratory experiments to address the specific aims of the research and to quantify the:

1. confidence limits of measured skid resistance variation, which includes ‘seasonal’ and ‘short-term’ variability of skid resistance on various road surfaces
2. variability between measurement devices (SCRIM, GripTester and the DF Tester) on various surfaces
3. concentration and particle size distribution of the types of contaminants that accumulate on the road surface, and how they vary with time and rainfall
4. effects of various washing treatments on the pavement surfacing, to determine whether the presence of detritus in itself reduces measured skid resistance
5. effects of wet and dry accelerated polishing on prepared laboratory specimens
6. effects of various contaminants on skid resistance due to accelerated polishing on prepared laboratory specimens.

The specific hypotheses that were tested for statistical significance were:

1. that skid resistance fluctuates in a band about an ‘equilibrium level’, once initial aggregate polishing has been completed

2 that the relative confidence limits of the band about the ‘equilibrium level’ are approximately 0.1SFC[12] units or 0.15GN[13] units from upper to lower limits

3 that the time period since the last rain has a significant effect on the short-term deterioration of measured skid resistance; ie that the slope of the short-term deterioration line is significantly different from zero and approximately 0.01SFC units (or equivalent GN) per day

4 that the type and classification of the contaminants that accumulate on the road surface are significant in determining the magnitude of the short-term variation of measured skid resistance.

The following sections provide the conclusions of the research in respect to the above research aims, objectives and hypotheses.

9.3 Seasonal and short-term variations of measured skid resistance

9.3.1 Outline

Seven field sites were regularly tested with the GripTester over a two- to three-year period. Two sites were asphalt mix surfaces in Auckland and five sites were chipseal surfaces on state highways in the Northland region. Conclusions addressing the specific study aims and objectives with regard to the seasonal and short-term variations in measured skid resistance are addressed below.

> ***Research aim 1:*** *Quantify the confidence limits of measured skid resistance variation, which includes ‘seasonal’ and ‘short-term’ variability of skid resistance on various road surfaces.*

9.3.2 Variations in the mean value

9.3.2.1 Auckland asphalt mix sites

Two Auckland asphalt mix sites were measured approximately monthly for almost three years. The two sites (Tamaki Campus and the Ports of Auckland) were considered to be acting in an equilibrium skid resistance phase. The Ports of Auckland surface was over seven years old, and the Tamaki Campus surface was approximately one year old at the beginning of the data collection period. Both sites exhibited signs of acting in an equilibrium skid resistance phase (especially in the second year of testing the Tamaki Campus site). GripTester measurements from both sites were normalised together and analysed. The results of the analysis demonstrated no clear noticeable or predictable patterns of the variation of skid resistance measurement over time. This was partly due to the very different and unpredictable trafficking actions at the two sites (heavy transverse trafficking at the Ports of Auckland site and very light traffic at the Tamaki Campus site).

A summary statistical description of the skid resistance measurements at each of the sites, including the average 95th percentile confidence interval, the standard deviation (σ) and the coefficient of variation

12 Sideways friction coefficient (SFC) is the coefficient of friction as measured by the SCRIM device.

13 GripNumber (GN) is the coefficient of friction as measured by the GripTester.

(CoV) of the site mean measured skid resistance (*x*), for the two sites, and for the GripTester and DF Tester devices respectively, were:

- Tamaki Campus asphalt mix site, using the GripTester (32 data points):

$$x \pm 0.020\,GN30 \qquad \sigma = 0.057 \qquad CoV = 7.4\%$$

- Tamaki Campus asphalt mix site, using the DF Tester (11 data points):

$$x \pm 0.019\,DFT20\mu \qquad \sigma = 0.034 \qquad CoV = 4.8\%$$

- Ports of Auckland asphalt mix site, using the GripTester (24 data points with heavy-vehicle traffic movements):

$$x \pm 0.028\,GN50 \qquad \sigma = 0.067 \qquad CoV = 10.9\%$$

- Ports of Auckland asphalt mix site, using the DF Tester (14 data points with heavy-vehicle traffic movements):

$$x \pm 0.027\,DFT20\mu \qquad \sigma = 0.050 \qquad CoV = 9.5\%$$

It could be concluded that the mean skid resistance value for the asphalt mix sites remained relatively consistent over time, after an equilibrium level had been establised, as the 95th percentile confidence interval was less than 0.06GN between sites. Furthermore, the GripTester and the DF Tester device measurements were consistent in that they both demonstrated that the Ports of Auckland site, which had heavy traffic conditions, demonstrated a significantly greater 95th percentile confidence interval, standard deviation and coefficient of variation compared with the Tamaki Camus site, which had light traffic.

9.3.2.2 Northland state highway chipseal sites

Skid resistance measurements were undertaken approximately monthly for over two years using the GripTester device on five chipseal sites in Northland, and using the DF Tester when possible on the Hikurangi site. Due to the age of the seal, two of the Northland two-lane state highway chipseal surface sites, were expected to be acting within an 'equilibrium skid resistance' phase (ie the Hikurangi site and the Snooks–Tatton section 2 site). The HCV volumes for the Hikurangi and Snooks–Tatton sites were approximately 950vpd and 300vpd, respectively. The Hikurangi and Snooks–Tatton sites' skid resistance results were normalised together with stable 30m timeslice sections from the Kaiwaka, Brynderwyn and Kara Road sites. The normalised results were analysed and no distinct seasonal patterns were visually apparent. The average 95th percentile confidence interval, the standard deviation (σ) and the coefficient of variation (CoV) of the mean value of the Hikurangi and Snooks–Tatton (section 2) sites over the data collection period were:

- Hikurangi chipseal site, using the GripTester (32 data points):

$$x \pm 0.024\,GN50 \qquad \sigma = 0.068 \qquad CoV = 12.4\%$$

- Hikurangi chipseal site, using the DF Tester (8 data points):

$$x \pm 0.048\,DFT20\mu \qquad \sigma = 0.069 \qquad CoV = 11.0\%$$

- Snooks-Tatton section 2 chipseal site, using the GripTester (24 data points with a HCV loading that was approximately one-third of the Hikurangi site):

$$x \pm 0.019 GN50 \qquad \sigma = 0.046 \qquad CoV = 8.2\%$$

When the sites that were known to be in the initial polishing phase (due to a newly laid seal (ie Kaiwaka Slag, Brynderwyn, Kara Road and Snooks-Tatton sections 1 and 3 sites) were analysed and compared against those that were supposed to be acting in an 'equilibrium level phase', there was very little difference in the measured 95th percentile confidence intervals of the site mean. This was surprising. It was initially expected that the extent of the variation would be less for surfaces that had reached an 'equlibrium level' of polishing (experiencing only seasonal and/or short-term variations) compared with sites that were still in the initial polishing phase from a new surface level. However, the results did not show this. In fact, the results showed that in terms of the 95th percentile confidence interval, the standard deviation (σ) and the coefficient of variation (CoV) of the mean value, the reverse had occurred. As shown below, the greater variation occurred on the sites that were supposedly at a stable equilibrium level of polishing.

- Kaiwaka slag chipseal site, using the GripTester and sealed with an iron-making melter slag (28 data points):

$$x \pm 0.021 GN50 \qquad \sigma = 0.056 \qquad CoV = 7.9\%$$

- Brynderwyn South curve chipseal site, using the GripTester (29 data points):

$$x \pm 0.026 GN50 \qquad \sigma = 0.070 \qquad CoV = 11.7\%$$

- Kara Road S1 and S2 chipseal sites, using the GripTester. HCV loading was approximately one-third of the Kaiwaka, Brynderwyn and Hikurangi sites (26 data points) respectively for section 1 and section 2:

$$x \pm 0.016, 0.018 GN50 \qquad \sigma = 0.043, 0.045 \qquad CoV = 6.5\%, 6.9\%$$

- Snooks-Tatton section 1 and section 3 chipseal sites, using the GripTester. HCV loading was approximately one-third of the Kaiwaka, Brynderwyn and Hikurangi sites (24 data points) respectively for section 1 and section 3:

$$x \pm 0.019, 0.018 GN50 \qquad \sigma = 0.047, 0.046 \qquad CoV = 6.9\%, 6.5\%$$

It could be concluded that the mean measured skid resistance result (GN50) for the Northland chipseal sites remained relatively consistent over time, as did the standard deviation (σ). This result was true both after an equilibrium level of skid resistance had been established, and during the initial polishing phases. The 95th percentile confidence interval for the site mean was less than 0.05GN when the sites had high HCV content (SH1 sites with approximately 900–950 HCVs per day) and less than 0.04GN between sites with approximately one-third of the HCV content (SH14 sites with approximately 300HCVs per day). The only exception was the Kaiwaka melter slag site on SH1, which performed better and more consistently than the other SH1 sites with similar HCV volumes, its performance being similar to the sites with one-third of the HCV volumes.

These conclusions must, however, be put into context with the aggregates that were used in the field and their resistance to polishing. As has been shown in the controlled laboratory experiments, the lower PSV aggregates (such as the Otaika aggregate which was the aggregate used on all of the Northland field sites except the Kaiwaka melter slag site) lost a lesser percentage of their initial value of skid resistance than those aggregates with a higher PSV (such as the Moutohora aggregate). Furthermore, the lower PSV aggregates could vary significantly with the addition of contaminants and could therefore mask any variation expected in the initial polishing phases.

One could therefore conclude from the field results of the five Northland chipseal sites and, to some extent, the two Auckland asphalt mix sites, that the variation in the measured skid resistance as described by the 95th percentile confidence interval range, the standard deviation (σ) and the coefficient of variation (CoV) increased with increasing percentage of HCVs, irrespective of the polishing phase of the aggregate.

The following two hypotheses were developed as part of the experimental design:

- **Hypothesis 1:** That skid resistance fluctuates in a band about an 'equilibrium level', once initial aggregate polishing has been completed.

  The above analysis demonstrated that this hypothesis is true.

- **Hypothesis 2:** That the relative confidence limits of the band about the 'equilibrium level' are approximately 0.1SFC units or 0.15GN units from upper to lower limits.

  The analysis showed that this hypothesis is not true, as the confidence interval around the true mean site value to the 95th percentile probability level was surprisingly small, being approximately 0.06GN for natural surfacing aggregates in the field. However, the variation shown from calendar month to month (discussed below) demonstrates that significant variation does exist on a monthly basis and also that distinct seasonal patterns can and do occur.

9.3.3 Seasonal variations by calendar months of year

9.3.3.1 Auckland asphalt mix sites

An analysis of the normalised GN results for the Auckland asphalt mix sites (Ports of Auckland and Tamaki Campus sites) by calendar month of the year resulted in the lowest monthly results in February (95th percentile normalised GripNumber confidence interval from 0.92 to 0.96) and the highest monthly results in August (95th percentile normalised GripNumber confidence interval from 1.03 to 1.07). These two monthly periods were separated by six months, with the lowest measured values in mid- to late summer and the highest mean measured values in August (late winter), with a 0.12GN difference in the mean result range.

The variations between other months on the Auckland asphalt mix sites had no distinct patterns. The months either side of February and August were highly variable and the data demonstrated no confidence at the 95% level that the result in those months would be higher or lower than the normalised mean monthly data. The within-month normalised NGN value (the difference between the maximum and minimum normalised monthly result) ranged from 0.06GN (recorded in February) to 0.27GN (recorded in June), with an average of 0.18GN for each month. This clearly demonstrated the significant and largely unpredictable variation that can occur in measured skid resistance within months of the year. Interestingly, the months of February (the lowest monthly mean result) and August (the highest monthly mean result) had the smallest range of result, 0.06GN and 0.08GN respectively. This demonstrated that for these two sites, there was some confidence that a measured coefficient of friction during those months would be close to the minimum or to the maximum result, respectively. However, it should also be noted that these two months had only six and 10 data points, compared with others that had up to 22 data points.

9.3.3.2 Northland state highway chipseal sites

An analysis of the normalised NGN results for the Northland chipseal sites by calendar month of the year resulted in a much more distinct seasonal pattern. The lowest mean monthly measured values occurred in April (late summer), with a 95th percentile confidence interval between 0.94 and 0.98 (an average of 0.96) and the highest mean measured values in August (late winter), with a 95th percentile confidence interval between 1.02 and 1.06. The difference in the mean monthly result between February and August was 0.08GN. Once again, the results either side of these months proved to be much more variable.

The within-month normalised NGN range for the Northland chipseal sites (the difference between the maximum and minimum normalised monthly result) ranged from 0.07GN (recorded in August) to 0.29GN (recorded in May), with an average normalised range of 0.17GN. This clearly demonstrated the significant and largely unpredictable variation that could occur in measured skid resistance within months of the year. The months of February, August (the highest monthly mean result) and December had the smallest range of monthly results: 0.07, 0.09 and 0.09GN, respectively. The normalised mean monthly results of the Northland chipseal sites also indicated a sinusoidal pattern, although unexpectedly, with a period of approximately six months rather than the expected 12-month period. However, the pattern was indicative only and was thought to be partly due to the inherent and somewhat variable nature of skid resistance and its measurement, and perhaps unusual rainfall events in the summer data collection periods. More data would be required to confirm whether these findings were repeatable.

The data analysis clearly showed that for Northland chipseal sites, testing in the month of April would produce a monthly result that was, at better than 95th percentile probability, significantly lower than the 12-monthly average for the site. Similarly, a skid resistance measurement obtained in August would have a greater than 95th percentile probability of being significantly higher than the 12-monthly average for the site.

It could be concluded from this research that whilst there was a clear seasonal variation in measured skid resistance (ie lower results occurred in late summer and higher results occurred in late winter), there were still significant variations that occurred within calendar months of the year. This indicated that there were other short-term variable factors that needed to be taken into account. The conclusions from this aspect of the research follow.

9.3.4 Short-term variations related to rainfall

The research considered that rainfall and detritus accumulation are significant factors in the variation of the skid resistance measurements. Rainfall records were kept on all of the sites and these were analysed with the measured GripTester results. Three rainfall functions were considered:

- days since last rainfall (DSLR) > *x*mm, where rainfall greater than *x* =1, 2 and 5mm was considered
- dry-spell factor (DSF), where 1, 2 and 5mm of rainfall was considered
- weighted rain function (WRF) over a period of 5, 7, 10 or 20 days.

These rainfall functions were analysed against the measured coefficients of friction for both the GripTester and SCRIM devices. The number of data points was significantly less for the SCRIM device.

The GripTester device measurements were analysed for the Hikurangi control site, a site that was clearly at an 'equilibrium skid resistance' level. The results demonstrated strongest positively sloped linear correlation with WRF for a period of either 7 or 10 days rainfall. The results were statistically analysed and the WRF function was able to explain up to 60% of the variation of the 2004/2005 measured skid resistance results when the data was split into annual groups. The slope of the equation line demonstrated an approximate increase of 0.003 x WRF (mm) over a 7-day rainfall period prior to a measured skid resistance result. Conversely, the 2003 measured GripNumber data did not demonstrate a positively sloped equation, as the results were inexplicably more variable. The DSLR and DSF rain functions explained little of the measured variation of the skid resistance as measured by the GripTester device.

The SCRIM device results on the Hikurangi site (in contrast to the GripTester results) indicated that a negative trend of decreasing measured skid resistance existed with increasing dry spells prior to a test measurement, for both the DSLR and DSF rain functions. The results of the negative logarithmic DSF rain function analysis were better than the DSLR rain function, and much better than the GripTester correlations with these rain functions. A coefficient of determination (R^2) of 0.25 and 0.53 was obtained for the increasing and decreasing directions respectively. The best DSF correlation occurred when >2mm rainfall depth and a previous rainfall period of 7 days was used. The slope of the equation in terms of the SCRIM coefficient of friction (SFC) demonstrated an approximate decrease of 0.02 x DSF >2mm over a 7-day rainfall period prior to a measured skid resistance result. However, the number of data points was significantly less than that for the GripTester measurements.

The WRF function, when correlated against the SCRIM device measurements, produced a lower coefficient of determination (R^2) result (maximum of 0.37) than the DSF function and the GripTester (GT) correlations for the 2004/2005 skid resistance measurements.

The SCRIM results however, compared well with the results of Hill and Henry (1981), who concluded that the DSF rain function was better than the WRF. This seeming anomaly between the results of the SCRIM machine and the GripTester results could be related to the testing device method, and especially the differences in percent slippage of the devices (the GripTester=15%, the SCRIM=34% and the locked wheel tester used by Hill and Henry (1981)=100%).

When the normalised results for various Northland sites or timeslice sections were combined, the coefficients of determination (R^2) became significantly lower than when the Hikurangi site alone was used. At best, only 5.5% of the measured variation could be explained by any of the rain functions with the normalised data.

It was concluded that other localised site and/or environmental factors also affected the measured variation. The other factors were expected to be:

- temperature
- localised contaminants/detritus
- geological makeup of the aggregates
- traffic-loading conditions.

Whilst the coefficients of determination were low for the normalised NGN results, the expected slope of the equations was, as expected, negative for the DSLR and DSF and positive for the WRF rain functions. The slopes of these equations were expected to depend upon the traffic loading, the susceptibility of the aggregate to polishing and the polishing agents/contaminants.

In summary, a hypothesis was developed as part of the experimental design stating:

- **Hypothesis 3:** That the time period since the last rain has a significant effect on the short-term deterioration of measured skid resistance; ie that the slope of the short-term deterioration line is significantly different from zero and of the magnitude of approximately 0.01SFC units (or equivalent GN) per day.

  The rainfall function analysis indicated that the hypothesis was true, because the WRF explained up to 60% of the variation in measured skid resistance with the GripTester device at the Hikurangi site for the 2004/2005 data. However, whilst the slope of the trend could be confirmed when the five Northland sites were normalised, only 5.5% of the variation was explained due to the WRF alone. When analysing the SCRIM results, the DSF rainfall function explained up to 53% of the variation.

The analysis indicated that a prior rainfall history of 7 days gave the best results, and an indication of the slope of the equation was:

- an increase of 0.003 x WRF (mm) over a 7-day rainfall period in terms of the GripTester device
- a decrease of 0.02 x DSF >2mm over a 7-day rainfall period in terms of the SCRIM device.

However, there were other factors that needed to be taken into account in the analysis, as the prior rainfall history could not fully explain the variation in measured skid resistance.

9.4 Washing trials

> ***Research aim 4:*** *Quantify the effects of various washing treatments on the pavement surfacing, to determine whether detritus in itself reduces measured skid resistance.*

A washing trial was undertaken on the Hikurangi site in Northland using three methods; gentle washing, washing and brooming, and waterblasting at relatively low pressure, using the Frimokar NZ Ltd hydrotexturising machine. The washing trial revealed some interesting, although inconclusive, results regarding the effectiveness of a range of washing treatments that can be applied for improving skid resistance levels. The conclusions of the washing trials were as follows:

- None of the washing treatments produced any improvement as measured by the GripTester device.
- The BPT results also showed no improvement between the benchmarked levels and the post-washed treated sections on all sections, except for the Frimokar-treatment section.
- After the Frimokar treatment, the BPT indicated an improvement in skid resistance of 5BPN, although this improvement was very temporary, as a further test a short time later showed a lower improvement of 2BPN.
- The relatively clean state of the washed pavement negated some of the expected increase in skid resistance.

Washing trials were also undertaken with the DF Tester on surfaces that were initially tested and then retested after waterblasting. The results from the Tamaki Campus, Ports of Auckland and Hikurangi sites (and after significant dry periods) also did not show marked improvements in the measured skid resistance results. It was hypothesised that washing of the surface does not improve the measured skid resistance, although the effect of the pavement surface being wet combined with the kneading and abrasion effect of traffic loads on the wet surface does help to rejuvenate the surface in terms of measured skid resistance. This hypothesis was tested as part of the accelerated polishing of laboratory prepared samples. The conclusions of this analysis are discussed in section 9.7.

9.5 Samples of detritus collected off the road

> ***Research aim 3:*** *Quantify the concentration and particle size distribution of the types of contaminants that accumulate on the road surface, and how they vary with time and rainfall.*

In this research, 29 samples of detritus were collected from seven field sites between January 2004 and May 2005. The samples were analysed for sediment load and particle distribution, heavy metals, TPH and TOC. Conclusions from the sample analysis and results were as follows:

- Sediment loads ranged from 1.5 to 14.4mg/m^2, depending upon local conditions (eg traffic volume, vehicle composition and site setting) and environmental factors (eg rainfall and wind speed).
- Samples collected during the same sampling event showed little variability, whereas samples collected at the same site on different days varied significantly.
- The sediment size distribution remained relatively similar, with particles ranging from 0.001 to 1mm, at different locations and time of sampling.
- The mean particle size d(0.5) was 21.5 ± 5.8μm, while the average d(0.1) was 5.7 ± 1.6μm. These results give somewhat finer distributions than those reported for stormwater sediments researched elsewhere.
- All metals collected from all sites, excluding one exception (the Ports of Auckland site), had low metal concentrations (Cd 1–4μg/L, Cu 0.4–1mg/L, Pb 0.3–2mg/L, and Zn 1–3mg/L).
- The samples collected from the Ports of Auckland site reported both 17-fold higher levels of zinc and 8-fold higher levels of lead over and above the average results observed for the other sites. This was understandable given the very heavy industrial-traffic nature of this site.
- The majority of the copper, zinc and lead measured in the samples appeared to be sediment-bound, while cadmium was primarily dissolved.
- The TPH concentrations were close to the detection limit of the analysis (ie 10mg/L). Although little or no TPH could be detected in the samples, the TOC values suggested the presence of non-TPH organic matter, primarily in the form of particulate matter.

Previous research has shown that rainfall volume appears to be the major factor in the removal of total road dust detritus, and rainfall frequency mainly affects the accumulation of particle-bound contaminants (O'Riley et al 2002). Unfortunately, due to the limitations in being able to sample the road surface-based detritus, insufficient samples were obtained at the same sites to enable a proper assessment of any relationship between road-based sediment and rainfall volume and frequency.

In summary, the analysis of the detritus results demonstrated that the variation of sediment and pollutants was site-specific and no differences between predominantly urban and rural settings could be detected other than for very heavy industrial sites. The analysis also demonstrated the following:

- Samples collected at the same time and same location had relatively little variability.

