Abrasion resistance of aggregates in asphalt
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An important note for the reader

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Executive summary

The objective of this project was to investigate the durability and mechanical integrity of aggregate with a high (>60) polished stone value (PSV) used in hot mix asphalt (HMA), particularly chips or coarse aggregates in stone-on-stone mixes such as stone mastic asphalts (SMA) and open graded porous asphalts (OGPA). The research was carried out in 2009–2010.

The structure formed by the aggregate particles and the bituminous binder carries and distributes the applied wheel load to the underlying pavement layers. A major difference between dense graded asphalt and the more open graded or stone-on-stone mixes is the way that the load is distributed through the layer. In dense mixes, the coarse aggregate is fully supported by the smaller sized stone and the bitumen. In more open graded mixes, the load is transferred by stone-on-stone contact. As a consequence, the stability and long-term performance of the layer depends on the ability of the aggregate to resist the high point stresses that are generated during construction and later under traffic.

Flushing within the surfacing layer because of degradation of the aggregate or other reasons is not uncommon. For example, this project resulted from problems that were originally observed and investigated during the construction of the Transit New Zealand Grafton Gully Project in Auckland where, after a period of trafficking, it was observed that the macrotexture was reduced by flushing in the SMA surfacing. This was more apparent where a high PSV aggregate was used. A subsequent investigation indicated that some degradation of the aggregate had occurred, most probably during construction.

Therefore, the identification of the factors that influence degradation of the aggregates used in SMA and similar mixes will be of interest to all suppliers of surfacing aggregates, asphalt producers, pavement designers and asset managers. It is expected that this research will provide a better understanding of the aggregate properties that are required to support high friction-resistant surfacing. It should ultimately result in the incorporation of appropriate selection procedures in NZ Transport Agency specifications such as P/11 and the new M/10, which is soon to replace NAS 2004 plus the New Zealand supplement. Currently, P/11 and NAS (2004) cover New Zealand's stone-on-stone mix types. By using an appropriate durability test, which is included in these specifications, the pavement designer and asset owner will be able to determine the appropriateness of a particular aggregate source for use in asphalt at any particular location.

The properties of the aggregate are basically determined by the inherent characteristics of the rock being processed. The physical strength of the rock has a profound influence on the aggregate produced, particularly the particle size distribution, the quantity and nature of the fines and the shape of the particles.

The structure of this research project was as follows:

1 literature survey

2 selection of sites for test sections

3 selection of aggregates to cover a range of PSVs

4 testing to establish source properties of the aggregates

5 geological examination of samples of the aggregate used in project

6 construction of test sections in Auckland (three) and Taupo (one)

7 sampling and testing to establish baseline data

8 trafficking the test sections

9 sampling, primarily to establish change in the particle size distribution.

At an early stage in the project, it was decided to construct test sections within the plant yards at Auckland and Taupo operated by Higgins Contractors Ltd. These areas were relatively heavily loaded and were within a controlled environment, as well as being adjacent to the asphalt manufacturing plants. However, because of time constraints, it was only possible to traffic the test area in Auckland for seven months. In Taupo, it was limited to three months.

The aggregates used in the test sections were drawn from four different sources. They were:

- Brookby Quarry located south of Auckland City. It is a Waipapa greywacke rock with a PSV of 56.
- Moutohora Quarry in Poverty Bay. It is an East North Island greywacke rock with a PSV of 65.
- electric arc furnace (EAF) slag from Pacific Steel in Otahuhu, Auckland. It has a PSV of 65.
- Te Matai Pit in Palmerston North. This is a gravel with a PSV between 58 and 59 derived from the Torlesse greywacke of the central North Island.

Comparison of the particle size distribution (PSD) of each aggregate after construction with that of samples taken prior to laying showed that significant degradation took place during laying and compaction. A similar comparison of the PSD after construction and at the end of seven months' trafficking showed little degradation, if any. However, a slight decrease in air voids content was noted, particularly in the most heavily loaded area. A similar decrease in texture depth was also recorded.

Examination of the results of the source property tests showed that none of the tests could be used to predict the degradation that occurred in the test sections. The Los Angeles and micro-deval abrasion tests were probably the most useful.

At a late stage in the project, it was decided to evaluate the suitability of the gyratory compactor test as a prediction tool. The compactor gave a reasonably accurate measure of the degradation that occurred in the Moutohora aggregate (the most weathered of the greywacke rock types). However, the results for the other three aggregates were only 30–40% of the degradation measured in the test sections. It was noted that the load used in the test was 40% of that specified in the American Superpave specification, while the angle of gyration was 2.4 times larger. This suggests that each country has designed the test protocol to suit the type of aggregate most commonly used. New Zealand should adopt a similar approach.

The micro-deval abrasion test ranked the aggregates in a similar sequence to that achieved using the gyratory compactor test.

The following conclusions have been drawn:

- SMA mixes can be expected to degrade.
- Degradation occurs as the sharp point of one coarse particle is forced against another coarse particle. The product is predominantly fine sand and silt-sized particles.

- A geological evaluation provides a useful understanding of the properties of each aggregate and, in particular, the difficulties involved in selection of a high PSV aggregate that will withstand the high stress levels that occur within stone-on-stone mixes.
- None of the source property tests provided a useful ranking of the durability of the aggregates used in the test sections. The micro-deval abrasion test gave a reasonably accurate prediction of the breakdown that occurred in the gyratory compactor test but not of that measured in the test sections.
- Significant degradation occurred in all the aggregates used in the test sections as a result of the stresses imposed during laying and compaction.
- The air voids and surface texture values decreased as a result of trafficking but no measurable change was noted in the particle size distribution.
- A good set of baseline data has been established for all the test sections and it is recommended that further samples be obtained in about two years' time to ascertain the effects of trafficking.

Abstract

The objective of this project was to investigate the durability and mechanical integrity of aggregate with a high polished stone value (>60) used in hot mix asphalt, particularly chips or coarse aggregates in stone-on-stone mixes such as stone mastic asphalts and open graded porous asphalts. The research was carried out in Auckland, New Zealand, in 2009–2010.

Test sections were constructed within a roading contractor's yards at Auckland and Taupo. The aggregates used were drawn from four different sources. Significant degradation took place during laying and compaction, but trafficking produced little further breakdown, if any. However, a slight decrease in air voids and texture depth was apparent.

Most of the source property tests could not predict the degradation that occurred in the test sections. The Los Angeles and micro-deval abrasion tests were probably the most useful. The gyratory compactor test was also evaluated as a prediction tool without a great deal of success. The micro-deval abrasion test ranked the aggregates in a similar sequence to that achieved using the gyratory compactor test.

1 Purpose and description of the proposed research

1.1 Purpose

The objective of this project was to investigate the durability and mechanical integrity of high (>60) polished stone value (PSV) aggregates for hot mix asphalt (HMA), particularly chips or coarse aggregates in stone-on-stone mixes such as stone mastic asphalts (SMA) and open graded porous asphalts (OGPA).

The standard specifications published by the NZ Transport Agency (NZTA) such as M/4 (Transit New Zealand (TNZ) 2004a), M/6 (TNZ 2004b), M/10 (TNZ 2005), P/11 (TNZ 2007a) and BCA 9808 (Bitumen Contractors' Association 1999) all require that the aggregate shall be hard, durable, sound material crushed from natural gravel or quarried rock. However, some weathered aggregates in New Zealand meet the two standard source property tests of both crushing resistance and weathering, yet still degrade and break down, certainly under steel wheel roller compaction during construction. Experience also suggests that further breakdown occurs from trafficking, particularly on sites with high traffic-induced surface stresses associated with braking and turning traffic.

The structure formed by the aggregate particles and the bituminous binder carries and distributes the applied wheel load to the underlying pavement layers. A major difference between dense graded asphalt (eg HMA) and the stone-on-stone mixes is the way that the load is distributed through the layer. In dense mixes, the coarse aggregate is fully supported by the smaller sized stones and the bitumen. In SMA and OGPA, the load is transferred by stone-on-stone contact, and the stability and long-term performance of the layer depends on the ability of the aggregate to resist the high point stresses that are generated during construction and later under traffic.

The current source property tests and acceptance criteria in New Zealand need to be reviewed to assess whether they are appropriate for durable stone-on-stone mixes. Additional tests that will be evaluated include water absorption, Los Angeles (LA) abrasion (Standards Australia 1995a), wet/dry strength (Standards Australia 1995b), aggregate abrasion value, micro-deval (ASTM International 2003), gyratory compaction and soundness tests.

1.2 Original proposal

The issue that needed to be addressed was whether the high PSV required for skid resistance was being achieved at the expense of the durability of stone-on-stone mixes. Aggregate source property tests and acceptance criteria need to be reviewed to ensure that appropriate specifications are being applied.

It was originally intended that up to three sites would be identified where durability issues have occurred in SMA or OGPA mixes. Samples of material from these sites were to be removed to provide aggregate for testing. A suite of aggregate source tests, namely crushing resistance, weathering quality index, LA abrasion, wet/dry crushing strength and PSV (if the chip source is not known), and a soundness test were to be completed on these aggregates to determine which tests are the most appropriate for identifying the durability issue. In addition to this testing, it was proposed that up to four aggregates with high PSVs would be sampled and tested directly from the stockpile. The tests were to be repeated on a hard aggregate with a lesser PSV with good durability, for comparison.

However, in the preliminary stages of the research, it became apparent that sampling materials from existing pavements was fraught with problems, including:

- locating sites with specific durability issues
- obtaining the controlling authorities' permission to sample the pavements
- recovering representative samples from surface layers from heavily trafficked pavements
- determining the initial condition of the constituent materials prior to laying.

1.3 Modified proposal

As a result of discussions with Mr Robert Patience (peer reviewer and expert advisor), it was decided to modify the project as follows:

- Aggregates would be selected to cover a range of PSVs.
- Test sections would be laid in a suitable location.
- Samples would be taken immediately after construction and after a period of trafficking.

The benefits of this approach were:

- It did not require approval from a road controlling authority, or the consequent restrictions on access, sampling and the like.
- The characteristics of the materials prior to construction would be known.
- Construction could be easily organised and controlled.
- The characteristics of the aggregate immediately after construction could be determined.
- The applied traffic loading could be estimated with a reasonable degree of certainty.
- The characteristics of the materials after trafficking could be measured.

1.4 Benefits of the project

Flushing within the surfacing layer as a result of degradation of the aggregate or for other reasons does occur. For example, this project resulted from problems that were originally observed and investigated during the construction of the TNZ Grafton Gully Project in Auckland (Newby 2005). At Grafton Gully, sections of the pavement were surfaced with a 40mm thick layer of SMA 14. Generally, aggregate from the Brookby Quarry was used. However, a high PSV aggregate, which had been especially imported from Moutohora Quarry in Poverty Bay, was used in areas where high surface shear loads were likely to be generated by the traffic. It was later noticed that the macrotexture was reduced by flushing in the surfacing. This was more apparent where the Moutohora aggregate was used. The investigation indicated that some degradation of the aggregate had occurred, most probably during construction.

