SKID RESISTANCE : THE INFLUENCE OF ALLUVIAL AGGREGATE SIZE & SHAPE

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AN IMPORTANT NOTE FOR THE READER

The research detailed in this report was commissioned by Transit New Zealand when it had responsibility for funding roading in New Zealand. This funding is now the responsibility of Transfund New Zealand.

The material contained in this report is the output of research and should not be construed in any way as policy adopted by Transit New Zealand or Transfund New Zealand but may form the basis of future policy.

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EXECUTIVE SUMMARY

A research programme was formulated in 1996 to address skid resistance-related problems experienced in the Napier region where alluvial aggregates were found to polish in the field far quicker than expected. Both Polished Stone Values (PSV) laboratory tests and on-road investigations involving Opus Central Laboratories' GripTester and Transit New Zealand's stationary laser profilometer were carried out in 1996-97 with the specific aims of:

- improved understanding of the PSV test and its application to alluvial aggregates;
- identifying critical aggregate characteristics from the perspective of skid resistance performance;
- calibrating Transit New Zealand's stationary laser profilometer so that the speed number component of the International Friction Index (IFI) can be determined for New Zealand roads.

From the resulting research findings, the following conclusions and recommendations have been derived.

Relationship Between Polished Stone Value and Crushed Faces

The laboratory-based PSV tests identified that sealing chip processed from alluvial aggregates had a higher resistance to polishing than equivalent unprocessed material. The higher PSV of the sealing chip appears to be directly a function of the crushing process as crushed faces have significantly higher levels of grain scale microtexture (texture amplitude in the range 10-100 microns) and greater angularity (texture wavelengths in the 1-5 mm wavelength range which is a significant contributor to the hysteretic component of wet skid resistance).

Recommendations

- A stylus profilometer should be used as it allows surface profiles to be traced to a measuring accuracy of ±0.005 mm and a step length of 0.0125 mm. Accordingly, texture wavelengths down to 0.025 mm can be measured.

  Because binocular microscopy permits only qualitative assessment of changes in the aggregate surface structure related to the PSV test, such qualitative data should be supplemented by quantitative data. The time-dependent changes can then be more thoroughly investigated, leading to a better understanding of the polishing mechanism.

  A stylus profilometer has been commissioned by Auckland-based Measurement and Calibration Centre Ltd who conducted trials involving its application to sealing chip specimens that have proven successful. Therefore representative surface profile traces of the grade 4-6 PSV samples used as part of this research programme should be obtained to record and characterise changes between the crushed and uncrushed samples, and to correlate various texture measures such as third octave band spectral density, spacing between profile peaks, and profile slope to PSV.

- The polishing characteristics of aggregates in common use in New Zealand, other than greywacke, should also be investigated in a similar manner so that any differences in polishing mechanisms can be established, leading to better specification of material used in the construction of wearing courses.

The PSV Test

For both crushed and uncrushed aggregates, the length of the PSV test appears to be sufficient to allow samples to reach an equilibrium state of polish. Aggregate size was also shown to have no statistically significant effect on the PSV result. Perhaps the only question mark remaining over the PSV test concerns the consistency of the control specimens used to negate the effect of less than ideal polishing runs brought about by variations in equipment performance or inconsistency in the polishing grit.

Recommendation

- Given the importance of the control aggregate for normalising PSV, a detailed investigation of the consistency of the source and its production should be carried out. This would involve subjecting specimens made from control aggregates supplied by different Australasian PSV testing agencies to:
    (a) full petrological study to determine the degree of similarity in the structure and composition between specimens;
    (b) standard PSV testing to establish any variation in resulting PSV among the specimens;
    (c) before and after PSV test surface profile tracings made with a stylus profilometer to identify any differences in polishing behaviour that can be linked back to the petrological findings.

Skid Resistance Relationship to Seal Characteristics

The wet skid resistance of chipseal road surfaces was shown to be a function not only of the PSV of the aggregate but also of its size, shape and spacing. Therefore whenever the scope of increasing PSV in surfacing design is limited, attention should turn to optimising the surface geometry. In the case of alluvial-sourced material, small chips (i.e. grade 4 or less) are generally preferable to large chip (grade 2) as there is a smaller proportion of exposed alluvial faces.

Recommendations

- The general validity of the two skid resistance relationships derived as part of this research programme should be investigated by considering additional road test sections which cover a broad range of PSV and include hard rock quarried material in addition to alluvial-sourced material.

- An assessment of the processing characteristics of commonly used impact and gyratory crushers in use in New Zealand should be undertaken to identify those which generate significant surface texture in the 1-5 mm wavelength range. Texture in this wavelength has been shown to be a major contributor to the hysteretic component of tyre friction.

Correlation of Texture Measures

Measures of texture depth derived from laser profilometer-derived road surface profiles were compared with volumetric patch measurements to ASTM E965 (i.e. glass beads instead of sand) and outflow measurements. These measures were the mean profile depth (MPD) and root mean square (RMS).

For the range of chipseal surfaces tested, MPD correlated significantly better with mean texture depth (MTD) derived from the volumetric patch method ($R^2 = 0.92$) and reciprocal of outflow time, OT ($R^2 = 0.85$) than RMS (the corresponding R^2 values were 0.85 and 0.79 respectively).

A significant result of the outflow measurements was the identification of a limiting value of texture depth for chipseal surfaces above which no further gains in drainage ability can be had. This limiting value is 2.5 mm in terms of MPD.

Recommendations

- Profile-derived measures of surface texture depth should be specified in terms of mean profile depth (MPD) as defined by ISO Standard 13473-1 "Characterisation of Pavement Texture Utilising Surface Profiles - Part 1, Determination of Mean Profile Depth", because of strong correlations with the volumetric patch method and drainage ability of the road surface.

- The application of the outflow meter as a general field instrument for periodic testing of road surfaces, with respect to drainage ability and speed gradient of wet skid resistance, should be further investigated as a result of its low cost, ease of use, and good reproducibility.

International Friction Index (IFI)

IFI comprises two values: the wet skid resistance at a slip speed of 60 km/h (F60) and the speed number (Sp). Correct determination of Sp is important as it defines the speed-friction gradient. Unfortunately, application of IFI was found to be less than straightforward. Difficulties primarily stemmed from the selection of the volumetric patch method (ASTM E965), which is susceptible to operator influence, as the reference texture measure for calibrating Transit New Zealand's stationary laser profilometer to convert MPD values to speed number Sp. There was also a strong indication that recommended transformation coefficients used for deriving F60 are inappropriate for New Zealand chipseal road surfaces.

Recommendations

- The common skid testers in use in New Zealand use the British Pendulum Tester, GripTester and SCRIM. Accordingly, to enable reliable conversion from one skid resistance measure to another, it is recommended that either:

  (1) The survey speeds of the GripTester and SCRIM be standardised to 54 km/h and 29 km/h respectively to give a measuring wheel slip speed equivalent to that of the slider of the British Pendulum Tester, i.e. 10 km/h. The various measures of skid resistance (GN, SFC and BPN) should therefore have identical values.

or (2) Transformation coefficients required by the IFI transformation expressions be derived for local road surfaces. This would require GripTester and SCRIM skid resistance measurements, made over a range of survey speeds, to be correlated with British Pendulum Tester readings for a wide range of road surfaces and road texture depths.

Implications for TNZ M/6 Specification

Transit New Zealand's TNZ M/6 Specification for Sealing Chips (1993) incorporates PSV requirements. However, there is insufficient cognizance of the role of surface geometry with regard to amplitude, wavelength and mean slope in maximising available wet skid resistance.

Recommendation

- Additional research into defining the optimum shape of aggregates is required for incorporation in TNZ M/6 (1993). This research will also provide guidance to the aggregate industry as to how to optimise quarry production with regard to shape requirements so that sealing chips of a known PSV can be produced to meet specified skid resistance values.

ABSTRACT

This report presents the results of a research programme involving both laboratory and on-road investigations that has been carried out in 1996-97 with the aims of:

- improved understanding of the Polished Stone Value (PSV) test and its application to alluvial aggregates;
- identifying critical aggregate characteristics from the perspective of skid resistance performance;
- calibrating Transit New Zealand's stationary laser profilometer so that the speed number component of the International Friction Index (IFI) can be determined for New Zealand roads.

The experimental design utilised together with significant correlations identified between skid resistance and aggregate and surface profiles are described. The principal finding of the research was that the crushing process beneficially affects the polishing resistance of greywacke alluvial aggregates by exposing a greater degree of microtexture and also on-road skid resistance by increasing texture in the 1-5 mm wavelength range. Texture at this scale is a significant contributor to the hysteretic component of tyre rubber friction. Two predictive skid resistance models are presented, one relating skid resistance to easily measured seal characteristics, and the other to road surface profiles over 0.5 to 50 mm wavelengths. Both models were capable of explaining 75-80% of the total variation observed in the GripTester derived wet skid resistance values.

1. INTRODUCTION

The research programme detailed in this report was formulated in 1996 to address skid resistance-related problems experienced in the Napier region where alluvial aggregates were found to polish in the field far more quickly that expected. To ensure a proper level of wet skid resistance on New Zealand state highways, Transit New Zealand has incorporated polished stone values in the TNZ M/6 Specification for Sealing Chip (*Bituminous Sealing Manual*, Transit New Zealand 1993). The polished stone value (PSV) test is a measure of the resistance of aggregates to the polishing action of a tyre under conditions similar to those occurring on the road surface. The full PSV test procedure is outlined in British Standard BS 812 : 1989, and its implementation in New Zealand is covered by Bean & Pidwerbesky (1994).

Several possible explanations have been put forward as to the possible cause of the accelerated polishing of Napier alluvial aggregates, despite their ability to satisfy PSV requirements. These include:

(1) The sensitivity of the PSV test to which face of the aggregate (rounded or broken) is exposed on the polishing surface.

(2) The inadequacy of characterising pavement skid resistance by performing skid resistance measurements at only one pre-selected vehicle speed. The sideway-force coefficient (SFC) used to monitor the wet skid resistance condition of the state highway network using SCRIM (Sideways-Force Coefficient Routine Investigation Machine) surveys applies to a sliding speed of 17 km/h. This is almost double that of the British Pendulum Tester (BPT) used as part of the PSV test, yet it is known that the speed dependency of skid resistance is very much a factor of aggregate shape and spacing (Moore 1975).

Accordingly, a thorough laboratory and field measurement programme was undertaken in 1996-97 to resolve the cause of poor wet skid resistance performance of chipseal road surfaces in the Napier region.

The laboratory study involved PSV tests on crushed and uncrushed alluvial chip from a single source to determine whether or not the geometric characteristics of the exposed face of the tested aggregate and its size have a significant impact on the PSV result and on the time to reach the equilibrium value. The results from these controlled tests are presented in Section 2 of this report.

The field study concerned detailed road texture profile, GripTester skid resistance, and outflow meter drainage rate measurements of Napier sites displaying good and poor wet skid resistance, as determined by the 1995 SCRIM survey. The GripTester, operated by Opus Central Laboratories (OCL), is a trailer-based friction tester which has been shown to correlate well with both SCRIM and the British Pendulum Tester (PIARC 1995). The main component of this device is a blank rubber measurement wheel rolling on a road surface under controlled operating conditions (constant wheel load, constant slip, constant speed, and constant water film depth). It has an operating speed range from 5 km/h to 120 km/h corresponding to measurement wheel slip speeds 0.9 to 21.6 km/h respectively. Detailed road surface profiles over a 0.63 mm to 500 mm wavelength range were made with Transit New Zealand's stationary laser profilometer (Cenek et al. 1997). This enabled various derived texture measures, such as aggregate angularity and mean profile depth (MPD), to be correlated with GripTester and outflow meter results. Coarse and fine chipseal test sites were therefore utilised to contrast differences between high and low (a) texture depth, (b) % crushed faces, and (c) commercial vehicle volumes. The sensitivity of measured skid resistance to water film depth and sliding speed were additionally determined for each site so that aggregate shape characteristics significantly affecting in-field skid resistance qualities of New Zealand chipseal pavements could be identified. Section 3 details the experimental design of the field studies, and relationships between texture parameters and wet skid resistance are explored in Section 4 of this report.

The opportunity was also taken to investigate the validity of the International Friction Index (IFI) which resulted from the international PIARC experiment, to compare and harmonise texture and skid resistance measurements (PIARC 1995). Experiences gained from applying recommended IFI calibration procedures to the GripTester and Transit New Zealand's stationary laser profilometer are summarised in Section 5.

The principal conclusions and associated recommendations derived from the laboratory and field studies are presented in Section 6 of this report.

2. EVALUATION OF POLISHED STONE VALUE TEST

2.1 Background

Polishing refers to the smoothing, wearing down, or removal of the fine surface texture (or commonly called microtexture) present on individual road surfacing aggregates by traffic. Microtexture pertains to texture wavelengths less than 0.5 mm, and provides an important component of pavement skid resistance, particularly at lower vehicle speeds (less than 50 km/h). The polished stone value (PSV) is a relative measure of sealing chip resistance to the polishing action of a tyre, under conditions intended to simulate those that occur with traffic acting on a bituminous road surfacing. Prepared specimens of aggregate are polished on an accelerated polishing machine and measured for wet friction using a British Pendulum Tester (BPT). This friction value is the input to a transformation equation for obtaining PSV, which is expressed as a number and typically ranges between 40 and 60 for roading aggregates commonly used in New Zealand. Details of the test method are given in Section 2.2.1 below.

For this experiment, grades 4, 5 and 6 sealing chip produced from an alluvial source, and from equivalent sized unprocessed feedstock from the same alluvial source, were tested for PSV. Grade 4 corresponds to a maximum stone size of 13 mm, whereas grade 5 is to 10 mm and grade 6 is to 6 mm. The grade 4 samples were measured for skid resistance incrementally during testing and were subjected to additional polishing. Microtexture on unpolished and polished aggregates was investigated using a binocular microscope.

The objectives of the laboratory component of the research were:

- Compare the PSV-derived skid resistance provided by uncrushed alluvial aggregates with that provided by normally processed sealing chip that has been produced from alluvium.
- Investigate the polishing behaviour of crushed and uncrushed alluvial aggregates.
- Determine if aggregate size (i.e. macrotexture) has an effect on PSV.
- Determine if sample friction reaches a state of equilibrium during the PSV test period.

The aggregate investigated was greywacke extracted from the Ngaruroro River by Fraser Shingle Ltd, Napier. The PSV of sealing chip produced from this source ranges from the low to mid 50s. Petrographically the rock is moderately sorted, sub-angular, fine to medium sandstone with minor siltstone and rare argillite. The material is typical of other alluvial greywacke deposits derived from the axial ranges of the North Island, and from which sealing chip is produced in the Napier region. It is typical of aggregate processing operations such as Waipukurau Shingle in the Tukituki River and Knights in the Mohaka River.

2.2 PSV Tests on Napier Alluvial Aggregates

2.2.1 Description of PSV Test Method

Quarries submit a representative sample of grade 4 sealing chip to the testing agency. In New Zealand, PSV testing is performed by the Department of Civil Engineering at Canterbury University or by Fulton Hogan at their Christchurch laboratory.

Four specimens, comprising 35 to 50 stones embedded in a polyester resin mould, are created for each sample. The moulds are flat transversely, but curved longitudinally, and measure 91 mm x 45 mm. The stones are arranged with their flattest faces exposed in a single randomly placed layer with minimal voids. Specimens are clamped onto the road wheel of an accelerated polishing machine to form a continuous strip, with a 406 mm diameter, of stones. The wheel accommodates 12 test specimens and two controls. Control specimens are made using chip from a specific quarry (Criggon) in the UK with a known PSV (of 52.5). The purpose of the controls is to negate the effect of variation in equipment performance and inconsistency in procedures. Samples are tested over two runs, with one pair of specimens per run. Therefore six samples can be tested in each session.

A 200 mm diameter x 38 mm width solid rubber tyre is in contact with the surface of the specimens, and is loaded to 725 ±10 N. The wheel rotates at 320 rpm (24.5 km/h peripheral speed) and polishing is achieved through the combined action of the loaded tyre and water and emery grit which are fed into the system. Coarse grit is used for the first 3 hours and fine grit for another 3 hours. Two identical rubber tyres are used, one for each type of grit.

After polishing, the specimens are removed from the wheel, washed and immersed in water at 20 ±2°C for a period of between 30 minutes and 2 hours. The specimens are then tested for skid resistance with a BPT) on which the normal 50 mm-wide rubber slider is replaced by a 31.75 mm-wide slider. The control specimens created using stone from Criggon Quarry in the UK are used to check the slider before each set of measurements and also to condition new sliders. Test specimens are skid tested five times and the resulting skid numbers (SN), recorded to the nearest 0.1 unit, are divided by 0.587 to get PSV units. The last three readings are averaged for each specimen and the mean of these values is the raw PSV for a sample.

The final or adjusted PSV is equal to:

sample raw PSV + 52.5 – control raw PSV

2.2.2 Selection and Preparation of Samples

Samples were taken by laboratory staff of Napier office, Opus International Consultants Ltd, from stockpiles and from the Ngaruroro River source area of Fraser Shingle Ltd. Approximately 12 kg each of production grade 4, 5 and 6 sealing chip and unprocessed alluvial stock sieved to approximately grades 4, 5 and 6-sized aggregates, were dispatched to Opus Central Laboratories for the research on skid resistance detailed in this report.

The uncrushed material was sieved further, before sending samples to Canterbury University for PSV testing, as follows:

uncrushed grade 6 = all between 2.36 and 6.7 mm, and mostly between 4.75 and 5.6 mm
uncrushed grade 5 = all between 4.75 and 8 mm, and mostly between 5.6 and 6.7 mm
uncrushed grade 4 = all between 8 and 9.5 mm, and mostly between 6.7 and 9.5 mm

2.2.3 Test Procedure

For the grade 4 samples, three sets of specimens were prepared:

sealing chip only,
uncrushed aggregate only, and
a mixture of 50% crushed and 50% uncrushed material.

The specimens were skid tested immediately prior to polishing and at half hourly intervals thereafter until the equilibrium SN (Skid Number) value was reached. Equilibrium was defined as a difference of 1 SN unit between successive half hourly measurements. However, if equilibrium occurred before 6 hours, the polishing operation was to continue up to 6 hours so that a final PSV value could be obtained. A further deviation from the standard test procedure in which the samples are split into pairs and tested over two runs was that the grade 4 specimens were all included in a single run.

For comparison, standard PSV tests were carried out on specimens made up of grade 5 and 6 sealing chip and grade 5 and 6 uncrushed aggregate.

2.2.4 PSV Results

The PSV results for each sample are summarised in Table 2.1. The uncertainty of the PSV results is estimated to be ±2 units. As shown in Table 2.1, the sealing chip (crushed) has a significantly higher PSV than the uncrushed alluvial aggregate by between 6 and 14 units for the three grades investigated. The mixed grade 4 sample has a PSV which falls midway between the PSV of the constituents. This accords well with the observed crushed-uncrushed trend.

Table 2.1 PSV results for Napier alluvial aggregates.

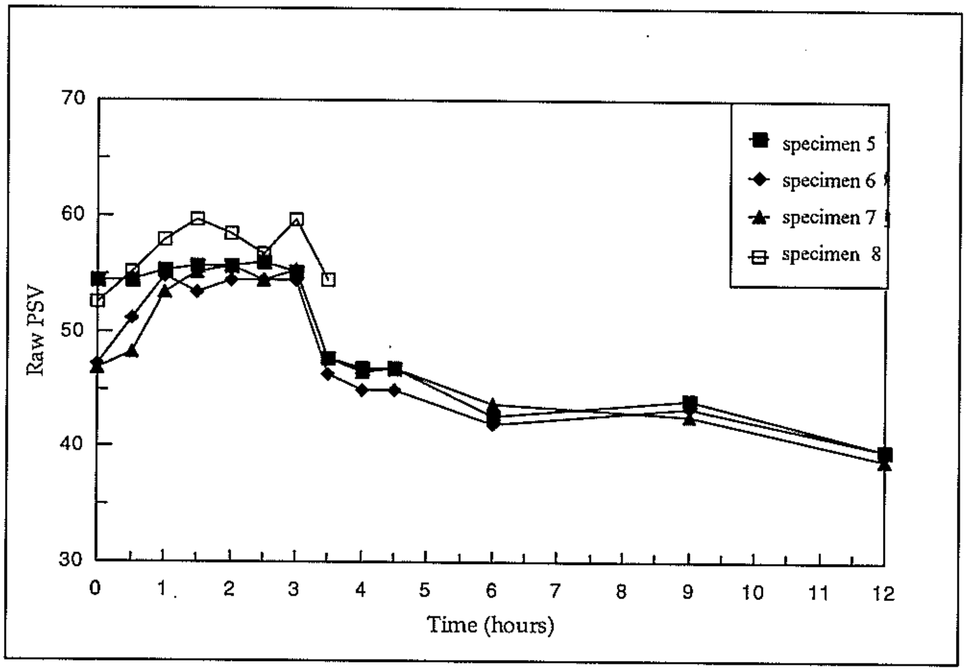
Sample	Uncrushed Measured PSV	Crushed Measured PSV
Grade 6	42.0	56.0
Grade 5	42.0	53.0
Grade 4	46.5	52.8
Grade 4, 50% uncrushed 50% crushed	49.6	

There is also a decrease in PSV with increase in aggregate size for the sealing chip grade 5 and 6 samples, but the results are not statistically significant. In contrast, the uncrushed grade 5 and 6 samples have the same PSV and the grade 4 sample has a higher value. A possible explanation for this result is presented in Section 2.4.

The specimen results of the incremental skid testing of the grade 4 samples are presented graphically in Figures 2.1, 2.2 and 2.3. Raw PSV data were graphed because the equation to derive final PSV includes a term for control stone value (PSV = 52.5) which is only valid for 6 hours of polishing. The use of raw PSV data was considered acceptable for comparing results within the sample set, particularly as the grade 4 samples were all polished in a single run.

Each of the grade 4 specimens attained ±1 SN within the first 3 hours of polishing. This may not be apparent on the graphs because 1 SN unit is equal to 1.7 raw PSV units. However, the operator continued incremental testing. All specimens exhibited a significant decrease in measured friction at 3½ hours (after the change from coarse to fine grit), and then a levelling off between 4 and 4½ hours, interpreted by the operator to be the cessation of polishing. Nevertheless, further decreases in measured friction (approximately 2 SN on average) occurred by 6 hours. Therefore the specimens were returned to Canterbury University for an additional 6 hour session of polishing with fine grit.

Figure 2.1 Raw PSV v. time, for grade 4 uncrushed sample.



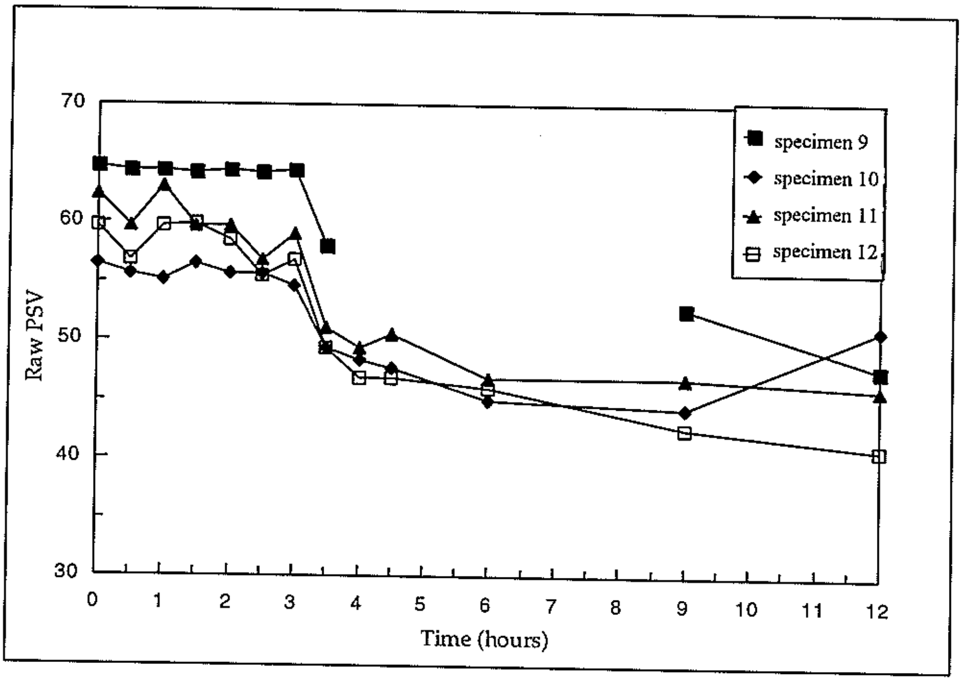


Figure 2.2 Raw PSV v. time for grade 4 mixed sample.

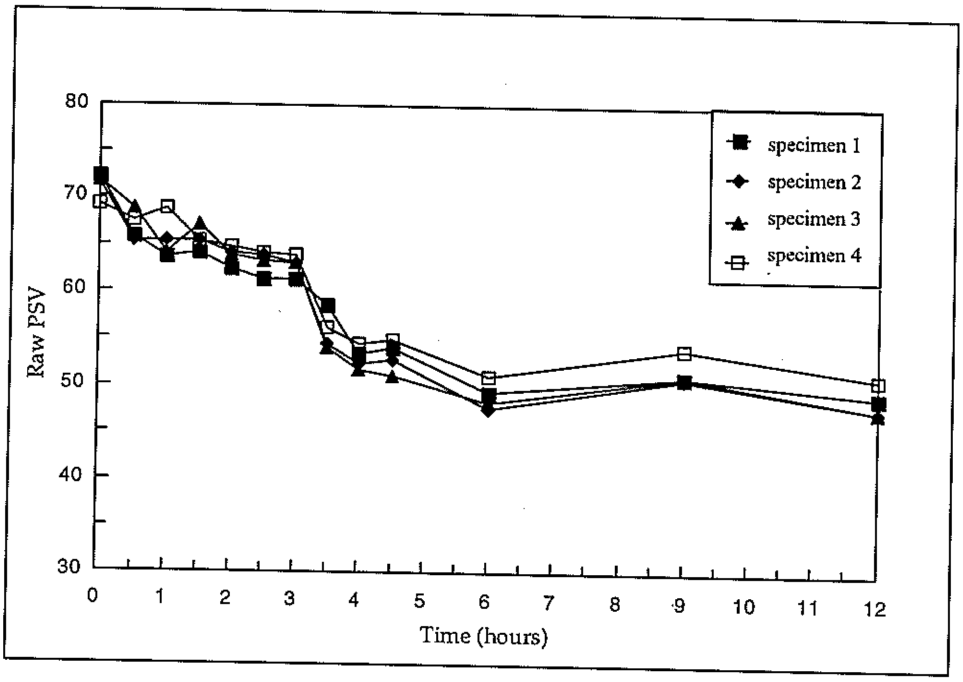


Figure 2.3 Raw PSV v. time for grade 4 crushed sample.