- Samples collected at the same location but at different times could vary significantly, indicating that site-specific environmental factors were significant and could be highly correlated with the variation in measured skid resistance.
- Compared with previous research, the particle size distribution of the collected samples was somewhat finer, but very consistent for all samples and sites, and provided confidence in determining particle size distributions for the controlled laboratory analysis.
- Compared with previous research, the sediment contained low concentrations of heavy metals except for the Ports of Auckland, where (as would be expected) significantly higher concentrations were found. The relatively low concentrations of metals on the highway sites indicated that the heavy-metal concentration did not play a significant role in the variation in measured skid resistance. However, more data is required to confirm this preliminary indication.

9.6 Accelerated polishing experiments

9.6.1 Outline

Controlled laboratory experiments were required to simulate the observed variation of skid resistance in the field on prepared samples. The experiments could then investigate the effects of accelerated polishing, rainfall and contaminants on measured skid resistance.

The experiments were undertaken in two stages. The first stage consisted of accelerated wet polishing to an 'equilibrium skid resistance' (ESR) level (stage 1 polishing). The second stage incorporated the addition of various contaminant to the accelerated polishing process (stage 2 polishing). The results demonstrated similar results and degrees of variation to those shown at field sites with normal heavy-traffic conditions.

Conclusions addressing the specific study aims and objectives (outlined below) with regard to the laboratory-based accelerated polishing experiments are outlined in the following sections.

> ***Research aim 5:*** *Quantify the effects of wet and dry accelerated polishing on prepared laboratory specimens.*
>
> ***Research aim 6:*** *Quantify the effects of various contaminants on skid resistance due to accelerated polishing on prepared laboratory specimens.*

9.6.2 Stage 1 accelerated polishing

The conclusions regarding the stage 1 accelerated polishing of the three natural aggregate samples and the melter slag artificial aggregate, using the machine developed at the University of Auckland, were as follows:

- The actual PSV of the aggregate sample generally predicted the ranking order of the initial level of skid resistance of natural aggregates prior to any accelerated polishing.
- The percentage reduction in the measured skid resistance from the initial level of skid resistance to ESR reduced as the aggregate PSV reduced (from 46% for the Moutohora PSV 63 to 24% for the Otaika PSV 52).

- Generally, the lower the PSV of the aggregate, the faster the aggregate polished to its ESR level (from seven hours of accelerated polishing for Moutohora PSV 63 to 2.5 hours for Otaika PSV 52).
- There was very little difference in the final level of ESR (as measured by the DF Tester) obtained for the three natural aggregate samples: DFT(μ)=0.47 for Moutohora PSV 63, DFT(μ)=0.39 for Holcim basalt PSV 52, and DFT(μ)=0.43 for Otaika PSV 52.
- The greywacke sandstone and the basalt aggregates polished by different mechanisms and therefore the deterioration rates varied under the same accelerated polishing loads.
- The time to a polished state and the ranking order of the final level of ESR for the natural samples were not necessarily the same as the PSV ranking – the basalt sample polished to a greater extent than the Otaika greywacke, even though similar PSVs were measured.

The results of the laboratory accelerated polishing and DF Tester friction tests on the artificial melter slag initially demonstrated very promising results, as that material did not deteriorate at the same rate or in the same manner as the natural aggregates. The main conclusions of the melter slag aggregate for the stage 1 polishing to ESR were as follows:

- Whilst the actual tested PSV of the melter slag was lower (PSV=55) than that for the Moutohora natural aggregate (PSV=63), the initial level of measured skid resistance DFT(μ)=0.90 was very similar.
- The percentage reduction in measured skid resistance from the initial level of skid resistance to ESR was significantly less for the melter slag than for the natural aggregates of higher or lower measured PSV (16% cf 46%, 39% and 24% for the Moutohora, Holcim and Otaika aggregates).
- The time to reach its equilibrium polishing level was approximately the same as those for natural aggregates of similar PSV (4–4.5 hours).
- The melter slag significantly outperformed all of the natural aggregates in terms of being resistant to polishing, including the Moutohora (PSV=63), which had a significantly greater PSV for the stage 1 polishing phase.

The Kaiwaka slag site in Northland was resurfaced with the melter slag material and used as a field test site. The field-based skid resistance measurements demonstrated long-lasting performance that was similar to the stage 1 controlled laboratory-based polishing. The rate of decrease even in high-stressed TNZ Site Category 2 corners was significantly lower over the data collection period than field sites that were resealed with natural aggregates.

9.6.3 Stage 2 accelerated polishing

The stage 2 polishing phase included extended accelerated polishing with the addition of contaminants (oedometer clay, Leighton Buzzard sand and emery powder) on the four laboratory-prepared samples. The effects of the addition of contaminants and accelerated polishing were measured by the DF Tester and by comparing microphotographs of the surface of the aggregates. Significant differences were measured and observed, proving that the methodology and equipment that was developed achieved its intended purpose. Specific conclusions from the stage 2 polishing and subsequent analysis were as follows:

- The addition of oedometer clay that was soft and well-graded from fine to coarse PSD (no matter what range of PSD was used (ie the fine fraction or the coarse fraction) when combined with dry polishing, generally increased the measured CoF to a small degree. The highest increase with the addition of oedometer clay was recorded for the Moutohora aggregate with a DFT(μ) of 0.12. Very minor increases were recorded for the Holcim basalt and Otaika greywacke aggregates.

- The addition of oedometer clay along with dry accelerated polishing had little effect on the results for the melter slag aggregate. Slight decreases in the measured CoF were observed in some cases.
- The Leighton Buzzard sand (hard and coarse material), when added to the sample and dry polished with the AAPD, significantly increased the measured skid resistance DFT(μ) on all natural aggregates. Furthermore, it raised the skid resistance DFT(μ), in most cases to significantly higher levels than the initially recorded value of ESR from wet polishing.
- For the Moutohora and Holcim aggregates, the skid resistance DFT(μ) value reverted almost back to the initial measured values prior to any polishing. For the Otaika aggregate sample, the polishing with Leighton Buzzard sand increased the DFT(μ) higher than the initially tested value.
- Accelerated dry polishing with Leighton Buzzard sand on the melter slag aggregate increased the value of measured skid resistance, but not to a level higher than that reached at ESR.
- The addition of emery powder (hard and fine) significantly decreased the measured CoF on all laboratory samples from the level that existed after the Leighton Buzzard sand had coarsened the microtexture. The Moutohora DFT(μ) level decreased down to approximately the same level as that obtained at ESR. The Otaika aggregate decreased almost to a third of its measured CoF when roughened by the Leighton Buzzard sand, and to a level significantly lower than the ESR level reached with wet polishing. The Holcim basalt DFT(μ) level also decreased significantly to a level significantly lower than that reached at ESR. The melter slag aggregate also reduced significantly with the addition of the emery powder and accelerated polishing.
- Subsequent cycles of adding Leighton Buzzard sand and emery powder to the Moutohora, Holcim basalt, and the Otaika greywacke indicated that an historical memory of ESR level may exist with a natural aggregate, as the measured CoF fluctuated about this value, but when wet polished, it had a tendency to revert to the ESR level.
- The results of continued cycles of the addition of contaminants and accelerated polishing on the melter slag demonstrated an overall trend of gradual decreasing measured CoF.
- The initial benefits of the melter slag under ongoing cyclical polishing with contaminants resulted in the melter slag DFT(μ) being reduced to a level that was similar to the Moutohora greywacke aggregate (0.39). It is currently unknown whether this would continue to decrease further, although a linear extrapolation of the stage 2 polishing results indicates that it could.
- Polishing with emery powder produced the lowest recorded skid resistance value (DFT(μ) for all of the laboratory sample aggregates. The lowest recorded DFT(μ) values for each of the aggregates, which included a second cycle of accelerated polishing with Leighton Buzzard sand and emery powder, were Moutohora=0.41, Holcim=0.23, Otaika=0.26 and melter slag=0.39.

9.6.4 Summary conclusions of the accelerated polishing laboratory experiments

Summary conclusions of the two-stage controlled laboratory experiments using accelerated wet polishing to an ESR level (stage 1) and accelerated polishing with the addition of contaminants (stage 2) were as follows:

- The significant variation in measured skid resistance observed in the field was intrinsically related to the geological properties of the aggregates themselves and the contaminants that ended up on the surfacings.
- The accelerated wet polishing of aggregates (without any contaminant additions) could polish natural aggregates to an ‘equilibrium skid resistance level’ (ESR).
- The level of polish achieved at ESR did not appear to relate to the polished stone value (PSV) results.
- Significant variations (both increases and decreases from ESR) in measured skid resistance could be simulated in the laboratory by the addition of various contaminants.
- Contaminants that were fine in size (less than 10μm) and that consisted of hard minerals (eg emery powder) polished the aggregate surfaces, thereby reducing the measured skid resistance.
- The amount of decrease in measured skid resistance that was achieved on a specific aggregate depended upon the difference in hardness and the geological makeup of the contaminants and the aggregate surface being polished (the greater the difference, the more the decrease in skid resistance).
- Contaminants that were coarse (greater than 1mm) and consisted of hard minerals (eg Leighton Buzzard sand) abraded, ground and scoured the aggregate surface, thereby increasing measured skid resistance.
- The amount of increase in measured skid resistance that was achieved on a specific aggregate depended upon the difference in hardness and the geological makeup of the contaminants and the aggregate surface being polished (the greater the difference, the more the increase in skid resistance).
- Contaminants that were soft in mineral content compared with the surfacing aggregate (eg oedometer clay), irrespective of particle size, were shown to increase only slightly the measured skid resistance when dry. However, when the polishing under the action of trafficking or accelerated laboratory polishing became damp (however, not so wet that the contaminants were washed away), the measured skid resistance could increase on aggregates that had a softer grain matrix and a variable particle size.

In summary, the following hypothesis was developed as part of the experimental design:

- **Hypothesis 4:** That the type and classification of the contaminants that accumulate on the road surface are significant in determining the magnitude of the short-term variation of measured skid resistance.

  The laboratory-based experiments, combined with the geological descriptions, classifications and analysis, clearly demonstrated this hypothesis to be true.

9.6.5 An analysis of the performance of the PSV test

The field site testing and analysis of a sample of state highway sites in Northland compared the initial skid resistance of the road surfacings, measured after each of the surfaces were treated and measurements later in its seal life. How the sites performed in relation to measured skid resistance over repeated traffic loads as a function of the Transit NZ-published PSV was determined. The conclusions of the analysis were as follows:

- A higher published PSV aggregate did not necessarily lead to a high initial skid resistance value as measured by the GripTester.
- The published PSV of the aggregate did not necessarily determine the level of equilibrium skid resistance (however, the sites did have varying traffic loading and geometric elements that would have affected the final level). This result tends to agree with research by Cenek et al (2003b), which states that there is very little relationship between the PSV of the aggregate and the in-field skid resistance as measured by SCRIM network surveys.
- The highest initial skid resistance was recorded where the site was treated during the monitoring period with grades 2 and 4 chip size. The other sites were treated with grades 3 and 5 chip. This result was not unexpected, as the larger chips with higher macrotexture were expected to produce higher initial skid resistance.
- For similar traffic loadings and curvature, approximately the same range of skid resistance was lost over the same period.
- Whilst the melter slag from the Glenbrook Steel Mill had the highest published PSV of 58, compared with a PSV of 52 and 53 for the other sites, its initial skid resistance was the second lowest. However, the performance of the slag over time, compared with the other aggregates and sites, even those with much higher traffic loading, was significantly better.

From the above analysis, it was concluded that the NZTA-published PSV of the aggregate, without taking other factors into consideration, cannot be reliably used as a predictor of the initial skid resistance of the aggregate, nor of the level of equilibrium skid resistance after polishing. Other methods, such as the use of the AAPD developed in this research, would be required to help road asset managers make good decisions. This would enable better predictions of how aggregates will perform over time and under specific traffic, geometric and braking stresses.

10 Conclusions

10.1 Overview

Previous research has clearly shown that as skid resistance decreases, generally the crash rate increases exponentially at varying rates for different sections of the road network. There are significant social cost–benefits of having a road agency skid resistance policy that attempts to equalise crash risk across the road network by providing higher-risk sites with surfacings that are more resistant to polishing and provide appropriate skid resistance throughout the surfacing's life. A recent report by Opus Central Laboratories for the NZTA (Henderson and Cenek 2010) found that for the 11-year period (1998–2008), it could be inferred that Transit New Zealand's T/10 original policy significantly contributed to the reduction of rural state highway wet-road crashes by approximately 47% over the 11 years.

This research did not contradict these findings, nor the overall benefits of having a skid resistance policy; rather, it investigated the factors that are known to affect the seasonal variation of skid resistance over time. However, this research did establish that a skid resistance measurement value (by whatever means) in New Zealand climatic conditions is clearly not a constant – it is considerably more variable over time than previously considered. Better understanding of the factors that affect this skid resistance performance, and how they interrelate, is required for more effective road surfacing and safety management. Policies and standards that move towards more effective long-term skid resistance management must recognise that current measurement techniques (as used in this study) have demonstrated an inherent and significant variability, which is more than previously considered. This amount of variability poses significant difficulties for RCAs and contractors tasked with managing road networks and their long-term skid resistance performance.

Predicting the skid resistance performance of various aggregate materials using current laboratory-based prediction methods (eg the PSV test method) has been shown to be unreliable as it is a very poor indicator of in-field skid resistance performance over the surface's life cycle. An alternative method, the Auckland Accelerated Polishing Device (AAPD), shows promise in New Zealand on chipseal surfaces and research is continuing to determine whether it can become an alternative method replacing the PSV test method. When selecting aggregates for a particular site location, geometry and traffic loading, consideration needs to be given to sustainability issues. Transporting aggregates from distant locations on the grounds that they achieve better performance, based on laboratory-based PSV tests that show slightly higher PSV points, may not lead to any improvement in field skid resistance performance but will significantly increase costs to road agencies and ultimately, road users. This will be especially so if other factors, such as higher crash rates at the location, do not justify it. The level of measured in-field skid resistance performance, for any skid-testing device, also currently seems to have significantly more variability than previously considered and this needs to be considered when selecting an aggregate for use. When this is combined with variability in driver behaviour, vehicle type, tyre tread depth, and tyre condition and hardness, it is evident that the performance of an individual vehicle on a given surface, and at a particular site location and time, is very difficult to predict.

The overall conclusions from this study, which fall into three main areas, are described in the following sections.

10.1.1 In-field skid resistance variation

The research found that short-term variation in measured skid resistance could be up to 30% over very short time-periods (days rather than months), meaning that predictive models (eg HDM 4 or dTIMS texture models) were unreliable. However, the measured variation in the mean of homogeneous sections of surfacing over a three-year data collection period was found to be relatively small (eg the 95th percentile confidence interval <0.06GN for the sites in this study). This was irrespective of whether the sites were asphalt mix types or chipseals, what the PSV of the surfacing aggregate was, or whether the surfacing sections were thought to still be in the initial polishing phase or after a theoretical 'equilibrium level' of skid resistance had been established.

The in-field results demonstrated that generally, the higher the total number of heavy commercial vehicles (HCV) per day at a site, the higher the 95th percentile confidence interval for the site mean, the standard deviation and the coefficient of variation (CoV) – except for the site that had been surfaced with the artificial melter slag. The melter slag performed better and more consistently than sites with similar HCV volumes, and also did not lose as much skid resistance from the beginning of the surface life to the end of study measurement period, compared with other natural aggregates. This better performance was also reflected in the controlled laboratory experiments, where the loss of skid resistance from a new surface to a polished surface was much less in the melter slag samples than in the natural aggregates.

The research demonstrated that there was a clear seasonal variation effect in measured skid resistance; ie lower skid resistance results in late summer (April) and higher results in late winter (August), to the 95th percentile confidence level. However this effect was not an obvious or predictable sinusoidal shape and there were still significant variations that occurred within the calendar months of the year. This indicated that there were other short-term variable factors that needed to be taken into account.

Rainfall function analysis, using the weighted rain function (WRF) over the previous seven-day period, at best explained up to 60% of the variation in skid resistance with the GripTester device at the control seasonal site (Hikurangi) for the 2004/2005 data, but much less at other sites. When analysing the SCRIM results with the dry-spell factor (DSF), up to 53% of the variation could be explained.

Another significant factor in the short-term variation of skid resistance was the ambient temperature, depending upon the testing device and whether it used correction factors. The SCRIM and PBPT both corrected their measured value based upon the ambient temperature, whereas others like the GripTester stated that as long as the device was conditioned and running at operating temperature, it was insensitive to ambient temperature.

Additional factors were the amount of detritus on the road surface, its associated particle size, and the mineral hardness and the petrology of the surfacing aggregate.

10.1.2 Skid-testing devices

The various skid resistance measurement devices, such as the SCRIM, GripTester, ROAR and Dynamic Friction (DF) Tester, are reasonably repeatable devices; however, transformation equations between devices (eg the IFI) do not currently provide good correlations for New Zealand highway surface conditions.

The GripTester is a more responsive device than the SCRIM device and better correlates with the DF Tester and the British Pendulum Tester (BPT); however, as it is significantly lighter than the SCRIM device, it is more sensitive to road roughness. In this research, the coefficient of variation (CoV) of the GripTester during winter months was significantly less (June, July and August – CoV = approximately 3.0%) than in the summer months (December, January and February – CoV = 5.0%). This indicated that an environmental effect existed, related to the contaminants/cleanness of the surface, which affected the run-to-run variability of the device. Further research is required to determine why skid resistance, as measured by the GripTester, increases with successive test runs, as was seen in this research during the washing trials.

The DF Tester is a very repeatable device (CoV = 1.6% on asphalt mix surfaces). It has proven to be reliable for static skid resistance measurement tests and is ideal to use both in controlled laboratory experiments and in the field (especially for calibration/correlation of CFME devices). However, due to the repeat testing action of the device itself, initial skid resistance reductions due to contaminants/short-term environmental effects are averaged out, whereas in-line continuous friction testers, such as the GripTester (and normal road users), will reflect a result that is due to an initially 'contaminated' surface with one pass of the device or vehicle. Furthermore, due to the circular line of measurement of the DF Tester, any in-field longitudinal vehicle wheel path differences are also averaged out, thereby producing a different result from in-line CFME devices.

It should be noted that all skid resistance testing devices are sensitive instruments that are being used in a very demanding, wet environment, and therefore require regular maintenance, calibration and correlation between devices. Given the importance of skid resistance to reducing the social cost of crashes in New Zealand, the NZTA could consider developing a skid resistance testing track that can be used regularly for both correlation of equipment and research purposes.

10.1.3 Laboratory tests

This research concurs with Cenek et al (2003b) that the PSV test method does not reliably predict the in-service long-term level of skid resistance and at best is a poor indicator. Less reliance should be placed on the PSV test device results, which can lead to unsustainable practices of transporting aggregate over large distances in the belief that it will perform better than local aggregates. More recent research by Cenek et al (2012), using in-field SCRIM performance, has shown a better method is to rank the performance of aggregate from various quarries in New Zealand.

However, the development of a new accelerated polishing machine and test method (the Auckland Accelerated Polishing Device – AAPD) for this study has shown that significant variations in the measured skid resistance of chipseal samples can be simulated in the laboratory. The addition of hard but fine-grained contaminants (eg emery powder) onto a surface that undergoes accelerated polishing will significantly reduce the measured skid resistance, as it will 'polish' the surface. The addition of coarse but hard contaminants (eg Leighton Buzzard sand) will 'scratch' and abrade the surface under accelerated trafficking and will significantly improve the measured skid resistance of the surface.

In summary, a geological interpretation of the aggregate properties and the types of contaminants that end up on the surface is required before an assessment can be made regarding the performance of the aggregate with regard to trafficking. Additionally, the seasonal and short-term variation of skid resistance is currently not able to be adequately predicted, as it is unknown how the multiple factors that affect skid resistance are interrelated.

11 Recommendations

11.1 Relevance of the research

This research has highlighted that there are many independent variables that determine the skid resistance of a section of road pavement at a particular time. Not all of these have been uncovered, at this point. Skid resistance is not a constant quantity and this research has shown that it can change markedly in just a few hours, the change depending not only on the surfacing aggregate petrology, but also on the degree of wetness, (heavy) traffic loading, and the properties of the contaminant/detritus.

The relevance of the research to industry can be categorised into three areas, based upon the organisations' varying roles and perspectives in terms of skid resistance policy, management and operation. These three areas are identified below.

11.1.1 Road controlling authorities (RCAs)

Road controlling authorities, such as the NZTA, have a desire to construct, manage, operate and maintain a road network such that it is safe, efficient, economic and sustainable in the long term. Achieving this requires the development of policies, standards, and performance indicators that are not only measurable (reliably and repeatably), but achievable (affordably and practically).

This research has shown that due to the inherent variability of skid resistance, two of the current cornerstone factors influencing consideration of the topic – namely PSV and 'seasonal correction' of road network surveys on an annual basis – that form the basis of current policy standards (NZTA T/10 and other international standards) cannot be used in isolation without the consideration of other factors to determine in-field aggregate performance. This is especially so when a great proportion of an RCA's network is measured at best only once a year and more often less.

The skid resistance surveys can and should be used as a network-level tool to determine whether the overall trend performance of a network is deteriorating or increasing. However, it must be recognised that at a project level, further investigations (including crash rate and on-site investigations) are required to determine whether intervention treatments are required. Depending upon both the geological properties of the aggregates at a site and the environmental conditions, the measured level could vary significantly from the true mean. It is recommended that continuance of the use of skid resistance surveys, at least at the current level of emphasis and policy, should be reviewed.

Use of specific skid-resistance measurements, such as key performance indicators (KPIs) in performance-specified maintenance contracts (PSMCs) also need to be carefully considered, given the inherent variability of skid resistance measurements. For example, climatic conditions immediately prior to or during network surveys can significantly affect KPIs yet are largely outside of the control of the contractor. Whilst the mean summer SCRIM coefficient (MSSC) and the yearly equilibrium SCRIM coefficient (ESC) correction factors are supposed to take account of these effects, this research has highlighted that these factors are unlikely to accurately account for the real differences, on a site-by-site basis, throughout the network. If they were used as a network-level tool, this would seem more reasonable.

Recognition of these factors will need to be strengthened in the operational and management arena. It may well be that because of its inherent variability, skid resistance at any location can be targeted only as a band or range of values, until at least alternative methods (eg the AAPD) are proven.

11.1.2 Road asset managers

It is important to reiterate that road asset managers should have a skid resistance policy that targets an equalisation of crash risk across the road network, especially in high-speed areas, where horizontal curves can have a design speed that are out of context with the approach speeds, and at approaches to intersections. Previous research has clearly proven the social cost–benefits of having such a skid resistance policy, as on most rural high-speed road sections, the crash rate generally increases exponentially as measured skid resistance decreases.