All aggregates used in the surface of a pavement become polished as a result of traffic wear. The matrix of an aggregate that can provide a high level of skid resistance over a comparatively long length of time is usually abraded by the traffic so that polished particles are removed and fresh, sharp particles are exposed. In the case of SMA, not only is the surface of the particles in contact with the traffic removed but the sharp corners of the aggregate within the layer are removed. As a consequence, the characteristics of the mix, such as the proportion of bitumen, the air voids content and the particle size distribution (PSD) of the aggregate, are changed.

The output of this project will therefore be of interest to all suppliers of surfacing aggregates, asphalt producers, pavement designers and asset managers. It is expected that the research will provide a better understanding of the aggregate properties that are required to support high friction resistant surfacing. This should ultimately result in the incorporation of appropriate selection procedures in NZTA specifications such as P/11 (TNZ 2007) and the new M/10 (TNZ 2005), which is soon to replace the *National asphalt specification 2004* (NAS 2004) (Australian Asphalt Pavement Association (AAPA) 2004) plus the New Zealand Supplement (Arnold 2006) . Currently, P/11 and NAS 2004 cover New Zealand's stone-on-stone mix types. By using an appropriate durability test included in these specifications, the pavement designer and asset owner will be able to determine the appropriateness of a particular aggregate source for use in asphalt at any particular location. An asset owner may, for example, on certain sections of road, decide to accept reduced durability (ie shorter service life) to ensure that the pavement surface has a high skid resistance.

1.5 Terminology

The following terms are used in this report:

In terms of skid resistance, the macrotexture of a road surface refers to the height of chips protruding above the bitumen in a chipseal or the depth of the voids between the coarse stone in asphalt surfacing. Microtexture refers to the actual surface of the stone exposed on the road surface.

The polished stone value (PSV) is a measure of the skid resistance of an aggregate after polishing in an accelerated polishing machine when the tests are carried out in accordance with *BS EN 1097-8:2000*[1] (British Standards Institution 2000).

1 This standard has since been replaced by BS EN 1097-8:2009.

2 Literature review

2.1 Introduction

The skid resistance of asphalt, and of SMA and OGPA, in particular, is of significant interest to the New Zealand and Australian roading industry. Good friction characteristics are a product of the macrotexture of the mix and the microtexture of the stone. It is believed that stone that wears under the action of traffic is required to preserve a skid-resistant surface. Some authorities transport particular aggregates over long distances to use them on sections of highway where a skid-resistant surface is required. If the stone used is easily abraded, it may tend to break down during mixing, laying and compaction, and during trafficking. The literature review, which involved a study of more than 30 technical papers, sought to find the results of any research being carried out overseas into the topics of skid resistance, aggregate durability, test procedures and mix design. The topics described in the papers that were reasonably relevant to the project generally fell into one or more of the following areas:

- skid resistance of chipseals
- skid resistance of asphalt surfacing
- durability of OGPA
- tests for aggregate durability
- management of skid resistance
- the significance of New Zealand geology
- asphalt mix design.

2.2 Skid resistance of chipseals

In 1995, TNZ adopted a new policy on skid resistance that achieved a substantial reduction in the number of wet road loss of control accidents. Owen and Donbavand (2005) reported a 30% decrease in three years between 1995 (immediately prior to the introduction of the policy) and 1998. This was achieved by improvements in the management and selection of surfacing types, along with measurement and the identification of problem sites. Each problem site was treated with a chipseal with a predetermined level of skid resistance. Over a similar period, developments within the quarrying industry resulted in the production of chip with the required shape as well as a high PSV.

Towler and Stevenson (2000) describe the development of a pilot performance based specification for a high PSV sealing chip (a ‘high’ PSV chip is one that does not polish readily). They believed that if some of the source requirements specified in the M/6 specification (TNZ 2004b) were relaxed, the amount of high PSV chips would be substantially increased. The reason that some high PSV chips do not meet M/6 was considered to result from the inverse relationship between PSV and chip strength and/or durability. The pilot specification differs from M/6 in several ways, including:

- Crushing resistance geared to the traffic volume. A value of 150kN is required for low traffic volumes, rising to 230kN for volumes greater than 10,000 annual average daily traffic.

- The weathering quality index may also vary from CB to AA, depending on the traffic volume.
- The cleanness value requirements were relaxed.

The suitability of aggregate produced in terms of the pilot specification is to be determined by field trials. The first trial sections were constructed during the 1998/99 sealing season, and the texture depth and skid resistance have been monitored since then. After 18 months of trafficking, the results of the monitoring tests were inconclusive.

Henderson et al (2006) comment that the relationships among aggregate microtexture, the proportion of crushed faces, chip shape and skid resistance are not well understood. They investigated the skid resistance of gravels and found that it increased linearly with the proportion of crushed stone. The effective resistance of freshly crushed unpolished aggregate is approximately 26% greater than that of uncrushed river gravel of similar size. The increase has two main causes:

- The microtexture of crushed faces is greater than that of uncrushed gravel.
- New and unpolished chips are more angular.

Nineteen percent of the increase was caused by the increased microtexture and 7% by the more angular chips. Aggregates with a lower level of microtexture need to be crushed more to achieve a given level of skid resistance. However, if crushed chips become highly polished and rounded, the difference between them and uncrushed gravel is negligible. The degree of polishing achieved in the accelerated polishing machine used in the study eventually reached an equilibrium level and further polishing did not have a significant effect on the skid resistance as measured using the British pendulum tester. The beneficial effect of crushing on microtexture remained after the equilibrium level of polishing was achieved. Chip size did not appear to have any significant effect on skid resistance.

2.3 Skid resistance of asphalt aggregates

A study in Northern Ireland (Woodward et al 2005) on the measurement of PSV highlighted the factors that control the skid resistance of aggregate used in asphalt. The researchers recommended that a holistic approach should be taken to the selection of the aggregate. They point out that:

> *...there is a complex interaction between factors such as differences in rock type, change in properties such as strength, soundness and skid resistance during the engineering life, variation in the contribution of properties such as strength depending on mix type, variation in traffic induced stressing on properties such as load transfer or polish resistance, adhesion to bitumen and the presence of moisture at the aggregate/bitumen interface, or the ability to cope with unexpected in-service conditions.*

A good understanding of all factors is necessary to reduce the risk of poor performance in the pavement.

Boyle (2005) describes practices used to achieve appropriate skid resistance levels on two sections of the Auckland state highway network. The practices include the use of Moutohora aggregate from Poverty Bay, PSV calculations based on field skid resistance measurements, and microtexture monitoring. The Moutohora aggregate was crushed from a slightly weathered ‘sandstone conglomerate breccia’, 80% of which was made up of greywacke particles. These particles were set in a matrix that slowly eroded under traffic so that fresh sand fragments were exposed. Trials using sealing chip from this quarry were unsuccessful because the stone was sheared, leaving part of the chip attached to the binder. However, it has performed well when bound in an asphalt layer.

The sections of highway surfaced with OGPA manufactured using Moutohora aggregate that were monitored were:

- approaches to the Auckland Harbour Bridge at St Mary's Bay
- State Highway (SH) 1 Schedewys Hill (north of Hadfield's Beach)
- SH1 Waiwera Hill (south of the turnoff to Waiwera village).

The use of Moutohora aggregate adjacent to the Harbour Bridge resulted in a 30% decrease in wet road accidents. The first section laid lasted seven years and failed by ravelling. Previously, asphalt manufactured from basalt aggregate became polished and had to be replaced after three years.

The Waiwera Hill and Schedewys Hill sections carry virtually the same traffic and are on grades of approximately 10% with frequent curves, some with radii of 60–70m. The surfacing on the Waiwera Hill section stood up well, with an average mean summer SCRIM[2] coefficient of ~0.55, while the value for the Schedewys site decreased in three years from 0.55 to 0.45. The author only speculates as to why that difference developed.

2.4 Durability of OGPA

The effect of the environment on OGPA is discussed by Herrington et al (2005). The most common form of distress is loss of chip from the surface caused by bitumen embrittlement through reaction with atmospheric oxygen. The durability of the mix, which is its resistance to chip loss, depends on the binder film thickness, the PSD and the air voids content, as well as the oxidation resistance of the bitumen. The research was directed at developing a test to compare the effect of different binders and mix design parameters on the durability of the asphalt.

The test procedure that was developed involved ageing 100mm × 65mm high cylinders of asphalt samples at 80°C for three days in air at a pressure of 2070kPa. The oxidation that occurred was estimated to be equivalent to approximately 4.5 years in the field. The abrasion resistance of the aged sample was then measured using the Cantabro test.

On the basis of the three samples tested during the project, the researchers suggest a design criterion of 15% for the loss in the Cantabro test on unoxidised mixes.

Poulikakous and Takahashi (2004) describe the research carried out jointly by Swiss and Japanese engineers. They studied the performance of samples of aggregate prepared in accordance with traditional mix design methods with samples prepared using a new theory based on the theoretical packing of aggregate particles. The procedure involved the use of dry aggregate split into five size fractions (A, B, C, D and E) that was then blended to produce the target porosity. The first step was to blend the coarse aggregate A with the next smallest size material B until the combination AB with the least porosity was found. The next finest fraction C was then blended with AB and so on until the target porosity was achieved. The dry packing method was then modified to a wet method by coating the aggregate with

2 SCRIM: sideways-force coefficient routine investigation machine

bitumen in a mixer prior to compaction. The paper discusses the results of the following test procedures that were used to compare the two types of mix:

- laboratory aging
- Cantabro particle loss
- porosity and water permeability
- interlayer shear strength
- indirect tensile test
- shear modulus of mixes using the coaxial shear test
- wheel tracking.

The researchers found that the new mix design method produced a more durable open graded asphalt.

2.5 Tests for aggregate durability

A review of research reports relevant to the impact of aggregate properties specified in the Superpave mix design method (Asphalt Institute 2001) on the performance of HMA is described by Powell et al (2009). The aggregate specification for the original method was compiled by a group of experts and not based on the results of any specific research. Since the conclusion of the Strategic Highway Research Programme (SHRP) in 1993, a variety of research projects have been carried out; the results of that work are described by Powell et al. The objectives of the review were to:

- identify the criteria that have experimentally been shown to have a positive relationship with the performance of HMA
- estimate the significance of any such relationship.

The researchers also surveyed current US specifications to identify where they deviate from the original Superpave criteria in order to document:

- the nature of the change
- the effect of the change on the performance of HMA.