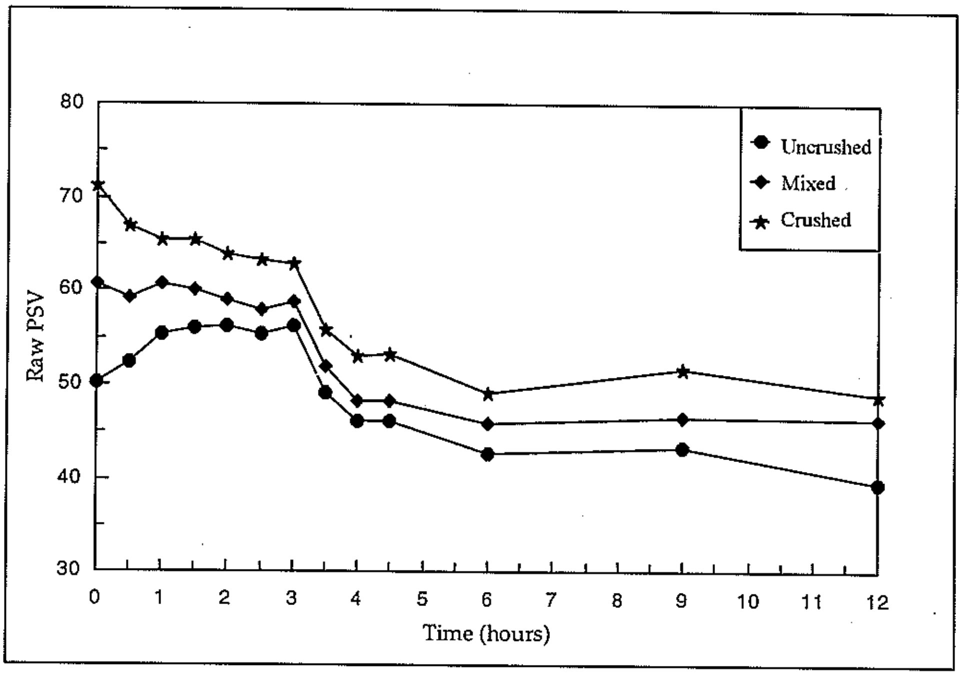
Continual removal and reattachment of the specimens to the road wheel produced stresses sufficient to cause stone loss. Only uncrushed aggregates were lost, presumably because the polyester resin did not always form an effective bond with their smooth surface.

Of the uncrushed sample, specimen 8 lost 40% of its stones and was unable to be skid tested after 3½ hours polishing. Specimen 6 lost 35% of its stones, and specimen 7 lost 12% of its stones. However, both these specimens, along with specimen 5, were able to be skid tested throughout the 12 hour period.

Of the mixed sample, specimen 9 was not skid tested after 3½ hours during the first polishing session as results were considered to be significantly affected by the loss of two uncrushed stones at the "leading edge" end of the mould (forward end with regard to the swing of the BPT). However, specimen 9 was skid tested during the second polishing session. Specimens 10 and 12 lost several stones during the second session. On specimen 10, two of the stones lost were from the central part of the mould and this may be responsible for the increase in skid numbers between 9 and 12 hours' polishing, although the loss of 13 stones (35%) from uncrushed specimen 6 during polishing did not have any noticeable adverse effect on BPT results.

The specimen averaged data for the three grade 4 samples are presented in Figure 2.4 so that the polishing behaviour of each sample can be compared and contrasted. As can be seen, the greatest differences occur during the coarse grit polishing phase which takes place over the first 3 hours.

Figure 2.4 Raw PSV v. time for specimen average data for all grade 4 samples.



The uncrushed sample increased 6 raw PSV units on average between 0 and 3 hours. Most of this increase (5.2 units) took place in the first hour. The crushed sealing chip sample decreased an average 8.4 units between 0 and 3 hours. The pattern of decrease was semi-exponential, with a reduction of 4.3 units occurring in the initial half hour. The mixed sample showed some fluctuation between 0 and 3 hours, but overall decreased an average 3.1 units.

In contrast, the grade 4 samples showed very similar polishing behaviour during the fine grit polishing (i.e. 3-6 hours). All samples, on average, exhibited a sharp decrease of approximately 7 raw PSV units between 3 and 3½ hours, and a decrease of approximately 13 units between 3 and 6 hours.

The changes in raw PSV over 6 hours of polishing can be summarised as follows:

- the uncrushed sample decreased an average 7.4 units;
- the mixed sample decreased an average 14.9 units; and
- the crushed sample decreased an average 22.1 units.

Additional polishing for 6 hours with fine grit did not produce marked changes in measured friction for the grade 4 samples. The only sample to show significant further change was the uncrushed sample which decreased another 3.3 raw PSV units on average. This gives a net reduction of 10.7 units over the whole 12 hours of polishing. The mixed sample showed an average 0.5 unit increase over this second 6 hour period, although this increase is attributable to the anomalous increase in raw PSV exhibited by specimen 10 between 9 and 12 hours. The crushed sample decreased a negligible average 0.2 units over the last 6 hours.

The PSV data used to generate Table 2.1 and Figures 2.1 to 2.4 are in Appendix 1.

2.3 Microtexture Assessment Using Binocular Microscopy

2.3.1 Methodology

Microtexture levels on unpolished and polished aggregates were analysed semi-quantitatively to assess microtexture retention and removal characteristics by observing a split of 100-150 stones from the bulk sample and the PSV specimens for each sample with a binocular microscope. The magnification range used was 7 to 45 times.

For the purposes of this assessment, microtexture was divided into three broad scales, coarse, medium and fine.

Microtexture designated as *coarse* comprises interfacial topography with wavelengths greater than 1 mm and can generally be observed by eye. Considerable diversity was observed within this scale of microtexture, with wavelengths of the micro roughness ranging from 1 to 10 mm, amplitudes from 0.2 to 3 mm, and angularity (angle of deviation from the mean facial plane) from less than 5° to 90°. The faces of the stones were found to be concave or convex, divided into sub-faces, regularly corrugated, and have superimposed sub-scales of texture or contain sharp points, escarpments or pits.

In performing the assessment, coarse microtexture asperities and depressions were described in terms of texture depth (i.e. amplitude), wavelength and profile (i.e. angularity). The texture depth and wavelength data was based on measurements performed on approximately 20% of stones and comparative estimation of the remainder. Because ruler measurements of texture depth at this microtexture scale were difficult to make, estimates were semi-quantified by measuring the distance from the zenith of asperities or the bottom of depressions to a point approximating the mean facial plane, judging the profile angle, and using trigonometry to calculate the height or depth. Texture depth of the coarse microtexture scale refers to the amplitude of intraface features that have wavelengths greater than 1 mm and not generally to basic facial curvature. However, coarse microtexture amplitude also refers to the maximum texture depth present which usually coincides with the longest wavelength features. These are often face-scale depressions that result in the edges of faces forming asperities and are sometimes face-scale asperities. Coarse microtexture profiles were estimated and characterised using descriptors such as broad (approximately 5° deviation from the mean facial plane), low (approximately 15°), moderate (approximately 30°) and sharp (approximately (45° and greater).

Microtexture designated as *medium* pertains to the individual sand grains that make up the rock and by multi-granular features with wavelengths less than 1 mm. The textural wavelength range covered by this level of microtexture is 0.05 mm to 1 mm.

Medium microtexture was assessed in terms of the asperities' amplitude to wavelength ratio and their density. Descriptors of medium microtexture were principally related to this ratio as follows:

- good (amplitude to wavelengths ratio about 1),
- moderate (0.5),
- poor (0.2), or
- absent.

For polished samples, medium microtexture data pertains to the "effective contact area" which is the exposed face area affected by polishing and considered to have been sampled by the BPT as part of the PSV test.

Microtexture designated as *fine* comprises sub-grain and matrix features, argillite grains and most of the siltstone grains. It refers to texture wavelengths less than 0.05 mm and so is difficult to examine, even at 45 times magnification. However, an indication of the removal of finest textural features can be gauged from light reflectance as the polished surface becomes shiny.

2.3.2 Binocular Microscopy Results

Detailed microtexture assessment of the PSV samples are in Appendix 1. A regular trend identified for all the samples was that proportions of coarse microtexture of a particular amplitude are consistent for unpolished and polished states. However, levels of medium microtexture decrease considerably during polishing. Correlations between the microtexture analysis and the PSV results are explored below.

2.4 Discussion

2.4.1 Correlation of Microtexture Analysis with PSV Results

In evaluating the effect that microtexture has on the PSV of the samples investigated, two basic questions are considered:

(1) What causes the decrease in measured skid resistance during polishing?

(2) Why does crushed aggregate have higher PSV than uncrushed aggregate?

Answering the first question involves comparison of the microtexture on unpolished and polished stones for each sample. Coarse microtexture does not show significant wear. However, levels of medium microtexture decrease considerably during polishing. To aid quantification of the change in medium microtexture, a factor can be evaluated by assigning an index to the ratio descriptors used to classify medium microtexture, multiplying the ratio percentage by this index and summing the results. The indices used are listed in Table 2.2. They are based on the amplitude to wavelength ratio of asperities in accordance with the medium microtexture descriptors detailed in Section 2.3.1 of this report.

Medium microtexture factors calculated from the results presented in Appendix 1, Sections A1.2.1 to A1.2.7, are listed in Table 2.3. The average decreases in this factor between the unpolished and polished state are 7.5 for the uncrushed samples and 32.5 for the crushed samples. The greater reduction in the factor for the crushed sample correlates with the greater decrease in measured skid resistance shown by the crushed grade 4 sample compared to the uncrushed grade 4 sample.

Table 2.2 Weightings given to medium microtexture descriptors.

Descriptor	Index
Absent	0.0
Absent to poor	0.1
Poor	0.2
Poor to moderate	0.35
Moderate	0.5
Moderate to good	0.75
Good	1.0

Table 2.3 Calculated medium microtexture factors for PSV samples.

Sample	**State of polishing**	**Medium micro-texture factor**
Grade 6, uncrushed	Unpolished Polished	25.5 13.75
Grade 6, crushed	Unpolished Polished	55.5 27.0
Grade 5, uncrushed	Unpolished Polished	19.85 13.75
Grade 5, crushed	Unpolished Polished	59.5 26.5
Grade 4, uncrushed	Unpolished Polished	21.75 17.25
Grade 4, mixed	Polished	20.5
Grade 4, crushed	Unpolished Polished	63.0 27.0

To answer the second question posed above, initial and polished microtexture must be compared for the uncrushed and crushed samples. As all samples are from the same source, the influence of petrological features on polishing rates should be minimal. Medium microtexture, which comprises the individual sand grains making up the greywacke, should be polished at the same rate for all samples. From analysis of the medium microtexture results it can be inferred that:

(a) For uncrushed samples,
- good initial medium microtexture is worn down to poor to moderate medium microtexture,
- moderate initial medium microtexture is worn down to poor medium microtexture, and
- proportions of absent to poor and absent medium microtexture are increased at the expense of poor initial medium microtexture.

(b) For crushed samples,
- good initial medium microtexture is worn down to moderate medium microtexture,
- moderate initial medium microtexture is worn down to poor medium microtexture, and
- poor medium microtexture is worn down to absent to poor medium microtexture.

Polishing rates for uncrushed and crushed aggregates are therefore essentially the same. This would suggest that, because levels of initial medium microtexture are higher on crushed compared to uncrushed aggregates, the levels of medium microtexture in the polished state will also be higher. Although this is true, the decrease in crushed grade 4 medium microtexture was much greater than the decrease in uncrushed grade 4 medium microtexture. In terms of medium microtexture factor, the difference is 4.5 for the uncrushed sample and 36 for the crushed sample.

It is important to distinguish polishing rate and polishing behaviour. While the rate of physical reduction of rock material during polishing is the same regardless of whether aggregates from an alluvial source have been produced by crushing or not, the microtexture initially present on sealing chip is greater than that of unprocessed aggregate, and this affects the pattern of frictional response during polishing.

Figure 2.4 shows that polishing rates and behaviour are very similar for the different grade 4 samples during fine grit polishing (3-6 hours). The greater decrease in measured friction over the PSV test period shown by the crushed samples is a function of polishing behaviour during coarse grit polishing, which is in turn a function of initial medium microtexture. The reduction in crushed grade 4 friction during coarse grit polishing is considered to reflect the removal of good medium microtexture. The increase in uncrushed grade 4 friction during coarse grit polishing obviously reflects an increase in the level of medium microtexture. It can be surmised that the influence of medium microtexture on skid resistance is proportional to the amplitude to wavelength ratio of asperities (i.e. good levels of medium microtexture have a greater influence than moderate levels).

Analysis of polished specimen coarse microtexture results show that 40-45% of exposed faces on the uncrushed samples are coarse microtexture-absent. By comparison, 5-10% of exposed faces on the crushed samples are coarse microtexture-absent. Consequently the proportion of each coarse microtexture depth category are greater on the crushed aggregates (e.g. grade 5 uncrushed polished has 10% of exposed faces with >1 mm amplitude coarse microtexture, whereas grade 5 crushed polished has 50% of exposed faces with >1 mm amplitude coarse microtexture). Furthermore, the maximum coarse microtexture amplitude is greater on crushed aggregates. This is significant given that the highest coarse microtexture asperities are commonly also the sharpest and most steeply profiled.

In conclusion, the higher PSV of crushed aggregates when compared with uncrushed aggregates can be attributed to higher levels of initial medium microtexture and greater proportions of coarse microtexture. However, the relative contribution of these scales of microtexture is unknown, and the role of effective contact area (ECA) is also difficult to evaluate. Dravitzki et al. (1997) consider that greater slider contact area probably increases friction. This has been derived from a result where test panels comprising hand-placed grade 2 chip yielded a higher skid number (SN) than equivalent panels with random chip placement. Hand placing enabled greater control of the orientation of the sealing chips so that a more uniform height surface results, thereby maximising contact with the BPT slider. In contrast, a study by Won & Fu

(1996) showed that BPT frictional energy loss is independent of the contact area of skid-tested samples.

The results of this present study offer few clues for resolving this issue since the uncrushed samples had ECAs of 70-80%, whereas the crushed samples had ECAs of approximately 30%. ECA itself is inferred to have a much smaller effect on wet friction than the actual microtexture present within the ECA. An alternative conclusion is that the relationship between ECA and wet friction is negative, i.e. a reduction in ECA increases wet friction. This is not considered plausible. In fact, a smaller ECA should result in more concentrated polishing leading to reduced wet friction.

On the crushed samples, the effect of concentrated medium microtexture polishing on the coarse microtexture asperity tips was countered by the overall level of surface unevenness. The variation in elevation appeared to offset the polishing process, creating areas where the medium microtexture was only marginally affected. Crushing provides microtexture that is continuous in scale, including coarse medium microtexture asperities composed of several grains. Where single grain medium microtexture is worn, multi-grain medium microtexture is often retained.

2.4.2 PSV Test Procedure

The rate of polishing becomes asymptotic within the standard PSV test period (i.e. 6 hours) and no significant change occurs after this time. The small increase in skid resistance at 9 hours is likely to relate to that particular skid testing session and reflect the fact that the additional polishing was a separate test done at a later time. Given the obvious reduction in skid resistance that occurs during fine grit polishing, it is considered unlikely that the samples actually roughened up between 6 and 9 hours. The trend is very similar to that shown between 4 and 4½ hours, which is considered to reflect a procedural effect rather than recording genuine variation in microtexture.

The congruity of skid number results for each specimen (Appendix 1) suggests that the skid testing procedure is acceptable.

PSVs are values that have been normalised to the theoretical control stone value. The main purpose of the control is to negate equipment and material effects. If the measured control value is below 52.5 then the polishing run has been more vigorous than it ideally should have been, and by adding 52.5 and subtracting the lower measured control value, sample values are raised. Given the critical role that the control has in ascribing PSV, it is important that the control material is consistent and this is a matter that perhaps deserves some enquiry or confirmation from the testing agencies.

2.4.3 Effect of Macrotexture on PSV

Although there is a trend within the crushed sample set of increasing PSV with decreasing aggregate size (increasing chip grade size), the only statistically significant result is the small increase in PSV between the uncrushed grade 5 and 4 samples. The sample PSV trends, however, correlate more strongly with the medium microtexture factor described in Section 2.4.1, although the degree of correlation is better for the uncrushed samples, as shown in Table 2.4.

An investigation of BPT repeatability and reproducibility and the influence of aggregate parameters on measured skid numbers has been undertaken by Dravitzki et al. (1997). The results of this investigation show that skid numbers of chipseal surfaces have no consistent and rarely any discernible relationship with chip size. However, repeatability of the SN measure decreases with increasing chip size (i.e. decreasing chip grade). As part of this investigation, a statistical regression of texture parameters was carried out in an attempt to derive relationships that would allow prediction of SN. For the relationships giving the highest degree of correlation between visually assessed texture data and measured skid number, the contribution of macrotexture parameters was small or non-existent, whereas the contribution of microtexture parameters was comparatively large. The observed lack of correlation between aggregate size and PSV is therefore not unexpected.

Table 2.4 Relationships between chip grade of sample, PSV and medium microtexture factor.

Sample	PSV	Medium microtexture factor (polished sample)
Grade 6, uncrushed	42	13.75
Grade 5, uncrushed	42	13.75
Grade 4, uncrushed	46.5	17.25
Grade 6, crushed	56	27.0
Grade 5, crushed	53	26.5
Grade 4, crushed	52.8	27.0

SN values obtained with the BPT are assumed to be closely related to microtexture, because at low slip speeds there is no problem with water drainage at the rubber slider-road interface (Sandberg 1990a). This drainage is mainly related to the macrotexture of the road surface where macrotexture is defined as texture that has wavelengths in the same order of size as tyre tread elements at the tyre/road interface. Therefore SN values are expected to only correlate well with SCRIM and GripTester values of wet skid resistance obtained at slow survey speeds. Sandberg's work showed that SN values correspond best to SCRIM sideway–force coefficient (SFC) values taken at survey speeds between 10 and 30 km/h. It also showed that SN values have a trend to become correlated with texture at short wavelengths (2-5 mm). This finding is consistent with the observed differences in PSV between crushed and uncrushed samples as the crushing process generates surface irregularities over the critical 2-5 mm wavelength range.

For sealing chip produced from alluvial material, a relationship between skid resistance and chip size is likely. This is because a small grade of chip produced from raw material of a particular size will have fewer exposed alluvial faces than a larger grade of chip produced from the same material. Although the grades 4, 5 and 6 chip assessed in this laboratory study had similar proportions of alluvial faces, the evaluation of 85 road sections, located in the Napier region, to find sites suitable for the field study component of this research programme (Section 3 of this report) identified a definite relationship between chip grade and the proportion of alluvial faces exposed in the seal, as shown in Table 2.5.

A higher proportion of exposed alluvial faces in a seal should therefore result in a lower wet skid resistance given that uncrushed alluvial aggregate has significantly lower PSV than sealing chip produced from the same source. The field study undertaken enabled this premise to be tested (Section 4 of this report).

Table 2.5 Relationship between chip size and exposed (rounded) alluvial faces of samples from Napier region.

Grade of sealing chip	Degree of exposed alluvial faces	
	Observed range (%)	Mean value (%)
2	5 to 75	24
3	5 to 30	17
5	5 to 30	12

3. FIELD STUDY EXPERIMENTAL DESIGN

3.1 General Requirements

The principal objective of the field study was to assess the sensitivity of the wet skid resistance of chipseal road surfaces, constructed from alluvial aggregates, to sliding speed, water film thickness, aggregate and texture characteristics, and heavy commercial vehicle (HCV) trafficking. Test surface selection is crucial for the outcome of an experiment such as this so that significant correlations are not masked by variances related to random measurement errors. This necessitates the investigated factors to have as wide a range as possible.

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

1. Chipseal size
   (a) coarse, i.e. grade 2
   (b) medium, i.e. grade 3 or 4
   (c) fine, i.e. grade 5 or 6
2. Percent crushed faces
   (a) low, i.e. 90%
   (b) high, i.e. 98-99%
3. Annual average daily heavy commercial vehicle volumes ($AADT_{HCV}$)
   (a) low, i.e. $AADT_{HCV} < 200$ vehicles/lane/day
   (b) high, i.e. $AADT_{HCV} > 500$ vehicles/lane/day
4. Pavement age
   (a) 2-4 years, i.e. relatively new
   (b) 4-6 years, i.e. relatively old.

The four critical factors and their associated sub-categories gave 24 possible combinations, resulting in the need for 24 test sites. Additional requirements were imposed on the site selection to minimise the possible effects of other unwanted factors. These comprised:

(a) close proximity of the test sites so that they experience very similar environmental conditions;

(b) absence of any unusual features such as adverse or excessive camber, poor drainage, etc.;

(c) absence of excessive repairs;

(d) a minimum surfacing age of about one year so that the wet skid resistance of the surfacing has sufficient time to settle to a constant value.

3.2 Selection of Test Sites

To select test sites that conformed to each of the combinations identified in the experimental design, a site category matrix containing 12 elements was devised (Table 3.1). Roading staff from Opus International Consultants, Napier office, utilised Transit New Zealand's RAMM* database to search for straight, level, road sections of at least 200 m length with nominally equivalent NAASRA* roughness counts that fall into each of the matrix's 12 categories. The search was performed for *SH50 and SH2 between Nuhaka and Takapau. SH5 and SH38 were not considered because of their winding and hilly nature.

HCV* figures were derived from AADT* and percentage HCV data. The high and low HCV criteria were assigned as greater than 500 and less than 200 respectively. A lack of 2-4 year old sites with low HCV meant that the seal age criterion for categories 1, 2 and 3 was extended to 1 to 4 years. Category 4 was empty after the first search and category 10 had only two road sections. Consequently the seal age criteria for these grade 2 categories was extended to 4 to 10 years.

Records of sealing works were accessed with the intention of using figures of percentage greater than 70% crushed faces to identify road sections within each category having a high or a low degree of crushed faces. (This % is an additional Transit New Zealand M/6:1993 criterion for sealing chips.) However, the set of such records for the candidate road sections selected by the search was largely incomplete. Therefore a visual inspection of the candidate road sections had to be carried out. Of the 115 candidate test sites, 85 were visited and the proportions of exposed rounded faces in the seal were estimated. This exercise enabled additional assessment of site suitability in terms of road geometry and seal condition (degree of repairs). The road sections with the highest and lowest percentages of crushed faces in each category were selected as the 24 field test sites. Full details of these road sections are listed in Table 3.2, and photographs of their surfaces are provided in Appendix 2.

Table 3.1. Test site selection matrix.

Chip grade	**$AADT_{HCV} < 200$**		**$AADT_{HCV} > 500$**	
	Seal Age			
	2-4 years	**4-6 years**	**2-4 years**	**4-6 years**
2	(1)	(4)	(7)	(10)
3-4	(2)	(5)	(8)	(11)
5-6	(3)	(6)	(9)	(12)

Figures in parentheses pertain to matrix category number.

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* RAMM - Road Asset Maintenance Management;
NAASRA - National Association of Australian State Road Authorities;
SH - State Highway; HCV - Heavy Commercial Vehicle;
AADT - Annual Average Daily Traffic

3.3 Test Site Analysis Using SCRIM Data

On the advice of Dr Robert Davies, a consulting statistician appointed to this project, a preliminary regression analysis was performed in order to identify the existence of relationships between road characteristics and wet skid resistance, which had been measured as part of the 1995 SCRIM survey of New Zealand state highways. A successful outcome would confirm that the experimental design, as detailed in Section 3.1, is appropriate for the intended purpose and that the number of sites selected is sufficient to yield statistically significant results.

Accordingly SCRIM data were obtained for the 24 sites listed in Table 3.2. These data comprised SCRIM sideway-force coefficient data corrected to a speed of 50 km/h (SFC_{50}), New Zealand Mean Summer SCRIM Coefficient (NZMSSC), and simulated mean texture depth (SMTD) derived from laser-based measurement of road profile elevations at 3.5 mm intervals. The NZMSSC is the SFC_{50} value adjusted to take into account seasonal variations.

Table 3.2 Details of test sites.

Site ID no.	**SH No.**	**Location in terms of RS/RP**	**PSV**	**Surfacing age (yr)**	**$AADT_{HCV}$**	**Chip grade**	**Estimated % crushed faces**	**Selection matrix category no.**
16	2	592/2.9-3.1	55	1.6	229	2	70	1
20	2	516/6.7-6.9	55	1.6	208	2	90	1
22	2	533/2.42-2.62	55	3.5	215	3	85	2
18	2	516/0.8-1.0	55	2.8	203	3	95	2
2	50	33/8.24-8.46	53	3.5	75	5	85	3
3	50	33/5.5-5.7	53	2.5	84	5	90	3
21	2	516/9.9-10.1	55	7.0	210	2	65	4
17	2	497/8.26-8.46	55	8.0	209	2	80	4
23	2	533/7.6-7.8	55	4.6	196	3	77	5
19	2	516/3.2-3.4	55	4.5	207	3	92	5
1	50	49/3.0-3.2	55	4.5	65	5	75	6
15	2	592/13.2-13.4	55	4.5	242	5	95	6
12	2	743/2.7-2.9	55	1.8	509	2	87	7
24	2	743/1.17-1.37	55	1.8	509	2	90	7
5	2	661/1.6-1.4	55	2.5	641	3	80	8
13	2	675/10.5-10.7	55	3.6	768	4	87	8
10	2	691/9.6-9.4	55	3.6	692	5	70	9
14	2	707/7.82-8.02	55	2.8	740	5	90	9
9	2	691/7.66-7.46	55	7.0	691	2	25	10
4	2	675/7.8-8.0	55	8.0	746	2	50	10
8	2	691/0.85-1.05	55	4.4	701	3	72	11
11	2	743/7.0-7.2	55	4.5	540	3	92	11
7	2	675/14.78-14.98	55	4.7	730	5	75	12
6	2	661/5.54-5.74	54	5.6	557	5	90	12

Order of listing is by matrix category number with low before high % crushed faces.

Measurements were retrieved for the left and right side of the selected road sections in the left and right wheel paths. The SCRIM-derived skid resistance and texture data were averaged to give one value per site, and analysed to determine its sensitivity to the following four predictor variables:

- seal age
- annual average daily commercial vehicle volumes
- chip grade
- % crushed faces.

The results of this analysis are summarised in Sections 3.3.1 - 3.3.4.

3.3.1 SCRIM SFC_{50} Values

The overall average SFC_{50} (sideway–force coefficient at 50 km/h) value for the selected sites is 0.44. The effects of changes in the predictor variables to a 95% confidence interval on this average value are presented in Table 3.3. The general size of the effect and tolerances in the last column of the table show that a variable is statistically significant when the range of values does not cross zero. This means that changes in the variable will change the overall SFC_{50} value. From Table 3.3, surface age and $AADT_{HCV}$ are the only statistically significant variables.

Table 3.3 SCRIM SFC_{50} sensitivity.

Variable	Sub-category	Change in average SFC_{50} value of 0.44	Size effect of variable on average SFC_{50}
Surface age	New Old	0.022 ±0.012 –0.022 ±0.012	0.044 ±0.024, i.e. 0.020 and 0.068
$AADT_{HCV}$	Low High	0.016 ±0.012 –0.016 ±0.012	0.032 ±0.024, i.e. 0.008 and 0.056
Chip grade	2 3 5	0.001 ±0.016 0.005 ±0.015 –0.006 ±0.016	0.011 ±0.048, i.e. –0.037 and 0.059
% crushed faces	Low High	–0.003 ±0.012 0.003 ±0.012	0.006 ±0.024, i.e. –0.018 and 0.030

3.3.2 NZMSSC Values

The overall average NZMSSC (NZ Mean Summer SCRIM Coefficient) value is 0.47. In Table 3.4, the significant variable for NZMSSC is age.

Table 3.4 NZMSSC sensitivity.

Variable	Sub-category	Change in average NZMSSC value of 0.47	Size effect of variable on NZMSSC
Surface age	New Old	0.024 ±0.012 –0.024 ±0.012	0.048 ±0.024, i.e. 0.024 and 0.072
$AADT_{HCV}$	Low High	0.011 ±0.012 –0.011 ±0.012	0.022 ±0.024, i.e. –0.002 and 0.046
Chip grade	2 3 5	–0.005 ±0.017 0.003 ±0.016 0.001 ±0.017	0.008 ±0.050, i.e. –0.042 and 0.058
% crushed faces	Low High	0.001 ±0.012 –0.001 ±0.012	0.002 ±0.024, i.e. –0.022 and 0.026

3.3.3 SMTD Values

The overall average SMTD (Simulated Mean Texture Depth) value is 1.32 mm. In Table 3.5, the significant variables are age and chip grade, as expected.

Table 3.5 SMTD sensitivity.