However, as with any pavement management system (eg HDM 4, NZ dTIMS), condition data (as well as inventory data) forms the core of all analyses performed. Data collection is also one of the most expensive items in an overall pavement management system, although is relatively insignificant compared with lifecycle asset costs. All of the components of the system interact with the data provided by the user, and predictive modelling is used to predict what the future condition will be. Therefore, the success of the long-term maintenance planning (in the case of skid resistance and road surface treatments) is a direct function of the comprehensiveness and the accuracy of the data.

Data forms the core of all pavement management systems and largely determines whether the output from the system is good or bad. Skid resistance measurement devices, such as the GripTester, SCRIM, ROAR, and the DF Tester, measure skid resistance objectively and reasonably economically, using high-speed data collection systems, and this is much better than subjective testing methods.

However, it is equally important to know what the natural variation is over time, to allow a proper understanding to enable appropriate decision making. This research has shown that the natural and largely unpredictable variations of skid resistance are much greater than previously understood. It therefore questions the fundamental basis behind skid resistance policy, which relies heavily on largely one network survey per year and does not take into account the factors that affect skid resistance variation. Furthermore, this research has demonstrated that the PSV test also does not predict the in-field level of skid resistance well, and as such its continued use should be reviewed. The research described herein has demonstrated that it is not feasible or appropriate at this point to use models for the prediction of skid resistance in New Zealand, as the natural variation is currently large and unpredictable.

This study has shown that artificial melter slag significantly outperforms natural aggregates, both in the laboratory and in the field. The application of artificial melter slag (and potentially other artificial aggregates) has significant safety and economic benefits where the surface friction demands are relatively high (eg Transit NZ Site Category 2 areas) and where the transportation costs do not outweigh the longer-lasting surface friction benefits.

From a road safety point of view, road managers also need to be able to develop further means of communicating information to road users: this includes continuing education of drivers, as well as an improved awareness of environmental conditions leading to sudden change in skid resistance. Improved real-time recording of weather and environmental conditions, and the use of variable-message signs at key sites on a road network, are suggested for future improvements in road safety.

11.1.3 Crash investigators

Current practice for crash investigators includes measuring a coefficient of friction (by various skid-testing methods), including locked wheel tests with tyres of similar tread depth and patterns to those that have been involved in a crash. This coefficient of friction (once obtained) is then used to back-calculate the probable operating speeds of the vehicles involved in the crash, by using equations of momentum.

However, this research has shown that unless the tests are undertaken almost immediately after the crash occurred and in the same environmental conditions, the measured coefficient of friction could significantly vary from that involved in the crash. This, in turn, means that the estimated speed of the vehicles prior to the crash could also vary significantly. This possible level of inaccuracy in the measurement and estimation of vehicle speeds poses some significant issues for legal proceedings in crash-reconstruction work.

11.2 Further recommended research

This research has provided considerable insight into some of the factors that affect the seasonal and short-term variation of measured skid resistance on typical New Zealand road surfacings. There is, however, still much research to do and the following gives recommendations for continuing this research work, grouped under three categories.

11.2.1 Policy and risk management

- Develop risk management procedures and skid resistance policy that incorporates not only the measured skid resistance of the surface, but other issues such as the geometric and topographical information, numbers of heavy vehicles, traffic-operating speeds, and the consequences of a crash at that specific location.
- Quantify the effects of the daily variation of skid resistance with rainfall and contaminants.

11.2.2 Skid-testing devices

- Determine why skid resistance as measured by the GripTester increases with successive test runs (variables to include tyre temperature and the possible cleaning or retarding effect on the road surface of surface water from multiple test runs).
- Quantify the effects of road roughness on measured skid resistance by various devices.
- Develop better IFI transformation coefficients for the correlation of various devices for typical New Zealand surfacings and textures.

11.2.3 Laboratory tests

- Standardise the Auckland Accelerated Polishing Device (AAPD) such that it is understood how variation in test conditions (eg load, polishing time, contaminant type and concentration) are understood.
- Evaluate the effects of accelerated polishing and the addition of contaminants on a wider range of New Zealand aggregates.

- Evaluate the effects of other contaminants in conjunction with accelerated polishing.
- Evaluate the effect of varying the load on the accelerated polishing machine and to correlate these effects with field results of the same aggregates.
- Evaluate the effects of accelerated polishing on different-textured laboratory samples by using a range of chip sizes.
- Evaluate the effects of continued accelerated polishing with contaminants, on the melter slag and other proprietary artificial aggregates.

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Appendix A Skid resistance testing devices

A.1 SCRIM device

The SCRIM device is a continuous friction measurement (CFME) device that uses an angled test wheel using the sideways force method – the Sideways-force Coefficient Routine Investigation Machine (SCRIM) – refer to figures A.1 and A.2. The sideways force coefficient (SFC) is defined as the force at right angles to the plane of the angled wheel, expressed as a fraction of the vertical force acting on the wheel:

$$Sfc = \frac{F_p}{Q} \qquad \text{(Equation A.1)}$$

where:

Sfc = sideways force coefficient

F_p = horizontal force at right angles to the plane of the angled wheel

Q = weight force (vertical force).

Figure A.1 Sideway force coefficient method

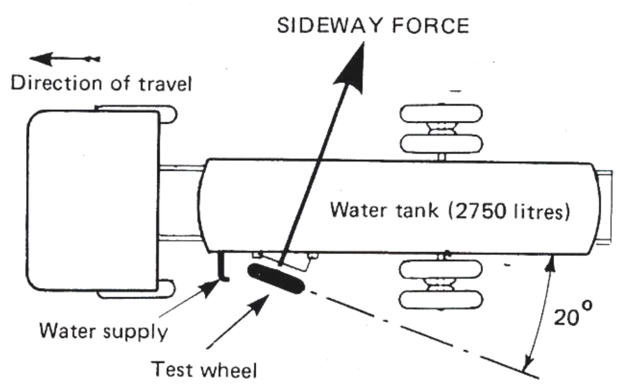
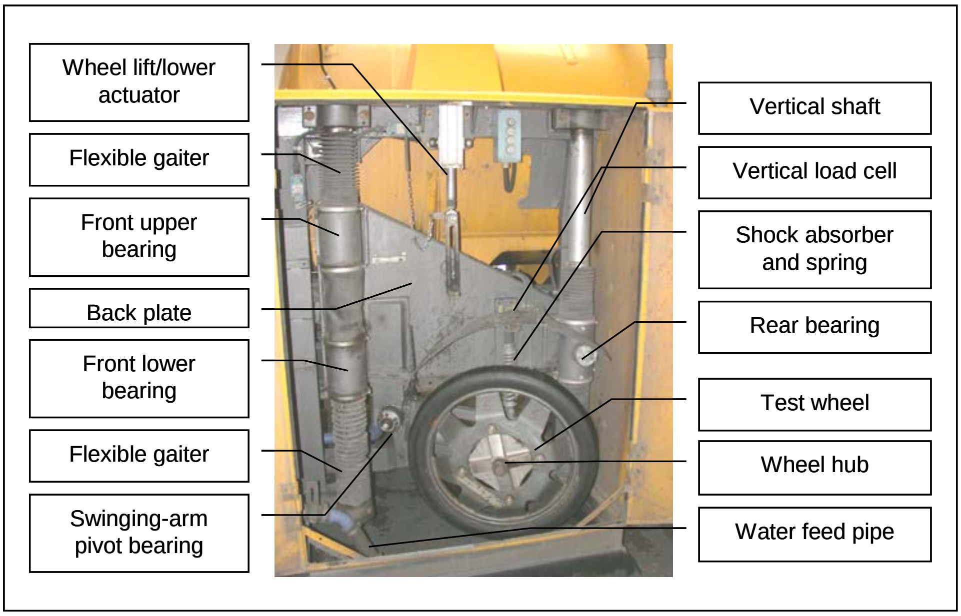


Figure A.2 WDM SCRIM apparatus

The test wheel on a SCRIM device is mounted on an angled beam known as the 'swinging arm' (see figure A.1). This is fixed at one end through a flexible bearing to a large, approximately triangular steel plate (the back plate), which is mounted on vertical shafts attached to the chassis through a rigid frame. Two bearing units on the forward edge of the back plate and one on the rearward edge allow the plate to move up and down shafts, which are protected from the elements by flexible gaiters. A spring and damper (shock-absorber) system links the swinging arm and back plate to provide a simple suspension for the test wheel. The combined mass of the back plate, the swinging arm, the wheel hub and the test wheel provides a 200kg static vertical load.

In 2004, all UK SCRIM devices (eg figure A.2) were fitted with a dynamic vertical load measuring (DVLM) system that enabled the vertical load applied to the test wheel to be measured dynamically. This enhancement allowed errors in the reported SFC to be automatically corrected. The errors could occur as a result of changes induced in the vertical load on uneven roads or around curves. The vertical load is measured by a strain-gauge system that is integral with the upper fixing point of the shock absorber. From this, the vertical load under the wheel is determined by measuring the reaction force between the swinging arm and the back plate transmitted through the damper system. The various features of the SCRIM wheel hub system are shown in figure A.3. The side force is measured with a load cell mounted behind the wheel hub.

Figure A.3 SCRIM wheel assembly unit (Roe and Sinhal 2005)



The SCRIM machine uses a smooth tyre fabricated from natural rubber (within a specified resilience range) to reduce errors through tyre wear. For a standard test at 50km/h, water is delivered in front of the test wheel at a rate that provides a nominal water film thickness of 1mm. The WDM Limited SCRIM device from the UK is contracted to test the Transit NZ state highway network (approximately 10,500kms) once every year in the summer months. This has been undertaken since 1995. The SCRIM device specified by Transit NZ requires a test wheel in both left-hand and right-hand wheel tracks. The SCRIM device collects much more than just skid resistance condition data. It also collects macrotexture and longitudinal roughness, transverse profiles (for rutting) by the use of laser profilometers, road centreline curvature by differential GPS, video capture and other road inventory data at in-highway speeds.

A.2 GripTester device

The GripTester device is a CFME device that utilises the braked wheel method and is shown in figure A.4a. It is a three-wheeled skid resistance tester that was originally designed in 1987 by Findlay Irvine Ltd, Scotland, for airport runway operations. It can be towed behind a vehicle with an automatic water delivery system or pushed by hand by the operator. The GripTester has one test wheel that is braked and two bogey driving wheels (see figure A.4b). Its mode of operation is the simultaneous measurement of drag force (F_d) and load force (Q) on a single, treadless ASTM-specified rubber test tyre (standard specification) of 254mm diameter, during braked skidding at approximately 15% of the survey speed. The fixed slip of the test tyre is achieved by means of a chain and sprocket transmission. The test wheel axle features strain gauges to measure the tractive longitudinal and dynamic vertical forces acting on the test tyre. The

GripTester reports the surface friction coefficient as a grip number (GN), which is the fraction of tractive drag force (F_d) over the load force (Q):

$$GN = \frac{F_d}{Q} \qquad \text{(Equation A.2)}$$

where:

GN = braked friction force coefficient by means of a GripTester (ranges from 0 to 1.2)

F_d = drag force (horizontal)

Q = weight force (vertical).

GripTester surveys typically use an automated (or manual) water delivery system that provides a 0.25mm water film depth beneath the testing tyre. The water film depth can be varied if required. The Grip Number (GN) is measured every 1m but is typically reported as an average over every 10 metre length.

Figure A.4 The GripTester (Findlay Irvine Ltd 2005)

(a) The GripTester (side view)

(b) GripTester measuring wheel & chain transmission

The GripTester is commonly used for friction measurements on airport pavements, for research purposes, and more recently for monitoring road networks in the UK, Europe, Australia and New Zealand. The braked wheel device can be operated in push mode of 5km/h up to a maximum speed of 130km/h. It is relatively easy to transport (at approximately 85kg weight) and can be used with any towing vehicle. The GripTester has only one test wheel, and therefore results are typically obtained for the left wheel path of a road lane only, which is usually the wheel path with the lowest measured surface friction. However, results can be obtained from the right wheel path separately, given appropriate on-road traffic management. Improvements to the axle system in the Type D GripTester have resolved earlier problems that were associated with the measurement of skid resistance on bends.

The GripTester is compact and highly manoeuverable, and is a flexible tool that allows testing on roads, airfield pavements and footway surfaces, and is relatively inexpensive to operate.

A.3 The Dynamic Friction (DF) Tester device

The Dynamic Friction Tester (DF Tester – refer to figure A.5a) is a stationary skid-testing device developed by Nippo Sangyo Co Ltd (2005). The DF Tester device was designed in Japan, mainly to measure the dynamic coefficient of friction on road surfaces. However, it can also be used as a static device to determine the friction on laboratory-prepared samples, paved surfaces of footpaths, promenades, amusement parks and on floor surfaces of buildings and gymnasiums. It has been found to be very stable with time and to give highly repeatable measurements, and has recently been chosen as the standard reference in the recently revised IFI ASTM International Standard (Henry 2003). The testing procedure and methodology is described in ASTM Standard Test Method E-1911 (2002).

The DF Tester consists of a horizontal spinning disk (refer to figure A.5b) that spins with its plane parallel to the test surface. The spinning disk is fitted with three spring-loaded rubber sliders centred on a diameter of 284mm. These contact the paved surface as the disk rotational speed decreases due to the friction generated between the sliders and the paved surface. The DF Tester can be used for laboratory investigations and in the field on actual paved surfaces. The disk is brought to the desired rotational velocity, corresponding to the maximum tangential velocity of the sliders (*V* up to a maximum of 90km/h). Water is introduced in front of the sliders and the disk is lowered to contact the test surface so that it bears the full velocity of the disk and motor assembly. The torque is monitored continuously as the disk rotational velocity reduces due to the friction between the sliders and the test surface. The torque signal is reduced to a measurement of friction by converting the torque to the force on the sliders and dividing by the weight of the disk and motor assembly. The coefficient of friction (μ) is then calculated as follows:

$$\mu = \frac{F}{Q} \qquad \text{(Equation A.3)}$$

where:

μ = coefficient of friction as measured by the DF Tester

F = torque force (horizontal)

Q = weight force on the three rubber sliders (vertical).

By holding Q constant and substituting K (a constant of proportionality) for *1/Q,*

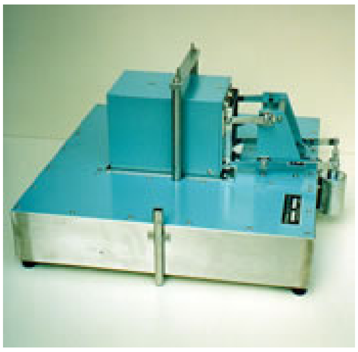
$$\mu = K.F \qquad \text{(Equation A.4)}$$

Thus, the coefficient μ varies in direct proportion to *F*. The DF Tester has a main motor-driven unit that consists of a fly-wheel and disc with three rubber sliders (refer to figure A.5b) attached by leaf springs, and a control unit. The sliders are pressed on the test surface by the weight of the device through three rollers. Each slider is loaded to 11.8N by the leaf springs. The disc and the fly wheel are connected by a spring balance mounted along a circle on which the rubber sliders are fixed. Due to the forces on the rubber sliders, displacement occurs in a spring balance. This displacement is converted to an electrical signal attached to the opposite side of the disc. The signal is output through a slip ring and brush, both of which are mounted on a driving shaft. The speed of rubber sliders is measured from the output of a rotational speed dynamo. The friction at 20, 40, 60 and 80km/h is recorded and the friction–speed relationship is plotted as shown in figure A.5c.

The slider assembly consists of a steel backing plate to which is bonded a 6 x 16 x 20mm rubber slider, shaped as shown in figure A.6. This shape provides a contact pressure of 150kPa. The rubber compound is synthetic rubber, as specified by ASTM E 501 (2000), and is required to have a shore hardness of 58 ± 2.

Figure A.5 DF Tester components (Nippo Sangyo Co Ltd 2005)

(a) DF Tester Main unit



(b) DF Tester spinning disk and rubber sliders

(c) DF Tester typical result output

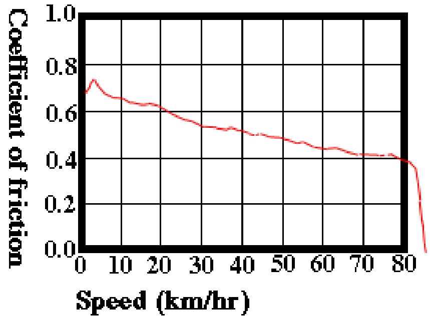
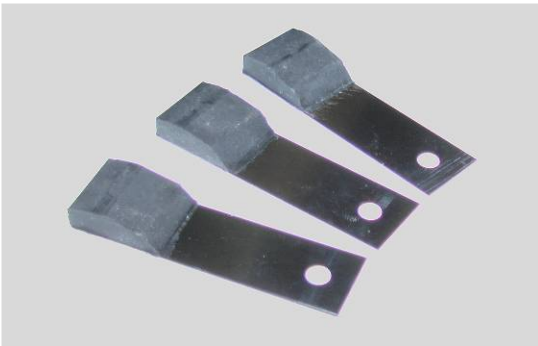


Figure A.6 DF Tester rubber sliders



The DF Tester has the advantage of being able to measure the friction as a function of speed over the range of zero to 80km/h. A test result of 0.60DFT20 signifies the DF Tester coefficient of friction (*μ=0.60*) at a spin speed of 20km/h. A significant benefit of the DF Tester is that whilst being a stationary device, it has a significantly larger contact area than the British Pendulum Tester (BPT), and is less affected by individual aggregate chips. It has been found to produce stable and highly repeatable measurements over time. These benefits enable the use of this device as a calibration device for other CFME devices such as the GripTester and ROAR (Wambold et al 1995).

Appendix B Field measurement test results

B.1 Tamaki Campus (University of Auckland) site

The Tamaki Campus section was one of the two Auckland asphalt mix (TNZ Mix 10) surface field sites. The testing section was divided into two sections for analysis, a flat-grade section and a sloped section on a 7.2% grade. The skid resistance testing was undertaken in both traffic directions (generally identified as being in the west and east directions) as shown in figure B.1. Minimum monthly skid resistance testing was undertaken at this site, beginning in July 2002. The average skid resistance test result was obtained for each test date by calculating the sample mean value of test runs one to five (excluding the warm-up run) for the following sections:

- west direction (flat section) – running distance 60–140m
- west direction (sloped section) – running distance 200–300m
- east direction (sloped section) – running distance 30–130m
- east direction (flat section) – running distance 190–270m.

Timeslice locations were also chosen, processed and analysed on the Tamaki site, many of which were coincident with repeated DF Testing locations. The timeslice locations are identified below, with the coincident DF Tester test locations denoted by the initials DFT and the position location shown in figure 3.7:

- west direction – 60m (DFT W1), 80m (DFT W2), 120m, 220m, 250m (DFT W3), and 270m (DFT W4)
- east direction – 70m (DFT E1), 80m (DFT E2), 110m, 210m, 250m (DFT E3) and 260m (DFT E4).

The performance of the Tamaki site (flat and sloped sections) in terms of its measured coefficient of friction over time, and as measured by the GripTester and the DF Tester (at a reported spin speed of 20km/h denoted as DFT20), is shown in figures B1 and B2. Tables B.1 and B.2 summarise the descriptive section statistics data for the flat and sloping sections respectively.