Finally, the data from relevant field trials was collected and reviewed.

The Superpave design method contained a description of materials suitable for use in pavements designed using the method. The specification for aggregate was divided into 'source properties' and 'consensus properties'.

The source properties relate to aggregate durability and to the presence of deleterious minerals such as coal and lignite. The criteria were to be set by the local agency to allow for regional differences in geology. The tests were to establish aggregate breakdown during handling, mixing and placement; abrasion or weathering of aggregate in the pavement structure; and durability under freeze–thaw conditions.

The Superpave method includes two methods to be used to evaluate these criteria. They were the LA abrasion test and the sulphate soundness test.

Four 'consensus properties' were set out in the Superpave method and these were to be universally adopted by all agencies. They were concerned with:

- coarse aggregate angularity (percent crushed faces)
- flat and elongated particles (percent flat and elongated particles)
- fine aggregate angularity (uncompacted voids in the fine aggregate
- proportion of clay type fines (sand equivalent test).

The committee of experts also set the volumetric properties for the mix including:

- air voids content
- voids in the mineral aggregate
- voids filled with asphalt
- the proportion of dust to asphalt.

Once the design method was put into operation through out the United States (US), it was found that a number of aggregates did not meet the specified criteria but had a long history of faultless performance. The limits set for PSD were of particular concern.

An extensive list of results for the review is described by Powell et al (2005). Several may be relevant to this project:

- No evidence suggested that the LA test, used for assessing breakdown during construction, should be replaced.
- The sulphate soundness test appears to be a good predictor of performance under freeze–thaw conditions but these are unlikely to occur in a HMA pavement because the aggregate is coated with bitumen.
- Flat and elongated particles are prone to breaking down during construction. In such circumstances, the broken faces will not be coated with bitumen.
- Micro-deval testing provides a measure of the possible loss caused by abrasion of particles under traffic loading.
- PSD has a significant impact on constructability and performance.
- Grading of both the fine and coarse aggregate has an influence on the rut resistance of the mix.
- For fines, D_{60} and the clay index were found to be related to rutting, while D_{10} and the clay index can be related to stripping.

Several reports of studies that have been carried out in the US were briefly reviewed for this project. Most refer to comparative studies of the various tests either to correlate the tests or to relate the tests to the performance of HMA. Some were reviewed as part of the study described by Powell et al (2005).

Bjarnason et al (2002) describes comparative tests carried out on 20 samples of basaltic basecourse aggregate produced in different areas of Iceland. Each of the 17 tests used could be classified into one of three groups:

- fragmentation (eg aggregate impact value)
- weathering (eg Icelandic freeze–thaw and sulphate soundness tests)
- abrasion (eg micro-deval test).

The study found a good correlation between all of the six fragmentation test methods.

The weathering tests could be grouped according to the type of test used. One group involved actually freezing and thawing the aggregate in a special refrigerated cabinet, while the other group involved soaking the aggregate in a solution of magnesium sulphate before it was dried. Two test methods in the first group correlated well, while the correlation between the two groups of tests was not strong.

The two abrasion tests used, the Nordic abrasion and the micro-deval test, had a strong correlation. The micro-deval test also correlated with the freeze–thaw tests.

Gatchalian et al (2006), studied the degradation of aggregates used in SMA mixtures. The six aggregates studied generally varied in shape, angularity and texture. The micro-deval test was used to measure the resistance to abrasion and an advanced imaging technique was used to record the changes in the characteristics of the aggregate caused by that test. The resistance of the aggregate to degradation when used in SMA was evaluated using a gyratory compactor by comparing the PSD after 100 and 250 revolutions with the distribution prior to the test. They recommended that the weight loss in the micro-deval test, the change in aggregate shape characteristics and the change in PSD be used to evaluate the resistance of aggregate particles to degradation in SMA mixes.

2.6 Geological aspects

The properties of the aggregate are basically determined by the type of rock being processed. The physical strength of the rock (ie crushing resistance) has a profound influence on the property of the aggregate produced, particularly the PSD, the quantity and nature of the fines, and the shape of the particles. The engineering properties of the aggregate will therefore be determined by:

- the type of rock (sedimentary, igneous or man-made)
- the mineral content (eg cementing characteristics, swelling or non-swelling clays)
- the degree of weathering
- the type of production process used.

We performed a geological assessment of the aggregate sources in the North Island of New Zealand. This assessment highlights the fact that New Zealand is a geologically young country when compared to Europe and North America, where many engineering tests to determine the engineering properties of aggregates have been developed. For example, greywacke rocks, which are a major source of aggregate in New Zealand, form a very small proportion of the materials used in Europe, North America, South Africa and Australia. The sandstones often used in those countries usually contain physically and chemically stable debris that has been through several cycles of sedimentation. It is therefore unlikely that such tests will be appropriate for unqualified use in New Zealand. This assessment included a review of the tests used by engineers to determine the properties of aggregates, and points out that most procedures measure a combination of physical properties and that it is difficult to interpret the results unless each variable is controlled. Ultimately, the properties measured are strongly related to:

- the geological nature of the rock
- the type of process used in the manufacture of aggregates.

Since many of the New Zealand rock types contain clay minerals and zeolites that absorb water and swell, the durability of aggregate should always be determined under wet conditions.

2.7 Mix design

Asphalt mix design is based on empiricism, with different approaches being taken in different countries. In the past, the Marshall and Hveem methods were adopted on a virtually universal basis. However, more recently, each agency has tended to either develop its own method or adopt one proven to be suitable for local materials and traffic.

The US developed the Superpave method (Asphalt Institute 2001) as part of the SHRP project carried out in the 1980s. This is a volumetric method that begins with the selection of a number of aggregates (based on their PSD) that will meet the specified volumetric and density requirements. Samples are then prepared and compacted in a gyratory compactor. The height of the specimen is recorded during the compaction process so that the rate of densification can be monitored. The most important criteria are the percentage air voids, which is fixed at 4% for all mixtures, and traffic levels. The voids in the mineral aggregate change as the nominal maximum particle size changes. The allowable percentage of voids in the mineral aggregate filled with bitumen is reduced as the design traffic loading is increased. The optimum design is based on the performance of each sample in the compactor compared with criteria established in terms of the design traffic loading and the expected maximum temperature on the road.

The process used in Australia and New Zealand is similar to that described above in that the mix stability is determined using a gyratory compactor. The method used in New Zealand to design OGPA is described by TNZ (2007a, b). The main difference, apart from the porosity and associated criteria, is the skid resistance requirement, which is described in terms of PSV and asphalt particle abrasion loss.

Sullivan (2005) comments that the current methods use historical data to produce a mix with a particular surface texture. However, designers do not have any way to estimate the effect that a small change in gradation or binder content might have on the texture. Sullivan used data from a test track operated by the National Centre for Asphalt Technology at Auburn University, Alabama, to show that mean particle depth could be predicted from the PSD and the binder content. The required stopping distance of the design vehicle could then be estimated from the mean particle depth and the polished aggregate friction value.

2.8 Conclusions

The literature review has provided an indication of the relevance of some aspects of the research to be carried out.

- Open graded mixes such as OGPA will be more prone to particle breakdown than dense graded HMA.

- Flat and elongated particles will break down more readily than more cubic shaped aggregate.
- The LA abrasion test should provide a good indication of the likely breakdown of aggregate during the batching, mixing, laying and compaction phases of construction.
- Micro-deval testing could be used to rank aggregate in terms of the likely abrasion loss under traffic.
- The likely breakdown of SMA mixes can be evaluated using the weight loss measured using the micro-deval test, the change in aggregate shape characteristics and the change in PSD.
- Open graded mixes can be designed to provide a particular level of skid resistance.
- Rock is a heterogeneous material so its strength and durability can be expected to vary from one sample to another.
- The skid resistance properties of an aggregate depend on the mineral composition and the grain size.
- The quality of any aggregate depends on the production processes used.

3 Selection of aggregates

3.1 Available sources

Five sources of aggregate were originally selected for use in the test sections. They provided a range of:

- the material used in SMA in the North Island
- skid resistance values when measured using the PSV test.

The five aggregates are listed in table 3.1.

Table 3.1 Aggregates selected for evaluation

Aggregate source		Region	Rock type	PSV	Mix
1	Brookby Quarry	South Auckland	Waipapa greywacke	55–56	SMA11
2	Horokiwi	Wellington	Torlesse greywacke	58–60	SMA11
3	Te Matai	Palmerston North	Greywacke (gravel)	58–59	SMA11
4	Moutohora	Poverty Bay	East North Island greywacke	65	SMA10
5	Electric arc furnace slag	Auckland	Man-made	65	SMA11

Previously, samples of similar aggregate had been subjected to a series of engineering tests as part of the quality assurance programme carried out by Higgins Contractors. The tests included:

- crushing resistance
- PSV
- weathering quality index
- wet/dry crushing strength
- specific gravity and absorption.

In addition, samples were subjected to the micro-deval abrasion test. The results of these tests are summarised in section 4.1.

Because of time and site constraints, it was only possible to construct four test sections. Regrettably, the aggregate from the Horokiwi Quarry in Wellington was deleted from the programme.

Samples of the aggregates used are shown in figures 3.1–3.4.

Figure 3.1 Sample of aggregate from Brookby Quarry

Figure 3.2 Sample of aggregate from Moutohora

Figure 3.3 Sample of electric arc furnace slag

Figure 3.4 Sample of aggregate from Te Matai

3.2 Geological characteristics

3.2.1 Introduction

Samples of chip manufactured from each of the five aggregates that were selected for this project were subjected to a geological examination (see appendix B, which includes an explanation of some of the geological terms used).

3.2.2 Significance of geological characteristics

The influence that the geological characteristics of a rock have on the level of polishing and the time taken to achieve it is determined by the inherent properties of the rock, and the frequency and type of traffic. In general, all types of rock have a number of aspects in common:

- Rocks composed of minerals with a similar hardness will polish uniformly.
- The rate of polishing is related to the hardness of the minerals and the variation in grain size of the minerals.
- Large grains will take longer to polish than smaller grains, and will stand proud above the general surface and retain the surface microtexture for longer.
- Rocks with fine grain sizes will polish more quickly than coarser grained rocks.
- Rocks composed of minerals with a wide range of hardness are more resistant to polishing.

The sand grains in greywacke rocks are chemically and physically the strongest components of the rock. All greywackes contain fragments of quartz (a hard, tough mineral) and physically strong grains of sand. The size, angular shape and the degree of grain size sorting may vary throughout the deposit so that a variation in the ease of polishing could be expected. The sand grains are held in a matrix of clay-type and other cementing minerals (zeolites, quartz and calcite). In the case of clastic sediments, such as the greywackes, the degree of induration and the level of diagenesis/metamorphism, which determines the level of cementation, is important. During diagenesis (see appendix B), it is usual for clay minerals to wrap around the detrital fragments. However, many of these clays swell and lose their strength when wet, so that the detrital fragments can be released. This process will revive the skid-resistant qualities of rock chips exposed on the surface of a road.