Variable	Sub-category	Change in average SMTD value of 1.32 mm	Size effect of variable on SMTD
Surface age	New Old	0.18 ±0.10 –0.18 ±0.10	0.36 ±0.20, i.e. 0.16 and 0.56
$AADT_{HCV}$	Low High	0.07 ±0.10 –0.07 ±0.10	0.14 ±0.20, i.e. –0.06 and 0.34
Chip grade	2 3 5	0.44 ±0.14 –0.04 ±0.13 –0.40 ±0.14	0.84 ±0.31, i.e. 0.53 and 1.15
% crushed faces	Low High	–0.01 ±0.10 0.01 ±0.10	0.02 ±0.20, i.e. –0.18 and 0.22

3.3.4 Concluding Remarks

The above analysis suggests that the experiment is barely sufficiently sensitive with 24 test sites, given that differences in SCRIM SFC_{50} readings of greater than 0.05 are considered significant. Another encouraging aspect is that the detected sensitivities, such as increasing skid resistance with increasing % crushed faces and decreasing macrotexture with decreasing age, all appear intuitively correct and, in general, agree with previous skid resistance research performed in the UK (Salt 1977). This analysis therefore gave confidence that significant correlations between skid resistance and aggregate and surface profile characteristics will be identified as part of the field study, leading to more rational surfacing design procedures.

3.4 Site Measurements

Skid resistance measurements at each of the 24 sites were made with Opus Central Laboratories' GripTester at a range of survey speeds and water film thicknesses so that surface friction sensitivity to slip speed and water depth could be determined. These measurements were made in both left and right wheel paths in the left and right lanes. Table 3.6 gives the notation used to identify Grip Number values of skid resistance measured at different speeds and water film thicknesses. The normal operating condition of the GripTester on New Zealand chipseal surfaces is a survey speed of 50 km/h corresponding to a slip speed of the measuring wheel of 9 km/h and a water film thickness of 0.5 mm.

One of the most significant performance characteristics of road surfaces is the gradient or slope of skid resistance versus velocity. Although the variation of friction with speed is generally complex, experience indicates that the coefficient of friction for a pneumatic tyre sliding on a wet road surface decreases with increase of speed over a very wide speed range. Furthermore, this decrease is almost uniquely a function of the macrotexture of the road itself, and depends only to a minor extent on tyre tread pattern (Moore 1975). The role of decay of the frictional coefficient is a function primarily of drainage ability in removing surface water from the tyre/road contact patch, combined with lesser contributions from adhesion and hysteresis factors. Accordingly, special care was taken to fully characterise the macrotexture characteristics of the test sites. This involved:

1. Texture profile measurements over 0.63 mm to 500 mm wavelengths made with Transit New Zealand's stationary laser profilometer. These measurements allowed correlations with texture wavelengths as well as standard measures of texture such as mean profile depth (MPD), estimated texture depth (ETD) and Root Mean Square (RMS). Definitions of these terms are in Cenek et al. (1997).

2. Volumetric patch method according to ASTM E965 (ASTM 1987). This method involves taking a known volume of glass spheres and spreading them out in a circle on the surface of the road. Measuring the diameter gives the area of the circle and then dividing the volume by the area gives the mean texture depth (MTD). In relation to the volumetric patch method, the sand circle test in common use in New Zealand "over-estimates" texture by about 0.3 mm on smooth surfaces (Sandberg 1990a).

3. Outflow measurements. The outflow is a test using a clear cylinder marked for a known volume and fitted with a rubber annulus seal between the cylinder and the pavement. The cylinder is filled with water and the time for the known volume to flow out is measured in seconds. An electronic timer is used to measure the time for the water level to fall between two electrodes suspended in the cylinder. The inverse of the number of seconds is a measure of road surface texture since it is texture that determines the water flow rate. The theory behind the outflow meter and calibration procedures can be found in Moore (1966).

The outflow meter used in the field study measured a water volume of 0.4054 dm^3 (52.35 mm water height drop by 99.3 mm diameter), giving an outflow time of 0.14 seconds under free draining conditions.

Use of the volumetric patch method and the GripTester allowed both the skid resistance and macrotexture measurements to be related to the findings of the international PIARC experiment undertaken to compare and harmonise texture and skid resistance measurements (PIARC 1995).

Table 3.6 Measured Grip Number (GN) combinations for survey speed (km/h) and water film thickness (mm).

Survey speed (km/h)	**Measuring wheel slip speed (km/h)**	**Applied water film thickness (mm)**					
		Dry 0.00	**0.05**	**0.1**	**0.2**	**0.5**	**0.8**
40	7.4	-	-	-	-	GN40/0.50	-
50	9.25	GN50/0.00	GN50/0.05	GN50/0.10	GN50/0.20	GN50/0.50	GN50/0.80
60	11.1	-	-	-	-	GN60/0.50	-
80	14.8	-	-	-	-	GN80/0.50	-
100	18.5	-	-	-	-	GN100/0.50	-

4. ANALYSIS OF FIELD STUDY MEASUREMENTS

Average texture and skid resistance readings obtained for the 24 test sites are tabulated in Appendix 3 for reference. The measured range of texture, as determined by the volumetric patch method, ranged from 1.54 mm to 3.70 mm, whereas skid resistance, expressed in terms of Grip Number, ranged from 0.46 to 0.72. Sections 4.1-4.2 consider relationships between the various measured parameters, tabulated in Appendix 3, and traffic and surfacing characteristics of each site.

4.1 Correlation of Recognised Texture Measures

In the three dimensional case, the term "texture depth" means the average distance, within a certain surface area in the same order of size as the tyre/road interface, between the surface and a plane through the top of the three highest particles "well spaced" within the surface area. The common measures of texture depth are:

1. Mean texture depth (MTD). In the application of the volumetric patch method, MTD is determined by the contact between a rubber pad and the surface when the pad is rubbed over the surface.
2. Mean profile depth (MPD). In the two dimensional case, MPD means the average difference, within a certain longitudinal distance in the same order of size as that of the tyre/road interface, between the profile and a line through the top of the highest particle within the profile sample considered.
3. Estimated texture depth (ETD). Estimation of ETD from MPD by means of a linear transformation equation, i.e. ETD (mm) = 0.8 MPD (mm) + 0.2.
4. Root mean square (RMS). Quadratic mean of the texture profile over a certain longitudinal distance in the same order of size as that of the tyre/road interface.
5. Inverse of time for the water level in an outflow meter to fall through a specified height (OT).

As a result of the international PIARC experiment to compare and harmonise texture and skid resistance measurements, there is a clear preference for profilometer-derived texture depth measurements to be reported in terms of MPD. This measure has been standardised by the International Standards Organisation (ISO) and the associated documentation has been published (ISO 1997). Therefore, site average MPD values were regressed against the other measures of site average texture to obtain coefficient of determination (R^2) estimates. These are summarised in Table 4.1, and associated regression plots and linear regression equations are given in Figures 4.1 to 4.4. Apart from outflow times, strong linear correlations were observed.

With regard to Figure 4.4, outflow times appear to plateau once a MPD value of 2.5 mm is reached. This result suggests, for chipseal surfaces, drainage ability is a direct function of texture depth up to a critical value. However, no further gains in drainage ability can be achieved by increasing the texture depth above this critical value.

Table 4.1 Texture measure correlations with MPD based on 24 observations.

Texture measure	**Correlation with MPD coefficient of determination (R^2)**
ETD (mm)	1.00
RMS (mm)	0.97
MTD (ASTM E965) (mm)	0.92
Outflow time (l/sec)	0.85

Figure 4.1 ETD v. MPD.

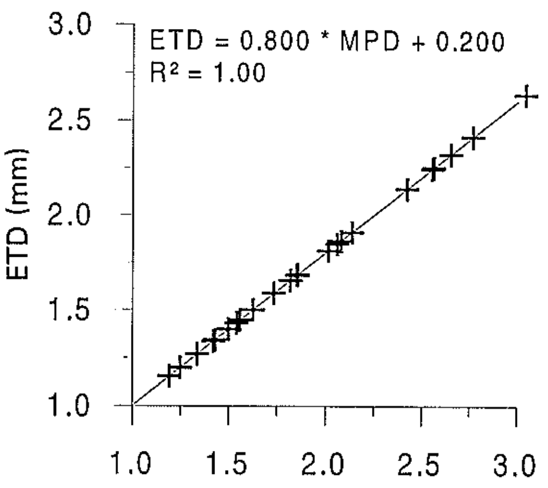


Figure 4.2 RMS v. MPD.

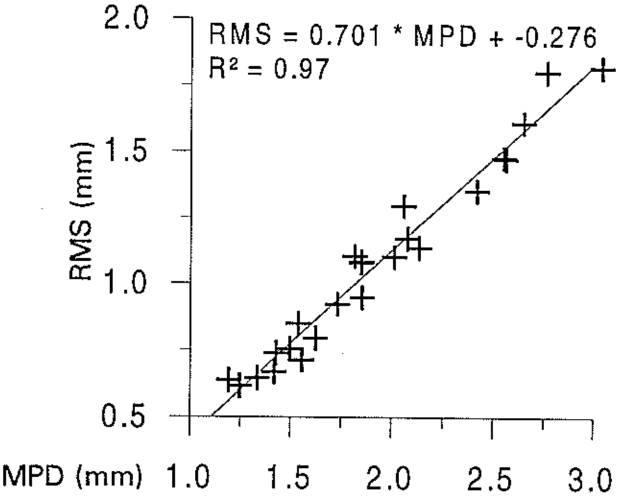


Figure 4.3 Volumetric MTD v. MPD

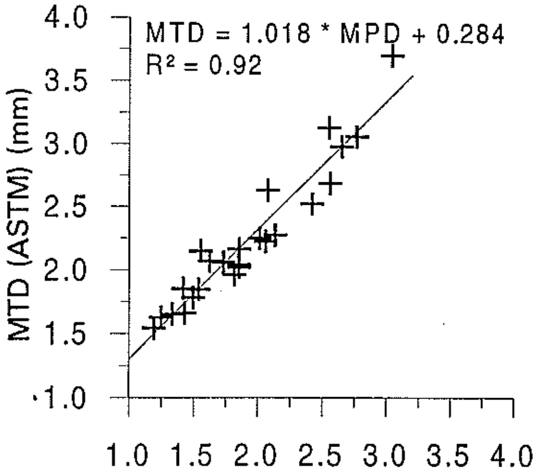
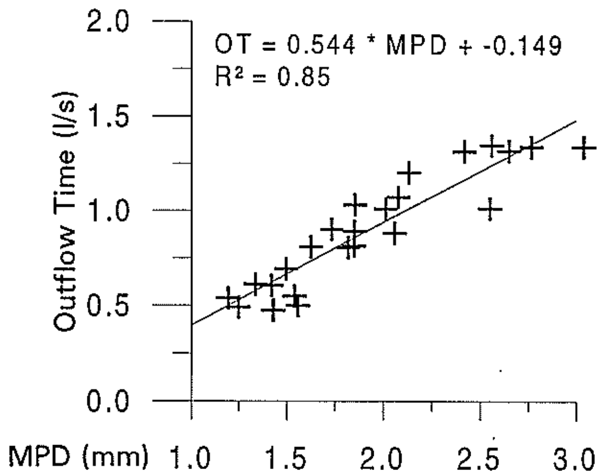


Figure 4.4 Outflow time v. MPD.



Cross-correlations of the average texture measures are given in Table 4.2. This shows that the mean profile depth (MPD) provides the best correlations with the volumetric patch method (MTD) for chipseal surfaces, vindicating PIARC's recommendation that macrotexture profiles should be reported in terms of MPD whenever possible.

Table 4.2 Cross-correlation of texture measures (R^2 values).

Factor	MTD	OT (l/s)	MPD	RMS
MTD	1.00	0.70	0.92	0.85
OT (l/s)	0.70	1.00	0.85	0.79
MPD	0.92	0.85	1.00	0.97
RMS	0.85	0.79	0.97	1.00

4.2 Skid Resistance Relationships

Besides the standard measures of texture described in Section 4.1 above, a third octave band spectral analysis, as detailed in Cenek et al. (1997), was performed on all the texture profiles obtained using the stationary laser profilometer for wavelengths between 0.63 mm and 500 mm. This analysis permits ready identification of critical texture wavelength ranges with regard to dry and wet skid resistance. All spectra were averages for all recorded profiles at each test site.

Table 4.3 is a matrix of correlation coefficients (R) for all the measured texture variables and Grip Number. The variables are listed in the column and row headings. Based on previous work, logarithmic texture values are preferred to linear texture values (Sandberg 1990b), Therefore, the texture units used are in decibels (relative to 10^{-6}m RMS). The dB (decibel) terms in the first column refer to the third octave band spectral level, with the numbers pertaining to the centre band wavelength in millimetres. Therefore dB 500 refers to the 500 mm third octave band level. The numbers within the table are the correlation coefficients (R) between the variables. The 1.00 entries on the diagonal of the table represent a perfect correlation as the row and column headings are the same. An absolute correlation value near 1.00 indicates that the variables in the row and column are dependent on each other. The sign of the correlation value indicates if an increase (+) or decrease (-) in one variable results in an increase in the dependent variable.

Table 4.3 shows good correlations between wet Grip Numbers and the different water film thicknesses and measuring speeds. Correlations between the Grip Numbers and standard and wavelength texture parameters are low, indicating that there is not a simple interaction between skid resistance and road texture.

The more significant of these correlations are explained in Sections 4.2.1 to 4.2.6.

Table 4.3 Texture measure correlations with Grip Number.

	MTD	OT(1/s)	MPD	RMS	GN50/0.00	GN50/0.05	GN50/0.10	GN50/0.20	GN50/0.50	GN50/0.80	GN40/0.50	GN60/0.50	GN80/0.50	GN100/0.5
MTD	**1.0000**	0.8341	0.9580	0.9243	-0.3709	-0.1672	-0.1866	-0.1777	-0.1293	-0.0912	-0.1205	-0.1734	-0.1430	-0.1150
OT(1/s)	0.8341	**1.0000**	0.9242	0.8915	-0.3315	-0.0329	-0.0269	0.0201	0.0589	0.0923	0.0793	0.0224	0.0494	0.0914
MPD	0.9580	0.9242	**1.0000**	0.9828	-0.3999	-0.0875	-0.1105	-0.0857	-0.0387	0.0012	-0.0313	-0.0746	-0.0363	-0.0085
RMS	0.9243	0.8915	0.9828	**1.0000**	-0.3375	-0.1317	-0.1597	-0.1301	-0.0830	-0.0440	-0.0826	-0.1122	-0.0645	-0.0309
GN50/0.00	-0.3709	-0.3315	-0.3999	-0.3375	**1.0000**	-0.0688	-0.0343	-0.0468	-0.1198	-0.1311	-0.0741	-0.0729	-0.0934	-0.0930
GN50/0.05	-0.1672	-0.0329	-0.0875	-0.1317	-0.0688	**1.0000**	0.9820	0.9657	0.9443	0.9215	0.9200	0.9383	0.9358	0.8461
GN50/0.10	-0.1866	-0.0269	-0.1105	-0.1597	-0.0343	0.9820	**1.0000**	0.9869	0.9653	0.9439	0.9419	0.9493	0.9452	0.8573
GN50/0.20	-0.1777	0.0201	-0.0857	-0.1301	-0.0468	0.9657	0.9869	**1.0000**	0.9887	0.9725	0.9706	0.9724	0.9648	0.8880
GN50/0.50	-0.1293	0.0589	-0.0387	-0.0830	-0.1198	0.9443	0.9653	0.9887	**1.0000**	0.9887	0.9774	0.9751	0.9700	0.9012
GN50/0.80	-0.0912	0.0923	0.0012	-0.0440	-0.1311	0.9215	0.9439	0.9725	0.9887	**1.0000**	0.9811	0.9695	0.9656	0.9195
GN40/0.50	-0.1205	0.0793	-0.0313	-0.0826	-0.0741	0.9200	0.9419	0.9706	0.9774	0.9811	**1.0000**	0.9749	0.9483	0.8978
GN60/0.50	-0.1734	0.0224	-0.0746	-0.1122	-0.0729	0.9383	0.9493	0.9724	0.9751	0.9695	0.9749	**1.0000**	0.9833	0.9405
GN80/0.50	-0.1430	0.0494	-0.0363	-0.0645	-0.0934	0.9358	0.9452	0.9648	0.9700	0.9656	0.9483	0.9833	**1.0000**	0.9532
GN100/0.5	-0.1150	0.0914	-0.0085	-0.0309	-0.0930	0.8461	0.8573	0.8880	0.9012	0.9195	0.8978	0.9405	0.9532	**1.0000**
dB500	0.5794	0.4786	0.5223	0.4560	-0.2489	0.0538	0.1077	0.1129	0.1142	0.1050	0.1130	0.0255	0.0267	-0.0977
dB400	0.7874	0.6732	0.7571	0.7260	-0.4740	-0.2594	-0.2689	-0.2483	-0.2050	-0.1954	-0.1787	-0.2244	-0.2238	-0.2054
dB315	0.6939	0.6893	0.7298	0.7376	-0.2340	-0.1336	-0.1958	-0.1541	-0.1354	-0.1434	-0.1394	-0.1360	-0.0969	-0.0884
dB250	0.7718	0.7756	0.8065	0.7807	-0.2843	-0.0759	-0.1161	-0.0786	-0.0315	-0.0083	-0.0027	-0.0814	-0.0554	-0.0597
dB200	0.8839	0.7891	0.8925	0.8822	-0.4096	-0.1763	-0.2059	-0.1962	-0.1229	-0.0940	-0.1181	-0.1546	-0.1395	-0.1179
dB160	0.8472	0.7382	0.8333	0.8229	-0.2406	-0.3919	-0.4149	-0.4040	-0.3556	-0.3226	-0.3487	-0.4166	-0.3876	-0.3598
dB125	0.8525	0.8177	0.8937	0.8800	-0.4320	-0.1145	-0.1747	-0.1502	-0.1053	-0.0898	-0.1276	-0.1671	-0.1407	-0.1375
dB100	0.8773	0.8579	0.9438	0.9370	-0.4572	-0.1424	-0.1897	-0.1639	-0.1145	-0.0672	-0.1039	-0.1487	-0.1120	-0.0576
dB80	0.8968	0.8554	0.9360	0.9210	-0.3823	-0.2201	-0.2579	-0.2324	-0.1884	-0.1610	-0.1903	-0.2391	-0.2099	-0.1724
dB63	0.8771	0.9299	0.9523	0.9629	-0.3218	-0.1639	-0.1785	-0.1412	-0.0976	-0.0694	-0.0893	-0.1249	-0.0881	-0.0584
dB50	0.9043	0.8532	0.9226	0.9100	-0.4097	-0.1653	-0.2060	-0.1771	-0.1136	-0.0893	-0.1188	-0.1448	-0.1192	-0.0815
dB40	0.8649	0.9228	0.9419	0.9417	-0.4104	-0.1731	-0.1968	-0.1537	-0.0947	-0.0683	-0.0989	-0.1313	-0.0910	-0.0529
dB31.5	0.8701	0.8947	0.9466	0.9567	-0.3788	-0.2205	-0.2563	-0.2124	-0.1633	-0.1317	-0.1586	-0.1817	-0.1445	-0.1159
dB25	0.8438	0.8853	0.9353	0.9475	-0.4183	-0.1730	-0.2157	-0.1829	-0.1418	-0.1063	-0.1413	-0.1622	-0.1121	-0.0714
dB20	0.8702	0.8810	0.9459	0.9575	-0.4408	-0.1617	-0.1975	-0.1625	-0.1089	-0.0800	-0.1224	-0.1433	-0.0928	-0.0691
dB16	0.8716	0.8470	0.9387	0.9588	-0.3504	-0.1356	-0.1804	-0.1586	-0.1088	-0.0743	-0.1165	-0.1293	-0.0772	-0.0422
dB12.5	0.8431	0.8206	0.9235	0.9529	-0.3139	-0.0881	-0.1323	-0.1049	-0.0551	-0.0112	-0.0596	-0.0659	-0.0073	0.0308
dB10	0.8770	0.7543	0.9167	0.9467	-0.2822	-0.1159	-0.1666	-0.1551	-0.1143	-0.0778	-0.1209	-0.1179	-0.0733	-0.0379
dB8	0.8593	0.6931	0.8857	0.9188	-0.2758	-0.1502	-0.1970	-0.1994	-0.1587	-0.1179	-0.1644	-0.1567	-0.0981	-0.0634
dB6.3	0.8233	0.6246	0.8433	0.8812	-0.2624	-0.1632	-0.2081	-0.2143	-0.1747	-0.1308	-0.1936	-0.1824	-0.1167	-0.0973
dB5	0.7772	0.5773	0.8021	0.8479	-0.2328	-0.1017	-0.1585	-0.1733	-0.1328	-0.0937	-0.1531	-0.1307	-0.0660	-0.0466
dB4	0.7879	0.5800	0.8070	0.8543	-0.2018	-0.0980	-0.1374	-0.1471	-0.1078	-0.0724	-0.1294	-0.1123	-0.0423	-0.0310
dB3.15	0.7918	0.5963	0.8155	0.8636	-0.2172	-0.1289	-0.1761	-0.1852	-0.1474	-0.1087	-0.1648	-0.1432	-0.0782	-0.0627
dB2.5	0.8238	0.6316	0.8463	0.8869	-0.2358	-0.1080	-0.1588	-0.1663	-0.1285	-0.0909	-0.1452	-0.1300	-0.0643	-0.0514
dB2	0.8172	0.6295	0.8404	0.8853	-0.2106	-0.1049	-0.1552	-0.1627	-0.1227	-0.0898	-0.1421	-0.1243	-0.0575	-0.0454
dB1.6	0.8229	0.6466	0.8510	0.8952	-0.2138	-0.0913	-0.1380	-0.1426	-0.1033	-0.0740	-0.1246	-0.1084	-0.0419	-0.0314
dB1.25	0.8158	0.6456	0.8496	0.8941	-0.2202	-0.0852	-0.1311	-0.1341	-0.0924	-0.0583	-0.1161	-0.0973	-0.0277	-0.0087
dB1	0.8362	0.6682	0.8665	0.9063	-0.2248	-0.1074	-0.1483	-0.1486	-0.1054	-0.0704	-0.1272	-0.1149	-0.0491	-0.0264
dB0.8	0.8597	0.6980	0.8864	0.9197	-0.2245	-0.0939	-0.1321	-0.1327	-0.0889	-0.0535	-0.1102	-0.1026	-0.0383	-0.0165
dB0.63	0.8604	0.7290	0.9008	0.9350	-0.2447	-0.0850	-0.1221	-0.1132	-0.0643	-0.0288	-0.0852	-0.0856	-0.0197	-0.0033

4.2.1 Relationship to MPD

There is no simple relationship to MPD as Figures 4.5 and 4.6 show that the regression coefficients are very poor, being $R^2 = 0.16$ for dry skid resistance and $R^2 = 0.00$ for wet skid resistance (GN - Grip Number).

Figure 4.5 Dry skid resistance v. MPD.

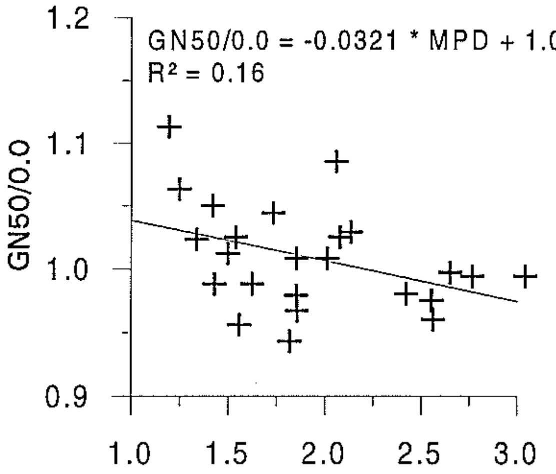
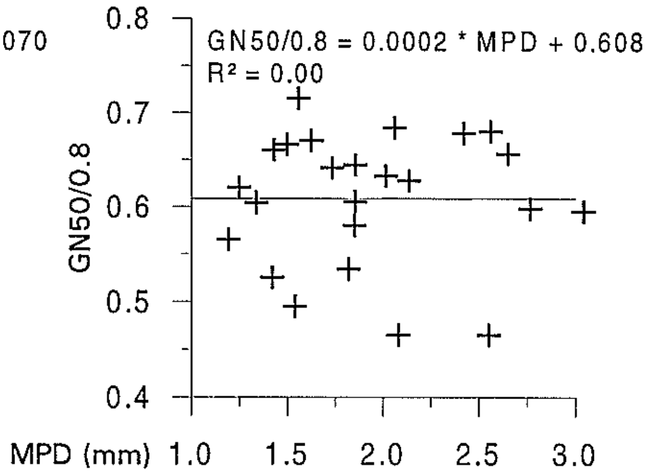


Figure 4.6 Wet skid resistance v. MPD.



4.2.2 Wet/Dry Relationships

Wet skid resistance is not related to dry skid resistance by simple proportionality. Figure 4.7 shows the degree of correlation between dry skid resistance and wet skid resistance for 0.05 mm water film thickness. The resulting best fit straight line gives an extremely poor regression constant of $R^2 = 0.00$. However, once the road surface is wet, the thickness of the water film is related to the change in wet skid resistance, as shown in Figure 4.8, where the 0.05 mm water film thickness is highly correlated to the 0.80 mm water film thickness.

Figure 4.7 Wet skid resistance v. dry skid resistance.

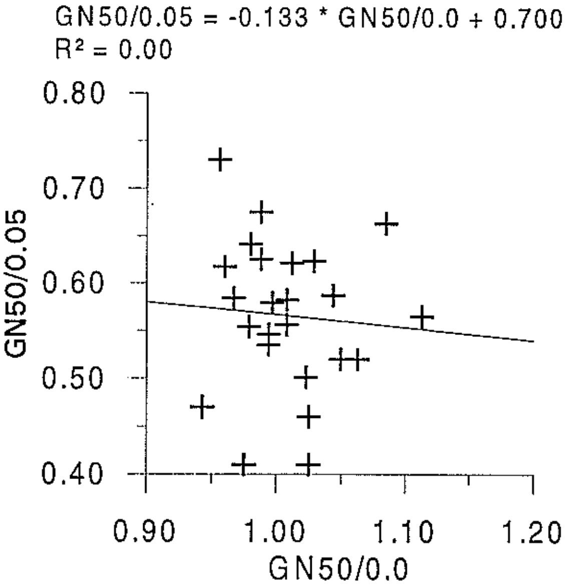
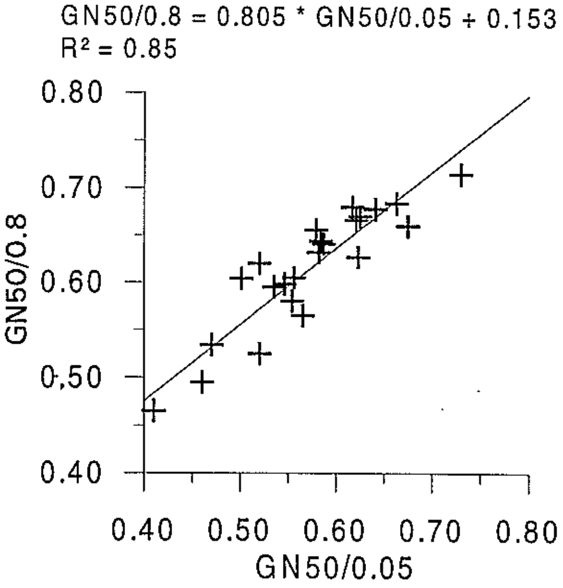


Figure 4.8 Effect of water film thickness.