Figure B.1 Tamaki Campus summary results over time (flat section, both directions)

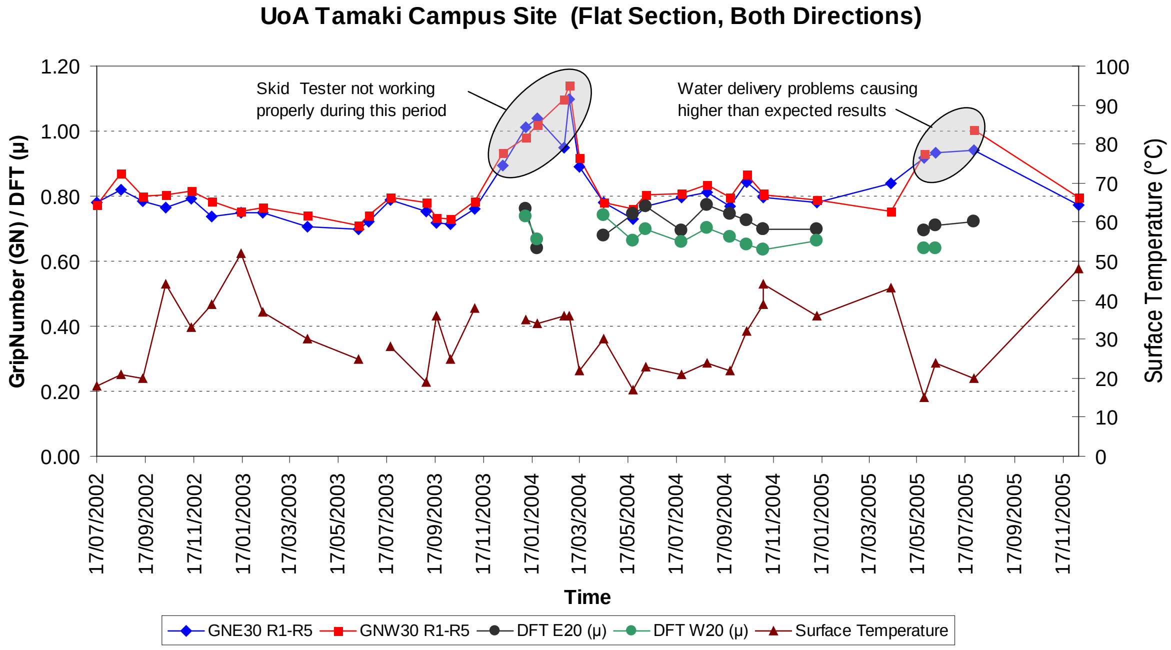


Table B1 Tamaki Campus site descriptive statistics (flat section)

Tamaki Campus Site (West Flat Section)

Sample Section Descriptive Statistics	Sect Ave GN 30 R1-R5	TIMESLICES GN T/S W1 60m	GN T/S W2 80m	GN T/S W3 120m	Ave DFT 20 (µ)	Temperature (ºC) Ambient (Start)	Surface (Start)
Sample count	31	30	30	30	11	30	30
Mean	0.80	0.79	0.76	0.83	0.73	19.4	30.2
Maximum	0.93	0.96	0.93	1.01	0.78	28.4	52.0
Minimum	0.71	0.67	0.67	0.73	0.66	13.5	15.0
Range	0.22	0.29	0.26	0.27	0.13	14.9	37.0
Standard Deviation	0.056	0.072	0.067	0.068	0.035	4.4	10.1
95% Confidence Interval	0.020	0.026	0.024	0.024	0.021	1.6	3.6
Variance	0.003	0.005	0.004	0.005	0.001	19.6	101.8
Coefficient of Variation (CoV)	0.070	0.091	0.088	0.082	0.048	0.228	0.334

Tamaki Campus Site (East Flat Section)

Sample Section Descriptive Statistics	Sect Ave GN 30 R1-R5	TIMESLICES GN T/S E4 210m	GN T/S E5 260m	GN T/S E6 280m	Ave DFT 20 (µ)	Temperature (ºC) Ambient (Start)	Surface (Start)
Sample count	32	26	26	26	15	30	30
Mean	0.79	0.77	0.79	0.77	0.72	19.4	29.8
Maximum	0.93	0.88	0.94	0.90	0.77	28.4	52.0
Minimum	0.70	0.70	0.70	0.69	0.64	13.5	13.0
Range	0.23	0.17	0.23	0.21	0.13	14.9	39.0
Standard Deviation	0.059	0.044	0.057	0.046	0.037	4.4	10.8
95% Confidence Interval	0.021	0.017	0.022	0.018	0.019	1.6	3.9
Variance	0.004	0.002	0.003	0.002	0.001	19.6	116.9
Coefficient of Variation (CoV)	0.075	0.057	0.073	0.060	0.051	0.228	0.363

Figure B.2 Tamaki Campus summary results over time (slope section, both directions)

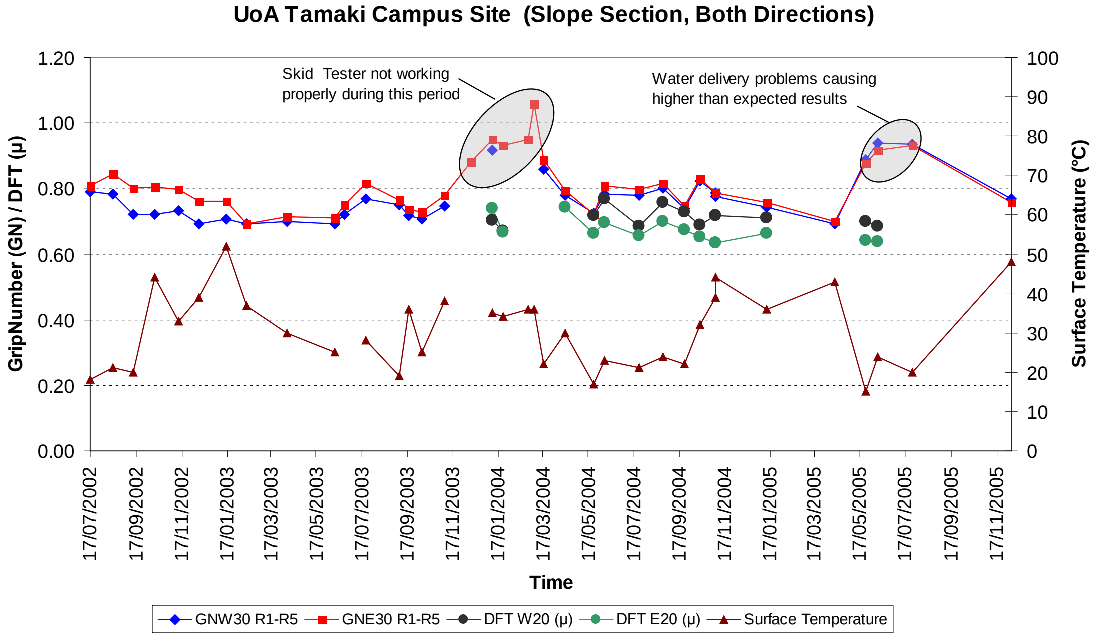


Table B.2 Tamaki Campus site descriptive statistics (slope section)

Tamaki Campus Site (West Slope Section)

Sample Section Descriptive Statistics	Sect Ave GN 30 R1-R5	TIMESLICES GN T/S W4 220m	GN T/S W5 250m	GN T/S W6 270m	Ave DFT 20 (μ)	Temperature (ºC) Ambient (Start)	Surface (Start)
Sample count	31	29	29	29	13	30	30
Mean	0.76	0.75	0.76	0.74	0.71	19.4	30.2
Maximum	0.94	0.90	0.94	0.91	0.77	28.4	52.0
Minimum	0.69	0.67	0.68	0.66	0.67	13.5	15.0
Range	0.25	0.23	0.26	0.25	0.10	14.9	37.0
Standard Deviation	0.059	0.060	0.060	0.058	0.028	4.4	10.1
95% Confidence Interval	0.021	0.022	0.022	0.021	0.015	1.6	3.6
Variance	0.003	0.004	0.004	0.003	0.001	19.6	101.8
Coefficient of Variation (CoV)	0.078	0.080	0.079	0.078	0.040	0.228	0.334

Tamaki Campus Site (East Slope Section)

Sample Section Descriptive Statistics	Sect Ave GN 30 R1-R5	TIMESLICES GN T/S E1 70m	GN T/S E1 80m	GN T/S E3 110m	Ave DFT 20 (μ)	Temperature (ºC) Ambient (Start)	Surface (Start)
Sample count	32	26	26	26	14	30	30
Mean	0.79	0.78	0.75	0.78	0.67	19.4	29.8
Maximum	0.92	0.87	0.89	0.90	0.74	28.4	52.0
Minimum	0.69	0.70	0.63	0.70	0.64	13.5	13.0
Range	0.23	0.17	0.26	0.20	0.11	14.9	39.0
Standard Deviation	0.056	0.043	0.061	0.052	0.035	4.4	10.8
95% Confidence Interval	0.019	0.017	0.024	0.020	0.019	1.6	3.9
Variance	0.003	0.002	0.004	0.003	0.001	19.6	116.9
Coefficient of Variation (CoV)	0.072	0.056	0.082	0.067	0.053	0.228	0.363

The Tamaki Campus site had been constructed only a few months prior to the commencement of the skid-testing measurement programme and was therefore expected to demonstrate an initial polishing phase, generally following a negative exponential form, to an 'equilibrium skid resistance' level. Thereafter, the expectation from previous research was that 'seasonal variations' throughout summer and winter seasons would occur. Initial observations of the first year of data on both sections did demonstrate an initial polishing phase reducing down to a low reading in February/March of 2003. However, the measured coefficient of friction then increased again over the next winter period, up to almost as high in August 2003, as the first tests in the preceding winter of July 2002. As this site was an internal campus road, the traffic during this period was predominantly composed of private cars and only minor HCV traffic due to on-site building construction vehicles.

As discussed earlier, the GripTester device coefficient of friction increased after the 2003/2004 summer period in comparison to the previous year (this was also seen on the other field test sites). It is unknown whether this increase was 'real' or related to the problems associated with the GripTester device over this period. After this period, the Tamaki site GN and DFT measurements varied around the total sample mean coefficient of friction (0.79–0.80 GN and 0.76–0.79 GN for the flat and sloped sections respectively) similar to that tested at the beginning of the testing period. However, when a water delivery problem occurred in May 2005, it caused, understandably, an increase in the measured GripTester coefficient of friction (GN) value compared with the DF Tester coefficient of friction. This high level close to the originally tested value was not initially expected, as the initial polishing phase was thought to polish the aggregate, thereby reducing this level to a lower 'equilibrium level' than the initial testing results close to the original surfacing date. The results tend to indicate that as the site was not heavily trafficked, this initial polishing phase might not occur at all, and only 'seasonal' and 'short-term' variations would occur. In support of this, the highest results were obtained in the 2004 year during the months of July, August and October, coinciding with the expected increase during winter.

A descriptive statistical analysis (refer to tables B.1 and B.2) of the coefficient of friction, as measured by the GripTester, for each of the four sections of the Tamaki site showed that there was very little statistical difference between the sample section means, maximums and minimum, standard deviations, the 95th percentile confidence interval, variance and coefficient of variation (CoV). The number of data sample points was either 31 or 32, and the sample mean (x) ranged from 0.76GN on the west slope section to 0.80GN on the west flat section. The remaining two sections had a sample mean (x) of 0.79. The flat section on average gave marginally higher means (0.80 and 0.79) than the sloped section (0.76 and 0.79) for the west and east directions respectively. This could be attributed to the higher traction forces on the sloped section (7% grade) causing greater aggregate polishing on the sloped section than on the flat section. The standard deviation was marginally below 0.06GN on all four sections and the CoV between GripTester test dates ranged from 7.2% to 7.8% for the section averages. The 95th percentile confidence interval was also very consistent between the four sections, as they ranged between 0.019 and 0.021, meaning, for example, that there was a 95% probability that the mean coefficient of friction would fall between 0.78 and 0.82GN for the west flat section.

The DF Tester-measured coefficient of friction had a maximum of 15 sample points for the various test point locations with a sample mean (x) ranging from 0.67–0.73(μ) and a sample standard deviation (σ) ranging from 0.028–0.037. The pattern that was demonstrated with the DF Tester was similar to that of the GripTester, as marginally lower coefficients of friction were obtained on the sloped section (0.71 and 0.67) than on the flat section (0.73 and 0.72) for the west and east directions respectively. The CoV between the DF Tester test dates at the 12 test-spot locations ranged from 4.0–5.1%, and the mean sample data demonstrated a 95th percentile confidence interval range of 0.015–0.021(μ) for the various test positions. This means, for example on the west flat section, that there was a 95% probability that the mean coefficient of friction, as measured by the DF Tester, would fall between a range of DF Tester (μ) value of 0.71 and 0.75 for the test positions.

The sample standard deviations (σ) and the CoV as measured by the DF Tester were lower than those for the GripTester. This was most probably due to the measuring method differences and the greater likelihood that the DF Tester position was recorded in exactly the same location. However, the variation from test position to test position was greater for the DF Tester than the averaged GripTester results, as two (out of the 12) of the test location positions for the DF Tester were chosen at the position that was most likely to polish the greatest (as also shown with the GripTester timeslice analysis for positions 80m in the west direction and 260m in the east direction). This would have skewed the averaging process and can be confirmed by comparing the CoV for the GripTester at these same locations; the values were higher by approximately 2% than the section means discussed above.

B.2 Ports of Auckland site

The Ports of Auckland site was the second Auckland asphalt mix surface (TNZ Mix 20). It was described earlier in section 3.8.4. The skid resistance testing was undertaken on a straight and level section adjacent to the Ports of Auckland Rail Grid site, where shipping containers are loaded onto rail cars (refer to figure 3.8). The rail grid site had predominantly very heavy forklift and container-straddler traffic. The principal traffic direction was predominantly transverse to the direction of skid measurement testing, although a significant amount of sharp-turning movements also occurred along the rail grid site. The site was tested in both the western and eastern traffic direction, as shown in figure 3.8. Two straight, white-painted lines, approximately 3.5m apart and for approximately 475m along the Rail Grid site, provided a reasonably good locational reference guide for the skid-testing line. Whilst there was no defined wheel path or traffic lane, the left wheel path (LWP) position was defined for the purposes of this study and tested in both directions, allowing a separation of the test lines. Minimum monthly skid resistance testing with the GripTester device was undertaken at this site beginning in September 2002 and predominantly between the times of 4:00 and 7:00pm, when access was allowed to the site. As no other vehicles used the testing location during the skid resistance measurements, other aspects of skid resistance could be investigated at various times (eg the relationship between texture, speed and skid resistance and a device's sensitivity to temperature).

Average skid resistance test results were obtained for each test date after post-processing, by calculating the sample mean value of test runs one to five (excluding the warm-up run) for the following sections:

- west direction – running distance 220–420m
- east direction – running distance 180–380m.

Six DF Tester test positions were also marked and repeatedly tested on the same date as the GripTester measurements from the date when the DF Tester device became available (February 2004). The test locations are shown on figure 3.8 and are listed below in each travel direction:

- west direction – 160m, 190m and 210m
- east direction – 240m, 270m and 290m.

The performance of the Ports of Auckland site in terms of its measured coefficient of friction over time and as measured by the GripTester and the DF Tester (at a reported spin speed of 20km/h denoted as DFT20) is shown in figures B.3 and B.4. Table B.3 summarises the descriptive section statistics data.

Figure B.3 Ports of Auckland site summary results over time (west direction)

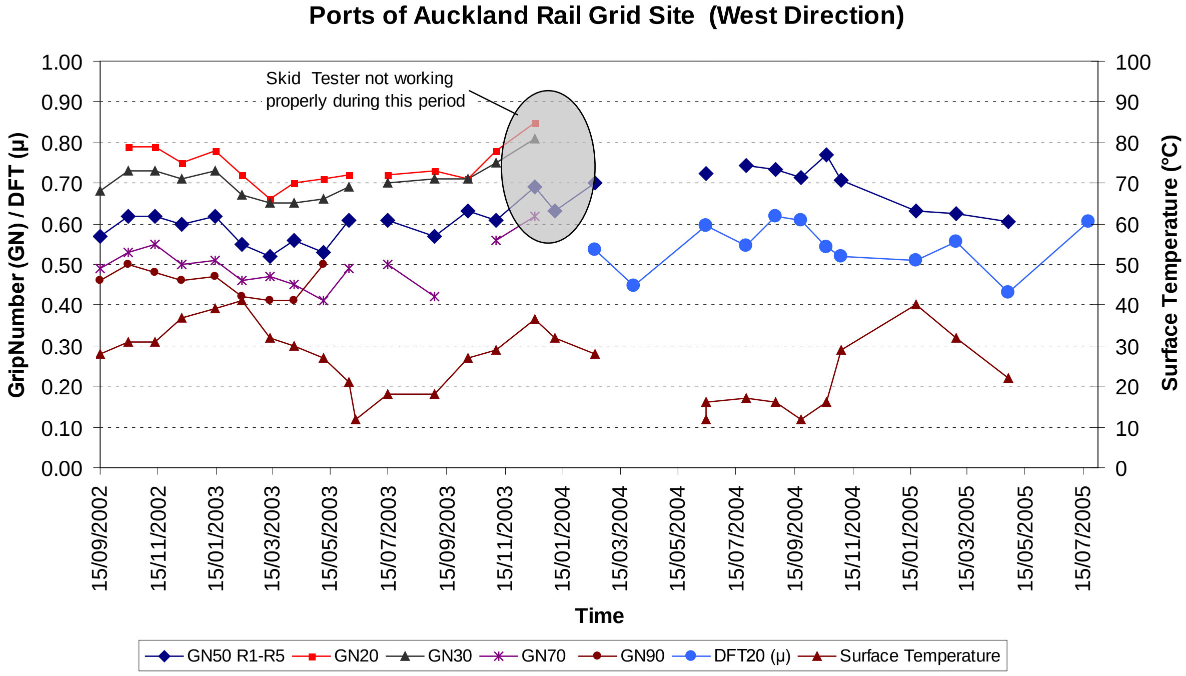


Table B.3 Ports of Auckland field site summary statistics (both directions)

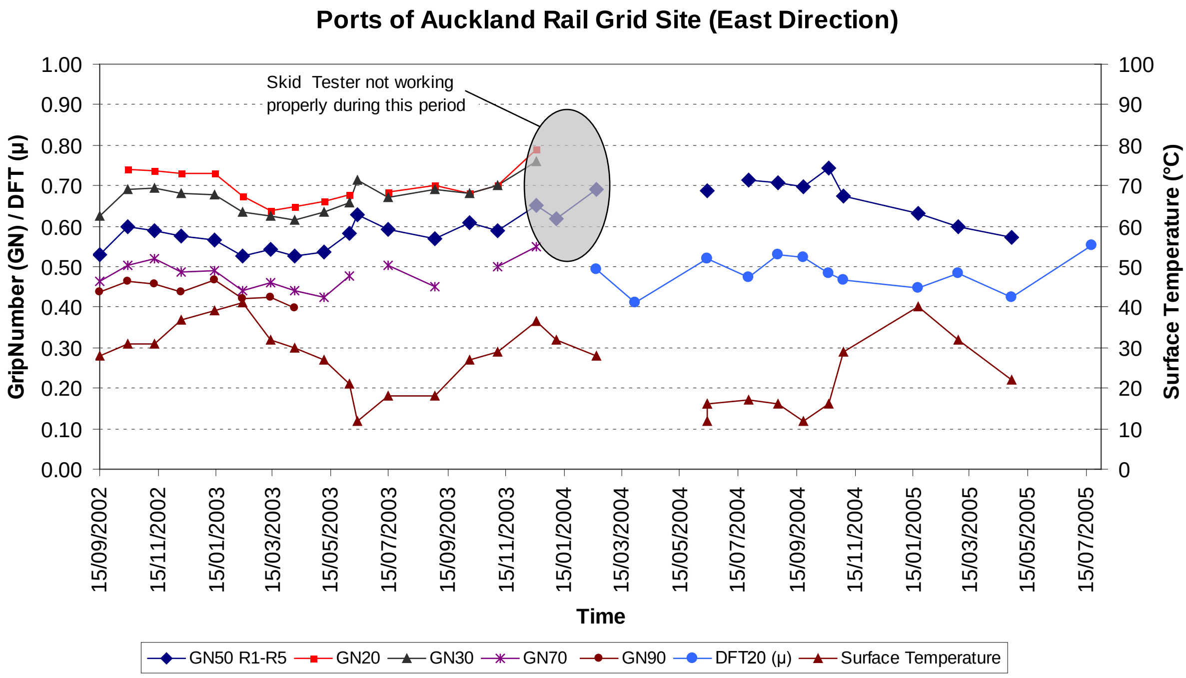
Ports of Auckland (West Direction)

Sample Section Descriptive Statistics	Sect Ave GN 20 R1-R5	Sect Ave GN 30 R1-R5	Sect Ave GN 50 R1-R5	Sect Ave GN 50 After	Sect Ave GN 70 R1-R5	Sect Ave GN 90 R1-R5	Ave DFT 20 (μ)	Temperature (ºC) Ambient (Start)	Temperature (ºC) Surface (Start)
Sample count	13	15	24	4	13	8	14	26	26
Mean	0.69	0.67	0.61	0.69	0.47	0.44	0.489	18.4	25.0
Maximum	0.74	0.72	0.74	0.71	0.52	0.47	0.551	29.0	41.0
Minimum	0.64	0.62	0.53	0.63	0.42	0.40	0.412	10.5	12.0
Range	0.10	0.10	0.22	0.08	0.10	0.07	0.139	18.5	29.0
Standard Deviation	0.034	0.032	0.064	0.038	0.030	0.024	0.041	5.3	9.1
95% Confidence Interval	0.019	0.016	0.026	0.038	0.016	0.017	0.022	2.0	3.5
Variance	0.001	0.001	0.004	0.001	0.001	0.001	0.002	27.6	83.3
Coefficient of Variation (CoV)	0.050	0.047	0.106	0.056	0.063	0.056	0.084	0.285	0.366

Ports of Auckland (East Direction)

Sample Section Descriptive Statistics	Sect Ave GN 20 R1-R5	Sect Ave GN 30 R1-R5	Sect Ave GN 50 R1-R5	Sect Ave GN 50 After	Sect Ave GN 70 R1-R5	Sect Ave GN 90 R1-R5	Ave DFT 20 (μ)	Temperature (ºC) Ambient (Start)	Temperature (ºC) Surface (Start)
Sample count	13	14	23	4	13	9	14	26	26
Mean	0.74	0.70	0.63	0.71	0.49	0.46	0.550	18.4	25.0
Maximum	0.79	0.75	0.77	0.75	0.56	0.50	0.618	29.0	41.0
Minimum	0.66	0.65	0.52	0.65	0.41	0.41	0.431	10.5	12.0
Range	0.13	0.10	0.25	0.10	0.15	0.09	0.187	18.5	29.0
Standard Deviation	0.040	0.032	0.070	0.045	0.045	0.036	0.058	5.3	9.1
95% Confidence Interval	0.022	0.017	0.029	0.044	0.025	0.023	0.031	2.0	3.5
Variance	0.002	0.001	0.005	0.002	0.002	0.001	0.003	27.6	83.3
Coefficient of Variation (CoV)	0.054	0.046	0.112	0.063	0.093	0.078	0.106	0.285	0.366

Figure B.4 Ports of Auckland site summary results over time (east direction)



The asphalt mix surface at the Ports of Auckland site was constructed in 1996 and was therefore expected to be well past the initial polishing phase and very clearly at an 'equilibrium skid resistance level', if such a phenomenon exists. Any variations in measured skid resistance levels were therefore expected to be due to 'seasonal' and 'short-term' environmental effects. The effects of varying the measurement test speed (from 20km/h to 90km/h) was investigated for the first 15 months of the data collection period at this site. After this date, a standard 50km/h measurement speed was utilised and DF Tester tests commenced. The first 15 months of data (refer to figures B.3 and B4) clearly demonstrated the effect of varying the device measurement speed and thereby the slip speed of the testing tyre on an asphalt mix surface; ie that the coefficient of friction reduces as the speed increases. The 90km/h test speed resulted in an almost 40% reduction in measured skid resistance compared with the skid resistance measured at 20km/h.

Careful visual observations of the GripTester measurements over the first and last year at the measuring speed of 50km/h at the Ports of Auckland site (refer to figures B.3 and B.4) indicate that measured skid resistance at this site did demonstrate a sinusoidal pattern, with the lowest measured coefficient of friction in the months of February/March in both years and the highest in approximately August to November. The results indicated that the phase minimum may actually coincide with late summer (March) and the phase maximum in spring (October), indicating that a clear seasonal variation effect occurred at this site.

As with the Tamaki Campus site, an increase in the GripTester device coefficient of friction also occurred at the Ports of Auckland site after the 2003/2004 summer period, compared with the previous year. It is unknown whether this increase was real or related to the problems associated with the GripTester device over this period. The results also showed that the measured skid resistance in the west direction was slightly lower than in the east direction for both the GripTester and the DF Tester device.

A descriptive statistical analysis (refer to table B.3), with the identified outliers removed, showed that the Ports of Auckland site, as measured by the GripTester device, with a maximum of 24 test surveys for the 50km/h testing speed, had very little difference in section means (x) by test direction. The sample mean (x) was 0.61GN and 0.63GN for the western and eastern directions respectively. The standard deviation of the averaged GripTester section survey results was 0.064GN (west) and 0.070GN (east), and the CoV was 10.6% (west) to 11.2% (east) respectively. The data resulted in a 95th percentile confidence interval that ranged from 0.026 to 0.029 respectively, meaning that there was a 95% probability that the mean GN value, for example in the west direction, would fall between the values of 0.58GN and 0.64GN at a 50km/h testing speed.