The results of the geological analysis of the samples of aggregate used in this project are summarised in the remainder of this chapter.

3.2.3 Petrology of the samples

3.2.3.1 Greywacke

In New Zealand, the term ‘greywacke’ has been adapted to encompass a wide range of sedimentary rock types and grain sizes from mudstone through to siltstone and sandstone, and to conglomerate. It is used extensively in the quarrying industry and, to some extent, by geologists. It is essential to recognise that such rocks are intrinsically heterogeneous and may show a range of properties within any one quarry.

3.2.3.2 Brookby (South Auckland – Hunua area)

The rock from which the Brookby aggregate was quarried is a member of the Waipapa greywacke group. Most of the Waipapa rocks are sandstones and siltstones that are dense and hard. The sand and silt particles are volcanic in origin. Clay minerals are predominantly chlorite with lesser amounts of illite and smectite. The deposits are faulted and sheared. The surfaces of the faults and shears are usually coated with smectite and chlorite.

Examination of samples of the Brookby aggregate show it to be a dense, strongly cemented volcaniclastic sandstone that has undergone low grade metamorphism and is locally sheared. The clasts were predominantly quartz and feldspar (albite) in almost equal amounts. The clay minerals were chlorite with lesser amounts of smectite and illite. The rock was heavily veined with prehnite, and some calcite and possibly laumontite.

Effectively, this rock contains equal proportions of tough, hard quartz, and hard but relatively weak feldspars in a comparatively soft, weak matrix.

3.2.3.3 Moutohora (Poverty Bay – East Cape area)

The Moutohora Quarry was located within the Eastern North Island type greywacke rocks. (Note that the quarry is no longer being operated.) The rocks in this sequence are well bedded and relatively undeformed sedimentary rocks made up of particles varying from volcaniclastic to quartzofeldspathic in nature. They show alternating beds of sandstone and siltstone, but may contain small pebble-sized particles. They have undergone an intermediate level of metamorphism.

The samples that were examined showed that:

- feldspar was more abundant than quartz
- the pebbles and coarse sand grains contained volcanic debris
- the sandstone was rich in silica and quartz
- the rocks are occasionally veined with zeolite.

The matrix comprised zeolite and laumontite, and a complex assemblage of clay minerals (chlorite, smectite, illite and a swelling interlayer mineral). The sand grains were not tightly held by the matrix, which was also quite porous. Overall, the surface was very rough and the grains were easily dislodged. The surface friction characteristics of this material would probably be similar to the other greywacke rocks but dominated by the softer, weaker feldspars held in a relatively weak matrix.

3.2.3.4 Electric arc furnace slag (Pacific Steel)

Electric arc furnace (EAF) slag is a by-product of the manufacture of steel reinforcing rods and wire at the Pacific Steel plant in Otahuhu. The process involves melting scrap steel in an electric arc furnace and adding lime to form a slag that contains oxidised impurities, and which provides a thermal blanket to the melt and helps to reduce erosion of the refractory lining. Later in the process, pulverised coal is added. The coal burns to form carbon monoxide gas, which causes the slag to foam on the top of the molten steel. This foam is permitted to overflow the melt vessel and fall into the slag pit below. The slag is allowed to cool to form a solid, glassy, vesicular, rock-like material that is subsequently broken up; any steel carried over is removed by magnetic separation, and then the material is crushed and screened to form aggregate and sealing chip.

According to the advertising material provided by Winstone Aggregates, who market the slag, overseas experience has shown that the most abundant mineral phase present in most basic steel-making slags is beta-dicalcium silicate (Winstone Aggregates 2007). The reaction of this phase, along with the hydration of any residual free CaO and MgO near the surface of slag particles, tends to re-etch areas that have already been polished under traffic. The effect helps to maintain the original PSV and so increase the potential performance.

The petrological analysis revealed that the major mineral constituents were:

- wustite – black mineral (FeO)
- larnite – dicalcium silicate (Ca_2Si0_4)
- other calcium silicates in lesser amounts.

Other points of interest were revealed by the analysis:

- Some calcite can occur on the surface of the slag as a result of carbonisation of the calcium silicates.
- An irregular surface texture is formed by large bladed crystals of larnite.
- The crystals are held by a glassy cement.

The roughness of the surface of this material would be controlled by the hard, tough larnite crystals held in a tough matrix. Weathering of the dicalcium silicates etches the surface and so preserves a high level of skid resistance.

3.2.3.5 Te Matai (gravel pit in Palmerston North)

The Te Matai aggregate was manufactured from river gravel, which was quarried from a pit in Te Matai Road, Palmerston North. The gravel was derived from Torlesse-type greywacke sandstone. The Torlesse greywacke is predominantly quartz and feldspar. It has undergone intense brittle deformation, and shearing, fracturing and faulting are common. It is strongly lithified by very low grade metamorphism. It shows widespread quartz veining, and chlorite and smectite can appear on the surfaces in shear zones. The clay minerals are predominantly illite; chlorite is minor and smectite is rare. These rocks are denser and generally stronger than the Waipapa rock types.

Te Matai aggregate is a very quartz-rich gravel that is typical of the Torlesse sandstone type. It shows some brown discolouration of the matrix caused by slight weathering. The clay minerals are kaolinite, illite and some chlorite. The naturally water-worn surface of the gravel is relatively smooth in comparison with the irregular surface of the crushed material. The grains in the surface of the crushed rock appear to be well cemented by the matrix.

The quality of chip manufactured from the Te Matai gravels could be expected to be very good because any soft, weak material would have been removed as the gravel was transported downstream.

3.2.4 Comments

SMA has been developed as a deformation-resistant, durable surfacing material that is suitable for heavily trafficked roads. A rough, durable surface is required to provide skid resistance, while the body of the mix must resist deformation and the stone must be hard enough to resist the point-to-point loads generated within the mix. The engineering performance of the aggregate used is determined by its geological characteristics. The requirements of high PSV and durability are not mutually exclusive. Some rocks have a good crushing resistance and can withstand the high stresses imposed during construction, in particular. However, the sharp, rough surfaces produced by crushing may deteriorate quickly to leave round, polished surfaces. The matrix of some rocks may not be strong enough to withstand the wear produced by traffic so that the coarse particles are progressively dislodged. In this case, the roughness of the exposed surface of the chip may be progressively revived but the overall surface of the pavement will deteriorate.

The geological examination has highlighted the differences between the four aggregates. Three of the four belong to the greywacke group of rocks but even though they have a similar chemical composition, they differ by virtue of the mineral composition of the grains and the matrix. These differences are caused primarily by the composition of the source rocks (ie the rocks that produced the sediment that became compressed to form the greywacke). It is likely that they would have been produced at different times and be from different geographical locations.

The Waipapa rock types, found approximately along the axis of the North Island from Lake Taupo northwards, contain sediments formed from volcanic rocks; in the south, the minerals in the Torlesse rock types are predominantly quartz and feldspars. The composition of the greywackes of the eastern North Island varies between the two, ie from volcaniclastic to quartzofeldspathic.

The characteristics of the greywackes are also determined by the effects of lithification, which is the process that transforms the soft sediment into hard rock. These effects may be produced by:

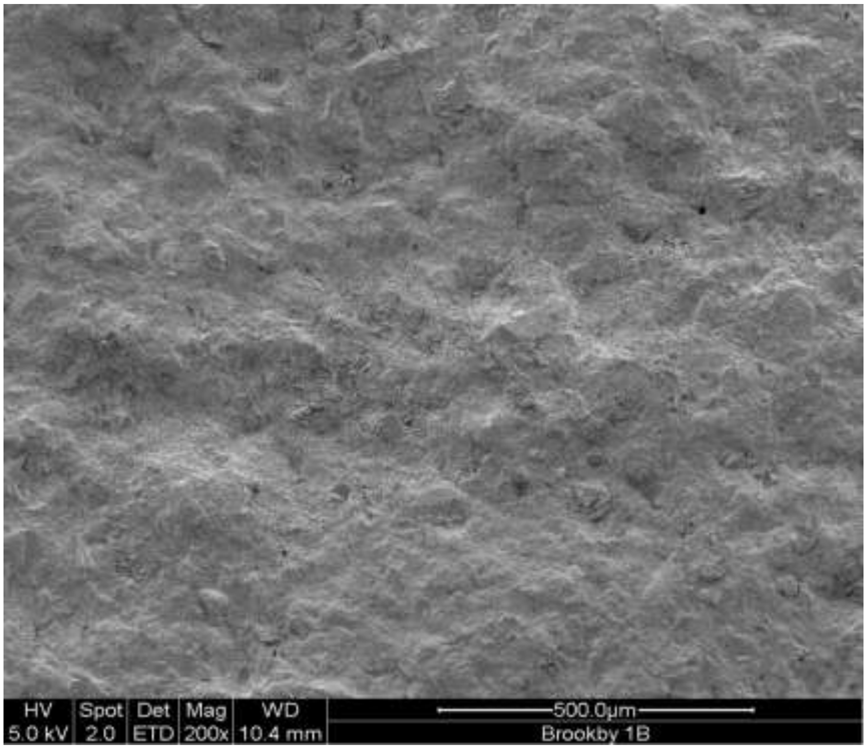
- the pressure of deep burial
- raised temperatures, in some cases
- the effects of ageing
- weathering.

The chemical composition and formation of the EAF slag is quite different to that of the greywacke rocks.

3.2.5 Characteristics affecting skid resistance

The surface of the Brookby sample (figure 3.5) appears to be relatively rounded, smooth and even. It has few significant protrusions. The matrix was said to be comparatively soft and weak, and could be expected to erode under traffic. This suggests that the frictional characteristics would vary depending on the coarseness of the sand grains. The surface exposed to the traffic would erode relatively quickly.

Figure 3.5 Surface texture of Brookby aggregate (1:200 scale)



The surface of the Moutohora sample (figure 3.6) appears to be much sharper and more uneven. However, it was noted that the sand grains were not held tightly by the matrix, which was also quite porous. Overall, the surface was very rough and the grains were easily dislodged. This suggests that while the frictional characteristics may be good, the chip would be easily eroded by the traffic.

The EAF slag (figure 3.7) has a surface that is vesicular and uneven with quite large protrusions. The larnite crystals that provide the roughness are held in a glassy matrix that would be resistant to weathering and traffic. The surface of the larnite crystals would be progressively etched by weathering.