4.2.3 Relationship to TNZ M/6 PSV Specifications

The relationship between wet skid resistance, PSV, and number of commercial vehicles per lane per day derived by Szatkowski & Hosking (1972) forms the basis of PSV specifications in the TNZ M/6:1993 Specification for Sealing Chips. This relationship has been subsequently modified by Catt (1983) to account for aggregate size, traffic speed, and degree of braking and turning as follows:

$$\mathrm{PSV} = \mathrm{SFC} \times \mathrm{T} + 0.00663 \times \mathrm{Q} - \mathrm{A} + \mathrm{B} - 2.4 \qquad (1)$$

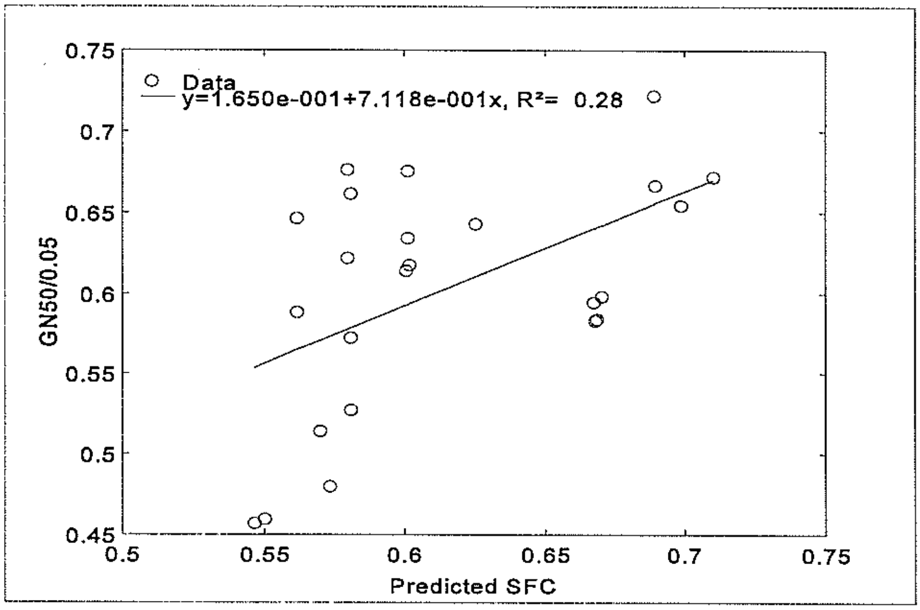
where: PSV is the polished stone value to provide the design SFC;
SFC is the SCRIM sideway–force coefficient at 30 miles per hour (48 km/h);
T is a factor dependent on traffic speed and texture depth (approximately 100);
Q is the number of commercial vehicles per day;
A is a factor dependent on the nominal size of aggregate;
B is a factor for braking and turning (B=0 for the 24 test sites).

Equation (1) can be re-arranged to give:

$$\mathrm{SFC} = 0.024 - 0.633 \times 10^{-4} \times \mathrm{Q} + 0.01 \times \mathrm{PSV} + 0.01 \times \mathrm{A} \qquad (2)$$

A comparison between the measured wet 50 km/h skid resistance (GN50/0.5) at the sites and the predictions from equation (2) are shown in Figure 4.9. The SCRIM sideways-force coefficient at 50 km/h is approximately equivalent to GN50/0.5. The agreement between predicted and measured skid resistance is poor, with a coefficient of determination (R^2) of only 0.28. Equation (2) gives a predicted value of skid resistance based only on the PSV, the number of commercial vehicles, and a small correction for aggregate size. Because the range of PSV values for the 24 test sites is small, with all values lying between 53 and 55, the volume of commercial vehicle traffic provides most of the variability for equation (2). This is in agreement with the statistical sensitivity analysis summarised in Section 3.3.1 which identified $\mathrm{AADT}_{\mathrm{HCV}}$ and chip grade as important predictors of wet skid resistance.

Figure 4.9 Comparison of predicted skid resistance from Catt (1983) and that measured.



4.2.4 Relationships to Seal Characteristics

The significant variables identified in Section 3.3 as affecting SCRIM sideway–force coefficient were seal age, $AADT_{HCV}$, chip grade, and percent crushed faces. A correlation analysis on the significant variables which influence wet skid resistance was performed on the measured data from the 24 test sites to give the results summarised in Table 4.4. All the skid resistance measurements in this table were undertaken for a 0.5 mm water film thickness. The significance of the correlation coefficient values are as described in Section 4.2.

Table 4.4 Correlation coefficient (R) of seal characteristics and wet skid resistance.

Factor	**GN40**	**GN50**	**GN60**	**GN80**	**GN100**	**MPD**	**% crush**	**$AADT_{HCV}$**	**Age**	**Grade**	**PSV**
GN40	**1.00**	0.98	0.99	0.95	0.90	–0.44	0.43	–0.57	–0.60	0.37	–0.35
GN50	0.98	**1.00**	0.98	0.98	0.91	–0.43	0.46	–0.62	–0.58	0.37	–0.36
GN60	0.99	0.98	**1.00**	0.98	0.93	–0.41	0.47	–0.65	–0.57	0.38	–0.37
GN80	0.95	0.98	0.98	**1.00**	0.96	–0.35	0.53	–0.67	–0.54	0.34	–0.37
GN100	0.90	0.91	0.93	0.96	**1.00**	–0.32	0.62	–0.65	–0.46	0.32	–0.27
MPD	–0.44	–0.43	–0.41	–0.35	–0.32	**1.00**	0.03	0.09	0.19	–0.38	0.31
% crush	0.43	0.46	0.47	0.53	0.62	0.03	**1.00**	–0.21	–0.35	0.38	–0.20
$AADT_{HCV}$	–0.57	–0.62	–0.65	–0.67	–0.65	0.09	–0.21	**1.00**	0.13	0.01	0.35
Age	–0.60	–0.58	–0.57	–0.54	–0.46	0.19	–0.35	0.13	**1.00**	–0.12	0.12
Grade	0.37	0.37	0.38	0.34	0.32	–0.38	0.38	0.01	–0.12	**1.00**	–0.47
PSV	–0.35	–0.36	–0.37	–0.37	–0.27	0.31	–0.20	0.35	0.12	–0.47	**1.00**

Some important general trends can be discerned in Table 4.4. As the GripTester's measuring speed increases, the correlation between skid resistance and % crushed faces increases while the influence of chip grade decreases. This suggests that a high percentage of crushed faces is important for high speed skid resistance while chipseal grade is more important at low speeds.

Taking the row headed by the skid resistance value GN50, it can be seen to be highly correlated with the friction measured at the other speeds GN40, GN60, GN80 and GN100. An increase in the value of GN50 is matched by an increase in the value of friction at the other speeds as the correlation coefficients are positive. The highest correlation to Grip Number was found with $AADT_{HCV}$. As the number of commercial vehicles increases, GN50 decreases as the correlation coefficient is negative ($R = -0.62$). This relationship between $AADT_{HCV}$ and GN50 is illustrated in Figure 4.10. The value of the coefficient of determination ($R^2 = 0.39$) is equal to the square of the absolute value of the correlation coefficient ($R = -0.62$).

From Table 4.4, a similar expression to that of Catt (1983) can be developed which predicts wet skid resistance from the most highly correlated variables. This results in equation (3). The agreement between measured wet skid resistance and that predicted is shown in Figure 4.11. The coefficient of determination (R^2) is 0.76 which is a significant improvement over equation (2) ($R^2 = 0.28$).

$$\begin{aligned} GN50/0.5 = {} & 0.3416 + 0.0162 \times \text{grade} + 0.0048 \times PSV + 0.0008 \times \text{crush} \\ & - 0.0145 \times \text{age} - 0.0001 \times AADT_{HCV} \end{aligned} \qquad (3)$$

where: GN50/0.5 is Grip Number at 50 km/h, 0.5 mm water film thickness;
grade is grade of chip (increasing grade corresponding to decreasing chip size);
PSV is polished stone value; crush is percentage of crushed faces;
age is age of the surfacing in years;
$AADT_{HCV}$ is annual average daily traffic flow of commercial vehicles per lane.

Normalising the variables of equation (3) with respect to their maximum value so that they all range between 0 and 1, allows their relative contribution to wet skid resistance to be established. The result of this exercise is tabulated in Table 4.5. With reference to Table 4.5, the most significant variable is PSV, though care must be taken with regard to this finding as all sites had very similar PSV. Catt's expression (equation (2)) also denotes PSV as being the most significant variable in predicting wet skid resistance. The age of the surfacing rated as the next most important with $AADT_{HCV}$, chip grade, and percentage crushed faces rating at about the same level.

Figure 4.10 Wet skid resistance v. $AADT_{HCV}$.

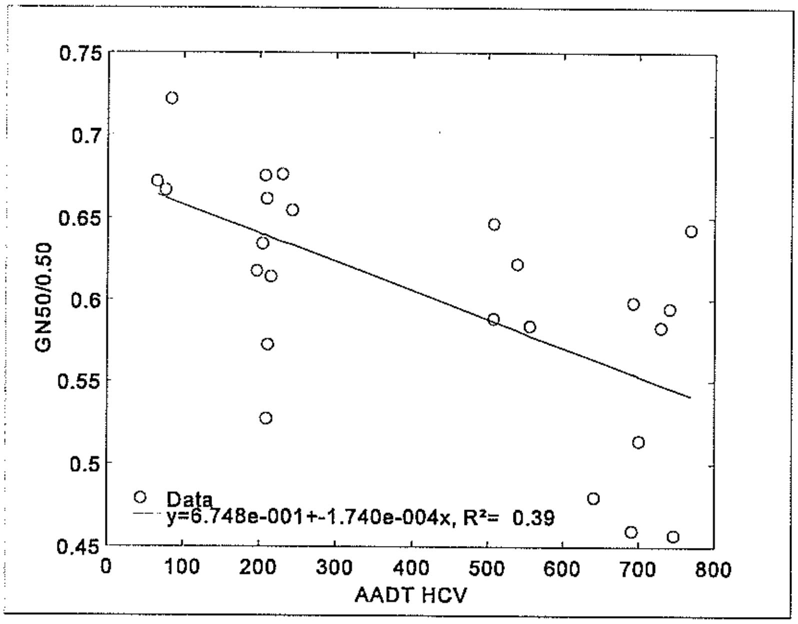


Figure 4.11 Predicted test site skid resistance from significant seal variables.

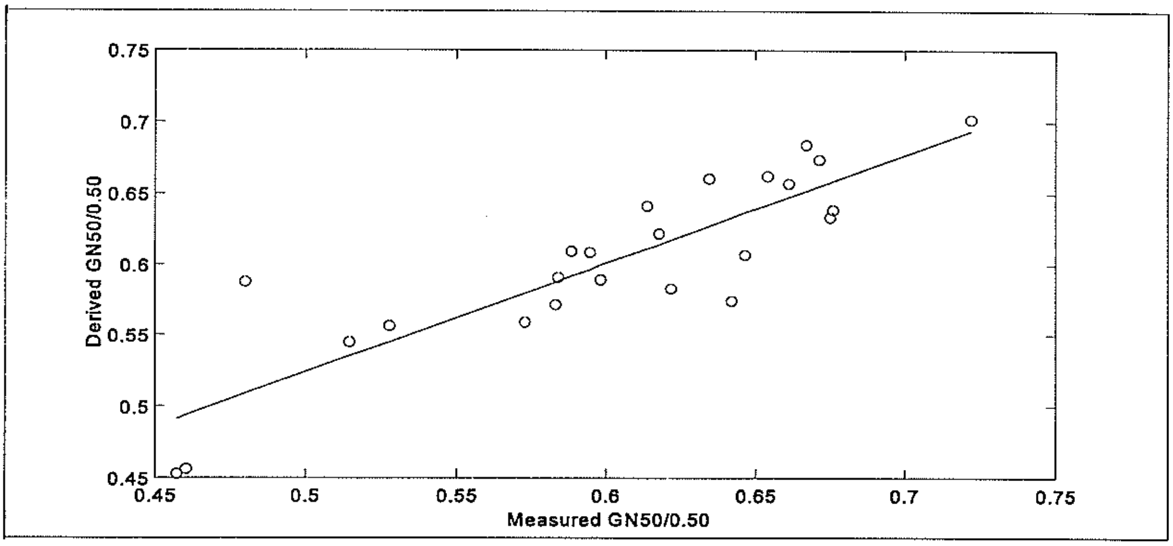


Table 4.5 Weighting of variables in derived skid resistance predictor equation (equation 3) and effect on predicted skid resistance.

Variable	Weighting	Effect
PSV	+53%	Increase
Age	−27%	Decrease
$AADT_{HCV}$	−18%	Decrease
Chip grade	+15%	Increase
% crushed faces	+15%	Increase

4.2.5 Variation with Water Film Thickness

Earlier analysis indicated that there is no simple relationship between wet and dry skid resistance (Figure 4.7). Once the surface is wet there is some dependency on the water film thickness, as suggested in Figure 4.8 and the correlation coefficients of Table 4.3.

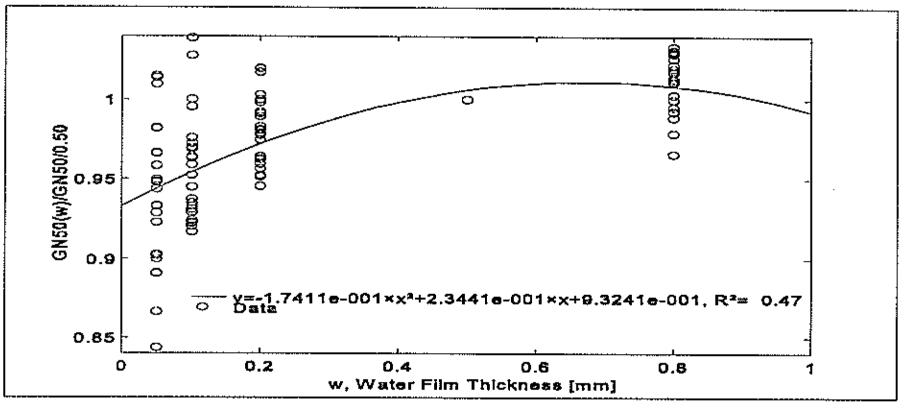
In Figure 4.12, wet skid resistance values have been normalised with respect to the standard GN50/0.5 values at each of the sites. There is a large spread of wet skid resistance values at low film thickness but there is a trend where the skid resistance increases to a maximum value with water thickness before it drops down again. The following polynomial fit of the data gives a coefficient of determination (R^2) of 0.47:

$$\text{GN50/w} = \text{GN50/0.5} \times (-0.1741 \times w^2 + 0.2344 \times w + 0.9324) \qquad (4)$$

where w = water film thickness (mm) if > 0

The polynomial fit has a low correlation with the measured Grip Number as there is a large spread of values. Initial measurements were made at the low water film thickness setting to allow the road surface to dry before increasing the film thickness for the next test. The initial runs produce a washing effect which frees the road surface of detritus and other lubricants. This washing effect is likely to give rise to the large spread of skid resistance values observed for the initial runs. Thus the skid resistance values measured at high water film thicknesses are conducted on a comparatively clean road surface, and so the measured values are expected to show much less variability than the initial runs. The general applicability of equation (4) therefore has to be questioned.

Figure 4.12 Variation of measured skid resistance with water film thickness.



4.2.6 Variation of Skid Resistance with Texture Wavelength Bands

The road surface is made up of a wide range of texture scales. Each grade is characterised by the nominal size of the aggregate used in construction, and it is known that the coarse grades give better high speed wet skid resistance. However, the mechanism by which the various chip sizes influence friction is not well established.

Friction is defined in this study by the ratio of drag and normal forces as shown in Figure 4.13. The GripTester measures friction with load cells which simultaneously log the drag and normal forces. If the forces generated at the tyre and road interface can be reasonably predicted, a method for estimating friction may be possible.

The normal tyre forces can be calculated from the laser profilometer texture profiles (Figure 4.14) and the characteristics of the GripTester tyre to give a computed texture induced contact pressure (Clapp et al. 1988). The drag forces are related to how a tyre keys in with the road texture, which in turn is related to the aggregate angularity. Parameters such as pavement age, grade and traffic flow influence the change in the road surface texture, and so are reflected in the texture profile.

Figure 4.13 Tyre forces which contribute to friction.

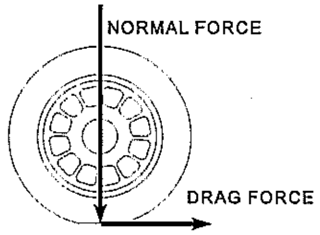
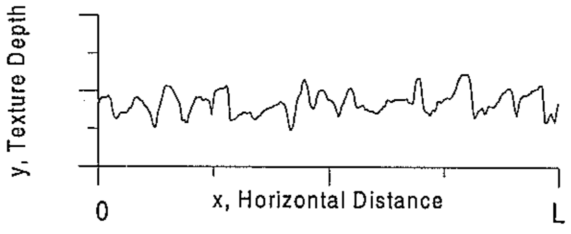


Figure 4.14 Typical road texture profile.



Myers (1962) found that the coefficient of friction for regular asperities was related to the angularity by the parameter z2, as defined by equation (5):

$$z2 = \frac{1}{L}\sqrt{\int_{x=0}^{x=L}\left(\frac{dy}{dx}\right)^2 dx} \qquad (5)$$

The road texture variables used to derive z2 are illustrated in Figure 4.14, in which y = texture depth (mm), x = horizontal distance (mm) and L = length (in mm).

The computed texture-induced contact pressure provides the normal force in Figure 4.13, and the texture parameter z2 provides the drag force.

Spectra of the contact pressure and z2 were calculated and a ratio was formed to investigate the relationship of the wavelength bands with the measured wet friction (GN50/0.05) for all the sites. The laser profilometer samples the texture depth at discrete points along the horizontal distance, so that at each sampled point there is a calculated z2 parameter and computed texture-induced pressure on the tyre. The following modified z2 parameter is used for the discretely sampled road profile:

$$z2_i = \frac{1}{L}\sqrt{\sum_{x_i=0}^{L}\left(\frac{dy}{dx}\right)_i^2} \tag{6}$$

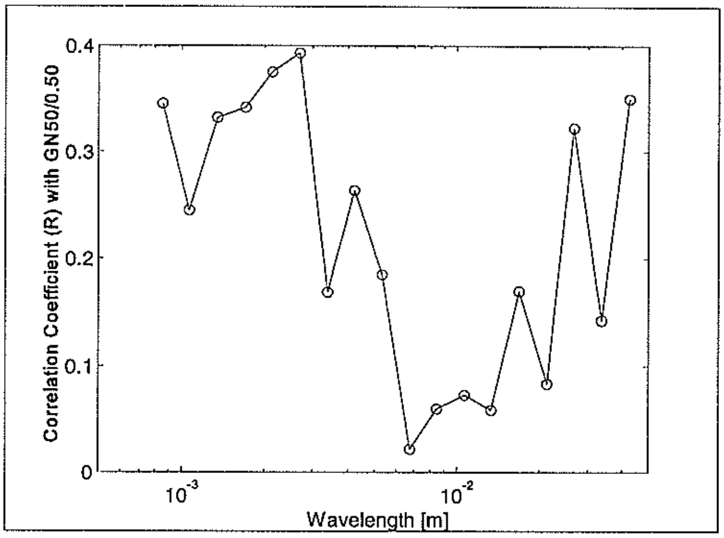
Decibel levels were calculated using equation (6). The decibel levels are referenced to a standard deviation of 0.001 N/m, i.e. 60 dB = 1 N/m. The spectral ratio z2' is then grouped into third octave wavelengths.

$$z2' = \frac{\text{power spectral density (contact pressure)}}{\text{power spectral density (z2)}} \tag{7}$$

The spectral variable z2' characterises the road surface by the measured texture and its interaction with typical tyre properties. At each wavelength there is a decibel level which indicates how much energy is present at that texture scale. Therefore z2' provides a more detailed measure than mean texture depth.

Positive correlations to decibel levels with wet skid resistance GN50/0.05 occur at a number of wavelength centres, as shown in Figure 4.15. The highest correlations are at texture wavelengths of 1.3, 1.7, 2.1, 2.7, 27 and 43 mm.

Figure 4.15 Texture wavelength correlations to wet skid resistance.



Using all the measured wavelength gives a multi-band relationship. However, the following equation gave the best predictions for wet skid resistance defined by GN50/0.05:

$$GN50/0.05 = -6.2127 + \sum (a_i \times dB_i) \tag{8}$$

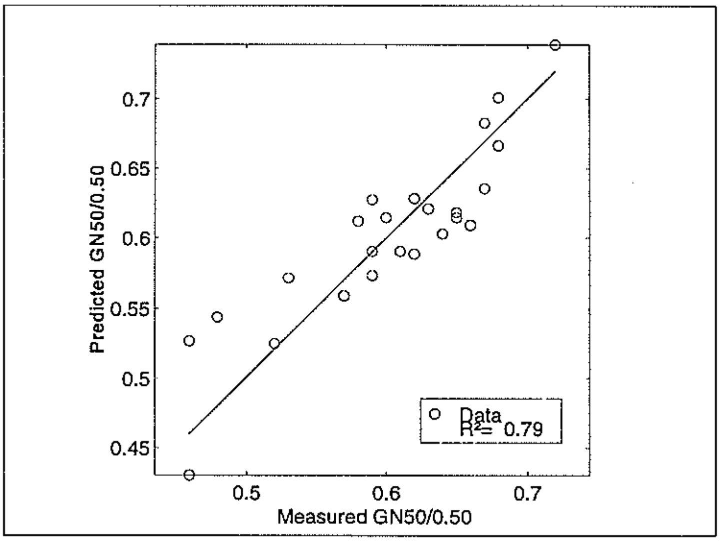
where: a_i is a constant listed in Table 4.6 for each texture wavelength i;
dB_i is the texture decibel level centred at each texture wavelength i (Table 4.6).

Table 4.6 Constants for use with equation (8).

Texture wavelength i	**43 mm**	**34 mm**	**27 mm**	**21 mm**	**17 mm**	**14 mm**	**11 mm**	**8.5 mm**	**6.7 mm**	**5.4 mm**	**4.3 mm**	**3.4 mm**	**2.7 mm**	**2.1 mm**	**1.7 mm**	**1.3 mm**	**1.1 mm**	**0.9 mm**
a_i	0.0320	−0.0074	−0.0071	−0.0278	0.0061	0.0047	0.0050	−0.0506	0.0151	0.0235	−0.0060	−0.0017	0.0432	0.0104	−0.0206	−0.0021	0.0075	0.0110

The correlation between measured and predicted GN50/0.05 values using equation (8) are shown in Figure 4.16. The resulting coefficient of determination (R^2) is 0.79.

Figure 4.16 Comparison of measured wet skid resistance with values (GN) predicted from road surface wavelengths.



The range of PSV of the test sites is small (53 ≤ PSV ≤ 55), so incorporating a PSV term in equation (8) did not improve the degree of correlation. Therefore, equation (8) suggests that skid resistance of roads constructed with aggregates with less than desirable PSV can be improved by paying particular attention to macrotexture characteristics, particularly in the 1-3 mm and 30-40 mm wavelength ranges.

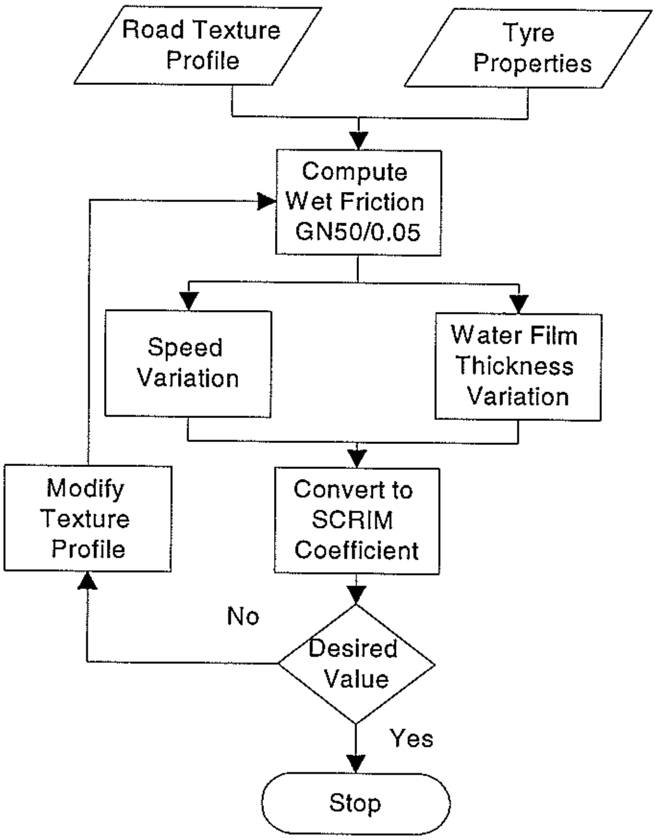
A selection of test sites with a wider range of PSV values is required to further refine equation (8) and improve its general applicability. However, in its present form and application, equation (8) is seen as providing more reliable estimates of wet skid resistance than either Catt's equation (equation 2) or equation (3) because the effects of traffic flow and chip size and shape are inherent in the road texture profiles which are used to derive the spectral variable z2'.

4.4 Concluding Remarks

The results of the field study clearly show that, for aggregates with a given PSV, gains in wet skid resistance are possible through paying particular attention to macrotexture geometry with respect to wavelength and slope characteristics of the sealing chips, so that they maximise tyre hysteresis and surface drainage characteristics. The critical wavelengths identified are between 1-3 mm corresponding to hysteresis effects, and 30-40 mm corresponding to drainage. The crushing process appears to have a significant impact on the 1-3 mm texture wavelengths.

Data presented in this section regarding the sensitivity of wet skid resistance to speed, water film thickness and texture wavelengths can be combined and used to optimise size, shape and spacing of sealing chips of a specified PSV. The flow chart shown in Figure 4.17 represents a possible procedure for predicting expected wet skid resistance for a particular seal design. Road texture profile, actual or desired, and typical tyre properties can be used to compute the wet skid resistance at a set slip speed and water film thickness. If required, corrections can then be made for different slip speeds and water film conditions.

Figure 4.17 Proposed sequence for deriving optimum road texture geometry.



5. APPLICATION OF THE INTERNATIONAL FRICTION INDEX

5.1 Background

The wet skid resistance at a slip speed of 60 km/h (F60) and speed number (Sp), which is directly calculated from texture depth, form the International Friction Index (IFI) which has been proposed by PIARC (1995). When these two values are known, the wet skid resistance of any other slip speed can be determined. In New Zealand, calibrations allowing wet skid resistance values, which are derived by SCRIM, GripTester and British Pendulum Tester, to be converted to F60 are available, because these devices were used in the international PIARC experiment to compare and harmonise texture and skid resistance measurements. By contrast, the only method presently available for generating Sp values is the volumetric patch method according to ASTM E965 (1987). The opportunity was therefore taken to calibrate Transit New Zealand's stationary laser profilometer to give Sp values and to test the validity of PIARC procedures for calculating wet skid resistance at any slip speed, by comparing measured and predicted GripTester derived values for a range of survey speeds.

5.2 Application of PIARC Procedures

The PIARC relationship from which wet skid resistance can be calculated at any slip speed is given by:

$$F(S) = F60 \times \exp\left(\frac{60 - S}{Sp}\right) \tag{9}$$

where: F(S) is the skid resistance value at the slip speed S
F60 is the locked wheel skid resistance at 60 km/h
S is the slip speed in km/h
Sp is the speed number

A high mean texture depth gives a high value of Sp which indicates that the skid resistance at the site is not very speed sensitive. Sp is calibrated by forming the following equation:

$$Sp\ (\text{km/h}) = a + b \times Tx\ (\text{mm}) \tag{10}$$

where: a and b are transformation constants
Tx is the texture parameter

F60 is the value of skid resistance at 60 km/h slip speed to which friction values are referenced to. The equation for F60 is:

$$F60 = A + B \times FR60 \tag{11}$$

where A and B are transformation constants
FR60 is the 60 km/h skid resistance value derived from equation (12).

$$\mathrm{FR60} = \mathrm{FRS} \times \exp\left(\frac{60 - S}{Sp}\right) \tag{12}$$

where: S is the slip speed in km/h
FRS is the measured skid resistance value at the speed S
FR60 is the derived skid resistance value at 60 km/h

Combining equations (10) and (12) gives the following expression from which the values of the constants a and b can be determined for a particular texture measuring device.

$$\mathrm{FR60} = \mathrm{FRS} \times \exp\left(\frac{60 - S}{(a + b \times Tx)}\right) \tag{13}$$

The skid resistance values used to calibrate the MPD measurements obtained from the laser profilometer are the Grip Number values for the measuring speeds 40, 50, 60, 80 and 100 km/h at 0.50 mm water film thickness. The GripTester tyre measures skid resistance at a slip speed of 18.5% of the measuring speed, so that the slip speed is 0.185 × measuring speed.