The DF Tester-measured coefficient of friction had a maximum of 14 test date points for the six test point locations (three in either direction, as shown earlier in figure 3.8) and resulted in a sample mean (x) of 0.49(μ) in the west direction and 0.55(μ) in the east direction. The sample standard deviation (σ) was 0.041 (west) and 0.058 (east), and the CoV between the DF Tester test dates at the 14 test spot locations was 8.4% (west) and 10.6% (east). The sample data demonstrated a 95th percentile confidence interval of 0.022 and 0.031 respectively, meaning that there was a 95% probability that the DF Tester (μ) value would, for example in the west direction, fall between the DF Tester (μ) values of 0.47 and 0.51.

As on the Tamaki site, the sample standard deviations (σ) and the CoV were lower for the DF Tester than those for the GripTester. This would be expected, due to the differences in measuring method (continuous in comparison to stationary) and because the variability due to the operator and transverse measuring position for the GripTester is removed from the DF Tester. The total variation in measured skid resistance at the Ports of Auckland site was greater than the Tamaki site (10.9% CoV cf 7.4% CoV), as would be expected due to the considerably greater proportion and movements of HCVs at the Ports of Auckland site causing greater polishing effects.

B.3 Kaiwaka Slag site

The Kaiwaka slag test site was the first of five Northland state highway test sites. Its physical attributes were described earlier in section 3.8.5 and shown in figure 3.9. The site was on state highway 1 and was made up of two reverse horizontal curves of radii of approximately 200m, and was therefore categorised under TNZ T/10 (Transit NZ 2002) specification as a Site Category 2 section. The site had been resurfaced in April 2003 with a two-coat chipseal utilising a TNZ grade 3/5 artificial steel melter slag aggregate with a reported PSV of 58. Skid resistance measurements with the GripTester began in the month prior to the new surfacing being constructed. The annual average daily traffic (AADT) was recorded in the RAMM database as being 8650vpd, with an HCV composition of 9.6%. The section operated under a 100km/h posted speed limit. The site was tested approximately monthly between March 2003 and May 2005 in both the increasing (southbound) and decreasing (northbound) linear directions. A defined longitudinal wheel path and therefore regular tyre/aggregate contact area and polishing mechanism occurred at this site. However, as the horizontal curve radii of the two curves were reasonably low (radius = 200m) and there were reasonably wide, sealed shoulders, the transverse wheel tracking width was expected to be wider than on a straight section of road.

Average skid resistance test results were obtained for each test date after post-processing, by calculating the sample mean value of test runs one to five (excluding the warm-up run) for the following sections:

- increasing direction – running distance 220–710m
- decreasing direction – running distance 170–760m.

Timeslice locations were also chosen, processed and analysed on the Kaiwaka site. The timeslice locations are identified below and were shown earlier in figure 3.9:

- increasing direction – 170m, 230m, 260m, 360m, 440m, 590m, 690m and 800m
- decreasing direction – 100m, 210m, 310m, 460m, 540m, 640m, 670m and 730m.

The performance of the Kaiwaka slag site in terms of its measured coefficient of friction over time and as measured by the GripTester device is shown in figure B.5 below. Table B.4 summarises the descriptive section statistics data.

Figure B.5 Kaiwaka Slag site summary results over time (both directions)

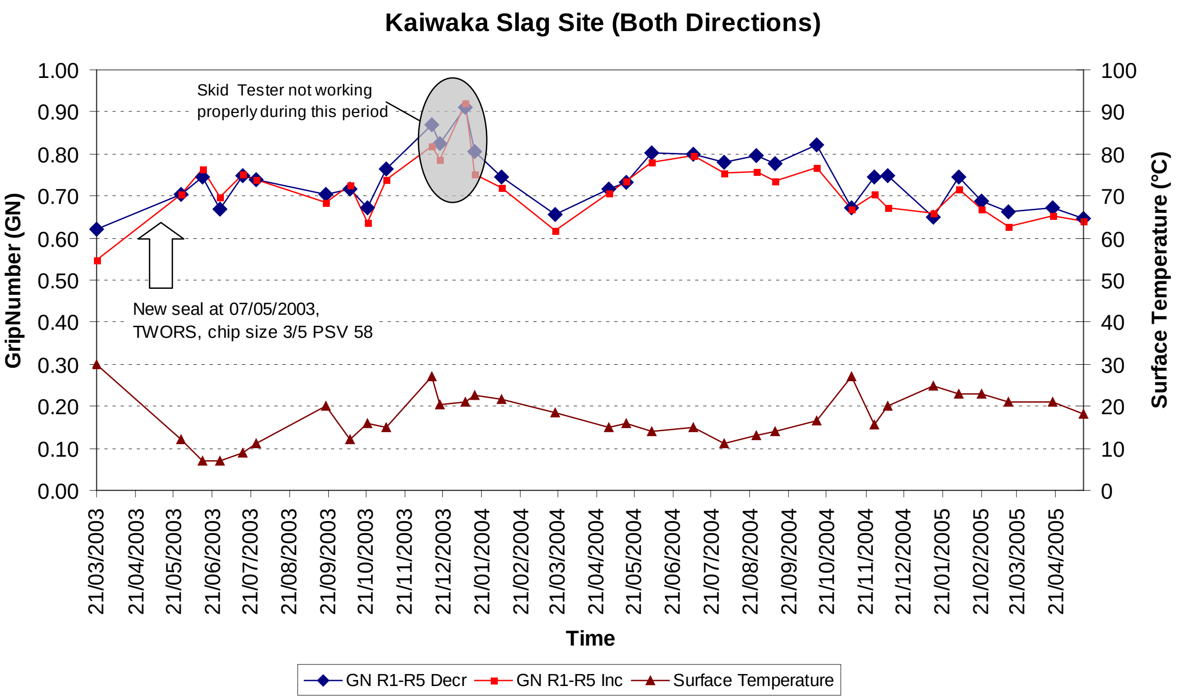


Table B.4 Kaiwaka Slag site summary statistics (both directions)

Kaiwaka Slag Site (Both Directions)

Sample Section Descriptive Statistics	Sect Ave GN Mean W/Up INC	Sect Ave GN Mean R1-R5 INC	Sect Ave GN Mean W/Up DEC	Sect Ave GN Mean R1-R5 DEC	Timeslice GN Mean 800m INC	Timeslice GN Mean 100m DEC	Temperature (ºC) Ambient (Start)	Temperature (ºC) Surface (Start)
Sample count	27	28	27	28	27	27	28	28
Mean	0.69	0.70	0.69	0.72	0.58	0.55	16.4	16.6
Maximum	0.82	0.80	0.83	0.82	0.71	0.66	23.9	30.0
Minimum	0.54	0.55	0.60	0.62	0.49	0.45	10.0	7.0
Range	0.29	0.25	0.23	0.20	0.23	0.21	13.9	23.0
Standard Deviation	0.074	0.057	0.059	0.055	0.058	0.057	3.8	5.7
95% Confidence Interval	0.028	0.021	0.022	0.020	0.022	0.021	1.4	2.1
Variance	0.006	0.003	0.004	0.003	0.003	0.003	14.1	33.0
Coefficient of Variation (CoV)	0.108	0.082	0.086	0.076	0.100	0.103	0.229	0.346

The Kaiwaka slag site was not expected to display seasonal type variations over time, as the site was newly sealed. It was thought that an initial polishing phase would, over the first year, reduce the measured skid resistance from an initial value down to an equlibrium level. However, as can be seen from figure B.5, the first approximately 18 months of skid resistance tests showed little microtexture polishing, with the new chipseal utilising the melter slag aggregate. As was consistent with other testing sites, there was a slight increase in GN values in the second year of testing that coincided with replacing significant parts of the GripTester device in the summer between the two years of data. There is also visible evidence (refer to figure B.5) that an approximately seasonal sinusoidal variation effect was displayed at the site, resulting in a lower measured coefficient of friction in March and April, compared with higher results in September and October.

Statistical analysis of the processed data (refer to table B.4), with identified outliers removed, shows that the averaged Kaiwaka slag site survey results, with a maximum of 28 test surveys, had a sample mean (x) of 0.70GN and 0.72GN (the warm-up runs were not included in this analysis) for the increasing and decreasing directions respectively. The standard deviation of the averaged GripTester section survey results (excluding the warm-up runs but including the first skid resistance measurement on the old seal surface) was 0.057GN and 0.055GN for the increasing and decreasing directions respectively. The CoV of the section averages ranged from 8.3% for the increasing direction to 7.6% for the decreasing direction. The data resulted in a 95th percentile confidence value that was 0.021 for the increasing direction and 0.020 in the decreasing direction. The implication is that for the increasing direction, for example, there was a 95% probability that the mean GN value would fall between the values of 0.68GN and 0.72GN at a 50km/h testing speed. An analysis of the warm-up runs in comparison to the subsequent test runs in either direction resulted in a higher recorded standard deviation, 95th percentile confidence interval, variance and CoV for either direction. This indicated that the first run of the GripTester was more susceptible to changes due to environmental factors such as the conditioning of the measuring tyre and possibly the level of detritus on the surface.

The averaged GripTester device section results show that, in general, the measured skid resistance values in each direction were very similar. There is some indication from figure B.5 that the measured skid resistance was beginning to reduce (polish) to a lower level, and it is unknown at this point whether this would have increased again to a level close to the initial measured value with the new seal surface. A close observation of the data and on site inspections shows that the new seal section length was now quite variable in the longitudinal direction. This was due to a number of areas that were now ‘flushed’ and/or ‘bleeding’ with excess bitumen that had migrated from lower chipseal layers. This would certainly produce lower measured skid resistance.

The total variation in measured skid resistance at the Kaiwaka slag site was similar to the Ports of Auckland site, but higher than the Tamaki site. However, if the first test result (on the old seal) was removed from the subsequent analysis, the total CoV would reduce to similar section values of approximately 7.0%.

B.4 Brynderwyn South curve site

The Brynderwyn South curve site was the second of five Northland state highway test sites. Its physical attributes were described earlier in section 3.8.6 and shown in figure 3.10. The site was on SH1 and was made up of one relatively sharp horizontal curve of 160m, and was therefore categorised under TNZ T/10 specification (Transit NZ 2002) as a Site Category 2 section. The horizontal curve geometry was inconsistent with the speed environment and relatively high approach speeds, and therefore the demand for friction was often close to, or exceeding, the available supply. This meant that the polishing forces were high on the corner section, thereby requiring regular maintenance treatment intervention. The treatment in the last few years had consisted of Works Infrastructure Ltd (the network maintenance contractors on behalf of Transit NZ) applying a new chipseal surface in March 2003 and April 2004 as shown in figure B.6 and during the data collection period, with the aim of increasing the skid resistance levels.

Skid resistance measurements with the GripTester began in the month prior to the first new surfacing being constructed. The AADT was recorded in the RAMM database as being 8650vpd, with an HCV composition of 9.6%. The section operated under a 100km/h posted speed limit. The site was tested approximately monthly between March 2003 and May 2005 in both the increasing (southbound) and decreasing (northbound) directions. A defined longitudinal wheel path and therefore regular tyre/ aggregate contact area and polishing mechanism occurred at this site. However, as the horizontal curve radii of the curves were low (radius=160m) with reasonably wide, sealed shoulders, the transverse wheel-tracking width was expected to be wider than on a straight section of road.

Average skid resistance test results were obtained for each test date after post-processing, by calculating the sample mean value of test runs one to five (excluding the warm-up run) for the following sections:

- increasing direction – running distance 230–410m
- decreasing direction – running distance 210–400m.

Timeslice locations were also chosen, processed and analysed on the Brynderwyn site. The timeslice locations are identified below and were shown earlier in figure 3.10:

- increasing direction – 150m, 300m and 490m
- decreasing direction – 110m, 200m and 350m.

The performance of the Brynderwyn South curve site in terms of its measured coefficient of friction over time and as measured by the GripTester device is shown in figure B.6. Table B.5 summarises the descriptive section statistics data.

Figure B.6 Brynderwyn South curve site summary results over time (both directions)

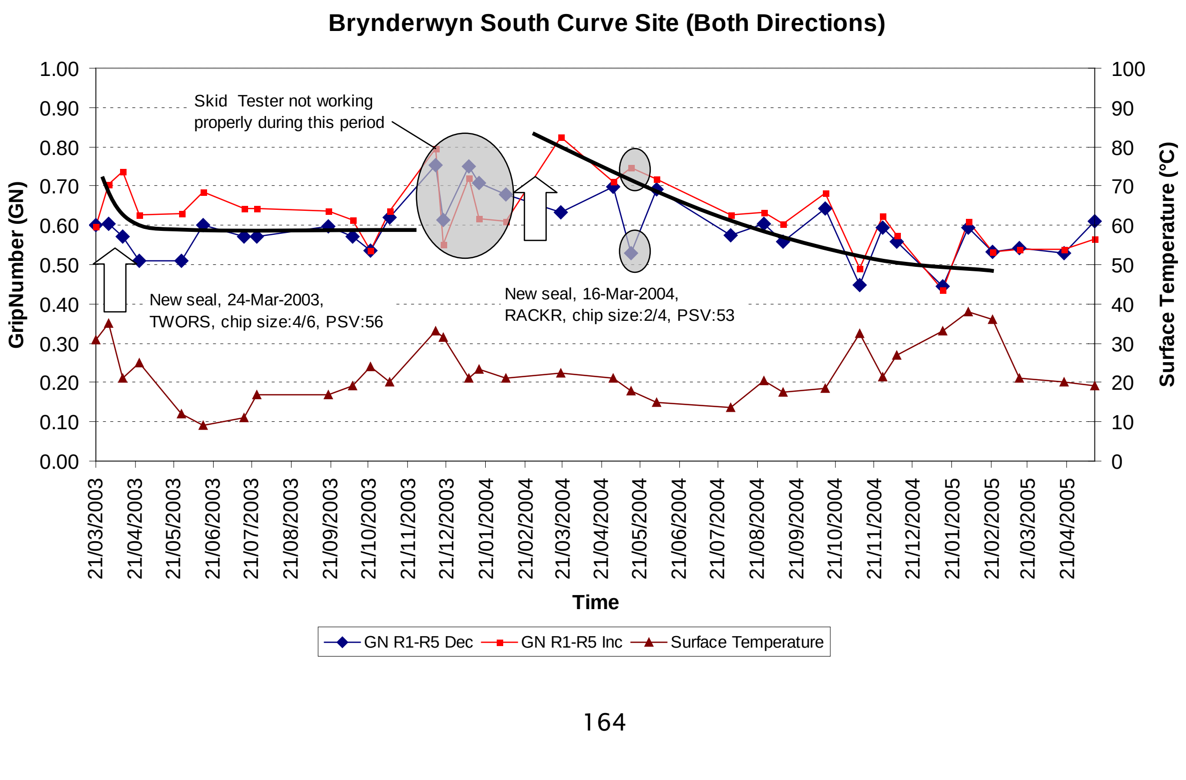


Table B5 Brynderwyn South curve site summary statistics (both directions)

Brynderwyn South Curve Site (Both Directions)

Sample Section Descriptive Statistics	Sect Ave GN Mean W/Up INC	Sect Ave GN Mean R1-R5 INC	Sect Ave GN Mean W/Up DEC	Sect Ave GN Mean R1-R5 DEC	Timeslice GN Mean 490m INC	Timeslice GN Mean 110m DEC	Temperature (ºC) Ambient (Start)	Temperature (ºC) Surface (Start)
Sample count	28	29	28	29	26	28	29	29
Mean	0.60	0.63	0.54	0.57	0.57	0.55	18.9	21.9
Maximum	0.73	0.83	0.68	0.70	0.64	0.69	27.0	38.0
Minimum	0.45	0.44	0.39	0.44	0.49	0.45	11.5	9.0
Range	0.28	0.39	0.29	0.25	0.16	0.24	15.5	29.0
Standard Deviation	0.074	0.082	0.067	0.058	0.041	0.054	4.2	7.6
95% Confidence Interval	0.027	0.030	0.025	0.021	0.016	0.020	1.5	2.8
Variance	0.005	0.007	0.005	0.003	0.002	0.003	17.3	57.6
Coefficient of Variation (CoV)	0.123	0.132	0.126	0.102	0.073	0.098	0.220	0.346

Due to a high degree of transverse and longitudinal polishing on the sharp curve, the site had a high demand for friction, largely due to the high operating speeds compared with the safe design speed. This had led to relatively frequent overlaying of chipseal surfaces with aggregate that could not naturally withstand the high polishing demands required of it. Subsequently, it was not expected that the site would display seasonal type variations over time, but would remain in a typical initial negative exponential polishing phase from an initial value down to an equlibrium level. The length of time interval required for this polishing to occur was investigated as part of the skid resistance testing programme.

Statistical analysis of the processed data (refer to table B.5 above), with identified outliers removed, shows that the Brynderwyn South curve site, with a maximum of 29 test surveys, had a sample mean (x) of 0.63GN and 0.57GN (the warm-up runs were not included in this analysis) for the increasing and decreasing directions, respectively. The standard deviation of the averaged GripTester section survey results (including the previous old seal surfaces) was 0.082GN and 0.058GN, and the CoV was 13.2% and 10.2% for the increasing and decreasing directions, respectively. These statistical variation descriptors would be expected to be higher than on a site that was in its second seasonal variation phase after initial polishing was completed, such as the Hikurangi site. The data resulted in a 95th percentile confidence value that was 0.030 (increasing) and 0.025 (decreasing). Thus, for example, there was a 95% probability that the mean GN value would fall between the values of 0.60GN and 0.66GN at a 50km/h testing speed, for the increasing direction.

The averaged GripTester device section results (refer to figure B.6) show that generally, the measured skid resistance in the increasing direction was higher than in the decreasing direction, by up to 0.06GN. This was especially apparent for the first seal constructed in March 2003. The differences could possibly be attributed to a probable lower approach speed in the increasing direction compared with higher approach speeds (and therefore higher polishing forces) in the decreasing direction. This also aligns with Land Transport NZ crash statistics, which reported a higher crash rate in the decreasing direction than in the increasing direction.

Figure B.6 also shows an attempt to visually demonstrate the averaged initial polishing phase from the measured skid resistance data, and the polishing factors involved. Of significance is how quickly the newly surfaced aggregate polished to a level that was very similar to that prior to the surface construction. The first two-coat surface seal lasted only approximately three months before the skid resistance reduced it to a level as low, or lower, than the previous seal.

The aggregate used from Bellingham's quarry had a reported PSV of 56, and the results show that it was not polish-resistant enough to prevent the polishing of the microtexture. An analysis/calculation of the

TNZ T/10 PSV equation, as an established method, predicted that an aggregate PSV of approximately 60 should have been used before the addition of any PSV stress points for this TNZ T/10 Site Category 2 curve. The previous history of known aggregate polishing and the volume of HCV could have been utilised to determine how many additional PSV points should have been added to the calculated PSV equation above to determine an appropriate aggregate to use.

Unfortunately, the problems that arose with the GripTester in the summer of 2003/2004 meant that what occurred was not known in the summer months, when the lowest results were expected. The expectation was (and the last few data points tended to indicate this trend) that the measured coefficient of friction would reduce further in the summer months. In fact, on-site visual surveys during this period showed noticeable 'flushing' in the increasing wheel track direction during these hotter summer months, due to multiple layers of unstable seals. The SCRIM survey on 18 December 2003 adequately demonstrated this effect of losing macrotexture by returning an SFC result of 0.29 in the increasing direction (well below the threshold level (TL) of 0.40SFC required for the site) and a 0.53SFC in the decreasing direction. This effect can be seen with the last few credible GripTester reported results in figure B.6, where the increasing coefficient of friction (GN) sharply decreases to the same level as the decreasing direction. The results after this point, however, unfortunately coincide with the period where problems occurred with the GripTester and therefore the results are not credible.

The surface was again resurfaced in March 2004, this time with a racked-in seal with a PSV of 52, with much closer attention to temporary traffic control to ensure low speeds and proper embedment of the chip during construction. The initial effect of the treatment and then its rate of reduction over the ensuing months is again evident on figure B.6, although the rate of polishing was somewhat less than the previous seal. This was surprising, as it was expected that a lower reported aggregate PSV would polish at a faster rate than a higher reported PSV. However, by the following summer, some 9–10 months later, the skid resistance values had reduced to a level where the SCRIM and GripTester surveys in December 2004, and then later in May 2005, showed it was right on the boundary of the TL,[14] the trigger level for determining priority for treatment. The SCRIM and GripTester surveys had shown a slight increase in the surveyed results from the December 2004 surveys to the May 2005 surveys, indicating that perhaps this was the equilibrium level of polishing at the site, and that seasonal fluctuations were now occurring around this level and that further reductions would not occur. However, according to the TNZ T/10 specification, this again triggered priority for treatment, as the measured coefficient of friction levels was well below the 'investigatory level',[15] and on the border of the TL, which is set at 0.1SFC below the investigatory level.

The total variation in measured skid resistance at the Brynderwyn site (approximately 13% over the two-year period) was higher than at the other reported field sites – probably because of the high polishing demand in the initial polishing phases from the low radii curve and the high operating speeds.

B.5 Hikurangi site

The Hikurangi site was chosen as a control seasonal site and was the third of five Northland state highway test sites. Its physical attributes were described earlier in section 3.8.7 and shown in figure 3.12. The site

14 The TL is currently set at 0.1 below the investigatory level (IL), and is the trigger level for determining priority for treatment.

15 The IL is the level of skid resistance at or below which a site investigation is to be undertaken, and the information is used as a priority for programming treatment.

was on SH1, north of Whangarei, immediately south of the Hikurangi township, and comprised a straight and level section with a chipseal surface that was more than five years old. The macrotexture levels had been stable over time and the site had also been used as a SCRIM seasonal site over the previous few years.

Skid resistance measurements with the GripTester began in March 2003 and continued through to May 2005 in both the increasing and decreasing directions. The AADT was recorded in the RAMM database as being 9700vpd, with an HCV composition of 9.7%. The section operated under a 100km/h posted speed limit. A defined longitudinal wheel path, and therefore regular tyre/aggregate contact area and polishing mechanism, occurred at this site and therefore any variation in measured skid resistance due to transverse location of the measuring wheel was expected to be minimal. Average skid resistance test results were obtained for each test date after post-processing, by calculating the sample mean value of test runs one to five (excluding the warm-up run) for the following sections:

- increasing direction – running distance 160–450m
- decreasing direction – running distance 250–550m.