The surface of the Te Matai sample (figure 3.8) is much more uneven than the other samples of greywacke and looks to be nearly as sharp as the Moutohora sample. The high proportion of quartz held in a strong matrix would suggest that the chip would have a hard, tough, durable surface that would be slow to degrade. The frictional characteristics may vary depending on the size of the sand grains and the proportion of broken faces.

Figure 3.6 Surface texture of Moutohora aggregate (1:200 scale)

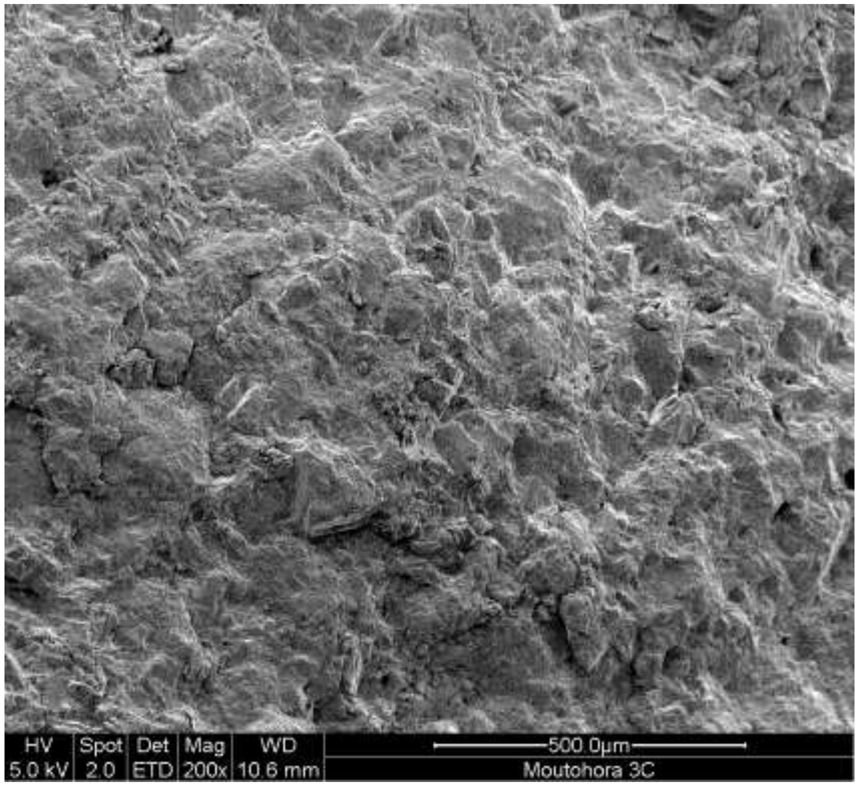


Figure 3.7 Crystals of larnite on the surface of EAF slag (1:200 scale)

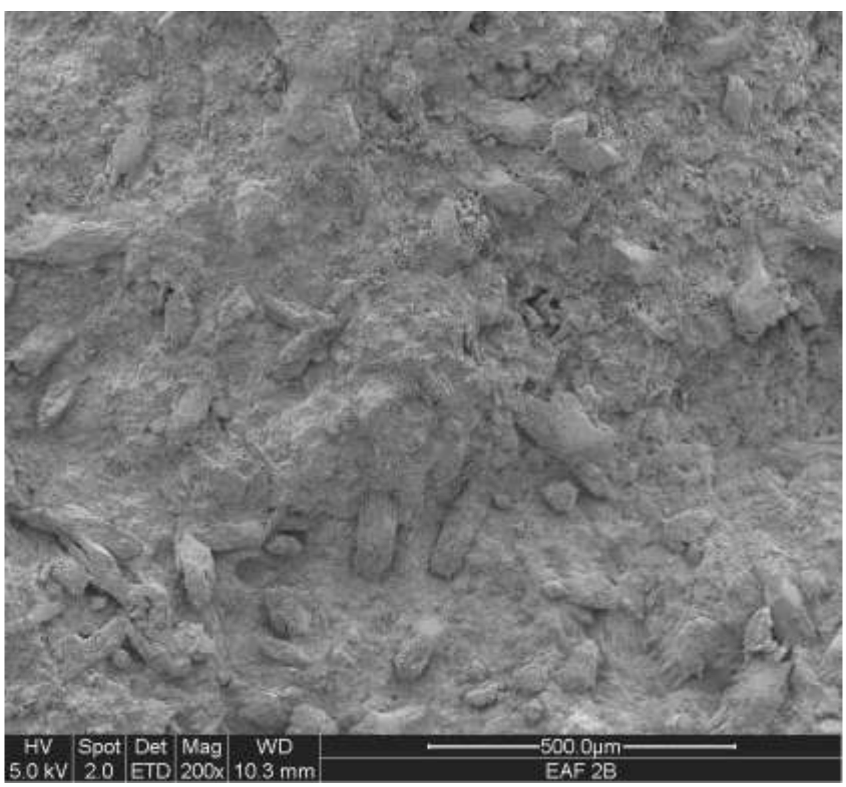
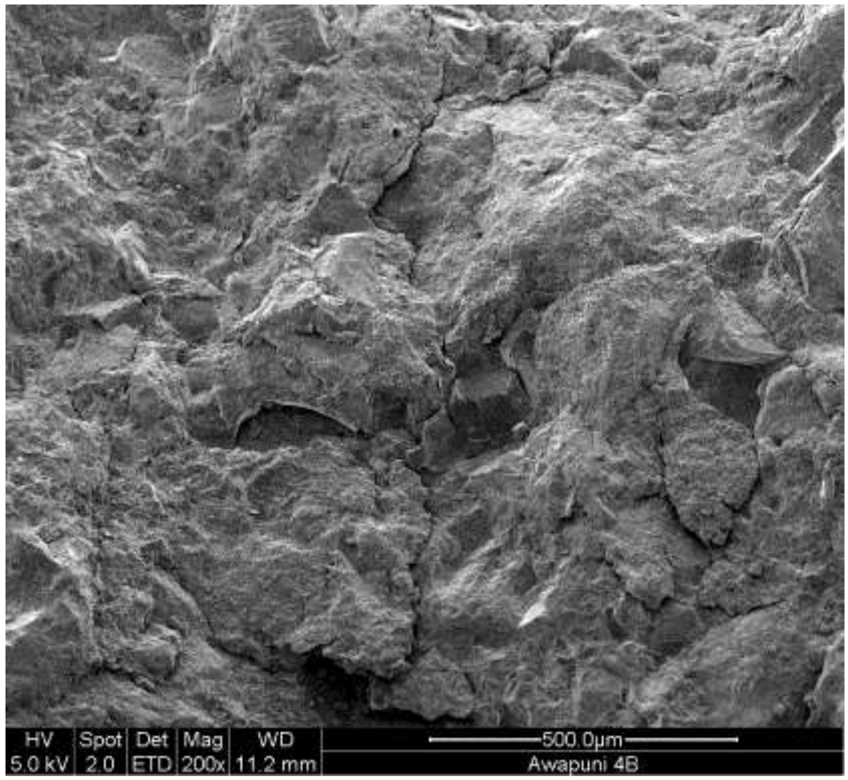


Figure 3.8 Surface of Te Matai aggregate (1:200 scale)



4 Laboratory evaluation of engineering characteristics

4.1 Aggregate source properties

The source properties of the aggregates are based on the results of quality assurance tests carried out by Higgins Contractors or their suppliers, and on one set of micro-deval tests carried out for this project by Fulton Hogan (Hamilton).

The results of each test are summarised in tables set out in appendix C. Table 4.1 provides the mean values from the data in appendix C.

Table 4.1 Summary of source properties of sample aggregates

Aggregate	Crushing resistance[a]	Weathering quality index		PSV	Abrasion resistance test results (%)		Wet/dry strength[f] (%)
		CV[b]	$R_{4.75}$ (%)[c]		LA[d]	Micro-deval[e]	
Brookby	4.1	95	99	56	11	5.9	20
Moutohora	7.4	87	94	66	26	15.2	-
EAF slag	7.2	97	98	65	13	3.4	13
Te Matai	3.3	97	98	58	13	5.7	24

Notes to table 4.1

a Crushing resistance: percent loss at a load of 230kN

b CV: cleanness value

c $R_{4.75}$: percent retained on 4.75mm sieve

d LA: LA abrasion test

e In calibration, the aggregate loss for all four aggregates was 8.1%.

f Wet/dry: (dry strength – wet strength)/ dry strength

4.2 Servopac gyratory compactor tests

A set of samples was evaluated using the Servopac gyratory compactor. This equipment evaluates the potential degradation of aggregate during construction. Compaction is achieved by the simultaneous actions of static compression and the shearing action generated by the rotational movement of the base plate set at a slight oblique angle to the axis of the cylindrical sample.

The test was in accordance with AS 2891.2.2 (Standards Australia 1995b) and was based on the following criteria:

- mould diameter =150mm
- ram pressure = 240kPA
- rate of rotation = 60 cycles per minute
- base plate compaction angle = 3°.

For these tests, the bituminous binder normally used was replaced with glycerine, which has a viscosity at room temperature (25°C) that is similar to the normal mixing temperature for bitumen (150°C). Samples were obtained after 80 revolutions and again after 350 cycles.

The results of the tests are recorded in the test summary in appendix C. The degradation of the aggregate is illustrated in figures 4.1–4.4.

Figure 4.1 Increase in fines content after gyratory compactor tests for the Brookby sample.