The recommended PIARC calibration procedure requires a relationship between a calibrated texture measurement device such as the ASTM E965 MTD and the texture measurement device of interest. The MTD relationship to Sp is given by the following PIARC calibrated equation:

$$Sp\ (\mathrm{km/h}) = -11.5981 + 113.63426 \times \mathrm{MTD}\ (\mathrm{mm}) \tag{14}$$

The correlation between the laser profilometer measured MPD and ASTM E965 MTD shown in Figure 4.3 is substituted into equation (14) to give the following expression for Sp in terms of the MPD:

$$Sp\ (\mathrm{km/h}) = 20.6740 + 115.67968 \times \mathrm{MPD}\ (\mathrm{mm}) \tag{15}$$

Figure 5.1 shows a plot of the measured Grip Numbers of various speeds and the observed Grip Number based on equation (9) with a fixed FR60 value and different slip speed. The fixed FR60 value of each site was found by minimising equation (13) over the range of survey speeds and associated Grip Numbers. Each set of connected circles in Figure 5.1 represents the measured and derived values from each site, giving 24 lines in total which cross the one-to-one relationship datum line. The correlation between the derived and measured Grip Numbers is $R^2 = 0.94$ using the calibration procedure for Sp recommended by PIARC.

By using the Grip Numbers measured at the different speeds at each site, an alternative Sp calibration can be performed. This procedure uses the Grip Numbers measured at 40, 50, 60, 80 and 100 km/h in equation (12) to calculate a common value of FR60 at each site. The resulting speed number relationship is:

$$Sp\ (\mathrm{km/h}) = 53.2646 + 13.5707 \times \mathrm{MPD}\ (\mathrm{mm}) \tag{16}$$

Figure 5.1 Level of agreement between measured and predicted Grip Numbers using PIARC calibration of Sp (i.e. equation 15).

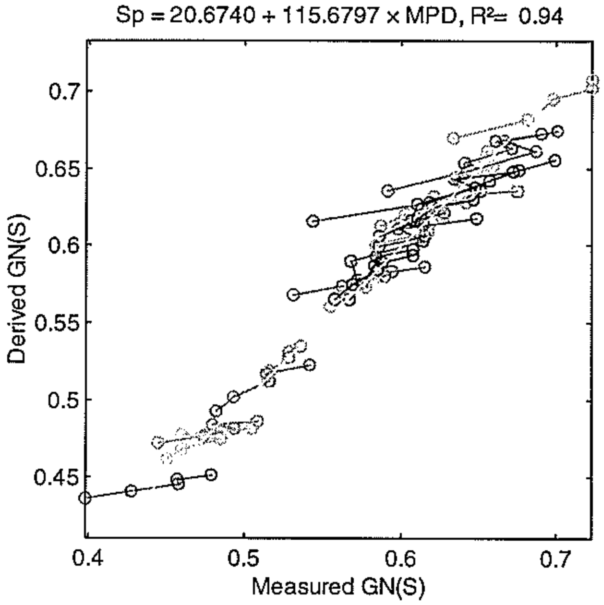
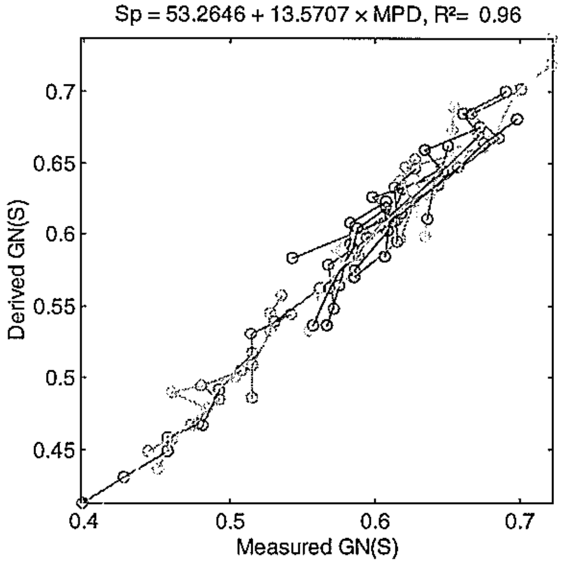


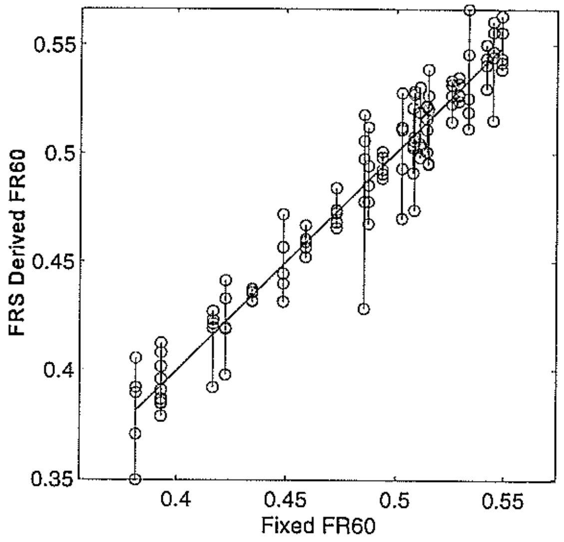
Figure 5.2 is the equivalent to Figure 5.1 but with equation (16) used to calculate Sp. This shows that the agreement between derived and measured Grip Numbers is considerably improved with the site scatter lines now more closely packed around the one-to-one relationship datum line. The resulting correlation between derived and measured Grip Number improves to give a coefficient of determination (R^2) of 0.96.

Figure 5.2 Derived and measured Grip Number correlations resulting from alternative calibration of Sp.



A comparison of equation (15) with equation (16) shows a significant difference in the calibration constants. Another cause for concern is the degree of variability in the calculated FR60 value. Figure 5.3 shows the variation in FR60 calculated from equations (13) and (15) and fixed FR60 value. The vertical lines and circles represent the speed variation of FR60 at each of the 24 sites.

Figure 5.3 Degree of variability in derived FR60 values.



In summary, this practical application of IFI has highlighted a number of deficiencies in the procedures detailed in PIARC (1995). These deficiencies appear to relate to the following two factors. Firstly the transformation expressions have been derived over a very large slip range (0-60 km/h). However only very low slip speed ranges are likely to occur in practice with the skid testers in common use in New Zealand (e.g. 7-18.5 km/h in the case of the GripTester). Secondly, the transformation coefficients have been derived from different road surfaces to those found in New Zealand. As a result, the spread in F60 values was found to be typically 0.05 for the 24 test sites and as great as 0.1.

Using IFI instead of the measured skid resistance value will therefore cause a considerable confidence interval for the expected true skid resistance. This wide interval poses problems from asset management and contractual perspectives because the chances of wrongly identifying sections of road which are below specified levels will be high. This finding is consistent with that of Jordens & Bennis (1996). However, the spread in F60 was significantly reduced if actual measurements of speed sensitivity were used to derive the transformation coefficients, suggesting that the general forms of the transformation expressions are essentially correct.

6. CONCLUSIONS AND RECOMMENDATIONS

Within the scope and limitations of the laboratory and field studies undertaken for this project, the following conclusions and recommendations are warranted.

6.1 Relationship Between Polished Stone Value and Crushed Faces

The laboratory-based PSV tests identified that sealing chip processed from alluvial aggregates had a higher resistance to polishing than equivalent unprocessed material. For the grade 4-6 greywacke samples derived from Ngaruroro River stock, the crushed aggregate had PSVs 6.3 to 14 units higher than the uncrushed aggregates, and this corresponds to percentage increases of 14 to 33% respectively.

The higher PSV of the sealing chip appears to be directly a function of the crushing process because crushed faces have significantly higher levels of grain scale microtexture (texture amplitude in the range 10-100 microns) and greater angularity (texture wavelengths in the 1-5 mm wavelength range). This range of wavelength is a significant contributor to the hysteretic component of wet skid resistance).

The reduction of skid resistance during the PSV test appears to be caused by the removal of grain scale microtexture during coarse grit polishing, because the overall shape (angularity) of the individual aggregate specimens remains relatively unchanged.

Recommendations

- A stylus profilometer should be used as it allows surface profiles to be traced to a measuring accuracy of ±0.005 mm and a step length of 0.0125 mm. Accordingly, texture wavelengths down to 0.025 mm can be measured.

  Because binocular microscopy permits only qualitative assessment of changes in the aggregate surface structure related to the PSV test, such qualitative data should be supplemented by quantitative data. The time-dependent changes can then be more thoroughly investigated, leading to a better understanding of the polishing mechanism. A stylus profilometer has just been commissioned by Auckland-based Measurement and Calibration Centre Ltd, and their trials involving its application to sealing chip specimens have proven successful.

  Therefore representative surface profile traces of the grade 4-6 PSV samples used as part of this research programme should be obtained to record and characterise changes between the crushed and uncrushed samples, and to correlate various texture measures such as third octave band spectral density, spacing between profile peaks, and profile slope to PSV.

- The polishing characteristics of aggregates in common use in New Zealand, other than greywacke, should also be investigated in the same way so that any differences in polishing mechanisms can be established, leading to better specification of material used in the construction of wearing courses.

6.2 The PSV Test

For both crushed and uncrushed aggregates, the length of time taken for the PSV test, i.e. 6 hours, appears to be sufficient to allow samples to reach an equilibrium state of polish. Additional polishing for more than 6 hours did not result in significant decreases in measured skid resistance, determined by the modified BPT.

Aggregate size was also shown to have no statistically significant effect on the PSV result.

Perhaps the only question mark remaining over the PSV test concerns the consistency of the control specimens used to negate the effect of less than ideal polishing runs brought about by variations in equipment performance or inconsistency in the polishing grit. The control specimens are made using chip from a specific quarry in the UK with a known PSV (52.5).

Recommendation

- Given the importance of the control aggregate for normalising PSV, a detailed investigation of the consistency of the source and its production should be carried out. This would involve subjecting specimens made from control aggregates supplied by different Australasian PSV testing agencies to:

  (a) full petrological study to determine the degree of similarity in the structure and composition between specimens;

  (b) standard PSV testing to establish any variation in resulting PSV among the specimens;

  (c) before and after PSV test surface profile tracings made with a stylus profilometer to identify any differences in polishing behaviour that can be linked back to the petrological findings.

6.3 Relationship of Skid Resistance to Seal Characteristics

Twenty four sites located on state highways in the Napier region and constructed from alluvial-sourced aggregates with a nominal PSV of 54 were selected to contrast differences between high and low texture depths, % crushed faces, and heavy commercial vehicle volumes. Measurements at each site comprised skid resistance by SCRIM and GripTester, macrotexture by laser profiling techniques and volumetric patch method, and drainage ability by outflow meter.

Statistically significant correlations identified were as follows.

1. SCRIM sideway–force coefficient values were sensitive to surface age and commercial vehicle volumes.

2. The more detailed GripTester measurements of wet skid resistance showed negative correlations with increasing heavy commercial vehicle volume ($R = -0.62$), surface age ($R = -0.58$), and texture depth ($R = -0.43$), and positive correlation with increasing percentage of crushed faces ($R = 0.46$).

3. As the slip speed increased, the correlations between wet skid resistance and % crushed faces increased while the influence of chip grade decreased, suggesting that a high percentage of crushed faces is important for high speed skid resistance while chip grade is more important at low speeds.

Two predictive models were derived that explained 75-80% of the total variation in the measured Grip Number. The first is a modification of the well known TRRL expression that inter-relates skid resistance to PSV and heavy commercial traffic volumes. Its form is

$$\begin{aligned} GN50/0.5 = {} & 0.3416 + 0.0162 \times grade + 0.0048 \times PSV + 0.0008 \times crush \\ & - 0.0145 \times age - 0.0001 \times AADT_{HCV} \qquad (R^2 = 0.76) \qquad (3) \end{aligned}$$

where: GN50/0.5 is the Grip Number at 50 km/h, 0.5 mm water film thickness;
grade is grade of chip (increasing grade corresponding to decreasing chip size);
PSV is polished stone value;
crush is percentage of crushed faces;
age is age of the surfacing in years;
$AADT_{HCV}$ is annual average daily traffic flow of commercial vehicles per lane.

Better agreement ($R^2 = 0.79$) between predicted and measured skid resistance was achieved when actual surface profiles derived from laser profilometer measurements were utilised. This is because texture depth and shape changes related to ageing and traffic-induced wear are implicitly accounted for.

The second predictive model derives horizontal and normal tyre forces directly from the road texture profiles. Using the model, significant texture wavelengths influencing wet skid resistance were found to range from 1 to 50 mm, with the highest correlations occurring at 1.3, 1.7, 2.1, 2.7, 27 and 43 mm.

In summary, the wet skid resistance of chipseal road surfaces is not only a function of the PSV of the aggregate, but also its size, shape and spacing. Therefore whenever the scope of increasing PSV in surfacing design is limited, attention should turn to optimising the surface geometry. In the case of alluvial-sourced material, small chips (i.e. grade 4 or less) are generally preferable to large chip (grade 2) as there is a smaller proportion of exposed faces that have been smoothed by alluvial action.

Recommendations

- The general validity of the two skid resistance relationships derived as part of this research programme should be investigated by considering additional road test sections, to cover a broader range of PSV and to include hard rock quarried material in addition to alluvial-sourced material.

- An assessment of the processing characteristics of commonly used impact and gyratory crushers in use in New Zealand should be undertaken to identify those which generate significant surface texture on crushed aggregates in the 1-5 mm wavelength range. Texture in this wavelength has been shown to be a major contributor to the hysteretic component of tyre friction, thereby contributing to an improvement in road skid resistance.

6.4 Correlation of Texture Measures

Comprehensive surface texture depth measurements were made along each of the 24 test sites. Each site was 200 m long. For each site, average texture depth measurements were derived for 11 x 1.7 m long profiles measured with a laser profilometer taken at 20 m intervals, 11 volumetric patch measurements to ASTM E965 (i.e. glass beads instead of sand), and 44 outflow measurements.

The profiles were analysed to yield measures of mean profile depth (MPD) and root mean square (RMS). The MPD measure is generally preferred to the RMS measure because it represents the difference between the peak profile level and the average profile level and so, in effect, is a two dimensional representation of the volumetric patch method. In contrast, the RMS measure does not discriminate between upwards and downwards departures of the texture profile from the average profile level, whereas only downwards departures are of importance with respect to a surface's drainage ability.

For this study the drainage ability of each test site surface was directly measured with an outflow meter. The outflow measures were for a water volume of 0.4054 dm^3 (52.35 mm water height drop by 99.3 mm diameter), giving an outflow time of 0.14 seconds under free draining conditions.

For the range of chipseal surfaces tested, MPD correlated significantly better with mean texture depth (MTD) derived from the volumetric patch method ($R^2 = 0.92$) and reciprocal of outflow time, OT ($R^2 = 0.85$), than RMS (the corresponding R^2 values were 0.85 and 0.79 respectively).

Comparison with texture profile spectra showed outflow times to be most sensitive to texture wavelengths centred at 40 and 63 mm, corresponding to the outflow meter's 50 mm diameter opening, and the volumetric patch method to 50 and 80 mm wavelengths. In contrast, the derived texture measures, MPD and RMS, displayed sensitivity to a broad wavelength range which spans from 0.63 to 125 mm.

A significant result of the outflow measurements was the identification of a limiting value of texture depth for chipseal surfaces above which no further gains in drainage ability can be had. This limiting value is 2.5 mm in terms of MPD.

Recommendations

- Profile-derived measures of surface texture depth should be specified in terms of mean profile depth (MPD) as defined by ISO Standard 13473-1, "Characterisation of Pavement Texture Utilising Surface Profiles - Part 1, Determination of Mean Profile Depth", because of strong correlations with the volumetric patch method and drainage ability of the road surface.

- The application of the outflow meter as a general field instrument for periodic testing of road surfaces for drainage ability and speed gradient of wet skid resistance should be further investigated as a result of its low cost, ease of use, and good reproducibility.

6.5 International Friction Index (IFI)

Application of IFI was less than straightforward. Difficulties primarily stemmed from selecting the volumetric patch method (ASTM E965) as the reference texture measure for calibrating Transit New Zealand's stationary laser profilometer to convert MPD values to speed number, Sp.

IFI comprises two values: the wet skid resistance at a slip speed of 60 km/h (F60), and the speed number (Sp). Correct determination of Sp is important as it defines the speed-friction gradient. Unfortunately the volumetric patch method is too susceptible to operator influence. Therefore, while one operator can make very repeatable measurements and can obtain a very good correlation between MTD and MPD measurements, another operator can obtain a very different regression.

With regard to this study, a considerable difference was seen between the relationship between MTD and MPD suggested by PIARC of MTD = 0.8 MPD + 0.2 and the relationship of MTD = 1.018 MPD + 0.284 derived from the site measurements.

The corresponding Sp relationships are Sp (km/h) = 90.91 MPD + 11.13 using the PIARC-derived MTD-MPD conversion, and Sp (km/h) = 115.68 MPD + 20.67 using the experimentally derived MTD-MPD conversion. Therefore, for a MPD value of 2 mm, the difference in calculated Sp is 59 km/h (i.e. 193 cf. 252 km/h).

The F60 value also showed significant spread (up to ±11%) when derived for each site, even using PIARC-specified coefficient values in the IFI transformation expressions in which the GripTester measurements made at different survey speeds were input. This spread was reduced if actual measurements of speed sensitivity were used to derive transformation coefficients required by the IFI transformation expressions.

This result suggests that the general forms of the IFI transformation expressions are essentially correct. However, PIARC-derived coefficients appear inappropriate for New Zealand chipseal road surfaces.

Recommendations

- The common skid testers in use in New Zealand use the British Pendulum Tester, GripTester and SCRIM. Accordingly, to enable reliable conversion from one skid resistance measure to another, the recommendation is that either:

    1. The survey speeds of the GripTester and SCRIM be standardised to 54 km/h and 29 km/h respectively to give a measuring wheel slip speed equivalent to that of the slider of the BPT, i.e. 10 km/h. The various measures of skid resistance (GN, SFC and BPN) would then have identical values.

or 2. Transformation coefficients required by the IFI transformation expressions be derived for local road surfaces. This would require GripTester and SCRIM skid resistance measurements made over a range of survey speeds to be correlated with BPT readings for a wide range of road surfaces and road texture depths.

6.6 Implications for TNZ M/6 Specification

The results of the field studies undertaken as part of this research programme confirms previous overseas research that size and shape characteristics of sealing chips are important determinants of wet skid resistance along with PSV.

The Transit New Zealand M/6 Specification for Sealing Chips (1993) incorporates PSV requirements. However, insufficient cognizance of the role of surface geometry is made with regard to amplitude, wavelength and mean slope in maximising available wet skid resistance. The only existing geometric constraints relate to a 2.25 maximum aspect ratio (i.e. average greatest dimension (AGD) to average least dimension (ALD) ratio).

The present research findings suggest that, for material of a given PSV value, about 75-80% of the observed on-road wet skid resistance values can be explained by surface texture over 0.5 to 50 mm wavelengths.

Recommendation

- Additional research into defining the optimum shape of aggregates is required for incorporation in TNZ M/6: 1993. This research will also provide guidance to the aggregate industry as to how to optimise quarry production with regard to shape requirements so that sealing chips of a known PSV can be produced to meet specified skid resistance values.

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APPENDIX 1
POLISHED STONE VALUE TEST RESULTS

APPENDIX 1. PSV TEST RESULTS

A1. SAMPLE DESCRIPTIONS BASED ON BINOCULAR MICROSCOPY

A1.1 Definitions

mT1 = coarse microtexture scale (wavelengths $\geq$ 1 mm)
mT2 = medium microtexture scale (0.05 mm $\leq$ wavelengths < 1 mm)
mT3 = fine microtexture scale (wavelengths < 0.05 mm)
ALD = average least dimension)
AID = average intermediate dimension) as defined in Transit New Zealand's Bituminous
AGD = average greatest dimension) Sealing Manual (1992)

mT1 descriptors - broad (deviation from mean facial plane ≈ 5°)
low (≈ 15°)
moderate (≈ 30°)
sharp (≈ 45° and greater)

mT2 descriptors - good (amplitude to wavelength ratio ≈ 1)
moderate (≈ 0.5)
poor (≈ 0.2)
absent

A1.2 Descriptions

For each PSV sample, proportions of faces with mT1 of a particular height or depth interval and proportions of mT2 grade are reported. Basic size and shape data are also given.

A1.2.1 Grade 6 uncrushed

Unpolished

Size: ALD 2-5 mm
AID 4-7 mm
AGD 5-13 mm

Shape: AGD:ALD range 1.1-3.3
Average 1.7
Stones are sub-rounded to rounded and typically sub-equant.

Faces: 90% of stones are dominated by faces or sub-faces defined by rounded edges and corners. 10% are sub-spherical, dominated by curved surface area rather than distinct faces. There is gradation between these divisions as follows:

- 5% of stones are composed of flat faces with smoothed edges and corners
- 55% are composed of faces and have rounded edges and corners
- 30% are dominated by faces but have a significant proportion of curved surface area (20-40%)

- 5% are dominated by curved surface area but have one or more distinct faces
- 5% are highly rounded and have no distinct faces

Overall, the stones comprise 25% curved or rounded surface area and 75% faces. Curved surface area is generally devoid of mT1 features.

Faces are flat, broadly concave and, less commonly, broadly convex. At least 50% of faces have mT1 features and therefore up to 40% of stone surface area is mT1-bearing. The majority of mT1-absent faces are flat or convex, facial concavity tends to be the result of mT1.

mT1: mT1 ranges from face-scale concave features with depths of <0.5mm to sharp defects. mT1 features result from parts of a stone being broken off and are consequently dominated by depressions. Asperities are often coupled with depressions but can occur as isolated points. mT1 wavelength ranges from 2-7 mm and height/depth from 0.5-2 mm with an average of 0.8 mm. Escarpments are common forming asymmetrical asperities and depressions. Ridge/valley features occur where the rock shows micro-veining in several orientations.

Most mT1 features are related to generic discontinuities such as veins, joints, fractures, shears and sedimentary structures (namely bedding); mT1 also results from localised concentrated grain loss. Variation in mT1 profile is a function of the angle between the plane of discontinuity and the facial plane, and of the amount of alluvial wear that has occurred since the texture forming event.

mT2: On curved surfaces mT2 is absent to poor and on faces mT2 is poor on average; grains have been planed down by alluvial wear. Pitting from grain loss contributes moderate mT2 on approximately 50% of stones. Siltstone (10% of the sample) and argillite (rare) are generally mT2-absent because granular texture is commonly mT3 for these lithotypes. Slightly weathered material (5%) is more susceptible to grain loss, the majority has moderate mT2 on average. mT2 is best preserved in concave mT1 features; the level of mT2 (e.g. poor, moderate or good) is dependent on the characteristic of the mT1 depression, i.e. sharper, deeper, shorter wavelength topography allows better preservation of mT2.

Overall, mT2 is: 10% absent,
25% absent to poor,
40% poor,
20% moderate,
5% good.

Polished

80-85 stones per PSV specimen.

mT1: mT1 is smoothed but otherwise retained.
40% of exposed faces are flat or broadly convex and are mT1-absent;
25% about 0.5 mm mT1: face-scale, low profile concave topography and around 2 mm wavelength asperities and depressions;

25% 0.5-1 mm mT1: commonly planar faces with 2-5 mm wavelength, moderate to low profile asperities and depressions, and escarpments;
10% >1mm mT1: 2-5 mm wavelength, sharp to moderate profile asperities and depressions.

mT2: The effective contact area is 70-75% of exposed face surface area; within this mT2 is:
15% absent,
40% absent to poor,
40% poor,
5% poor to moderate.

Moderate mT2 usually occurs on weathered stones but not all weathered material exhibits better mT2 retention. mT2-absence is typical of fine siltstone and argillite which retain, on average, poor to absent granular texture that is technically mT3, and strongly quartz-veined and silicified material which polishes very evenly due to its mono-minerallic nature. At least half of the mT2-absent faces are on sandstone aggregates although many of these stones are likely to originally have had low levels of mT2 due to alluvial wear.

A1.2.2 Grade 6 crushed

Unpolished

Size:
ALD 2-6 mm
AID 3-7 mm
AGD 5-11 mm

Shape:
AGD:ALD range 1.3-3.4
Average 1.8
Stones are sub-angular to angular and range from equant to shardy (high AGD:ALD,AID) and less commonly to platy (high AGD,ALD:AID); edges and corners are sharp.

mT1: 15% of faces lack mT1. Two thirds of these (10% total) are convex or, less commonly, flat alluvial surfaces. The remainder (5% total) are joint, vein or fresh broken but planar surfaces.

25% of faces have subtle mT1 topography with ≤0.5mm height or depth,
40% 0.5-1mm mT1,
20% 1-1.5mm mT1.

mT1 features are highly varied, there is a tendency for either low profile, uneven topography or sharp, prominent defects. Wavelength ranges from 1mm to face-scale. Ridges, often classifiable either as mT1 asperities or edges defining sub-faces, and depressions with coupled face-edge asperities are the most common forms of mT1. Asperities frequently have sharp apexes. Escarpments are typical where breakage has occurred due to joints and veins intersecting the face.

mT2: 5% absent,
15% poor,
55% moderate,
25% good.

mT2 is absent or poor for highly silicified material and faces formed by breakage along silicified planes, on joint, fracture and vein-coincident faces, alluvial surfaces and for siltstone particles (although some non-granular but mT2-scale microtexture is created during crushing of siltstone). On the majority of fresh broken faces individual grains provide fairly continuous, moderate or good mT2 with 0.1-0.5 mm wavelength generally superimposed on coarser mT2 contributed by groups of grains with 0.5-1 mm wavelength.

Polished
100 stones per PSV specimen.

mT1: mT1 appears unaffected by the polishing process.
10% of exposed faces are flat or lack significant mT1,
20% 0.5mm mT1,
50% 0.5-1mm mT1,
20% >1 mm mT1, one third of these are technically sub-faced with only half of their surface area parallel to the plane of polishing.

mT2: Overall mT2 proportions are:
5% absent (alluvial faces, siltstone/argillite, highly quartzose and silicified material),
25% poor,
55% moderate,
15% good.

Effective contact area is considerably less than the uncrushed polished specimens comprising a maximum 30% of the exposed face surface area. Effective contact area is principally a function of mT1. Additional factors in this case are that 5% of exposed faces slope away from the plane of polishing and 5% of exposed faces sit lower than neighbouring stones and are protected from polishing. mT1-absent faces are susceptible to mT2-polishing over their whole surface. The 10% of exposed faces that lack mT1 are mT2-absent or poor. However, given the observations of unpolished aggregates, most are likely to be alluvial, joint or vein surfaces that originally had low levels of mT2.

Polishing of mT2 occurs on the upper parts of mT1 asperities, the extent of polishing is strongly dependent on the wavelength and texture depth of mT1 features. Differences in elevation on the exposed faces causes significant variation in mT2 removal on single faces. This can make the effective contact area difficult to recognise. Shininess caused by mT3 removal can be used as an indicator of obvious polishing.

Within the effective contact area, mT2 is:
5% absent,
10% absent to poor,
55% poor,
30% moderate.

Most moderate mT2 is the coarser type formed by groups of grains.

A1.2.3 Grade 5 uncrushed

Unpolished

Size: ALD 3-6 mm
AID 6-9 mm
AGD 7-19 mm

Shape: AGD:ALD range 1.3-4.7
Average 2.0
Stones are sub-rounded to rounded and tend to be elongated.

Faces: The stones comprise 80% flat, slightly concave or slightly convex faces and 20% curved surface area. 10% of particles are highly rounded but have at least one distinct face. Faces are defined by edges that are mostly well rounded but range to sharp.