The performance of the Hikurangi site in terms of its measured coefficient of friction over time, and as measured by the GripTester and the DF Tester where this was possible (at a reported spin speed of 20km/h denoted as DFT20), is shown in figure B.7. Table B.6 summarises the descriptive section statistics data.

Figure B.7 Hikurangi control site summary results over time (both directions)

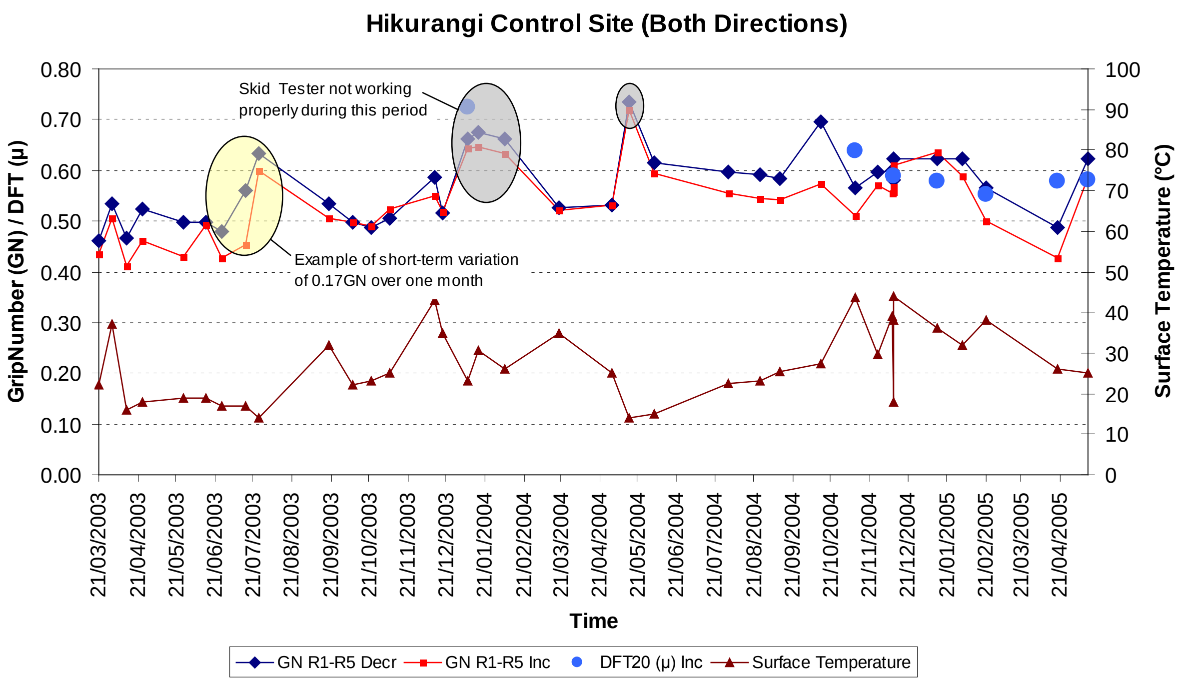


Table B.6 Hikurangi site summary statistics (both directions)

Hikurangi Control Site (Both Directions)

Sample Section Descriptive Statistics	Sect Ave GN Mean W/Up INC	Sect Ave GN Mean R1-R5 INC	Sect Ave GN Mean W/Up DEC	Sect Ave GN Mean R1-R5 DEC	Ave DFT 20 (μ)	Temperature (ºC) Ambient (Start)	Surface (Start)
Sample count	32	32	32	32	8	32	32
Mean	0.47	0.53	0.51	0.56	0.62	21.7	26.2
Maximum	0.61	0.72	0.64	0.73	0.73	34.5	44.0
Minimum	0.34	0.41	0.42	0.46	0.55	11.5	14.0
Range	0.27	0.31	0.21	0.27	0.17	23.0	30.0
Standard Deviation	0.068	0.069	0.063	0.066	0.069	5.3	8.9
95% Confidence Interval	0.024	0.024	0.022	0.023	0.048	1.8	3.1
Variance	0.005	0.005	0.004	0.004	0.005	27.6	78.6
Coefficient of Variation (CoV)	0.146	0.130	0.124	0.117	0.110	0.243	0.339

The Hikurangi site was expected to display seasonal type variations over time, as the site was stable and over five years in age. The site was chosen on the basis that if a sinusoidal seasonal pattern of skid resistance variation did exist, then this site was expected to show this effect. However, as can be seen from the section averaged results in figure B.7, the skid resistance levels were surprisingly variable and clearly not predictable, although initial aggregate polishing phases were plainly completed prior to the data collection period.

As was consistent with other testing sites, there was an increase in GN values in the second year of testing that coincided with replacing significant parts of the GripTester device in the summer between the two years of data. There was also some evidence (refer to figure B7) that an approximately seasonal variation effect was displayed at the site, resulting in a lower measured coefficient of friction in March and April, compared with higher results in August, September and October. The averaged GripTester device section results also show that generally, the measured skid resistance in the increasing direction was marginally lower than in the decreasing direction.

Of surprise was how much the measured coefficient of friction varied over such a short period of time. Figure B.7 shows the results of the skid resistance monitoring, which shows that more than 30% variation could occur (a difference of 0.17GN or approx 0.13SFC) within one month. A check of periodic macrotexture measurements over the two-year survey period showed that this remained reasonably constant and could therefore not explain the differences in skid resistance measurement. It must therefore be concluded that this skid resistance variation was due either to contamination of the surface and/or real microtexture changes during this period. The amount of this variation is of considerable concern to road network managers, as sites that have been surveyed and passed can fail within weeks, and sometimes even days, later.

Statistical analysis of the processed data (refer to table B.6), with the identified outliers removed, shows that the Hikurangi site with a maximum of 32 test surveys, had a sample mean (x) of 0.53GN and 0.56GN for the increasing and decreasing directions respectively. The standard deviation of the averaged GripTester section survey results was 0.069GN (increasing) and 0.066GN (decreasing), and the CoV was 13.0% and 11.7% for the western and eastern directions respectively. The data resulted in a 95th percentile confidence value that was 0.024 and 0.023, meaning that there was a 95% probability that the mean GN value, for example, would fall between the values of 0.50GN and 0.55GN in the increasing direction at a 50km/h testing speed.

The total variation in measured skid resistance at the Hikurangi site was greater than at all of the other field test sites. This was an unexpected result, as the Hikurangi site should only have displayed ‘seasonal’ variations after an initial equilibrium level had been reached. All other Northland sites (Brynderwyn, Kaiwaka, Kara and Snooks–Tatton) had sections that had new chipseal surfaces, and it was expected that these sites would have demonstrated greater standard deviations and coefficients of friction over the data collection period due to the inclusion of initial polishing phases. If anything, the Hikurangi site results showed that skid resistance had increased in total over the testing period.

The Hikurangi site was also tested, whenever traffic control was possible, with the DF Tester at three defined locations. Only eight different test survey dates were possible during the survey data period and only in the increasing direction. The DF Tester test data resulted in a sample mean (x) ranging from 0.47 to 0.62(μ) and a sample standard deviation (σ) of 0.069. The CoV between the DF Tester test dates at the eight test spot locations was 11.0% and this corroborates with the GripTester data and other DF Tester field sites in the Auckland region, which demonstrated that this site had considerably more variation than the other field test sites. The results of the data analysis showed that there was a 95% probability that the mean DF Tester (μ) result would fall between the values of 0.57 and 0.67.

A comparison was made between the Hikurangi site variation data (up to 14.7% CoV) and the middle section on the Snooks–Tatton Road site, (section 2, with an increasing direction CoV of 8.1%). The sites were similar in that they were sections that were at least six years old and that should only display 'seasonal variations'. This confirmed that the Hikurangi site was unusually high in terms of its measured variation in skid resistance. Whilst it is difficult to understand exactly what was causing the greater degree of skid resistance variation at this site, a possible site-specific explanation could be that there is a lime quarry north of the site. It is possible that some of the variability in measured skid resistance was due to either contamination and/or variable traffic loading/skid resistance/rainfall rejuvenation cycles.

B.6 Kara Road site

The Kara Road test site was the fourth of five Northland state highway test sites. Its physical attributes were described earlier in section 3.8.8 and shown in figure 3.13. The site was on SH14 and was approximately 8.5km west of Whangarei. It consisted of a series of reverse horizontal curves of radii as low as 15–160m and was therefore categorised under TNZ T/10 (Transit NZ 2002) specification as a TNZ Site Category 2 section. The site had been resurfaced in January 2003 with a racked-in grade 3/5 chipseal surface with an aggregate sourced from Otaika quarry with a reported PSV of 51/52. Skid resistance measurements with the GripTester began in March 2003. The AADT was recorded in the RAMM database as being 5500vpd, with an HCV composition of 5.5%. The section operated under a 100km/h posted speed limit. The site was tested approximately monthly between March 2003 and April 2005 in both the increasing (southbound) and decreasing (northbound) directions. A defined longitudinal wheel path and therefore regular tyre/aggregate contact area and polishing mechanism occurred at this site. However, as the horizontal curve radii of the reverse curves were reasonably constrained, the transverse wheel tracking width was expected to be somewhat wider than on a straight section of road.

The field test site was split into two sections, one predominantly on a flat grade and the other predominantly on a grade of 7.2%. Average skid resistance test results were obtained for each test date after post-processing, by calculating the sample mean value of test runs one to five (excluding the warm-up run) for the following sections:

- section 1 (increasing direction) – running distance 50–170m
- section 2 (increasing direction) – running distance 210–570m

- section 1 (decreasing direction) – running distance 50–460m
- section 2 (decreasing direction) – running distance 470–590m.

Timeslice locations were also chosen, processed and analysed on the Kara Road site. The timeslice locations are identified below and were shown earlier in figure 3.13:

- increasing direction – 40m, 120m, 220m, 450m, 520m, 600m, and 650m
- decreasing direction – 30m, 110m, 180m 410m, 450m, 570m and 610m.

The performance of the Kara Road site in terms of its measured coefficient of friction over time and as measured by the GripTester device is shown in figure B.8. Table B.7 summarises the descriptive section statistics data.

Figure B.8 Kara Road site summary results over time (both directions)

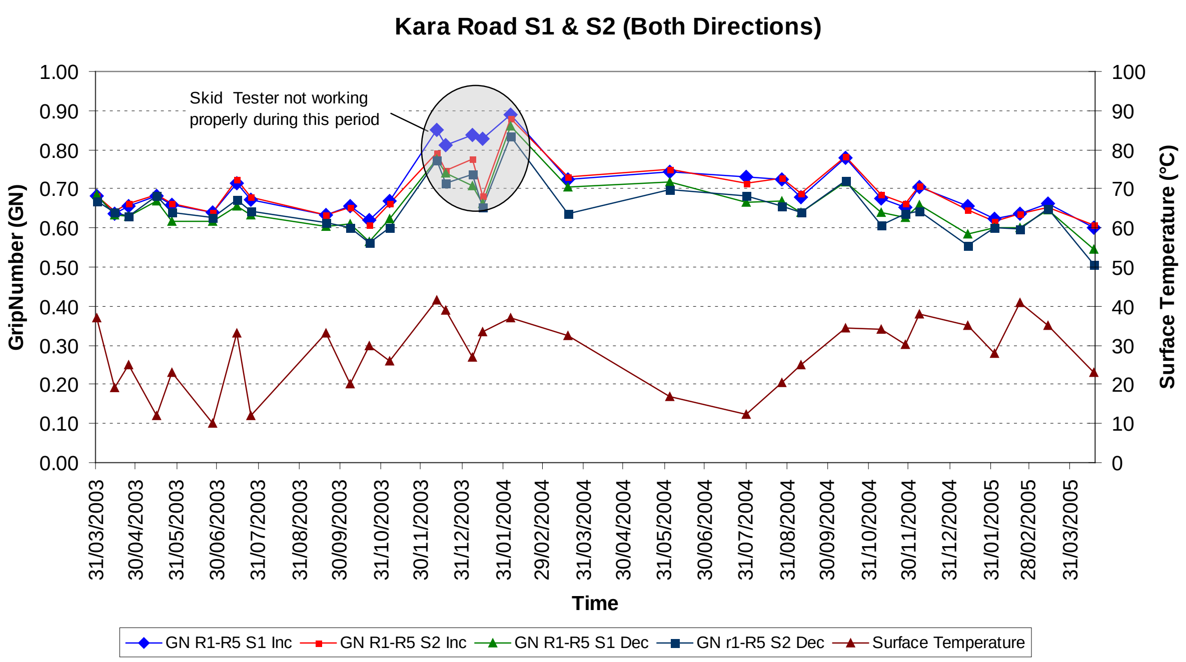


Table B.7 Kara Road site summary statistics (both directions)

Kara Road Site (Both Directions)

Sample Section Descriptive Statistics	Sect Ave GN Mean S1 INC	Sect Ave GN Mean S2 INC	Sect Ave GN Mean S1 DEC	Sect Ave GN Mean S2 DEC	Timeslice GN Mean 40m INC	Timeslice GN Mean 650m DEC	Temperature (ºC) Ambient (Start)	Temperature (ºC) Surface (Start)
Sample count	26	26	26	26	26	25	26	26
Mean	0.67	0.67	0.64	0.63	0.66	0.65	20.1	26.4
Maximum	0.78	0.78	0.72	0.72	0.79	0.76	27.0	41.0
Minimum	0.60	0.61	0.55	0.51	0.55	0.55	10.8	10.0
Range	0.18	0.18	0.17	0.21	0.24	0.21	16.3	31.0
Standard Deviation	0.043	0.044	0.043	0.046	0.058	0.058	4.3	9.0
95% Confidence Interval	0.016	0.017	0.016	0.018	0.022	0.023	1.6	3.4
Variance	0.002	0.002	0.002	0.002	0.003	0.003	18.1	80.3
Coefficient of Variation (CoV)	0.063	0.065	0.067	0.073	0.089	0.089	0.211	0.340

The Kara Road site was not expected to display seasonal type variations over time, as the site had recently been sealed prior to skid resistance monitoring. It was thought that an initial polishing phase would continue for the first year or so, as HCV volumes were approximately one-third of those for SH1. Hence, the measured skid resistance would decrease from an initial value down to an equilibrium level. This decreasing effect is evident in figure B.8, where the skid resistance levels for all section averages generally reduce over the data collection period, although at a lesser rate than on the Brynderwyn South curve site, which has three times the amount of HCVs. As was consistent with other testing sites, there was an increase in GN values in the second year of testing, which coincided with replacing significant parts of the GripTester device in the 2003/2004 summer between the two years of data. There is also visible evidence from the second year of data (refer to figure B.8) that a seasonal variation effect occurred at the site, resulting in a lower measured coefficient of friction in March and April, compared with higher results in September and October.

Statistical analysis of the processed data (refer to table B.7), with the identified outliers removed, shows that the Kara Road site, with a maximum of 26 test surveys, had a sample mean (x) of 0.67GN for both sections 1 and 2 of the increasing direction. In the decreasing direction, a mean (x) of 0.64GN and 0.63GN was obtained for sections 1 and 2 respectively (the warm-up runs were not included in this analysis). The standard deviations for all sections and directions were very consistent, the results ranging between 0.043GN and 0.046GN. The CoV ranged from 6.3% to 7.3%. The data resulted in a 95th percentile confidence value that ranged from 0.016 to 0.018, meaning that there was a 95% probability that the mean GN value would fall, for example, between the values of 0.65GN and 0.69GN on section 1 in the increasing direction at a 50km/h testing speed.

The averaged GripTester device section results show that generally, the measured skid resistance in the increasing direction was marginally higher than in the decreasing direction. The total variation in measured skid resistance at the Kara Road site was the lowest of the chipseal surfaces in Northland – but not as low as the asphalt mix surface at the Ports of Auckland.

B.7 Snooks-Tatton Site

The Snooks-Tatton Road field test site physical attributes were described earlier in section 3.8.9 and shown in figure 3.14. The site was the longest field site (1700m) and was separated into three sections, two of which had been resealed in Jan 2003, a few months before the skid resistance monitoring commenced at the site, plus a middle 300m section that retained the old seal surface, which was constructed in February 2000. The site was also on SH14, and was approximately 5.5kms further west than the Kara Road field site and 13.9kms west of Whangarei. It consisted of a series of reverse horizontal curves of radii as low as 140-160m, and was therefore also categorised under TNZ T/10 (Transit NZ 2002) specification as a TNZ Site Category 2 section. The two newly sealed sections were resurfaced with a two-coat grade 3/5 chipseal with aggregate sourced from Otaika quarry with a reported PSV of 51/52. Skid resistance measurements with the GripTester began in March 2003. The AADT was recorded in the RAMM database as being 5500vpd, with an HCV composition of 5.5%. The section operated under a 100km/h posted speed limit and was level. The site was tested approximately monthly between March 2003 and April 2005 in both the increasing (southbound) and decreasing (northbound) directions. A defined longitudinal wheel path and therefore regular tyre/aggregate contact area and polishing mechanism occurred at this site. However, as the horizontal curve radii of the reverse curves were reasonably constrained, the transverse wheel tracking width was expected to be somewhat wider than on a straight section of road.

As discussed above, the field test site was split into three sections, separated by the change in seals. The average skid resistance test results were obtained for each test date after post-processing, by calculating the sample mean value of test runs one to five (excluding the warm-up run) for the following sections:

- section 1 (increasing direction) – running distance 120–590m
- section 2 (increasing direction) – running distance 610–930m
- section 3 (increasing direction) – running distance 950–1690m
- section 1 (decreasing direction) – running distance 140–850m
- section 3 (decreasing direction) – running distance 1220–1690m.

Section 2 in the decreasing direction was not analysed, as this section had had a few recent routine maintenance patches that had considerably modified the chipseal skid resistance performance. Timeslice locations were also chosen, processed and analysed on the Snook-Tatton site. The timeslice locations are identified below and the increasing direction was shown earlier in figure 3.14):

- increasing direction – 80m, 300m, 630m, 1100m, 1280m, 1450m, 1600m and 1740m
- decreasing direction – 60m, 200m, 350m 520m, 700m, 1170, 1500 and 1720m.

The performance of the Snooks-Tatton Road skid resistance site in terms of its measured coefficient of friction over time and as measured by the GripTester device is shown in figure B.9. Table B.8 summarises the descriptive section statistics data.

Figure B.9 Snooks-Tatton site summary results over time (both directions)

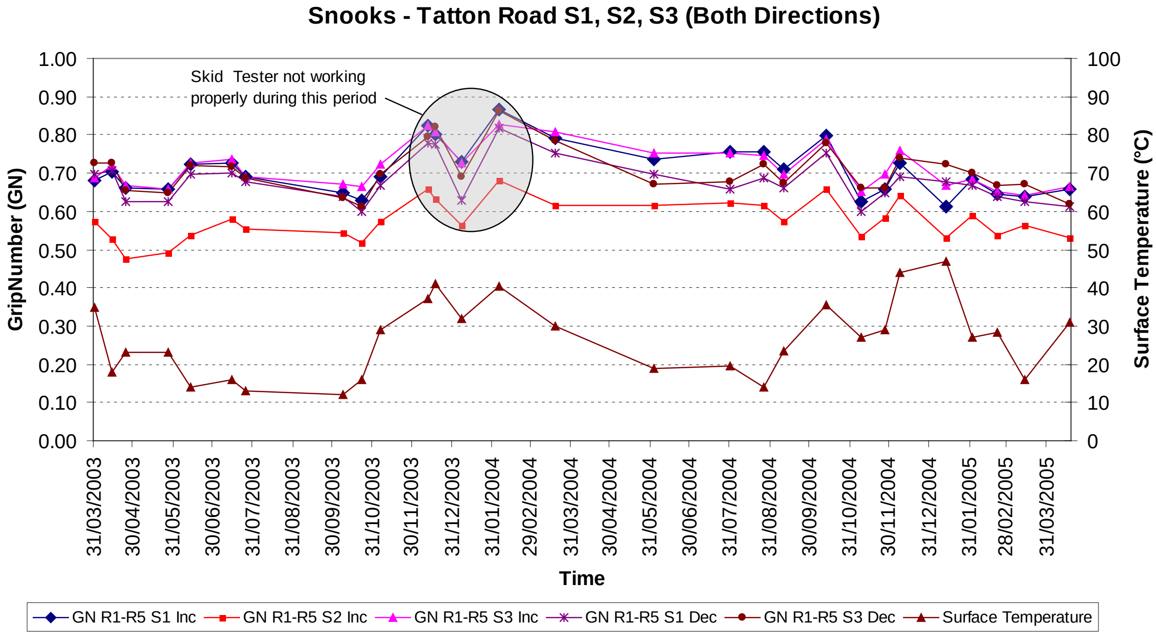


Table B.8 Snooks–Tatton Road site summary statistics (both directions)

Snooks - Tatton Road Site (Both Directions)

Sample Section Descriptive Statistics	Sect Ave GN Mean S1 INC	Sect Ave GN Mean S2 INC	Sect Ave GN Mean S3 INC	Sect Ave GN Mean S1 DEC	Sect Ave GN Mean S3 DEC	Timeslice GN Mean 700m DEC	Temperature (ºC) Ambient (Start)	Temperature (ºC) Surface (Start)
Sample count	24	24	24	24	24	20	24	24
Mean	0.69	0.57	0.70	0.67	0.69	0.56	20.4	24.6
Maximum	0.80	0.66	0.81	0.75	0.78	0.69	48.0	47.0
Minimum	0.61	0.47	0.64	0.60	0.61	0.48	9.0	12.0
Range	0.18	0.18	0.17	0.16	0.17	0.21	39.0	35.0
Standard Deviation	0.051	0.046	0.046	0.042	0.045	0.057	7.5	9.5
95% Confidence Interval	0.021	0.019	0.018	0.017	0.018	0.025	3.0	3.8
Variance	0.003	0.002	0.002	0.002	0.002	0.003	56.3	90.8
Coefficient of Variation (CoV)	0.074	0.082	0.065	0.063	0.065	0.101	0.368	0.388

The Snooks–Tatton Road site (sections one and three) was not expected to display seasonal-type variations over time, as the site had been sealed in January 2003, a few months before the skid resistance monitoring commenced. However, section 2 in the increasing direction was over three years old and was expected to demonstrate seasonal variations, as the seal would be at an equilibrium level. As with the Kara Road site, the number of HCVs was approximately one-third that of SH1 at the Kaiwaka, Brynderwyn and Hikurangi sites. Figure B.9 shows that the individual sections behaved very similarly over the data collection period. However, the newly chipsealed surface was clearly but slowly deteriorating and thereby converging towards the middle section 2 skid resistance levels. As was consistent with other testing sites, there was an increase in GN values in the second year of testing that coincided with replacing significant parts of the GripTester device in the 2003/2004 summer between the two years of data. There is also visible evidence from the second year of data (refer to figure B.9) that a seasonal variation effect occurred at the site, resulting in a lower measured coefficient of friction in March and April, compared with higher results in September and October. The averaged GripTester device section results show that, generally, the measured skid resistance in the increasing direction was marginally higher than in the decreasing direction.