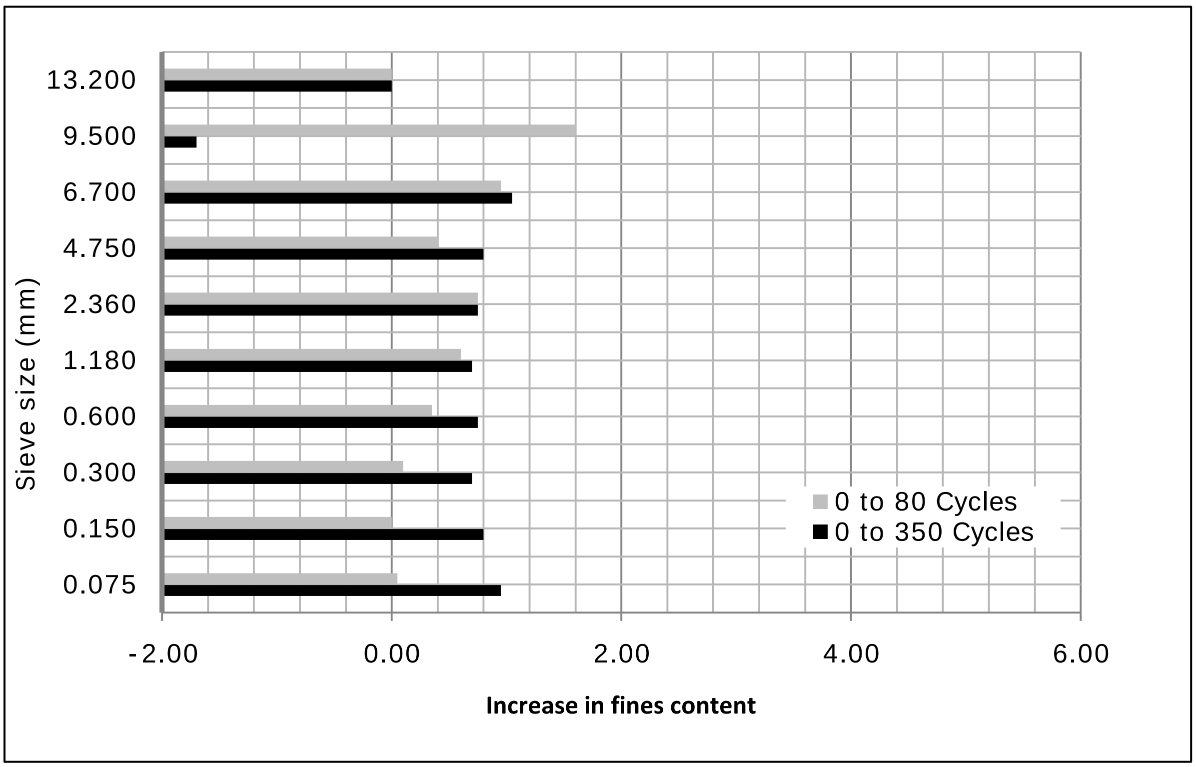


Figure 4.2 Increase in fines content after gyratory compactor tests for the Moutohora sample

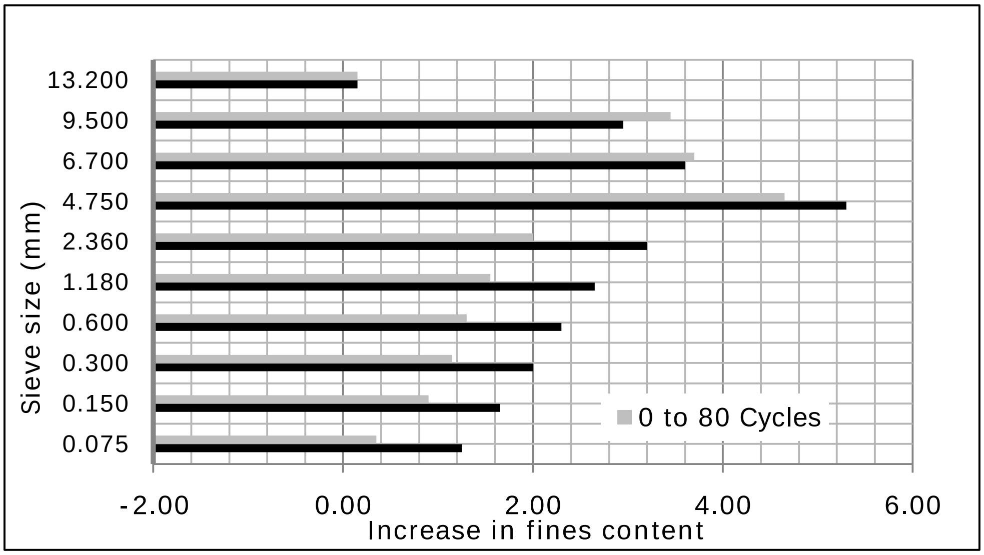


Figure 4.3 Increase in fines content after gyratory compactor tests for EAF slag

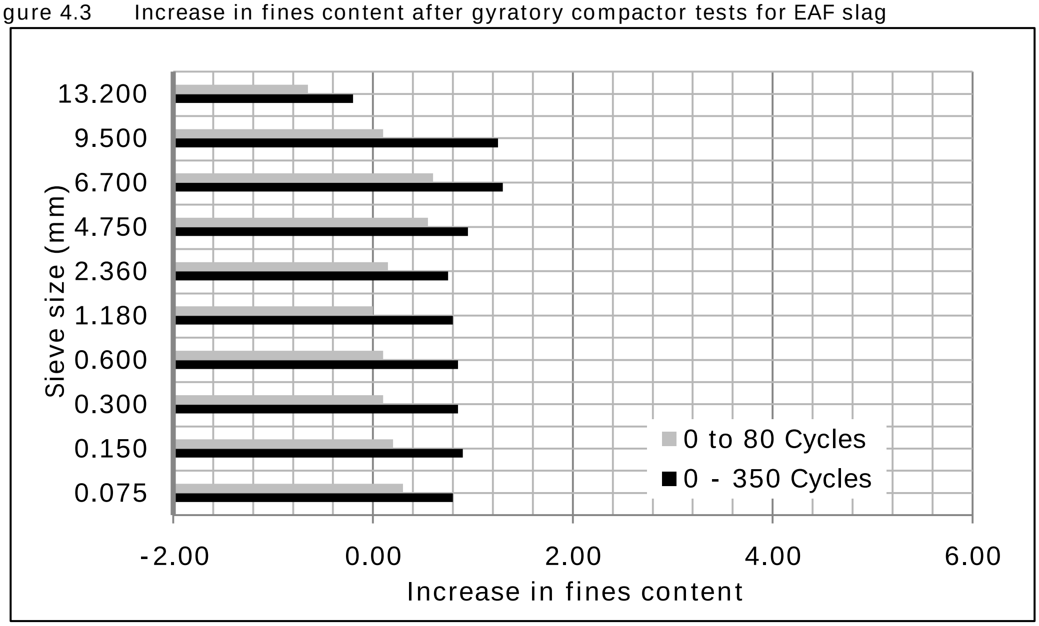
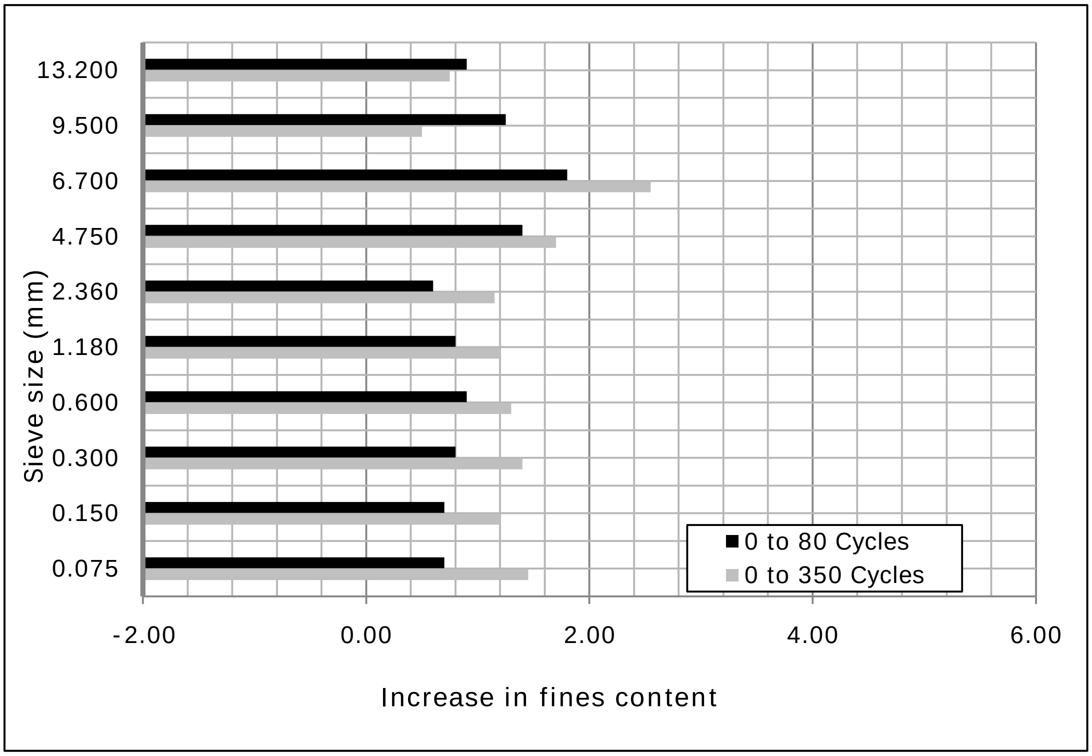


Figure 4.4 Increase in fines content after gyratory compactor tests for the Te Matai aggregate



These graphs show that some of the larger particles (predominantly 9.5–4.75mm) have been reduced in size and that the material produced is primarily fine sand that has passed through the whole nest of sieves. Note that the negative values shown in figures 4.1 and 4.3 are probably an aberration caused by possibly an elongated particle or two.

5 Test sections

5.1 Introduction

As discussed earlier, the original concept of sampling and testing material from existing pavements was replaced by a plan to construct test sections under controlled conditions and then to sample and test from each test section. By this means, it was possible to measure the changes that occurred in the layers that were constructed using aggregates from four different sources.

The mix used for each test section was designed and manufactured by Higgins Contractors to meet the requirements of *National asphalt specification NAS 2004* (Australian Asphalt Pavement Association 2004). The manufacture, laying and compaction of the mix followed protocols developed by Higgins Contractors to meet the requirements of the relevant NZTA or local authority specifications.

The test sections were 40mm (nominal) thick.

All the test work related to the test sections was carried out at Higgins Laboratory at East Tamaki.