45% of faces (35% of stone surface area) have mT1 topography.

mT1: Of faces with mT1:
45% 0.5 mm mT1: concavities with ≥5mm wavelengths and defects with 2-3 mm wavelengths,
30% 0.5-1 mm mT1: approximately 5 mm wavelength, low profile asperities and depressions;
10% approximately 1 mm mT1: features with 2-4 mm wavelengths,
15% 1.0-1.5 mm mT1: approximately 5 mm wavelength, moderate profile asperities and depressions.

About 35% of mT1 features relate to breakage on a quartz vein that intersects the face, another vein, a joint, fracture or bedding. The majority of mT1-forming breakage occurs where two roughly conjugate discontinuities intersect, one sub-parallel to the original face and the other sub-perpendicular. The face is basically split into two levels separated by a sloping or vertical segment (escarpment). This segment and the lower level form a asymmetrical depression and, with alluvial rounding, the upper level forms an asperity.

mT2: 10% absent,
35% absent to poor,
35% poor,
15% moderate,
5% good.

Polished
50 to 55 stones per PSV specimen.

mT1:
40% of exposed faces are flat or broadly curved mT1-absent surfaces,
30% 0.5 mm mT1,
20% 0.5-1 mm mT1,
10% >1 mm mT1.

mT2:
The effective contact area is 75% of the exposed face surface area; within this mT2 is:
15% absent,
40% absent to poor,
40% poor,
5% poor to moderate.

mT2 is mostly absent for siltstone (10% of the sample) and highly quartzose and silicified material (5-10%). 5% of stones are slightly weathered and retain poor to moderate or at least poor mT2. mT2 retention is aided by differential wear of grains but is primarily a function of grain loss. Most stones classified with absent to poor mT2 show very even grain wear that is partially offset by pitting from lost grains. In general "absent to poor" refers to even wear of grains with some retained coarser (multi-grain) mT2.

mT3 removal is common on mT2 asperities and over mT2-absent or -absent to poor areas that are inferred to have originally lacked mT2.

A1.2.4 Grade 5 crushed

Unpolished
Size:
ALD 3-8 mm
AID 4-11 mm
AGD 7-18 mm

Shape:
AGD:ALD range 1.3-4.5
Average 1.9

Stones are sub-angular to angular and mostly equant tending shardy; approximately 5% are strongly shardy (AGD:AID,ALD >3:1) or platy (AGD,AID:ALD >3:1). Stone edges and corners are sharp.

mT1:
30% of stones have a single alluvial face and on a few stones up to half of the surface area comprises remnant alluvial surface.
Overall, 5% of faces are alluvial; these are mT1-absent.
5% of faces are joint, fracture or vein surfaces which have little or no mT1;
15% approximately 0.5mm mT1: surface rippling or unevenness continuous from coarse mT2 with 1-3 mm wavelength and low profile, 3-5 mm wavelength domes;
25% 0.5-1 mm mT1: approximately 5 mm wavelength, low profile concavities which have corresponding asperities usually present at the edges of faces and 2-3 mm wavelength, moderate profile depressions with coupled asperities;

25% about 1 mm mT1: moderate profile, 3-4 mm wavelength asperities and ridges which often result in sub-facing;
20% 1-1.5 mm mT1: approximately 5 mm wavelength, moderate profile concavities with corresponding face-edge asperities and 2-3 mm wavelength, sharp profile asperities and depressions;
5% >1.5 mm mT1: sharp, fracture or joint related features.

mT2: 5% absent,
10% poor,
55% moderate,
30% good.

Polished
50 stones per PSV specimen.

mT1: 5% of exposed faces are flat,
5% ≤0.5 mm mT1,
40% 0.5-1 mm mT1,
40% 1-1.5 mm mT1,
10% ≥1.5 mm mT1.

mT2: Effective contact area varies from 25% to 35% of the exposed face surface area on the different specimens and is 30% overall. Within this, mT2 is:
10% absent to poor,
65% poor,
25% moderate.

mT2 retention is greatest in areas where shorter wavelength mT1 and coarse mT2 create an uneven surface from which only finer mT2 is removed, and particularly where original mT2 was good.

A1.2.5 Grade 4 uncrushed

Unpolished
Size: ALD 3-9 mm
AID 7-13 mm
AGD 9-20 mm

Shape: AGD:ALD range 1.3-4.7
Average 1.8

Stones are rounded to sub-rounded and have equant to elongate and equant to flattened form but are rarely strongly shardy or platy.

Faces: Stones are faced and have well rounded edges and corners. 15% have smoothed rather than rounded edges and 10% have highly rounded edges but are still dominantly facial. On 5% of stones, relatively recent alluvial breakage has produced a face rimmed by sharp edges. Overall the stones comprise 85% faces and 15% curved surface area.

40% of faces (35% of stone surface area) have mT1 features.

mT1: Face-scale, very low profile, convex or concave features with less than 0.5 mm height or depth are considered to be natural facial curvature and are not classed as mT1. Of faces with mT1:
40% approximately 0.5 mm mT1: mainly alluvially worn depressions with an average wavelength of 5 mm, small escarpments and 2-3 mm wavelength pitting from grain loss;
45% 0.5-1 mm mT1: also mainly depressional features with corresponding, usually face-edge, asperities; commonly related to linear defects.
12.5% 1-1.5 mm mT1: asperities coupled to asymmetric defects and moderate profile, face-central asperities that are not ridge-like enough to divide a face into sub-faces;
2.5% >1.5 mm mT1: valleys with corresponding prominent face-edge asperities that mostly form due to joint-joint or joint-vein interaction and, except where sharply profiled, dominate a face.

mT2: 15% absent,
35% absent to poor,
35% poor,
15% moderate or good.

Polished (12 hours polishing)
35 to 40 stones per PSV specimen.

mT1: 45% of exposed faces are flat to broadly convex or concave and are mT1-absent;
20% about 0.5 mm mT1: small escarpments; 2-3 mm wavelength asperities and depressions; and 5 mm wavelength, very low profile features.
20% 0.5-1 mm mT1: 5-8 mm wavelength, low profile depressions and rises; and 3 mm wavelength face-edge asperities.
15% >1 mm mT1: ridges that divide the exposed face into sub-faces; ca. 5 mm wavelength, moderate profile asperities and depressions; and large escarpments.

mT2: Effective contact area is approximately 80% of the exposed face surface area. Non-contact area consists parts of exposed faces that slope or curve away from the plane of and areas protected from polishing by mT1. Within the effective contact area mT2 is: 15% absent,
40% absent to poor,
40% poor,
5% poor to moderate.

A1.2.6 Grade 4 crushed

Unpolished
Size: ALD 3-9 mm
AID 7-13 mm
AGD 9-21 mm

Shape:	AGD:ALD range 1.4-4.1 Average 1.9 Stones are angular and sub-angular and are sub-equant with equal tendency to shardy and platy form. Stone edges and corners are sharp.
mT1:	10% mT1-absent faces: either alluvial, flat joint or vein surfaces or fresh broken but planar faces; 10% approximately 0.5 mm mT1: mostly 1-3 mm wavelength domed and pitted topography; 30% 0.5-1 mm mT1: long wavelength, broad to low profile features and about 2-4 mm wavelength points, ridges and escarpments with corresponding depressions; 40% 1-1.5 mm mT1: highly variable texture, 10% >1.5 mm mT1: large face-edge asperities and sharp craggy topography in veined or silicified material.
mT2:	15% poor: alluvial faces, siltstone/argillite, silicified material, most quartz vein and joint faces. Includes mT2-absent to poor surfaces which are approximately 5% total. 50% moderate, 35% good.

<u>Polished</u> (12 hours polishing)
40 stones per PSV specimen.

mT1:	Exposed face mT1 proportions are essentially the same as those on the unpolished aggregates. 10% of faces are flat, or the majority of their surface is planar and parallel to the plane of polishing, and have <0.5 mm mT1; 10% approximately 0.5 mm mT1: much of this is ≤2 mm wavelength, moderate profile topography that is continuous from coarse mT1. Also common are slightly domed plateaus and lowly stepped escarpments. 30% 0.5-1 mm mT1: about 5 mm wavelength, low profile and approximately 3 mm wavelength, moderate profile asperities and depressions; escarpments. 40% 1-1.5 mm mT1: face-scale deviations of 1-1.5 mm with finer mT1 superimposed; about 3 mm wavelength, moderate to sharp profile asperities and depressions; plateaus separated by steep sided furrows. 10% ≥1.5 mm mT1: long wavelength depressions with corresponding face-edge asperities; 4-6 mm wavelength, moderate profile ridges; large escarpments.
mT2:	Effective contact area is 30% within which mT2 is: 20% absent to poor, 50% poor, 30% moderate: mostly coarser mT2.

A1.2.7 Grade 4 mixed (12 hours polishing)

35 to 40 stones per PSV specimen.

The specimens were constructed with 45% to 55% of each end member and average 50:50.

Microtexture retention and removal on the crushed and uncrushed stones is very similar to the stones in the all-crushed and all-uncrushed specimens.

For uncrushed stones:

mT1: 40-50% of exposed faces are flat, convex or, less commonly, broadly concave and have no significant mT1;
approximately 40% 0.5≥1.0 mm mT1;
10-20% >1 mm mT1.

mT2: Effective contact area is roughly 80% in which mT2 is:
10% absent,
40% absent to poor,
45% poor,
5% poor to moderate.

For crushed stones:

mT1: 5% of faces are flat with <0.5 mm high/deep mT1;
10% approximately 0.5 mm mT1,
35% 0.5-1 mm mT1,
40-45% 1-1.5 mm mT1,
5-10% >1.5 mm.

mT2: Effective contact area is 25% in which mT2 is:
15% absent to poor,
55% poor,
30% moderate.

For the total mixed specimen:

mT1: 25% flat, mT1-poor faces;
15% approximately 0.5 mm mT1,
30% 0.5-1 mm mT1,
25% 1-1.5 mm mT1,
5% >1.5 mm mT1.

mT2: Effective contact area varies from 50% to 60% and is 55% on average; within this mT2 is:
5% absent,
30% absent to poor,
50% poor,
15% moderate.

APPENDIX 1. PSV TEST RESULTS (continued)

A2. PSV DATA

PSV results for each specimen (four specimens to a sample) are tabulated below. For the grade 5 and 6 samples, the skid numbers (SN) are converted to raw PSV as reported by the testing agency. However, for the grade 4 samples, only the skid number is listed for each time increment.

A2.1 Grades 5 and 6

Sample	Raw PSV					Specimen average	Uncorrected sample PSV	Corrected sample PSV
Grade 6, uncrushed	47.7	46.0	46.0	44.3	44.3	44.9	42.4	42.0
	44.3	43.4	42.6	42.6	42.6	42.6		
	46.0	44.3	42.6	42.6	42.6	42.6		
	42.6	41.7	40.9	39.2	39.2	39.8		
Grade 6, crushed	63.0	60.5	59.6	59.6	59.6	59.6	56.1	56.0
	59.6	59.6	57.9	57.9	57.1	57.6		
	58.8	56.2	54.5	54.5	54.5	54.5		
	56.2	54.5	52.8	52.8	52.8	52.8		
Grade 5, uncrushed	44.3	42.6	41.7	41.7	41.7	41.7	43.0	42.0
	47.7	46.8	46.8	46.0	45.1	46.0		
	49.4	46.0	46.0	46.0	46.0	46.0		
	42.6	40.9	39.2	38.3	37.5	38.3		
Grade 5, crushed	57.1	56.2	55.4	54.5	54.5	54.8	53.6	53.0
	59.6	58.8	57.9	57.1	55.4	56.8		
	55.4	52.8	51.1	51.1	51.1	51.1		
	51.1	51.1	49.4	49.4	49.4	49.4		
Controls	57.9	56.2	55.4	54.5	54.5	54.8	53.0	
	57.1	54.5	53.7	52.8	52.8	53.1		
	52.8	56.2	52.8	56.2	55.4	54.8		
	51.1	51.1	49.4	49.4	49.4	49.4		

Note: (1) Specimen average is the average of the last three raw PSV readings.
(2) Uncorrected sample PSV = average of the specimen averages.

A2.2 Grade 4

Specimen number	Time (hr)	Skid numbers					Specimen average	Raw PSV
5 (Uncrushed)	0.0	32.0	32.5	32.0	32.0	32.0	32.0	54.5
	0.5	33.0	32.5	32.0	32.0	32.0	32.0	54.5
	1.0	34.0	33.0	32.5	32.5	32.5	32.5	55.4
	1.5	34.0	34.0	33.0	32.5	32.5	32.7	55.7
	2.0	34.0	33.0	33.0	32.5	32.5	32.7	55.7
	2.5	34.0	33.0	33.0	33.0	32.5	32.8	55.9
	3.0	33.0	33.0	32.5	32.5	32.0	32.4	55.1
	3.5	29.0	29.0	28.0	28.0	28.0	28.0	47.7
	4.0	28.0	28.0	27.5	27.5	27.5	27.5	46.8
	4.5	28.0	28.0	27.5	27.5	27.5	27.5	46.8
	6.0	27.0	26.0	25.0	25.0	25.0	25.0	42.6
	9.0	27.0	27.0	26.0	26.0	25.5	25.8	44.0
	12.0	25.0	24.0	24.0	23.0	23.0	23.3	39.8
6 (Uncrushed)	0.0	29.0	28.0	28.0	27.5	27.5	27.7	47.1
	0.5	32.0	31.0	30.0	30.0	30.0	30.0	51.1
	1.0	34.0	33.0	32.5	32.0	32.0	32.2	54.8
	1.5	33.0	32.0	32.0	31.0	31.0	31.3	53.4
	2.0	34.0	32.5	32.0	32.0	32.0	32.0	54.5
	2.5	34.0	33.0	32.0	32.0	32.0	32.0	54.5
	3.0	33.0	32.0	32.0	32.0	32.0	32.0	54.5
	3.5	28.0	28.0	27.5	27.0	27.0	27.2	46.3
	4.0	27.0	27.0	27.0	26.0	26.0	26.3	44.9
	4.5	28.0	27.0	27.0	26.0	26.0	26.3	44.9
	6.0	26.0	25.0	25.0	25.0	24.0	24.7	42.0
	9.0	27.0	26.0	25.5	25.5	25.5	25.5	43.4
	12.0	25.0	24.0	24.0	23.0	23.0	23.3	39.8
7 (Uncrushed)	0.0	29.0	28.0	27.5	27.5	27.5	27.5	46.8
	0.5	30.0	29.0	29.0	28.0	28.0	28.3	48.3
	1.0	33.0	32.0	32.0	31.0	31.0	31.3	53.4
	1.5	34.0	34.0	32.5	32.5	32.0	32.3	55.1
	2.0	34.0	33.0	33.0	32.5	32.5	32.7	55.7
	2.5	33.0	32.5	32.0	32.0	32.0	32.0	54.5
	3.0	34.0	33.0	33.0	32.5	32.0	32.5	55.4
	3.5	30.0	29.0	28.0	28.0	28.0	28.0	47.7
	4.0	28.0	28.0	27.5	27.5	27.0	27.3	46.6
	4.5	29.0	28.0	27.5	27.5	27.5	27.5	46.8
	6.0	27.0	27.0	26.0	26.0	25.0	25.7	43.7
	9.0	26.0	25.5	25.0	25.0	25.0	25.0	42.6
	12.0	24.0	23.0	23.0	23.0	22.5	22.8	38.9

A2.2 (cont'd)

Specimen number	Time (hr)	Skid numbers					Specimen average	Raw PSV
8 (Uncrushed)	0.0	32.0	31.0	31.0	31.0	30.5	30.8	52.5
	0.5	34.0	33.0	32.5	32.5	32.0	32.3	55.1
	1.0	36.0	35.0	34.0	34.0	34.0	34.0	57.9
	1.5	37.0	36.0	35.0	35.0	35.0	35.0	59.6
	2.0	36.0	35.0	35.0	34.0	34.0	34.3	58.5
	2.5	36.0	35.0	34.0	33.0	33.0	33.3	56.8
	3.0	38.0	36.0	35.0	35.0	35.0	35.0	59.6
	3.5	33.0	32.0	32.0	32.0	32.0	32.0	54.5
	4.0							
	4.5							
	6.0							
	9.0							
	12.0							
9 (Mixed)	0.0	39.0	38.0	38.0	38.0	38.0	38.0	64.7
	0.5	38.0	38.0	38.0	38.0	37.5	37.8	64.5
	1.0	39.0	39.0	37.5	38.0	38.0	37.8	64.5
	1.5	38.0	38.0	38.0	37.5	37.5	37.7	64.2
	2.0	38.0	38.0	38.0	38.0	37.5	37.8	64.5
	2.5	38.0	38.0	38.0	37.5	37.5	37.7	64.2
	3.0	38.0	39.0	38.0	38.0	37.5	37.8	64.5
	3.5	34.0	35.0	34.0	34.0	34.0	34.0	57.9
	4.0							
	4.5							
	6.0							
	9.0	32.0	31.0	31.0	31.0	31.0	31.0	52.8
	12.0	31.0	30.0	28.0	28.0	28.0	28.0	47.7
10 (Mixed)	0.0	36.0	34.0	33.5	33.0	33.0	33.2	56.5
	0.5	34.0	33.0	33.0	32.5	32.5	32.7	55.7
	1.0	34.0	34.0	32.5	32.5	32.0	32.3	55.1
	1.5	35.0	35.0	33.5	33.0	33.0	33.2	56.5
	2.0	34.0	33.0	33.0	32.5	32.5	32.7	55.7
	2.5	33.0	33.0	33.0	32.0	33.0	32.7	55.7
	3.0	34.0	33.0	32.0	32.0	32.0	32.0	54.5
	3.5	29.0	30.0	29.0	29.0	29.0	29.0	49.4
	4.0	30.0	30.0	29.0	28.0	28.0	28.3	48.3
	4.5	30.0	29.0	28.0	28.0	28.0	28.0	47.7
	6.0	28.0	27.0	27.0	26.0	26.0	26.3	44.9
	9.0	26.0	26.0	26.0	26.0	26.0	26.0	44.3
	12.0	32.0	30.0	30.0	30.0	30.0	30.0	51.1

A2.2 (cont'd)

Specimen number	Time (hr)	Skid numbers					Specimen average	Raw PSV
11 (Mixed)	0.0	37.0	37.0	37.0	37.0	36.0	36.7	62.5
	0.5	37.0	36.0	35.0	35.0	35.0	35.0	59.6
	1.0	38.0	37.0	37.0	37.0	37.0	37.0	63.0
	1.5	37.0	36.0	35.0	35.0	35.0	35.0	59.6
	2.0	38.0	35.0	35.0	35.0	35.0	35.0	59.6
	2.5	35.0	34.0	34.0	33.0	33.0	33.3	56.8
	3.0	37.0	35.0	35.0	35.0	34.0	34.7	59.1
	3.5	32.5	31.0	30.0	30.0	30.0	30.0	51.1
	4.0	32.0	30.0	29.0	29.0	29.0	29.0	49.4
	4.5	32.0	30.0	30.0	30.0	29.0	39.7	50.5
	6.0	30.0	27.5	27.5	27.5	27.5	27.5	46.8
	9.0	30.0	28.0	27.5	27.5	27.5	27.5	46.8
	12.0	28.0	27.0	27.0	27.0	27.0	27.0	46.0
12 (Mixed)	0.0	36.0	35.0	35.0	35.0	35.0	24.0	59.6
	0.5	36.0	34.0	34.0	33.0	33.0	33.3	56.8
	1.0	36.0	36.0	35.0	35.0	35.0	35.0	59.6
	1.5	37.0	36.0	35.5	35.0	35.0	35.2	59.9
	2.0	36.0	35.0	35.0	34.0	34.0	34.3	58.5
	2.5	34.0	33.0	32.5	32.5	32.5	32.5	55.4
	3.0	35.0	34.0	34.0	33.0	33.0	33.3	56.8
	3.5	40.0	29.0	29.0	29.0	29.0	29.0	49.4
	4.0	40.0	27.5	27.5	27.5	27.5	27.5	46.8
	4.5	29.0	28.0	27.5	27.5	27.5	27.5	46.8
	6.0	28.0	27.0	27.0	27.0	27.0	27.0	46.0
	9.0	27.0	26.0	25.0	25.0	25.0	25.0	42.6
	12.0	26.0	25.0	24.0	24.0	24.0	24.0	40.9
1 (Crushed)	0.0	42.0	43.0	43.0	42.5	42.5	32.4	72.1
	0.5	41.0	40.0	39.0	39.0	38.0	38.7	65.9
	1.0	39.0	38.0	37.5	37.5	37.0	37.3	63.6
	1.5	39.0	38.5	38.0	37.5	37.5	37.7	64.2
	2.0	38.0	37.0	37.0	37.0	36.0	36.7	62.5
	2.5	37.0	37.0	36.0	36.0	36.0	36.0	61.3
	3.0	37.0	37.0	36.0	36.0	36.0	36.0	61.3
	3.5	37.0	35.0	35.0	34.0	34.0	34.3	58.5
	4.0	32.5	32.0	32.0	31.0	31.0	31.3	53.4
	4.5	32.5	32.0	32.0	32.0	31.0	31.7	53.9
	6.0	30.0	29.0	29.0	29.0	29.0	29.0	49.4
	9.0	32.0	31.0	30.0	30.0	30.0	30.0	51.1
	12.0	30.0	29.0	29.0	29.0	28.5	28.8	49.1

A2.2 (cont'd)

Specimen number	Time (hr)	Skid numbers					Specimen average	Raw PSV
2	0.0	42.5	42.0	42.0	42.0	42.0	42.0	71.6
(Crushed)	0.5	40.0	39.0	39.0	38.0	38.0	38.3	65.3
	1.0	40.0	39.0	38.5	3.5	38.0	38.3	65.3
	1.5	41.0	39.0	39.0	38.0	38.0	38.3	65.3
	2.0	37.0	38.0	38.0	37.5	37.5	37.7	64.2
	2.5	39.0	37.5	37.5	37.5	37.5	37.5	63.9
	3.0	38.0	37.0	37.0	37.0	37.0	37.0	63.0
	3.5	34.0	32.5	32.0	32.0	32.0	32.0	54.5
	4.0	32.5	32.0	31.0	31.0	30.0	30.7	52.2
	4.5	32.0	32.0	31.0	31.0	31.0	31.0	52.8
	6.0	30.0	29.0	28.0	28.0	28.0	28.0	47.7
	9.0	31.0	30.0	30.0	30.0	29.5	29.8	50.8
	12.0	29.0	28.0	28.0	28.0	28.0	28.0	47.7
3	0.0	42.0	42.5	42.5	42.0	42.0	42.2	71.8
(Crushed)	0.5	42.0	41.0	41.0	40.0	40.0	40.3	68.7
	1.0	40.0	39.0	38.0	37.5	37.5	37.7	64.2
	1.5	40.0	40.0	39.0	40.0	39.0	39.3	67.0
	2.0	38.0	38.0	37.5	37.5	37.5	37.5	63.9
	2.5	39.0	38.0	37.5	37.0	37.0	37.2	63.3
	3.0	38.0	38.0	37.0	37.0	37.0	37.0	63.0
	3.5	33.0	32.0	32.0	32.0	31.0	31.7	53.9
	4.0	32.0	33.0	31.0	30.0	30.0	30.3	51.7
	4.5	31.0	31.0	30.0	30.0	30.0	30.0	51.1
	6.0	30.0	29.0	29.0	28.0	28.0	28.3	48.3
	9.0	32.0	30.0	30.0	30.0	30.0	30.0	51.1
	12.0	30.0	29.0	28.0	28.0	28.0	28.0	47.7
4	0.0	40.0	41.0	40.0	41.0	41.0	40.7	69.3
(Crushed)	0.5	40.0	40.0	40.0	40.0	39.0	39.7	67.6
	1.0	42.0	41.0	41.0	40.0	40.0	40.3	68.7
	1.5	40.0	39.0	39.0	38.0	38.0	38.3	65.3
	2.0	40.0	39.0	38.0	38.0	38.0	38.0	64.7
	2.5	39.0	38.0	38.0	37.5	37.5	37.7	64.2
	3.0	38.0	38.0	37.5	37.5	37.5	37.5	63.9
	3.5	34.0	33.0	33.0	33.0	33.0	33.0	56.2
	4.0	34.0	32.0	32.0	32.0	32.0	32.0	54.5
	4.5	34.0	33.0	32.5	32.0	32.0	32.2	54.8
	6.0	32.0	30.0	30.0	30.0	30.0	30.0	51.1
	9.0	33.0	32.0	32.0	31.5	31.5	31.7	53.9
	12.0	31.0	30.0	30.0	30.0	30.0	30.0	51.1

A2.2 (cont'd)

Specimen number	Time (hr)	Skid numbers					Specimen average	Raw PSV
13 (Control)	0.0	39.0	41.0	40.0	40.0	40.0	40.0	68.1
	0.5	38.0	37.5	37.5	37.5	37.4	37.5	63.9
	1.0	39.0	37.5	37.0	37.0	36.0	36.7	62.5
	1.5	38.5	37.5	37.0	37.0	37.0	37.0	63.0
	2.0	37.0	37.0	37.0	37.0	36.0	36.7	62.5
	2.5	37.0	36.0	35.0	35.0	35.0	35.0	59.6
	3.0	38.0	37.0	36.0	36.0	36.0	36.0	61.3
	3.5	33.0	32.0	32.0	32.0	31.0	31.7	53.9
	4.0	32.0	31.0	31.0	30.0	30.0	30.3	51.7
	4.5	32.5	32.0	31.0	31.0	30.0	30.7	52.2
	6.0	30.0	29.0	29.0	28.0	28.0	28.3	48.3
	9.0							
	12.0							
14 (Control)	0.0	38.0	38.0	37.5	36.0	36.0	36.5	62.2
	0.5	38.0	38.0	37.5	37.5	37.0	37.3	63.6
	1.0	38.0	37.5	37.0	37.0	37.0	37.0	63.0
	1.5	38.0	38.0	37.5	37.5	37.0	37.3	63.6
	2.0	38.0	37.0	37.0	37.0	37.0	37.0	63.0
	2.5	36.0	35.0	34.0	33.0	33.0	33.3	56.8
	3.0	37.0	37.0	37.0	37.0	37.0	37.0	63.0
	3.5	34.0	33.0	32.0	32.0	32.0	32.0	54.5
	4.0	34.0	32.5	32.0	32.0	32.0	32.0	54.5
	4.5	32.0	33.0	32.5	32.0	32.0	32.2	54.8
	6.0	30.0	29.0	29.0	29.0	29.0	29.0	49.4
	9.0							
	12.0							

Averaged Data

Time (hr)	Uncrushed raw PSV	Mixed raw PSV	Crushed raw PSV	Control raw PSV
0.0	50.2	60.8	71.2	48.9
0.5	52.3	59.2	66.9	
1.0	55.4	60.6	65.5	
1.5	56.0	60.1	65.5	
2.0	56.1	58.9	63.8	
2.5	55.4	58.0	63.2	
3.0	56.2	58.7	62.8	
3.5	49.1	52.0	55.8	
4.0	46.1	48.2	53.0	
4.5	46.2	48.3	53.2	
6.0	42.8	45.9	49.1	
9.0	43.3	46.6	51.7	
12.0	39.5	46.4	48.9	
	PSV	PSV	PSV	
	46.5	49.6	52.8	

APPENDIX 1. PSV TEST RESULTS (continued)

A3. PHOTOGRAPHS OF PSV SAMPLES AFTER POLISHING

Plate A1.1
Grade 4 uncrushed
(raw alluvial aggregate).