Statistical analysis of the processed data (refer to table B.8), with the identified outliers removed, shows that the two newly surfaced Snooks–Tatton Road sections, with a maximum of 24 test surveys, had a sample mean (x) ranging from 0.67GN to 0.70GN (the warm-up runs were not included in this analysis). The middle older seal section had a sample mean (x) of 0.57. The standard deviations of the averaged GripTester section survey results for all sections ranged between 0.042GN and 0.051GN, and the CoV ranged from 6.3% to 8.2%. The data resulted in a 95th percentile confidence value that ranged from 0.017 to 0.021, meaning that there was a 95% probability that the mean GN value would fall between the values of 0.65GN and 0.72GN at a 50km/h testing speed in either direction.

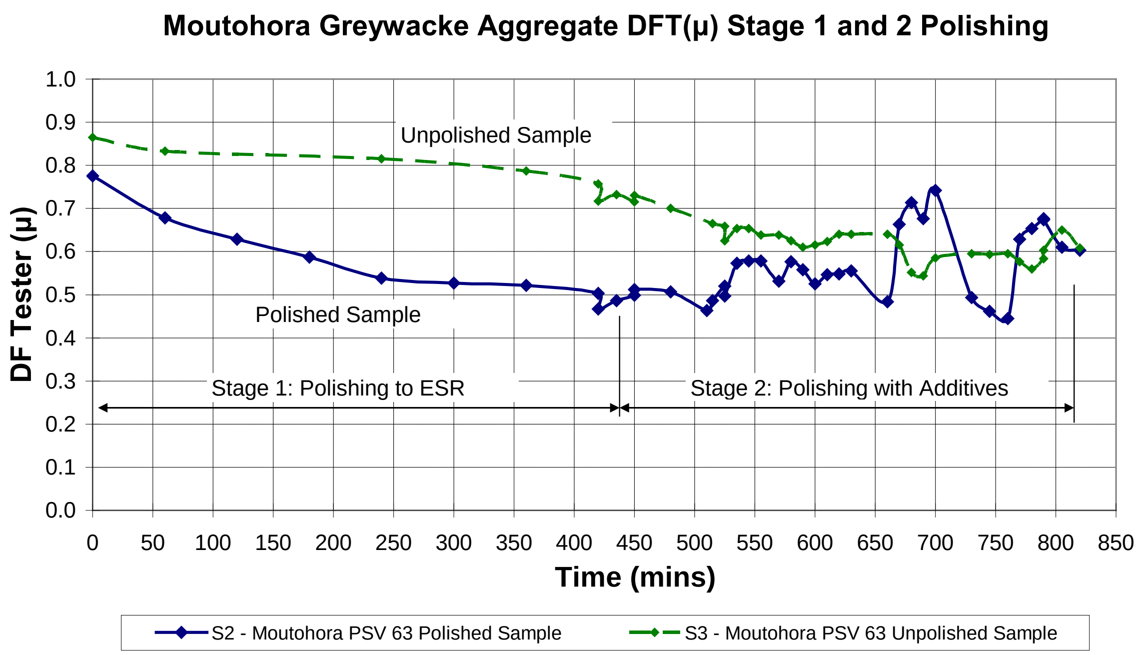
Appendix C Stage 2 laboratory polishing with contaminants

C.1 Moutohora greywacke

As discussed in section 8.3.2, the Moutohora sample that was wet polished using the AAPD changed in value from a stage 1 accelerated polishing value of DFT(*μ*)=0.87 to an equilibrium wet-polished level of DFT(*μ*)=0.47. The stage 2 polishing phase included the accelerated polishing of the sample (in wet, dry and damp conditions) with the addition of oedometer clay, emery powder or Leighton Buzzard sand. Figure C.1 shows the results of the two stages of polishing for the two Moutohora greywacke laboratory samples (one with accelerated polishing and the other with no polishing).

Some increases and decreases were expected that could be considered as being seasonal in their extent. However, the extent of the variation that could occur with the addition of contaminants and accelerated polishing was surprising. After only 10 minutes of accelerated polishing with Leighton Buzzard sand, measured skid resistance levels were reached that were very close to the initial measured coefficient of friction prior to any accelerated polishing. An increase of DFT(*μ*)=0.20 occurred after an ESR level of approximately DFT(*μ*)=0.50 had been established, after a total of 650 minutes of accelerated polishing (as shown in figure C.1).

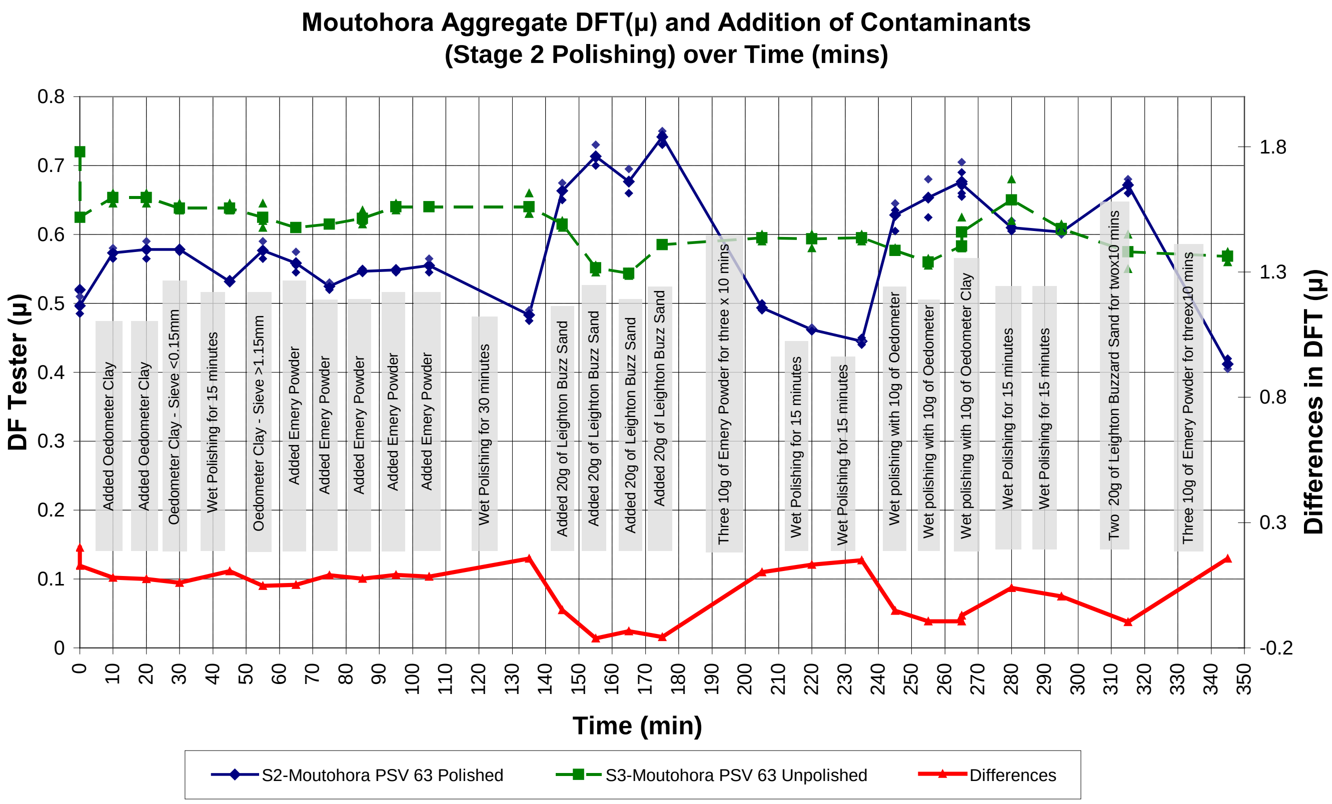
Figure C.1 Moutohora greywacke laboratory sample (stages 1 and 2 polishing phases)



These significant variations require explanation sequentially, in terms of which additive was used, the effect of the additive in terms of the measured coefficient of friction with the DF Tester (*μ*), and then what may have caused the variation. The explanation for the Moutohora greywacke sample is visually displayed in figure C.2. A chronological explanation and its effect in terms of measured coefficient of friction from the beginning of stage 2 polishing is as follows:

- The addition of 10 grams of oedometer clay and accelerated polishing for 10 minutes with no water increased the DFT(μ) value by 0.10 to 0.58, a percentage increase of 23.4%.
- Further additions of 10 grams of oedometer clay and samples that had been sieved to be less than 0.15mm PSD did not further modify the measured DFT(μ) result obtained from the first oedometer clay sample.
- The polished sample was then wet polished with no additives for 15 minutes and the subsequent measured DFT(μ) returned to a level similar (but slightly higher) to that determined as being the previous ESR level at the end of the stage 1 polishing phase, DFT(μ)=0.53.
- An addition of 10 grams of oedometer clay material that was retained on a 1.15mm sieve with dry accelerated polishing also increased the DFT(μ), back to 0.58.
- The addition of five 10-gram doses (5 x 10 grams) of emery powder every 10 minutes of dry accelerated polishing resulted in a minor decrease in measured DFT(μ) to 0.55.
- Wet polishing for 30 minutes with no contaminants then reduced the measured DFT(μ) to 0.48, almost exactly the same level that was obtained at the end of the stage 1 polishing.
- A series of 4 x 20 grams of Leighton Buzzard sand was then added to the sample every 10 minutes for accelerated polishing and a measured DFT(μ) result was obtained. The initial 10 minutes of polishing with the Leighton Buzzard sand produced a DFT(μ) rise of 0.18 to 0.66; a significant increase. Subsequent additions of the sand and 10 minutes of polishing produced only minor further increases in measured DFT(μ) compared with the first.
- The next dry-polishing phase comprised the addition of 3 x 10 grams of emery powder every 10 minutes after the Leighton Buzzard sand accelerated polishing phase was completed. A measured DFT(μ) was not obtained until the end of the 30-minute period, which resulted in a significant decrease in measured surface friction, back to the levels of the ESR level measured at the end of stage 1. The resultant value was a measured DFT(μ) of 0.49.
- A further 30 minutes of wet polishing with no contaminants was then undertaken, which resulted in a slight decrease in measured DFT(μ) to a level of 0.45, a little lower than the initial ESR level obtained.
- The full PSD of the oedometer clay was then added in 3 x 10 gram batches, with the surface being very lightly sprayed with water to keep the surface in a damp condition. The measured skid resistance level was increased, this time significantly higher than for the same dry-polishing additive undertaken previously, with a measured DFT(μ) of 0.67 being obtained.
- A further 30 minutes of wet polishing with no contaminants produced a characteristic decrease in measured DFT(μ) of 0.06 to 0.61.
- A repeated cycle of 2 x 20 grams of Leighton Buzzard sand for 10 minutes each, with accelerated polishing, produced an increase in the measured DFT(μ) value to 0.67, similar to that in the first cycle.
- A final 3 x 10 grams of emery powder every 10 minutes, with dry accelerated polishing, produced a measured DFT(μ) value of 0.41, the lowest obtained for the Moutohora sample.

Figure C.2 Moutohora greywacke laboratory samples (stage 2 polishing with addition of contaminants)

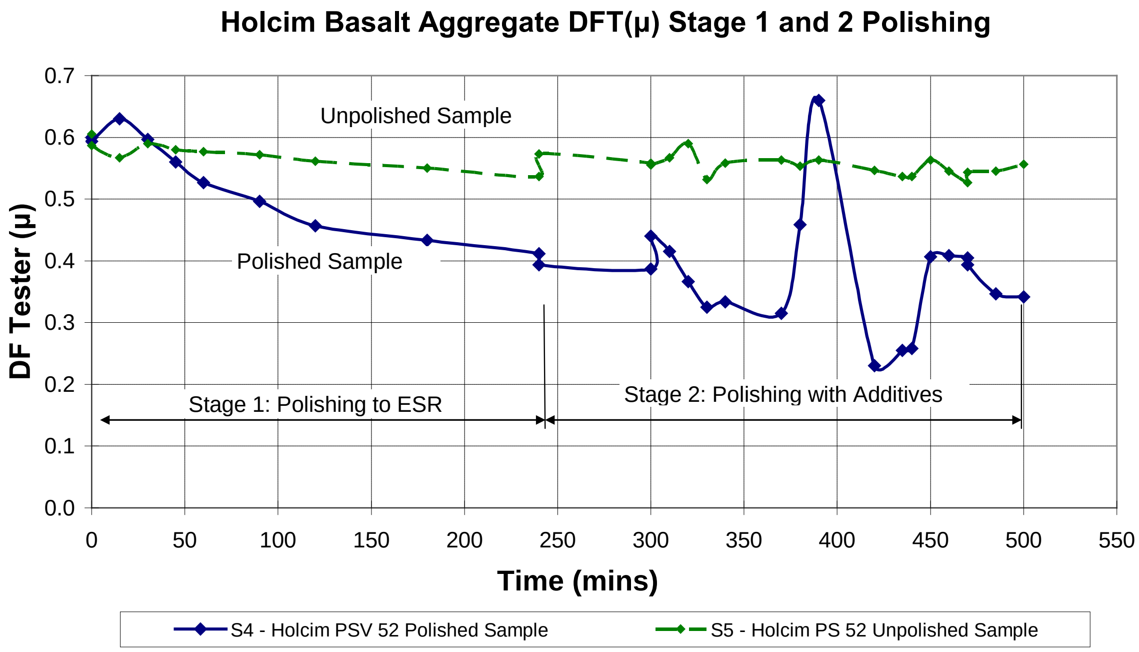


C.2 Holcim basalt

As discussed in section 8.3.3, the Holcim basalt sample that was wet polished using the AAPD initially roughened up to DFT(μ)=0.63 (from an initial value of DFT(μ)=0.60). It then decreased due to polishing, to an equilibrium wet-polished level of DFT(μ)=0.39 (stage 1 accelerated polishing). The stage 2 polishing phase included the accelerated polishing of the sample (in wet, dry and damp conditions) with the addition of oedometer clay, emery powder or Leighton Buzzard sand.

Figure C.3 shows the results of the two stages of polishing for the two Holcim basalt laboratory samples (one with accelerated polishing and the other with no polishing). Measured skid resistance levels were reached on the stage 2 contaminant-testing phase that were even higher than the initial measured coefficient of friction prior to any accelerated polishing. After only 10 minutes of accelerated polishing with Leighton Buzzard sand, an increase of DFT(μ)=0.35 occurred after an approximately DFT(μ) level of 0.31 had been established after 370 minutes of accelerated polishing. Furthermore, when emery powder was added for 10 minutes of accelerated polishing, the DFT(μ) reduced by 0.33 from the peak increase level (DFT(μ)=0.66 gained with the Leighton Buzzard sand.

Figure C.3 Holcim basalt laboratory sample (stages 1 and 2 polishing phases)



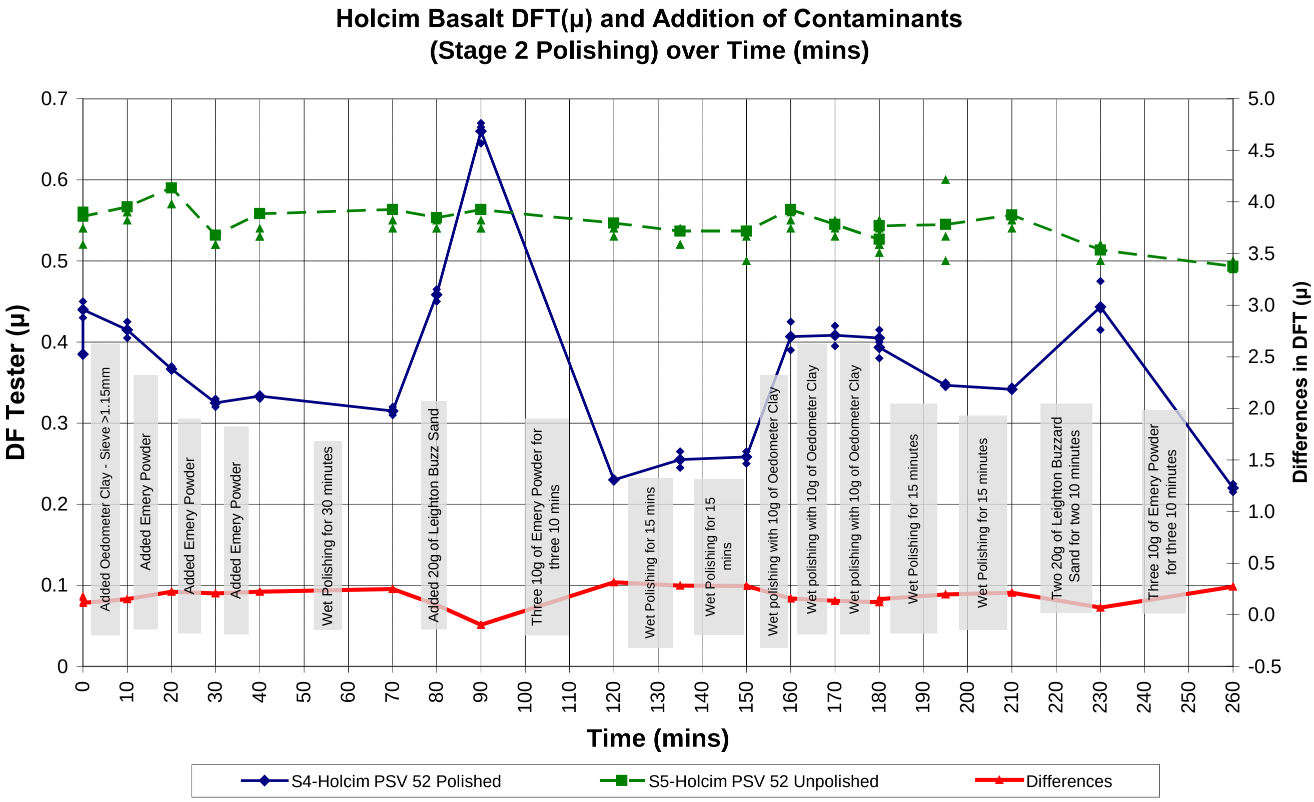
These significant variations require some explanation sequentially as to what additive was given, the effect of the additive in terms of the measured coefficient of friction with the DF Tester (μ), and then what may have caused the variation to occur. The explanation for the Holcim basalt sample is visually displayed in figure C.4. A chronological explanation and its effect in terms of measured coefficient of friction, from the beginning of stage 2 polishing, is as follows:

- The addition of 10 grams of oedometer clay material that was retained on a 1.15mm sieve, with dry accelerated polishing for 10 minutes, increased the DFT(μ) value by by 0.02 to 0.41, a percentage increase of 5.1%.
- The addition of 3 x 10grams of emery powder every 10 minutes of dry accelerated polishing resulted in a decrease in measured DFT(μ) to 0.33.
- The polished sample was then wet polished with no additives for 30 minutes and the subsequent measured DFT(μ) did not significantly alter from the level reached previously. It remained at a level of DFT(μ)=0.32, 0.01 lower than the level reached with the emery powder. This level was, however, significantly lower than the level determined as being the ESR level previously DFT(μ)=0.39 at the end of the stage 1 polishing phase.
- A series of 2 x 20 grams of Leighton Buzzard sand was then added to the sample every 10 minutes for accelerated polishing and a measured DFT(μ) result was obtained. The initial 10 minutes of polishing with the Leighton Buzzard sand produced a DFT(μ) increase of 0.15 to 0.46, and the second 10 minutes a further DFT(μ) of 0.19 to 0.65, both significant increases.
- The next dry-polishing phase comprised the addition of 3 x 10 grams of emery powder every 10 minutes after the Leighton Buzzard sand accelerated polishing phase was completed. A measured DFT(μ) was not obtained until the end of the 30-minute period, which resulted in a significant

decrease in measured skid resistance to lower levels than the recorded ESR level, measured at the end of stage 1. The resultant value was a measured DFT(μ) of 0.23 and a significant loss of DFT(μ) 0.43.

- A further 30 minutes of wet polishing with no contaminants was then undertaken, which resulted in a slight increase (that was against the commonly observed trend) in measured DFT(μ) to a level of 0.26, which was still lower than the original wet-polished ESR value obtained at the end of the stage 1 polishing phase.
- The full PSD of the oedometer clay was then added in 3 x 10 gram batches, with the surface being very lightly sprayed with water to keep the surface in a damp condition. The measured skid resistance level after the first 10 minutes of accelerated polishing increased to a level of DFT(μ)=0.41, which was 0.15 higher than that measured previously and (re-establishing the same level of ESR as at the end of stage 1). Two further 10 minutes of accelerated polishing, with additional skid resistance measurements, did not further alter the result.
- A further 30 minutes of wet polishing, with no contaminants added, produced a characteristic decrease in measured DFT(μ) of 0.07 to 0.34.
- A repeated cycle of 2 x 20 grams of Leighton Buzzard sand for 10 minutes each with accelerated polishing produced an expected increase (as with the earlier cycle) in the measured DFT(μ) value to 0.44, so did not attain the same level of measured skid resistance DFT(μ) as obtained in the first cycle.
- A final 3 x 10 grams of emery powder every 10 minutes with dry accelerated polishing produced a reduced measured DFT(μ) value of 0.22, a reduction of DFT(μ)=0.22 from the previous level of 0.44. This was the lowest value obtained for the Holcim basalt sample and any of the other three laboratory surface samples.