5.2 Location

5.2.1 Auckland

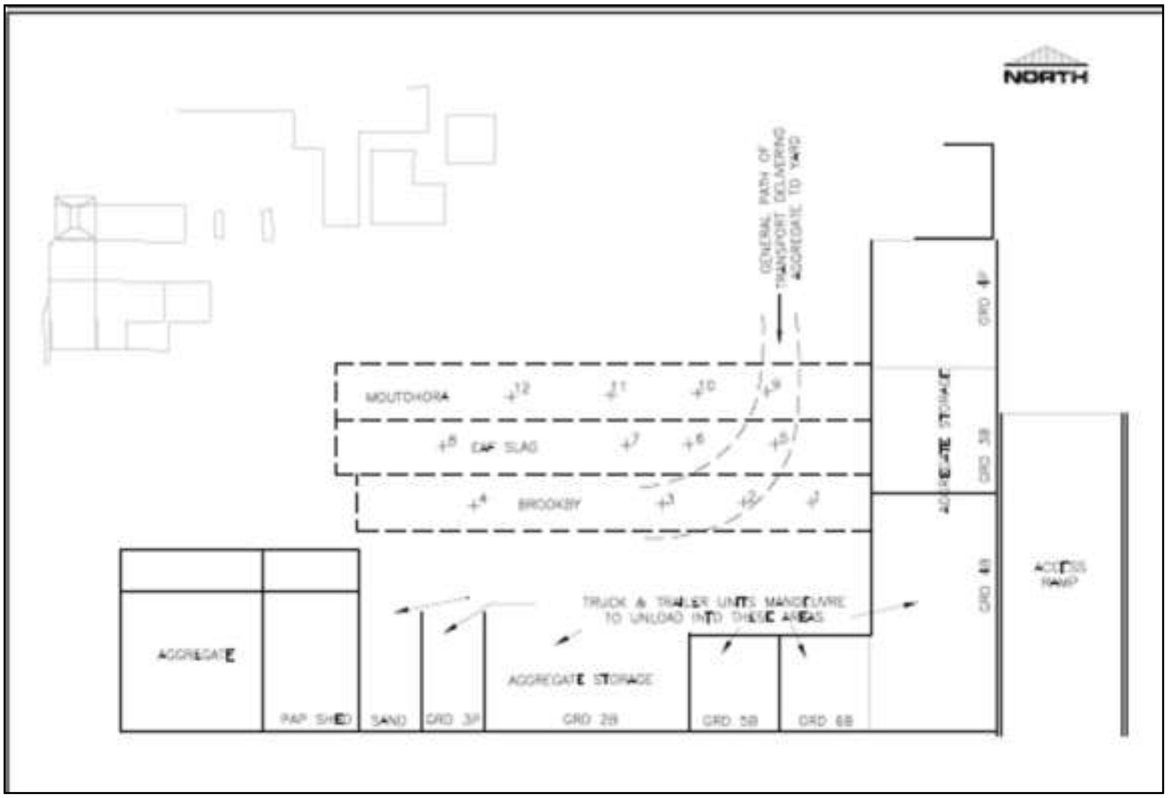
Three test sections of SMA were laid in the aggregate storage area at Higgins Contractors' Auckland yard in East Tamaki on 12 August 2009. The aggregates used were drawn from the Brookby Quarry south of Auckland City, the Moutohora Quarry north of Gisborne and the EAF slag from Pacific Steel's mill in Auckland.

Samples of the mix prior to laying were collected from the feed chute conveyor as the material was transferred from the mixer to the delivery hopper. Core samples were taken at the completion of construction and the density of each layer was measured using a Troxler nuclear density meter. The texture of the surface of each strip was determined using the standard sand circle test (TNZ 1981).

A further set of core samples was taken in April 2010 after eight months' trafficking. The texture was re-assessed at the same time.

The test sections were trafficked by truck and trailer units delivering aggregate to the stockpile bins.

Figure 5.1 Location of test sections at Higgins Contractors' yard in Auckland



+ Location of core sample

Figure 5.1 shows the location of each test strip, the aggregate used in each and the location of the core samples. It also indicates the area covered by delivery vehicles entering the stockpile area.

5.2.2 Taupo

The trial section at Taupo, which was 15m long by 3m wide, was constructed on 9 February 2010. The aggregate was sourced from the Te Matai gravel pit in Palmerston North but all other procedures were similar to those used in Auckland.

Samples of the mix and three core samples from the test section were sent to Higgins' Auckland laboratory for testing. A further set of slabs cut from the test section in April 2010 were also sent to the laboratory in Auckland.

5.3 Production properties

5.3.1 Test procedures

The core samples were returned to Higgins' laboratory, where the dimensions of each were measured and the following tests were carried out:

- bulk specific gravity at 25°C (ASTM D2726.08 (ASTM International 2008a))
- density (ASTM D2726.08)

- water absorption (ASTM D2726.08)
- percentage air voids (ASTM D3203.05 (ASTM International 2005a)).

Subsequently, the bitumen was extracted from the core samples, all cut stone was removed, and the PSD of the aggregate and the bitumen content were determined. Similarly, the bitumen was removed from the samples of uncompacted mix, and the PSD of the aggregate and the bitumen content were determined using the standard tests: ASTM D979-01(2006)e1, procedure 5.2.5 (ASTM International 2006), ASTM D2172.05 (ASTM International 2005b) and ASTM D5444.08 (ASTM International 2008b).

The results of these tests are summarised in appendix B.

5.3.2 Test results

5.3.2.1 Density, water absorption and air voids after construction

The density and water absorption properties of the core samples are summarised in table 5.1. In each case, the values are the mean of four results, except for Te Matai, which is the mean of three measurements. In April 2010, the surface was swept clean with a broom before a second set of cores was extracted. These tests were taken immediately adjacent to the cores taken in November 2009.

Table 5,1 Density, water absorption and air voids in the core samples: test results

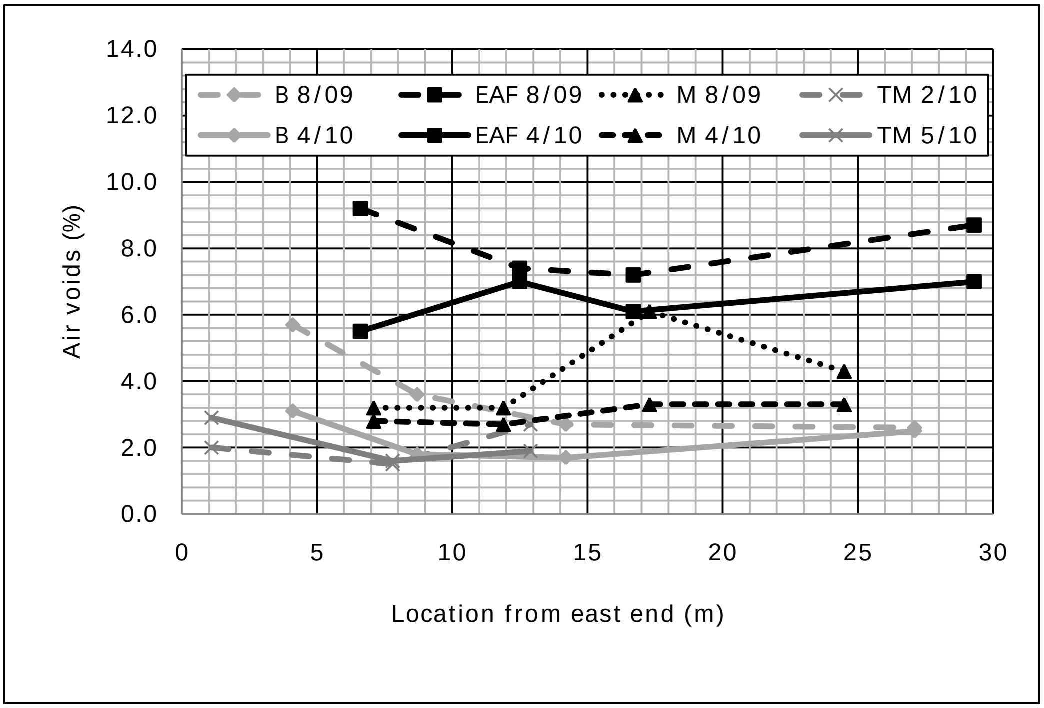
Aggregate	After construction			After trafficking		
	Density (t/m^3)	Water absorption (%)	Air voids (%)	Density (t/m^3)	Water absorption (%)	Air voids (%)
Brookby	2.359	0.7	3.7	2.392	0.7	2.3
Moutohora	2.291	0.7	4.2`	2.319	1.0	3.0
EAF slag	2.696	2.7	8.1	2.746	1.7	6.6
Te Matai	2.335	0.4	2.1	2.341	0.3	2.1

The air voids were measured again in the core samples taken in April 2010. The change that occurred is illustrated in figure 5.2.

Note that ASTM D2726.08 (ASTM International 2008a) should not be used for material that has a water absorption value greater than 2%. The high water absorption of the EAF slag may have distorted the air void values.

The water absorption results vary depending on the nature of the rock. The Brookby and Moutohora greywacke aggregates are more weathered than the Te Matai, and therefore have a higher water absorption. The EAF slag is vesicular and may also be hygroscopic because of its chemical composition.

Figure 5.2 Air voids in the SMA layer of the core samples at different dates



Notes to figure 5.2:

B = Brookby

EAF = EAF slag

M = Moutohora

TM = Te Matai

Numbers indicate month and year of measurement

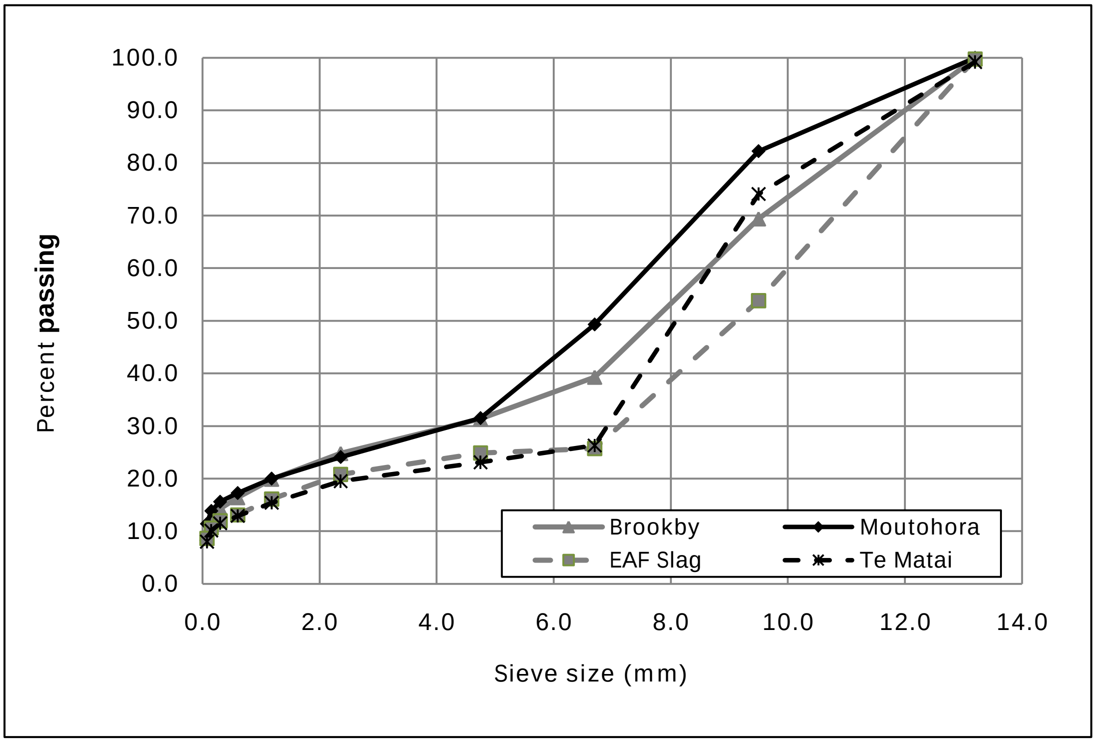
Some reduction in the air voids at the Auckland test sections occurred during the trafficking period, particularly at the east end, which was the most heavily trafficked. Trafficking has also reduced the variability.