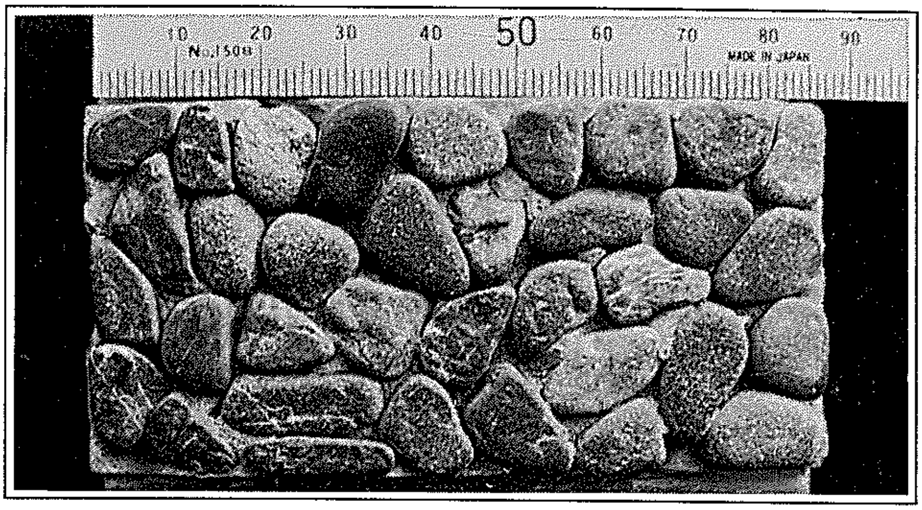


Plate A1.2
Grade 4 crushed (sealing chip)
plus grade 4 uncrushed:
50:50 mixture.

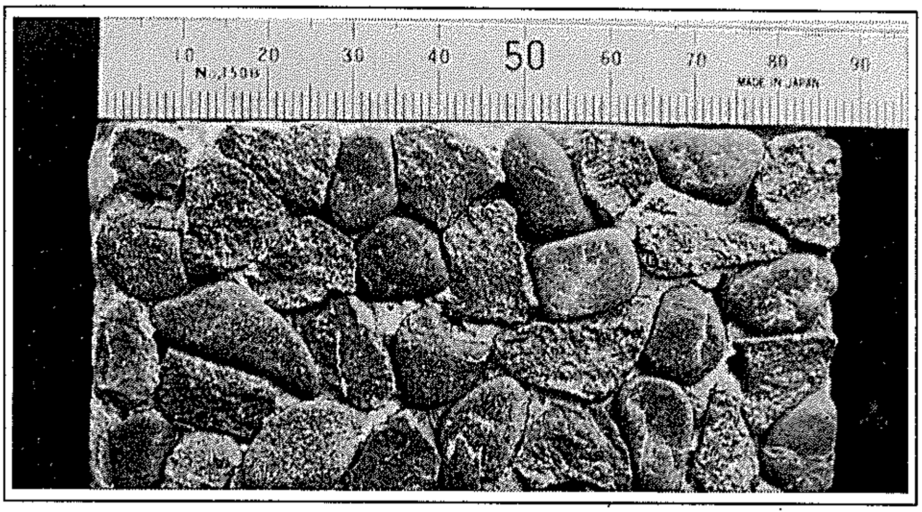
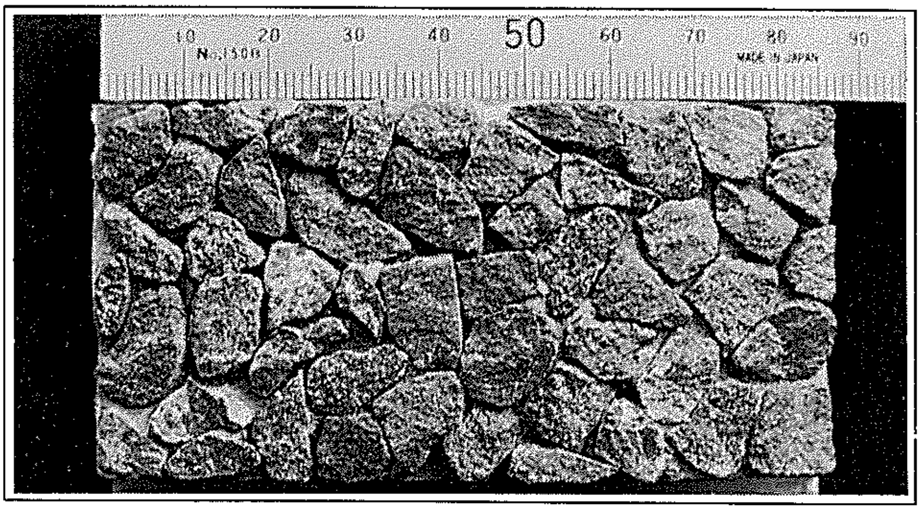


Plate A1.3
Grade 4 crushed (sealing chip).



Scale in mm

Plate A1.4
Grade 5 uncrushed
(raw alluvial aggregate).

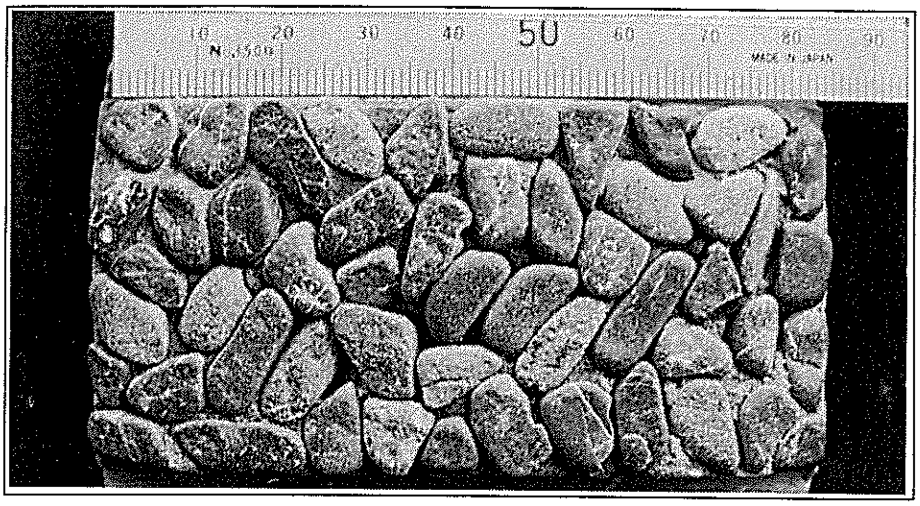


Plate A1.5
Grade 5 crushed (sealing chip).

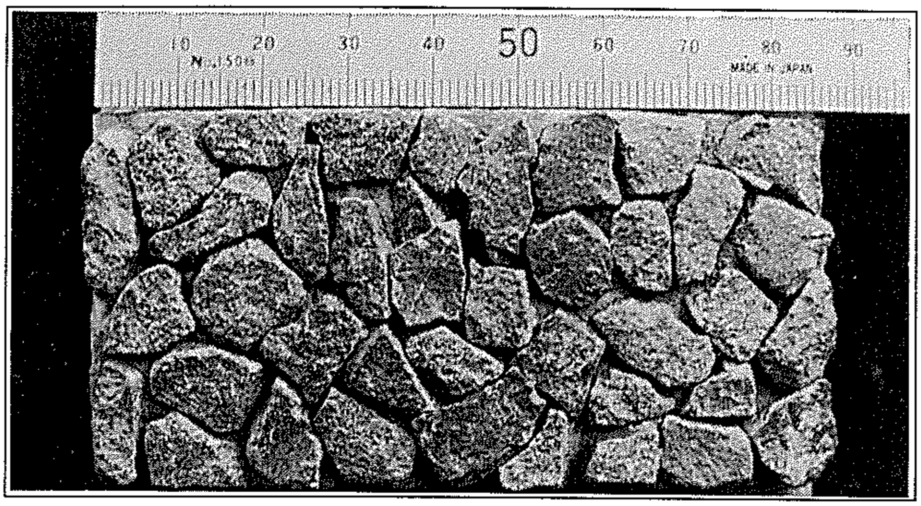
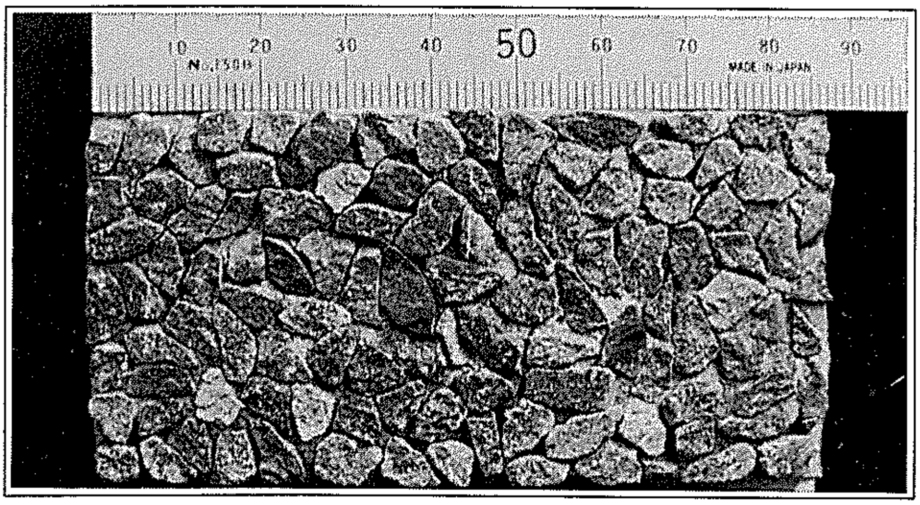


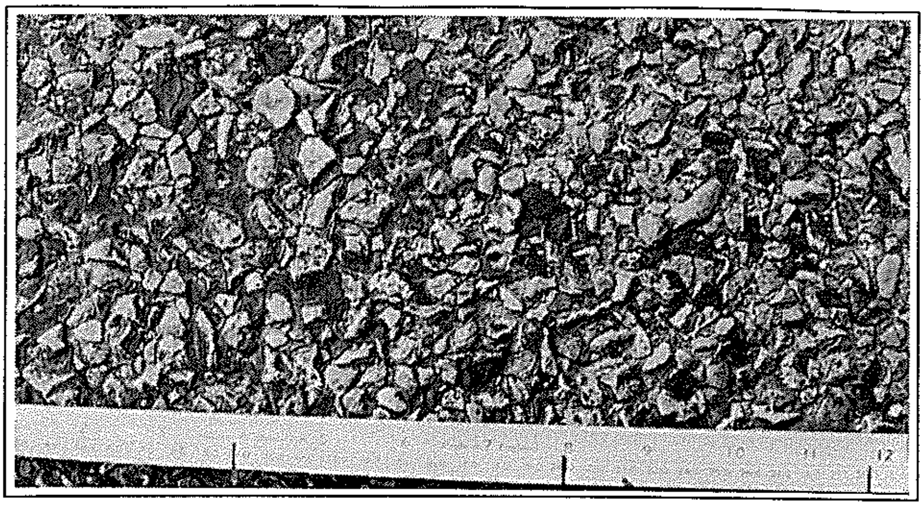
Plate A1.6
Grade 6 uncrushed
(raw alluvial aggregate).

Plate A1.7
Grade 6 crushed (sealing chip).

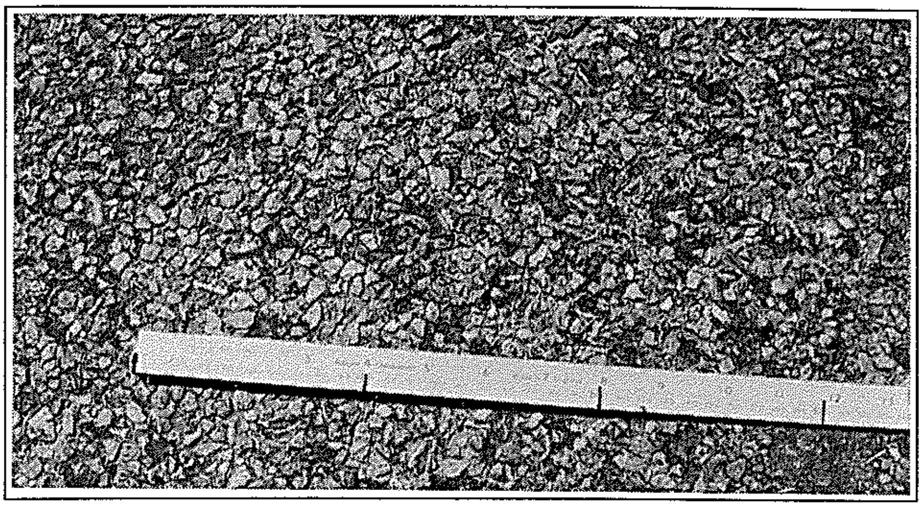


Scale in mm

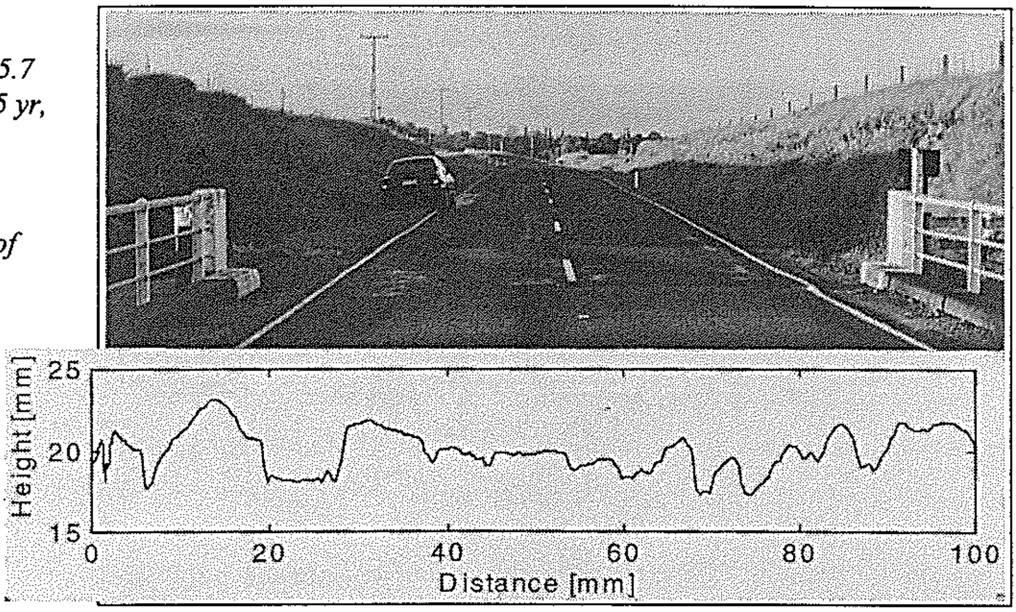
APPENDIX 2
ROAD SURFACES AT EACH TEST SITE



Site 1: SH50, RP 49/3.0-3.2
Grade 5, PSV 55, Age 4.5 yr,
Crushed faces 75%
Scale approx. 300mm

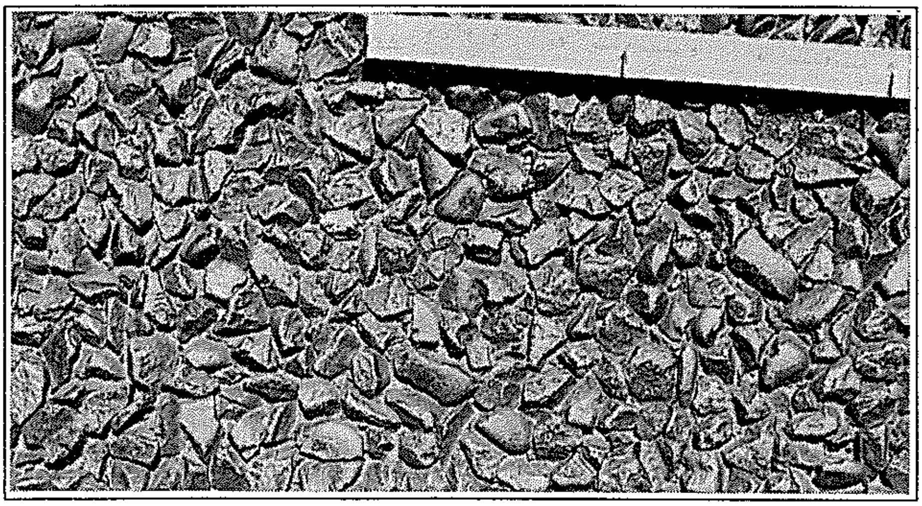


Site 2: SH50, RP 33/8.24-8.46
Grade 5, PSV 53, Age 3.5 yr,
Crushed faces 85%
Scale approx. 300mm



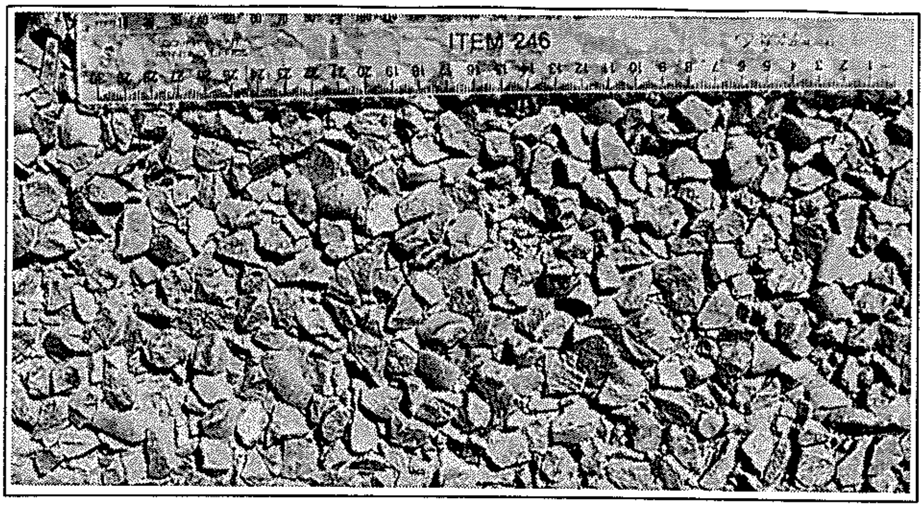
Site 3: SH50, RP 33/5.5-5.7
Grade 5, PSV 53, Age 2.5 yr,
Crushed faces 90%

Profilometer trace is the transverse road section of site

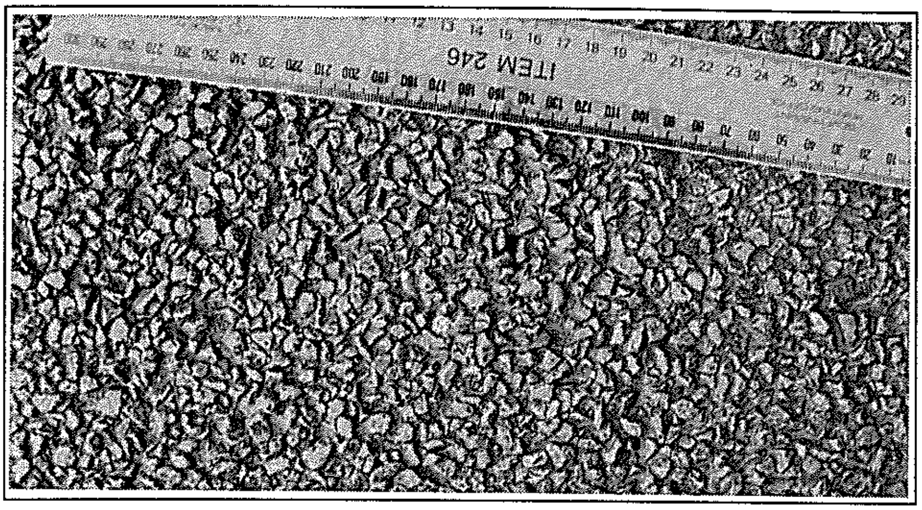


Site 4: SH2, RP 675/7.8-8.0
Grade 2, PSV 55, Age 8.0 yr,
Crushed faces 50%
Scale approx. 200mm

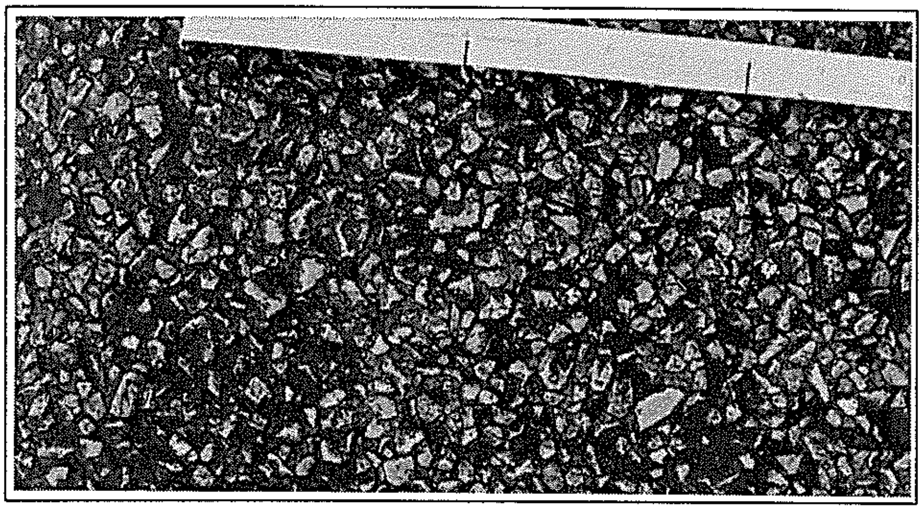
Site 5: SH2, RP 661/1.6-1.4
Grade 3, PSV 55, Age 2.5 yr,
Crushed faces 80%
Scale is 300mm long



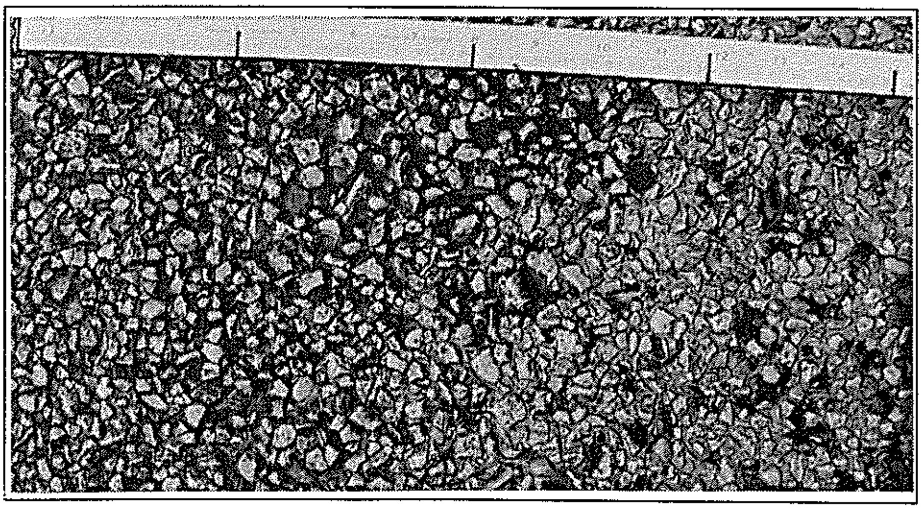
Site 6: SH2, RP 661/5.54-5.74
Grade 5, PSV 54, Age 5.6 yr,
Crushed faces 90%
Scale is 300mm long



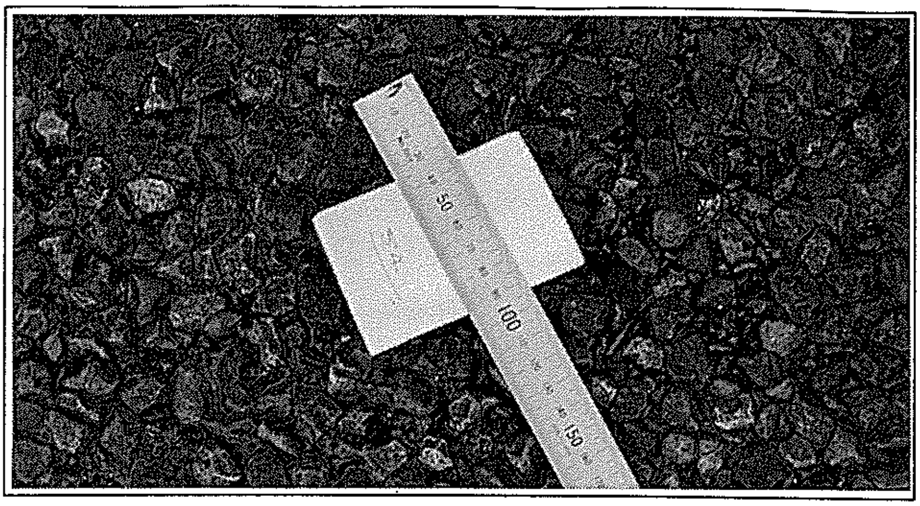
Site 7: SH2,
RP 675/14.78-14.98
Grade 5, PSV 55, Age 4.7 yr,
Crushed faces 75%
Scale marked at 100mm
intervals



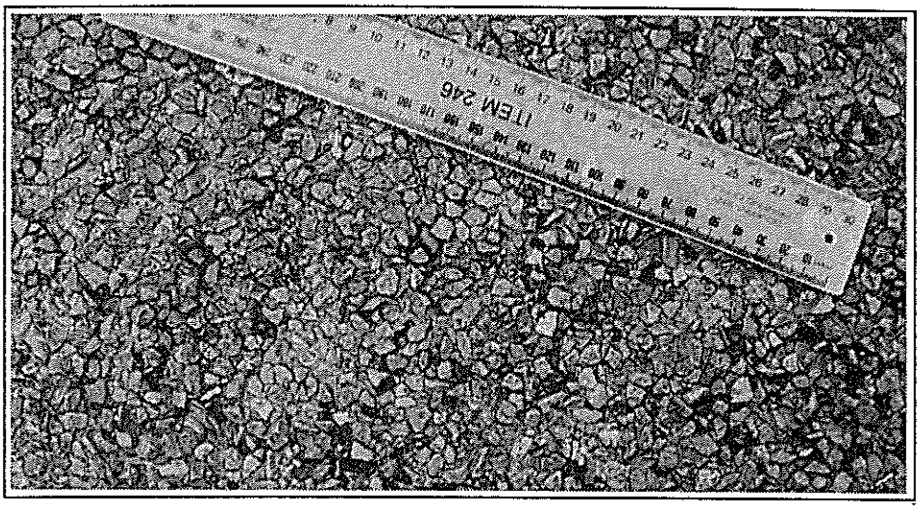
Site 8: SH2, RP 691/0.85-1.05
Grade 3, PSV 55, Age 4.4 yr,
Crushed faces 72%
Scale marked at 100mm
intervals



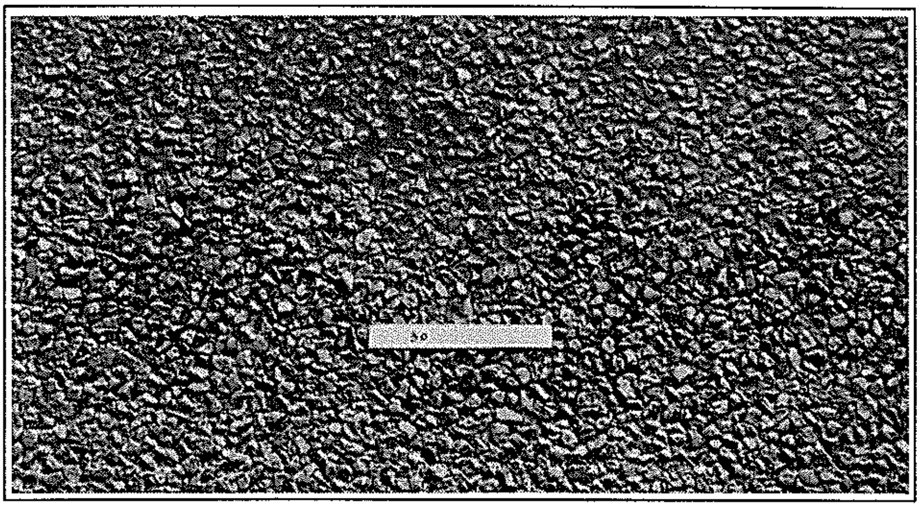
Site 9: SH2, RP 691/7.66-7.46
Grade 2, PSV 55, Age 7.0 yr,
Crushed faces 25%
Scale is a mm rule