Figure C.4 Holcim basalt laboratory samples (stage 2 polishing with addition of contaminants)

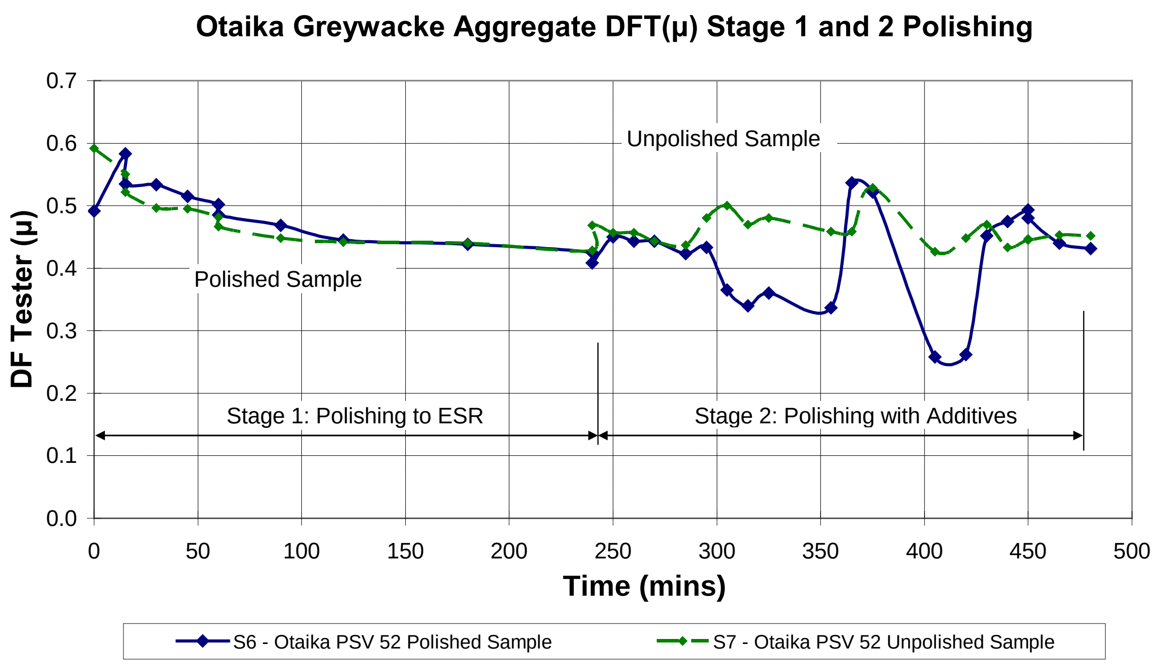


C.3 Otaika greywacke

As discussed in section 8.3.4, the Otaika greywacke sample that was wet polished using the AAPD initially roughened up to DFT(μ)=0.58 (from an initial value of DFT(μ)=0.49). It then decreased due to polishing, to an equilibrium wet-polished level of DFT(μ)=0.42. The stage 2 polishing phase included the accelerated polishing of the sample (in wet, dry and damp conditions) with the addition of oedometer clay, emery powder or Leighton Buzzard sand.

Figure C.5 shows the results of the two stages of polishing for the two Otaika greywacke laboratory samples (one with accelerated polishing and the other with no polishing). Measured skid resistance levels were reached on the stage 2 contaminant-testing phase that were almost as high as the initial measured coefficient of friction prior to any accelerated polishing. After only 10 minutes of accelerated polishing with Leighton Buzzard sand, an increase of DFT(μ)=0.20 occurred after a DFT(μ) level of approximately 0.33 had been established following 355 minutes of accelerated polishing (as shown in figure C.5). Furthermore, when emery powder was added for 10 minutes of accelerated polishing, the DFT(μ) reduced by 0.27 from the peak increase level (DFT(μ)=0.53) gained with the Leighton Buzzard sand.

Figure C.5 Otaika greywacke laboratory sample (stages 1 and 2 polishing phases)



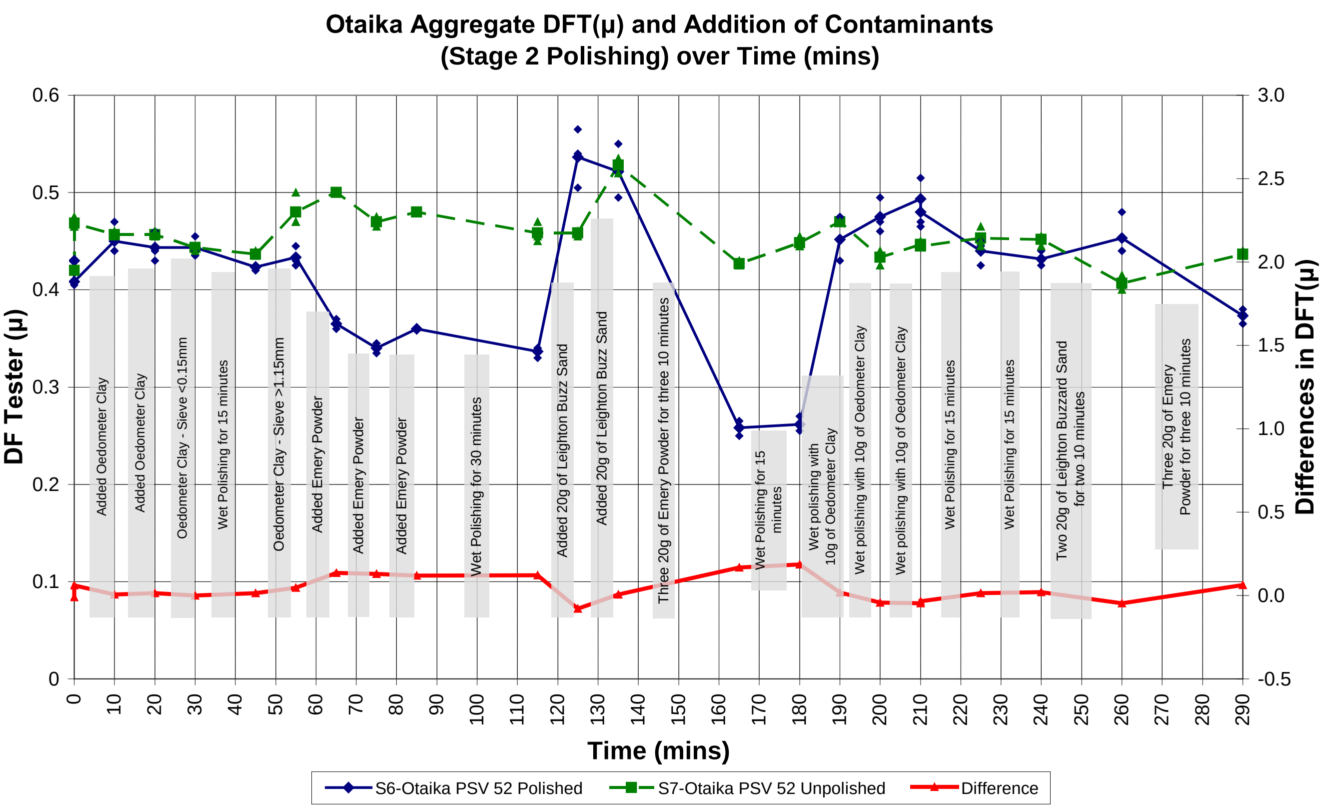
These significant variations require some explanation sequentially in terms of what additive was used, the effect of the additive in terms of the measured coefficient of friction with the DF Tester (μ), and then what may have caused the variation to occur. The explanation for the Otaika greywacke sample is visually displayed in figure C.6. A chronological explanation, and its effect in terms of measured coefficient of friction from the beginning of stage 2 polishing, is as follows:

- The addition of 10 grams of oedometer clay material that was either the full PSD of the sample, the material retained on a 1.15mm sieve, or the material that was sieved through a 0.15mm sieve with dry accelerated polishing for 10 minutes, increased the DFT(μ) value by 0.01/0.02 to 0.43, a percentage increase of 5.1%.
- The addition of 3 x 10 grams of emery powder every 10 minutes of dry accelerated polishing resulted in a decrease in measured DFT(μ) to 0.34.
- The polished sample was then wet polished with no additives for 30 minutes and the subsequent measured DFT(μ) did not significantly alter from the level reached previously, remaining at a level of DFT(μ)=0.34. This level was significantly lower than the level identified previously as the ESR level, DFT(μ)=0.42 (at the end of the stage 1 polishing phase).
- A series of 2 x 20 grams of Leighton Buzzard sand was then added to the sample every 10 minutes for accelerated polishing and a measured DFT(μ) result was obtained. The initial 10 minutes of polishing with the Leighton Buzzard sand produced a DFT(μ) increase of 0.20 to 0.53. The second 10 minutes resulted in a slight decrease in DFT(μ) of 0.01 to 0.52. Overall, this was a significant increase from the ESR level that was previously observed.
- The next dry-polishing phase comprised the addition of 3 x 10 grams of emery powder every 10 minutes after the Leighton Buzzard sand accelerated polishing phase was completed. A measured

DFT(μ) was not obtained until the end of the 30-minute period, which resulted in a signficant decrease in measured skid resistance to lower levels than the recorded ESR level measured at the end of stage 1. The resultant value was a measured DFT(μ) of 0.26 and a significant reduction of DFT(μ) of 0.26.

- A further 30 minutes of wet polishing with no contaminants was then undertaken. This resulted in a slight increase (which was against the commonly seen trend) in measured DFT(μ) to a level of 0.27, still lower than the original wet-polished ESR value obtained at the end of the stage 1 polishing phase.
- The full PSD of the oedometer clay was then added in 3 x 10 gram doses, with the surface being very lightly sprayed with water to keep the surface in a damp condition. The measured skid resistance level after the first 10 minutes of accelerated polishing increased to a level of DFT(μ)=0.45, which was 0.18 higher than that measured previously and also the same level as the ESR at the end of the stage 1 phase. Two further 10-minute spells of accelerated polishing with additional skid resistance measurements increased the measured DFT(μ) at a much slower rate to 0.49.
- A further 30 minutes of wet polishing, with no contaminants added, produced a characteristic decrease in measured DFT(μ) of 0.06 to 0.43.
- A repeated cycle of 2 x 20 grams of Leighton Buzzard sand for 10 minutes each with accelerated polishing produced an expected increase (as with the earlier cycle) in the measured DFT(μ) value to 0.45, but not to the same level of measured skid resistance DFT(μ) as obtained in the first cycle.
- A final 3 x 10 grams of emery powder every 10 minutes with dry accelerated polishing, produced a reduced measured DFT(μ) value of 0.37, a reduction of DFT(μ)=0.08.

Figure C.6 Otaika greywacke laboratory samples (stage 2 polishing with addition of contaminants)

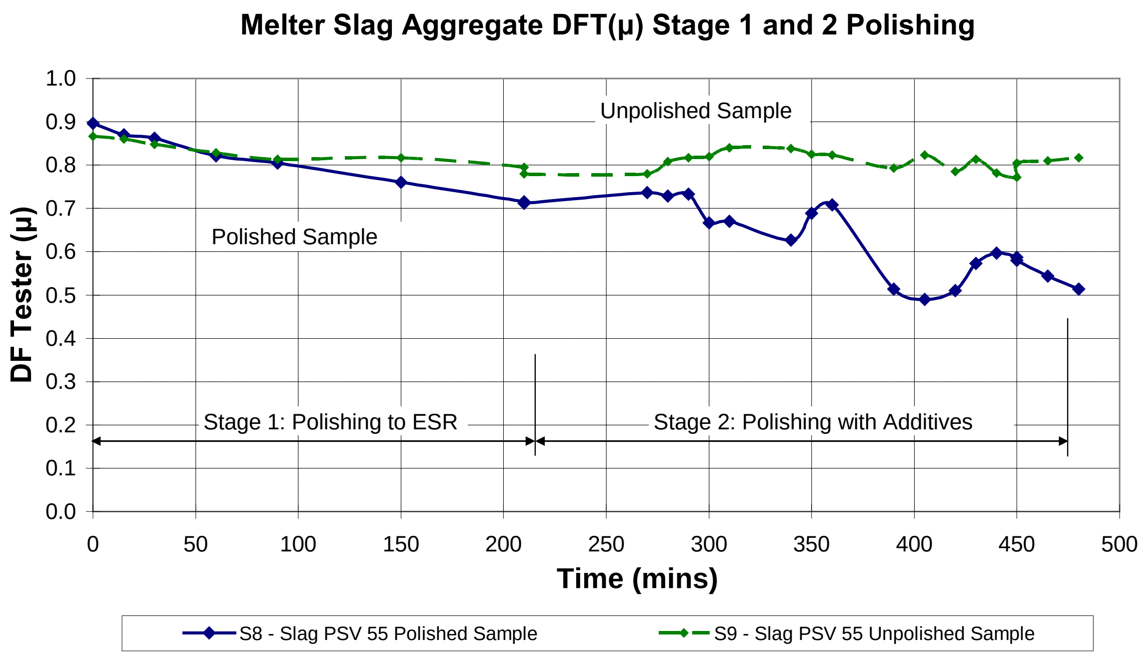


C.4 Melter slag

As discussed in section 8.3.5, the melter slag sample that was wet polished using the AAPD changed in value from a stage 1 accelerated polishing value of DFT(μ)=0.90 to an equilibrium wet-polished level of DFT(μ)=0.71. The stage 2 polishing phase included the accelerated polishing of the sample (in wet, dry and damp conditions) with the addition of oedometer clay, emery powder or Leighton Buzzard sand.

Figure C.7 shows the results of the two stages of polishing for the two melter slag laboratory samples (one with accelerated polishing and the other with no polishing). Initially, it appeared that the melter slag was performing very well, as it was retaining its high initial skid resistance measurement with the addition of contaminants and accelerated polishing. However, after the first cycle of Leighton Buzzard sand and emery powder, a trend of increasing loss of measured skid resistance began. This decreasing trend continued, increasing at a faster rate, which raises some concerns about the longevity of skid resistance of melter slag. After 10 minutes of accelerated polishing with Leighton Buzzard sand, an increase of DFT(μ)=0.08 occurred after a DFT(μ) level of approximately 0.62 had been established following 340 minutes of accelerated polishing (as shown in figure C.7). Furthermore, when emery powder was added, prior to 10 minutes of accelerated polishing, the DFT(μ) reduced by 0.22 from the peak increase (DFT(μ)=0.73) gained with the Leighton Buzzard sand.

Figure C.7 Melter slag laboratory sample (stages 1 and 2 polishing phases)

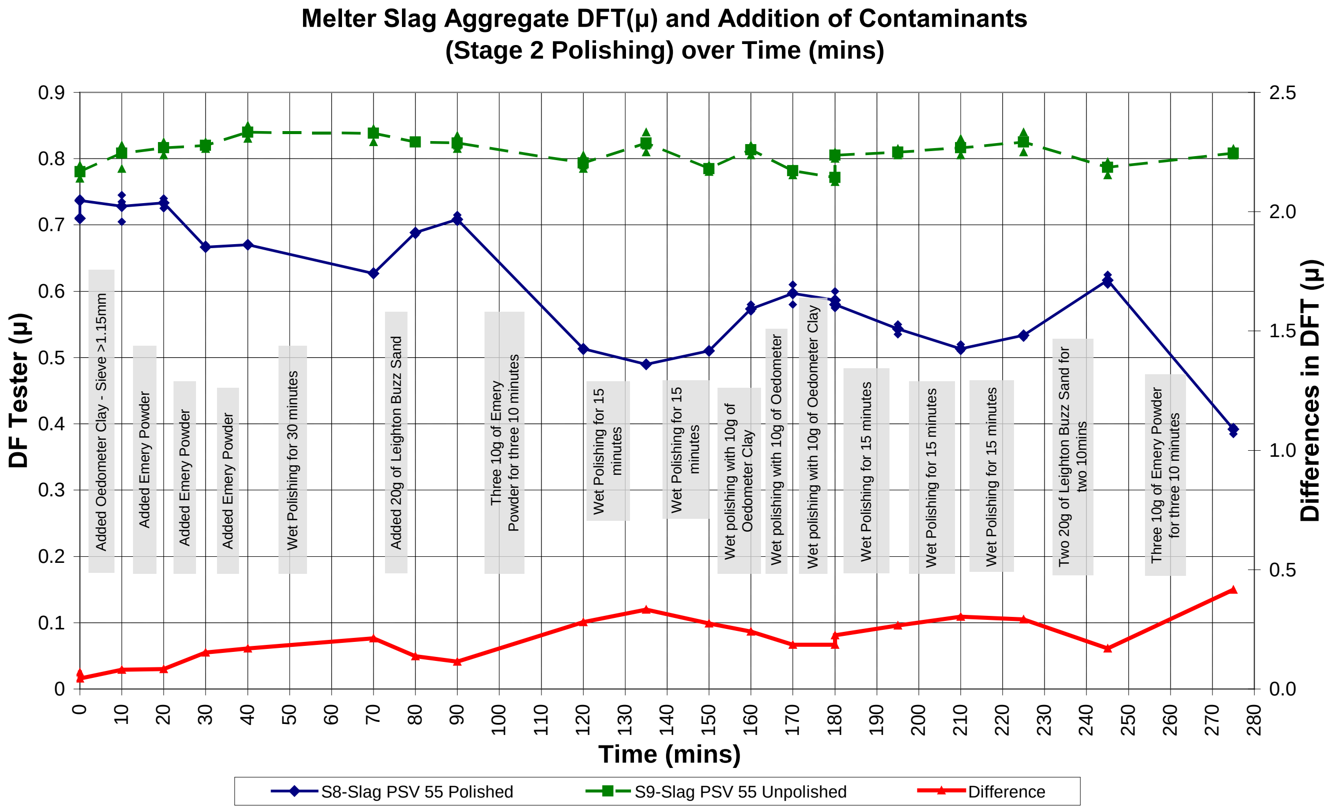


These significant variations require some explanation sequentially in terms of what additive was used, the effect of the additive in terms of the measured coefficient of friction with the DF Tester (μ), and then what may have caused the variation to occur. A diagrammatical explanation for the melter slag sample is shown in figure C.8.

A chronological explanation and its effect in terms of measured coefficient of friction from the beginning of stage 2 polishing is as follows:

- The addition of 10 grams of oedometer clay material that had been sieved and retained on a 1.15mm sieve, combined with dry accelerated polishing for 10 minutes, did not significantly alter the DFT(μ) value previously obtained by wet polishing to an ESR level of 0.74.
- The addition of an initial 3 x 10 grams of emery powder every 10 minutes of dry accelerated polishing decreased the measured DFT(μ) to 0.68.
- The polished sample was then wet polished with no additives for 30 minutes and the subsequent measured DFT(μ) decreased further to 0.63.
- The addition of a series of 2 x 20 grams of Leighton Buzzard sand to the sample every 10 minutes during accelerated polishing resulted in an increase in the measured DFT(μ) to 0.71. The initial 10 minutes of polishing with the Leighton Buzzard sand produced a DFT(μ) increase of 0.06 to 0.69; and the second 10 minutes resulted in a slight increase in DFT(μ) of 0.02 to 0.71.
- The next dry-polishing phase comprised the addition of 3 x 10 grams of emery powder every 10 minutes after the Leighton Buzzard sand accelerated polishing phase was completed. A measured DFT(μ) was not obtained until the end of the 30-minute period. This resulted in a decrease in measured skid resistance to significantly lower levels than the recorded ESR level measured at the end of stage 1. The value decreased significantly by a DFT(μ) of 0.20, resulting in a measured DFT(μ) of 0.51.
- A further 30 minutes of wet polishing with no contaminants was then undertaken, which resulted in little change in the measured DFT(μ) – it remained significantly lower than the original wet-polished ESR value obtained at the end of the stage 1 polishing phase of DFT(μ)=0.74.
- The full PSD of the oedometer clay was then added in 3 x 10 gram batches, with the surface being very lightly sprayed with water to keep the surface in a damp condition. The measured skid resistance level after the first 10 minutes of accelerated polishing increased to a level of DFT(μ)=0.58. Two further 10 minutes of accelerated polishing, with additional skid resistance measurements, did not significantly alter the measured DFT(μ) further.
- A further 30 minutes of wet polishing with no contaminants added produced a characteristic decrease in measured DFT(μ) of 0.07 to 0.51.
- A repeated cycle of 2 x 20 grams of Leighton Buzzard sand for 10 minutes each with accelerated polishing produced an expected increase (as with the earlier cycle) in the measured DFT(μ) value to 0.61, but not to the same level of measured skid resistance DFT(μ) as obtained in the first cycle.
- A final 3 x 10 grams of emery powder every 10 minutes, with dry accelerated polishing, produced a significant further reduction of DFT(μ)=0.22 in measured DFT(μ) value to 0.39.

Figure C.8 Melter slag laboratory samples (stage 2 polishing with addition of contaminants)



Glossary of terms used

AADT	average annual daily traffic volume
AAPD	Auckland Accelerated Polishing Device
AP	accelerated polishing
ASTM	American Society for Testing and Materials
AVE	average
BPN	British Pendulum Number
BPT	British Pendulum Tester
CFME	Continuous Friction Measurement Equipment
CoF	coefficient of friction
CoV	coefficient of variation
DF Tester	Dynamic Friction Tester device
DFT20	Dynamic Friction Tester CoF at 20km/h slip speed
DSF	dry-spell factor
dTIMS	Deigton's Total Infrastructure Management System
ESC	equilibrium SCRIM coefficient
ESR	equilibrium skid resistance
GN	grip number (CoF from GripTester device)
GN50	grip number at 50km/h
GT	GripTester device
HCV	heavy commercial vehicles
HMA	hot-mix asphalt
IFI	International Friction Index
LWP	left wheel path
μ	DF Tester CoF value
MPD	mean profile depth
MSSC	mean summer SCRIM coefficient
MTD	mean texture depth

NZ dTIMS	implementation of predictive modelling for road management software
NZS	New Zealand Standard
PBPT	Portable British Pendulum Tester
PSD	particle size distribution
PSMC	performance-specified maintenance contract
PSV	polished stone value
r	coefficient of correlation
R^2	coefficient of determination
RAMM	Road Assessment & Maintenance Management
RCA	road controlling authorities
ROAR	Road Analyser and Recorder machine
RWP	right wheel path
SCRIM	Sideways-force Coefficient Routine Investigation Machine
SFC	sideway force coefficient
SFC50	sideway force coefficient at 50km/hr
SN40, SN64	skid number at 40mph, skid number at 64km/h (US locked wheel tester)
SH	State Highway
TOC	total organic carbon
TPH	total petroleum hydrocarbons
vpd	vehicles per day
WRF	weighted rain function