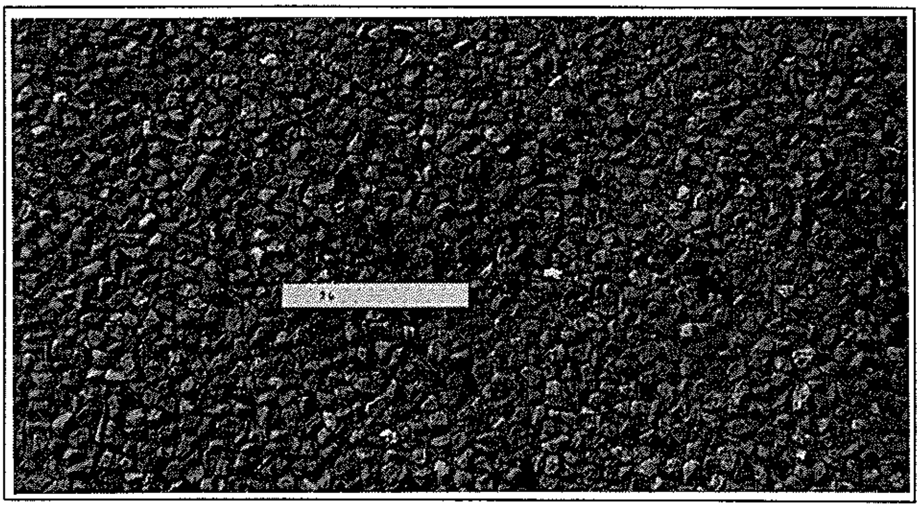
Site 10: SH2, RP 691/9.6-9.4
Grade 5, PSV 55, Age 3.6 yr,
Crushed faces 70%
Scale is a mm rule



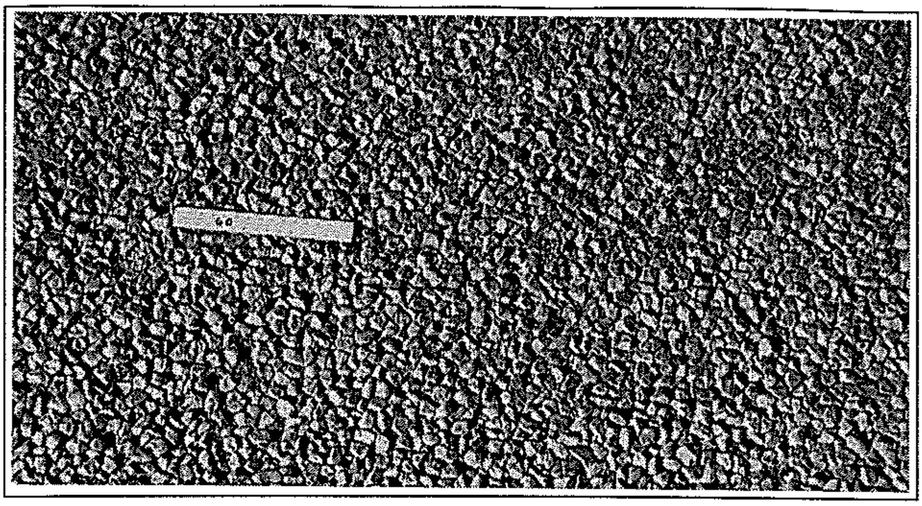
Site 11: SH2, RP 743/7.0-7.2
Grade 3, PSV 55, Age 4.5 yr,
Crushed faces 92%
Scale is 150mm long



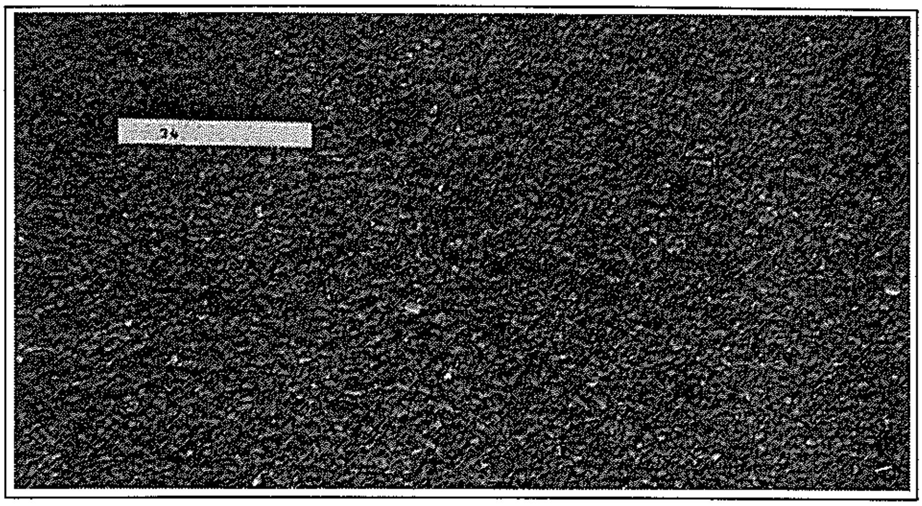
Site 12: SH2; RP 743/2.7-2.9
Grade 2, PSV 55, Age 1.8 yr,
Crushed faces 87%
Scale is 150mm long



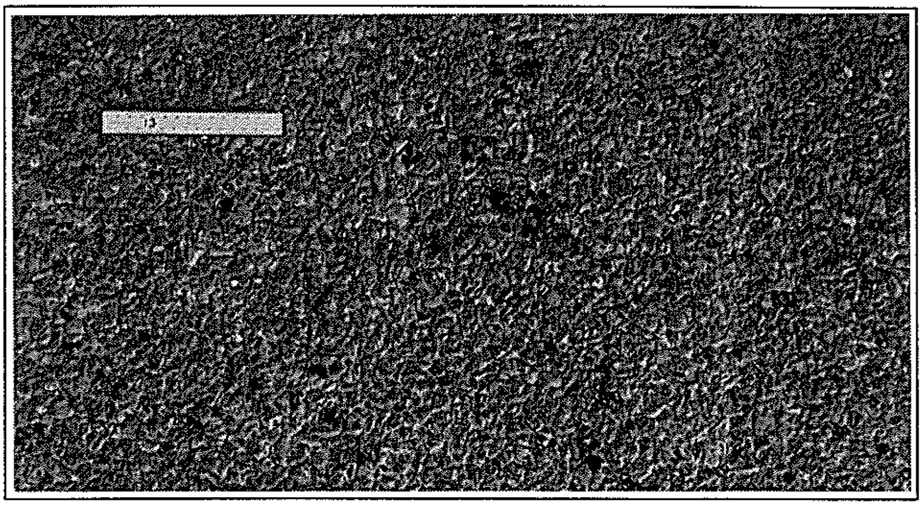
Site 13: SH2, RP 675/10.5-10.7
Grade 4, PSV 55, Age 3.6 yr,
Crushed faces 87%
Scale is 150mm long



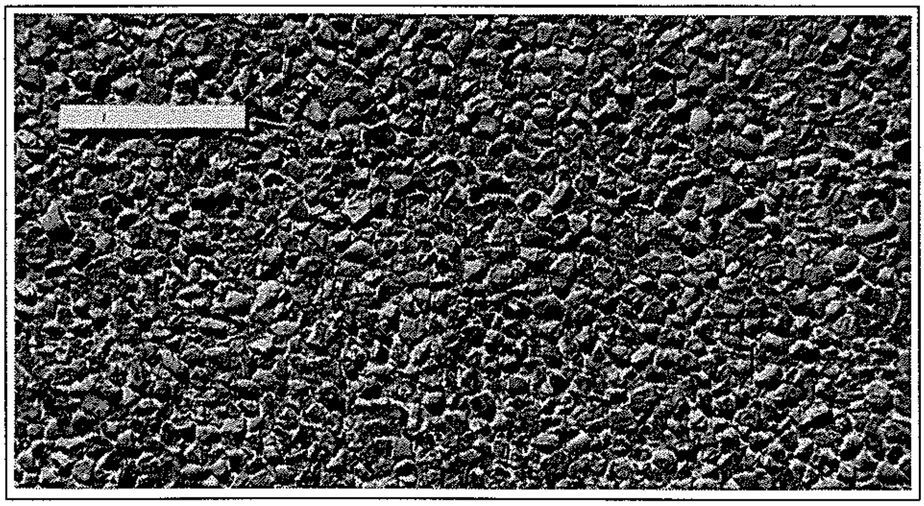
Site 14: SH2, RP 707/7.82-8.02
Grade 5, PSV 55, Age 2.8 yr,
Crushed faces 90%
Scale is 150mm long



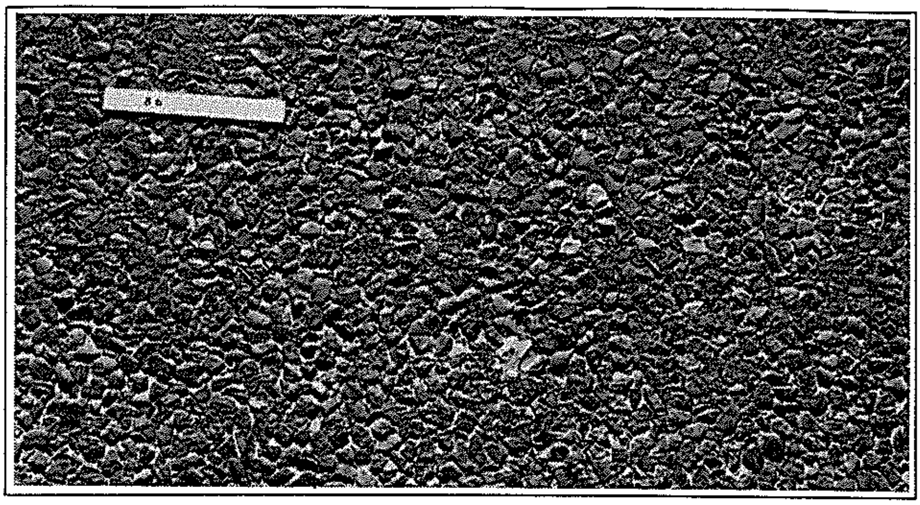
Site 15: SH2, RP 592/13.2-13.4
Grade 5, PSV 55, Age 4.5 yr,
Crushed faces 95%
Scale is 150mm long



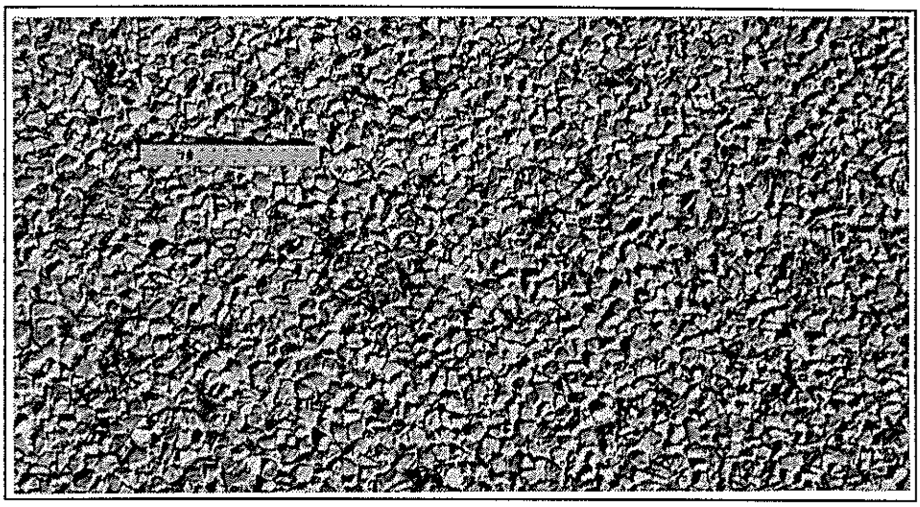
Site 16: SH2, RP 592/2.9-3.1
Grade 2, PSV 55, Age 1.6 yr,
Crushed faces 70%
Scale is 150mm long



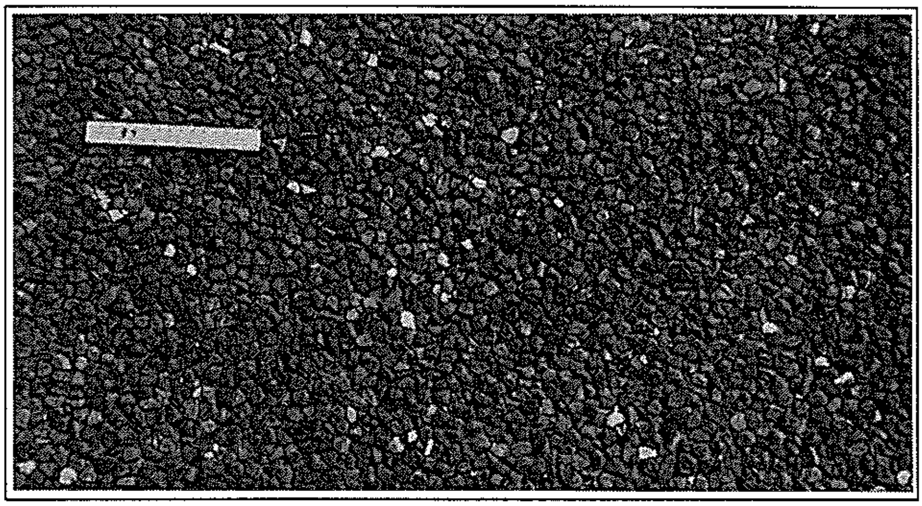
Site 17: SH2, RP 497/8.26-8.46
Grade 2, PSV 55, Age 8.0 yr,
Crushed faces 80%
Scale is 150mm long



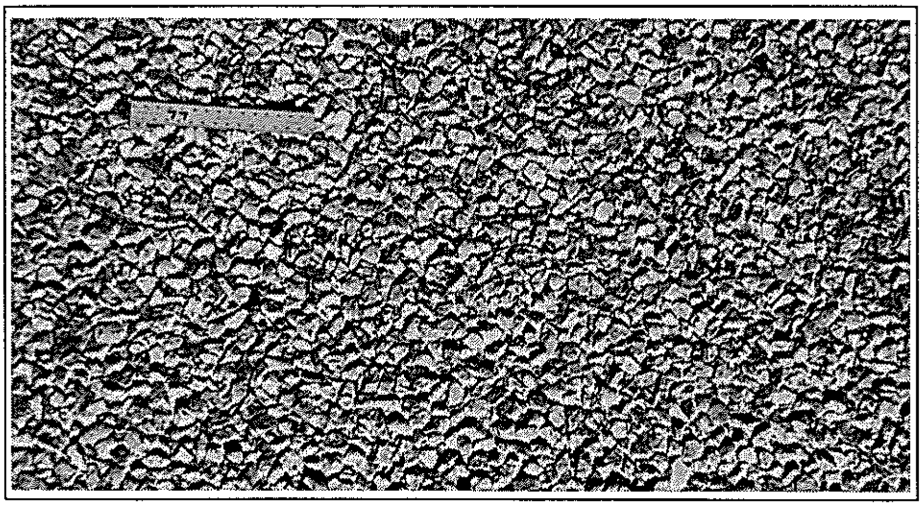
Site 18: SH2, RP 516/0.8-1.0
Grade 3, PSV 55, Age 2.8 yr,
Crushed faces 95%
Scale is 150mm long



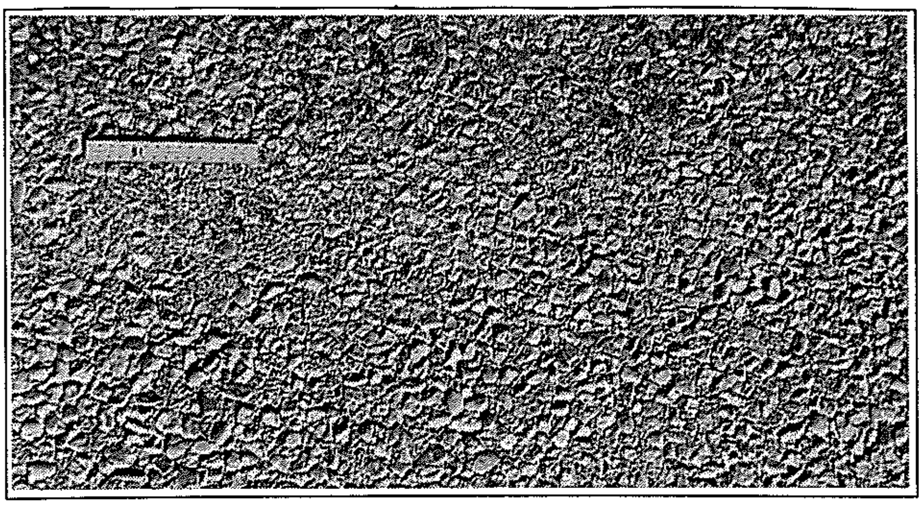
Site 19: SH2, RP 516/3.2-3.4
Grade 3, PSV 55, Age 4.5 yr,
Crushed faces 92%
Scale is 150mm long



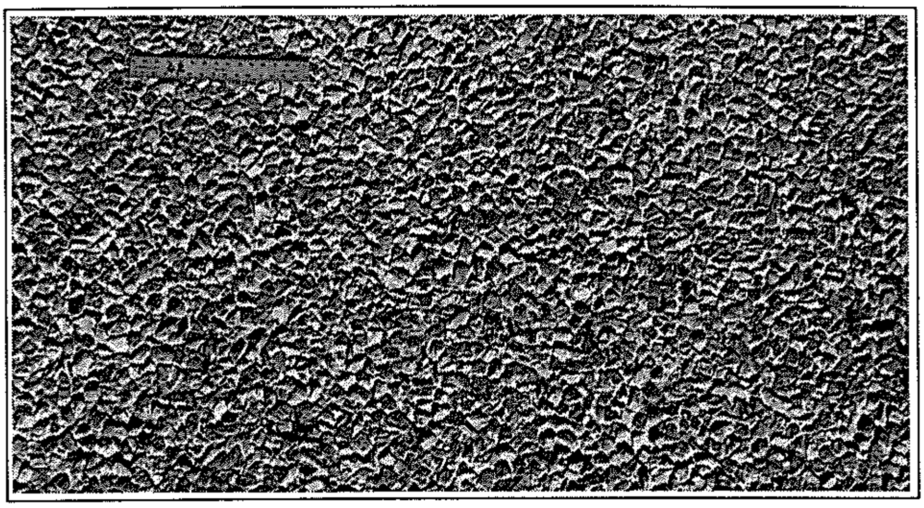
Site 20: SH2, RP 516/6.7-6.9
Grade 2, PSV 55, Age 1.6 yr,
Crushed faces 90%
Scale is 150mm long



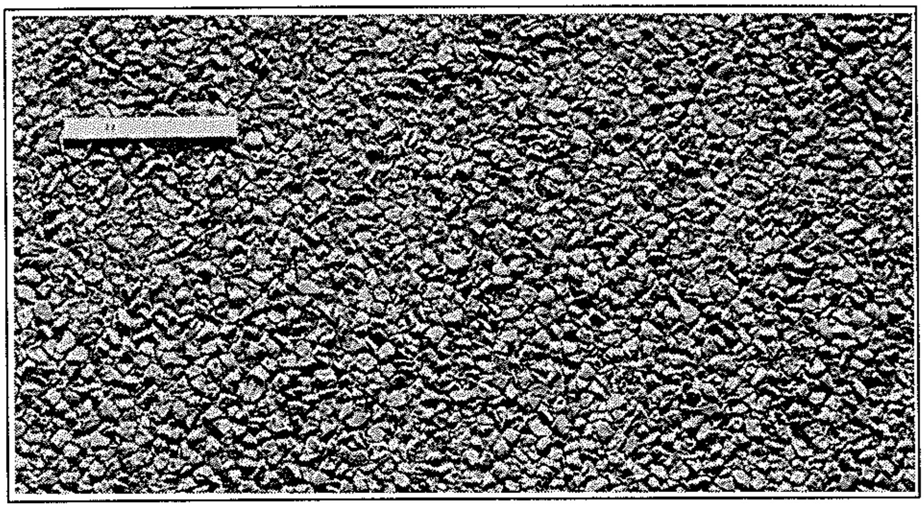
Site 21: SH2, RP 516/9.9-10.1
Grade 2, PSV 55, Age 7.0 yr,
Crushed faces 65%
Scale is 150mm long



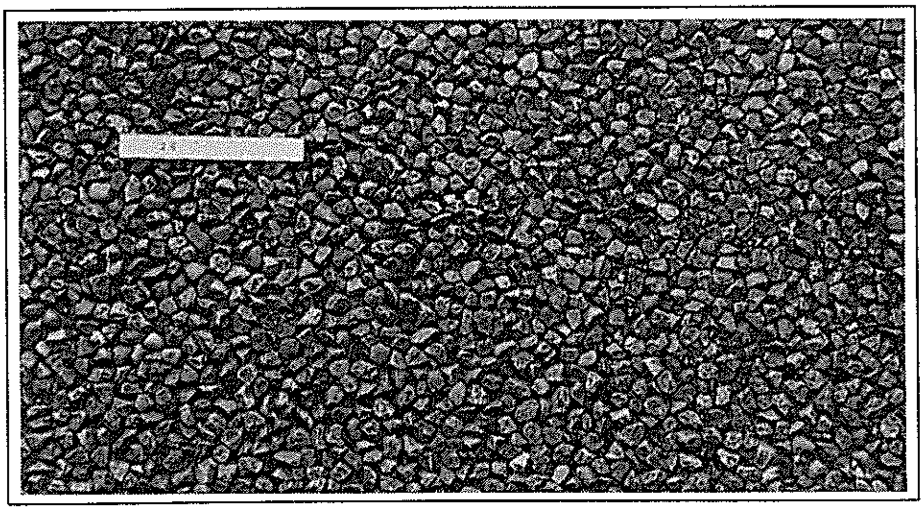
Site 22: SH2, RP 533/2.42-2.62
Grade 3, PSV 55, Age 3.5 yr,
Crushed faces 85%
Scale is 150mm long



Site 23: SH2, RP 533/7.6-7.8
Grade 3, PSV 55, Age 4.6 yr,
Crushed faces 77%
Scale is 150mm long



Site 24: SH2, RP 743/1.17-1.37
Grade 2, PSV 55, Age 1.8 yr,
Crushed faces 90%
Scale is 150mm long



APPENDIX 3

SUMMARY RESULTS OF TEST SITE MEASUREMENT PROGRAMME

A3.1 DEFINITIONS

MTD = mean texture depth (mm)
OT = reciprocal of outflow duration time (l/s)
MPD = mean profile depth (mm)
RMS = root mean square texture depth (mm)
GN50/0.0 = Grip Number at 50 km/h, dry surface
GN50/0.05 = Grip Number at 50 km/h, 0.05 mm applied water film thickness
GN50/0.1 = Grip Number at 50 km/h, 0.1 mm applied water film thickness
GN50/0.2 = Grip Number at 50 km/h, 0.2 mm applied water film thickness
GN50/0.5 = Grip Number at 50 km/h, 0.5 mm applied water film thickness
GN50/0.8 = Grip Number at 50 km/h, 0.8 mm applied water film thickness
GN40/0.5 = Grip Number at 40 km/h, 0.5 mm applied water film thickness
GN60/0.5 = Grip Number at 60 km/h, 0.5 mm applied water film thickness
GN80/0.5 = Grip Number at 80 km/h, 0.5 mm applied water film thickness
GN100/0.5 = Grip Number at 100 km/h, 0.5 mm applied water film thickness

A3.2 TABULATION OF SITE TEXTURE AND SKID RESISTANCE MEASUREMENTS

Site identifiers			Texture measurements				Skid resistance measurements (GN - Grip Number)									
Site	State highway	RS/RP	MTD (mm)	OT (l/s)	MPD (mm)	RMS (mm)	GN50/ 0.0	GN50/ 0.05	GN50/ 0.1	GN50/ 0.2	GN50/ 0.5	GN50/ 0.8	GN40/ 0.5	GN60/ 0.5	GN80/ 0.5	GN100/ 0.5
16	2	592/2.9-3.1	1.651	0.611	1.335	0.644	1.023	0.501	0.552	0.565	0.594	0.604	0.616	0.589	0.563	0.531
20	2	516/6.7-6.9	2.223	0.881	2.059	1.293	1.085	0.663	0.659	0.669	0.675	0.684	0.688	0.666	0.659	0.632
22	2	533/2.42-2.62	2.687	1.349	2.561	1.471	0.96	0.617	0.637	0.66	0.661	0.68	0.691	0.672	0.641	0.636
18	2	516/0.8-1.0	2.059	0.9	1.732	0.92	1.044	0.587	0.605	0.624	0.622	0.641	0.675	0.642	0.603	0.587
2	50	33/8.24-8.46	1.658	0.473	1.428	0.737	0.988	0.675	0.645	0.66	0.665	0.66	0.693	0.685	0.645	0.59
3	50	33/5.5-5.7	2.147	0.498	1.556	0.711	0.956	0.73	0.74	0.72	0.72	0.715	0.725	0.695	0.68	0.63
21	2	516/9.9-10.1	2.98	1.32	2.65	1.608	0.997	0.579	0.592	0.619	0.642	0.656	0.671	0.624	0.603	0.579
17	2	497/8.26-8.46	2.25	1.01	2.013	1.1	1.008	0.582	0.589	0.601	0.614	0.632	0.628	0.615	0.615	0.586
23	2	533/7.6-7.8	2.275	1.204	2.134	1.134	1.029	0.623	0.631	0.634	0.634	0.627	0.673	0.648	0.611	0.607
19	2	516/3.2-3.4	2.021	0.813	1.85	1.078	0.979	0.554	0.537	0.55	0.573	0.58	0.588	0.578	0.565	0.554
1	50	49/3.0-3.2	2.07	0.808	1.623	0.793	0.988	0.625	0.625	0.645	0.67	0.67	0.695	0.655	0.615	0.6
15	2	592/13.2-13.4	2.164	1.031	1.854	0.946	0.967	0.584	0.597	0.635	0.647	0.644	0.651	0.62	0.609	0.586
12	2	743/2.7-2.9	2.042	0.891	1.851	1.081	1.008	0.556	0.584	0.606	0.618	0.605	0.628	0.627	0.618	0.584
24	2	743/1.17-1.37	1.962	0.804	1.817	1.102	0.943	0.47	0.486	0.503	0.528	0.534	0.536	0.529	0.516	0.515
5	2	661/1.6-1.4	3.699	1.342	3.042	1.817	0.994	0.535	0.54	0.555	0.58	0.595	0.605	0.585	0.575	0.565
13	2	675/10.5-10.7	1.781	0.693	1.496	0.752	1.012	0.621	0.63	0.643	0.654	0.666	0.655	0.659	0.638	0.635
10	2	691/9.6-9.4	1.624	0.492	1.247	0.615	1.063	0.52	0.55	0.585	0.6	0.62	0.65	0.603	0.565	0.57
14	2	707/7.82-8.02	3.059	1.341	2.766	1.8	0.994	0.546	0.56	0.575	0.588	0.598	0.608	0.585	0.569	0.557
9	2	691/7.66-7.46	2.63	1.073	2.078	1.169	1.025	0.41	0.43	0.44	0.46	0.465	0.5	0.485	0.46	0.45
4	2	675/7.8-8.0	3.129	1.014	2.552	1.476	0.975	0.41	0.425	0.435	0.46	0.465	0.475	0.46	0.425	0.395
8	2	691/0.85-1.05	1.851	0.604	1.419	0.667	1.05	0.52	0.535	0.525	0.515	0.525	0.545	0.515	0.495	0.48
11	2	743/7.0-7.2	2.522	1.315	2.42	1.351	0.98	0.641	0.652	0.669	0.676	0.678	0.699	0.639	0.618	0.543
7	2	675/14.78-14.98	1.542	0.538	1.192	0.637	1.113	0.565	0.585	0.595	0.585	0.565	0.585	0.58	0.555	0.505
6	2	661/5.54-5.74	1.846	0.548	1.538	0.847	1.025	0.46	0.465	0.475	0.48	0.495	0.523	0.51	0.495	0.475