5.3.2.2 Particle size distribution

The results of the particle size analysis of the samples of the material used in this project are tabulated in appendix B and summarised in figure 5.3.

Note that the PSD of the aggregates prior to construction appear to fall into two groups. The Brookby and Moutohora samples make up in one group, while the EAF slag and the Te Matai samples make up the other. Such differences may have an influence on any degradation that may occur under load.

Figure 5.3 Particle size distribution of the core samples



The change between the mean of the PSD for the production samples (PM), the mean of the core samples taken post-compaction (PC) and after trafficking (AT) are shown in figures 5.4–5.7.

The figures indicate that generally the sampling and test methods used provided reasonably consistent results. The two samples of each aggregate type taken from the feed chute conveyor (PM) gave results that lay within the allowable range for single operator precision as recommended by ASTM International for that test (2008b).

Figure 5.4 Means of the PSD for the production samples (PM), core samples post-compaction (PC) and after trafficking (AT) for the Brookby aggregate

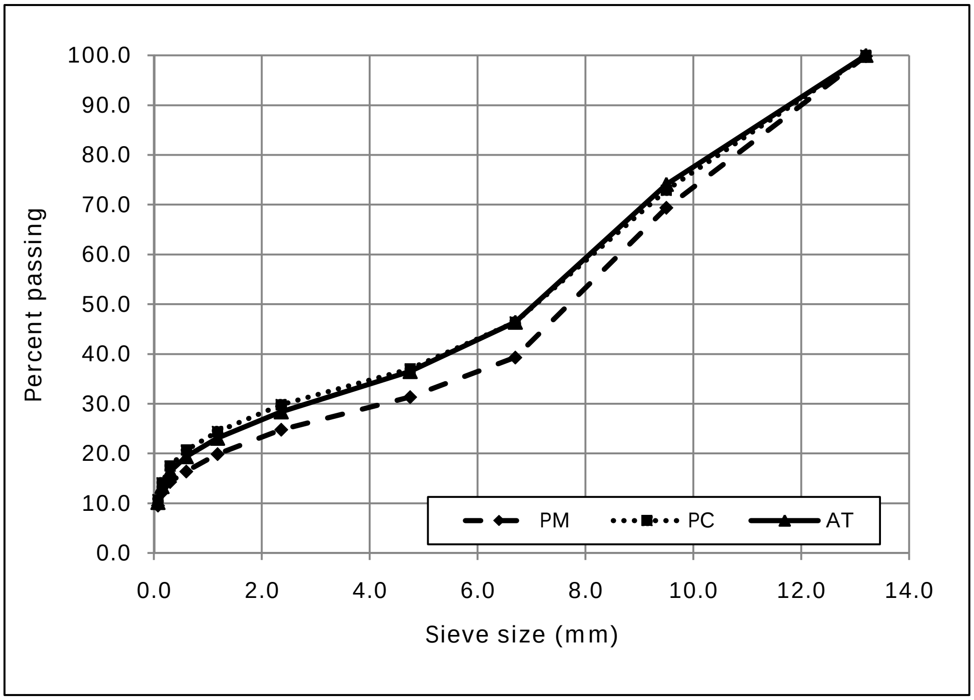


Figure 5.5 Means of the PSD for the production samples (PM), core samples post-compaction (PC) and after trafficking (AT) for the Moutohora aggregate

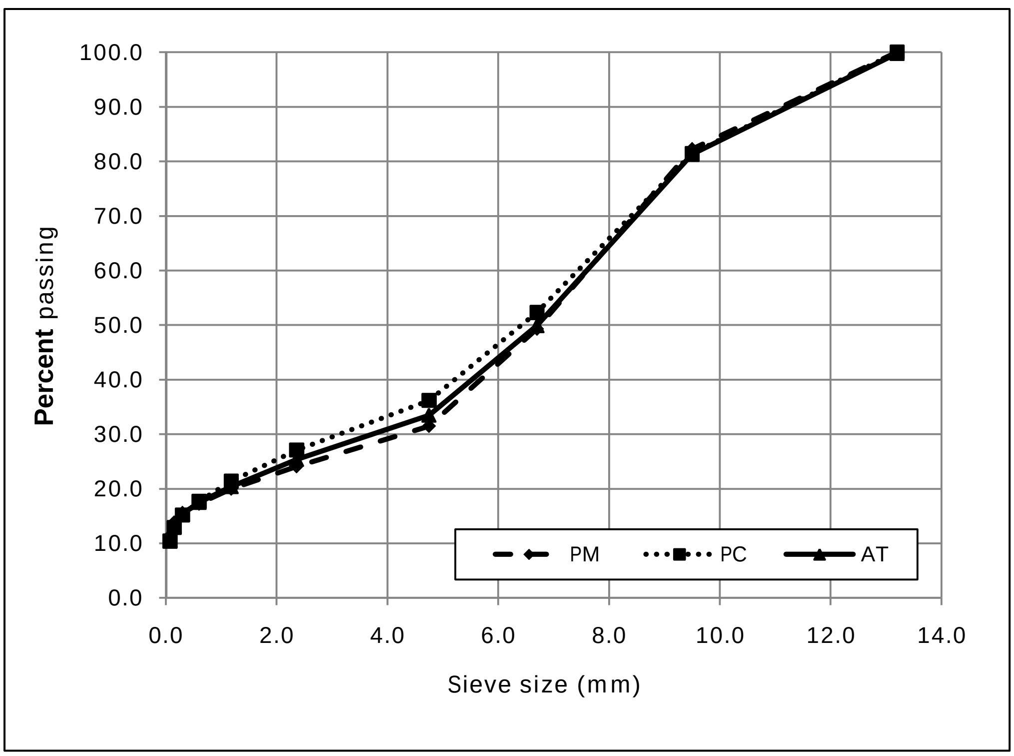


Figure 5.6 Means of the PSD for the production samples (PM), core samples post-compaction (PC) and after trafficking (AT) for the EAF slag

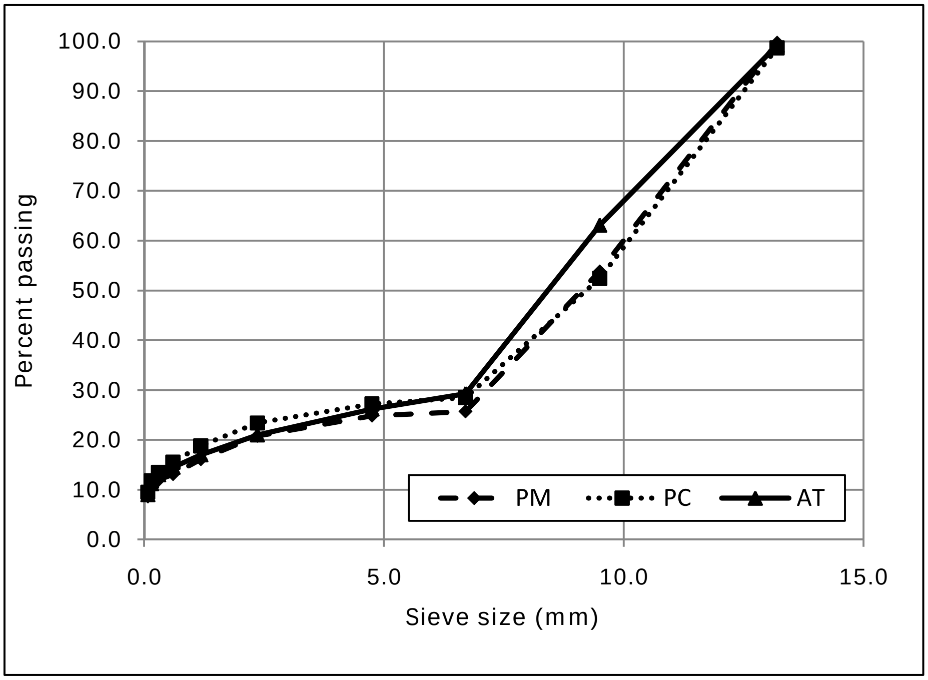
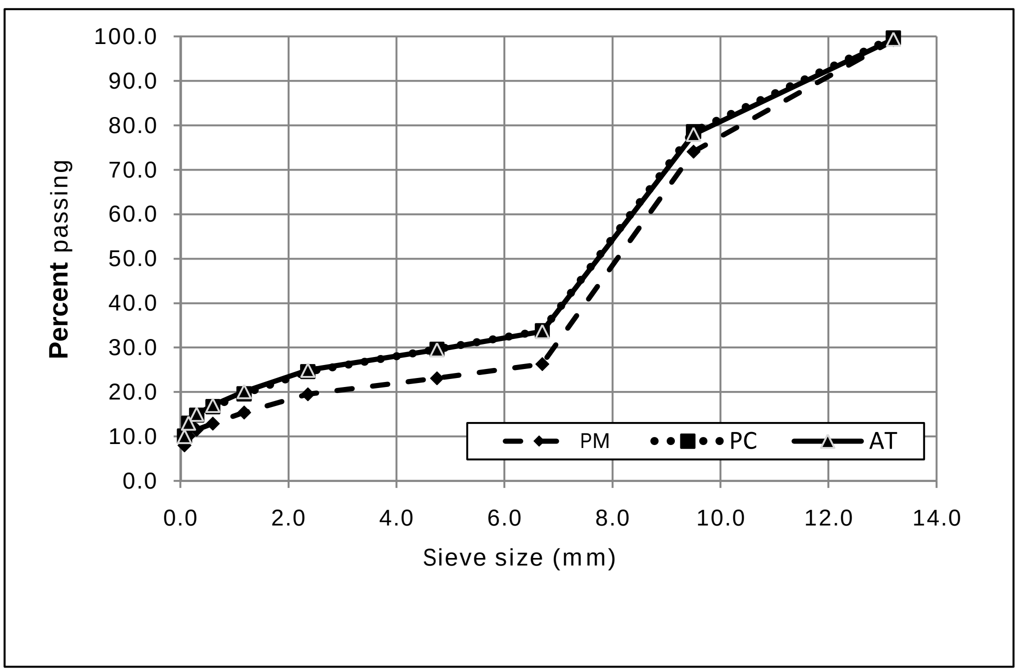


Figure 5.7 Means of the PSD for the production samples (PM), core samples post-compaction (PC) and after trafficking (AT) for the Te Matai aggregate



A comparison of the gradings after compaction and some trafficking is shown in figure 5.8. This graph is based on the mean PSD post-compaction and after trafficking, ie. (*PC* + *AT*)/2.

Figure 5.8 Mean of the core samples post construction and after trafficking for all samples

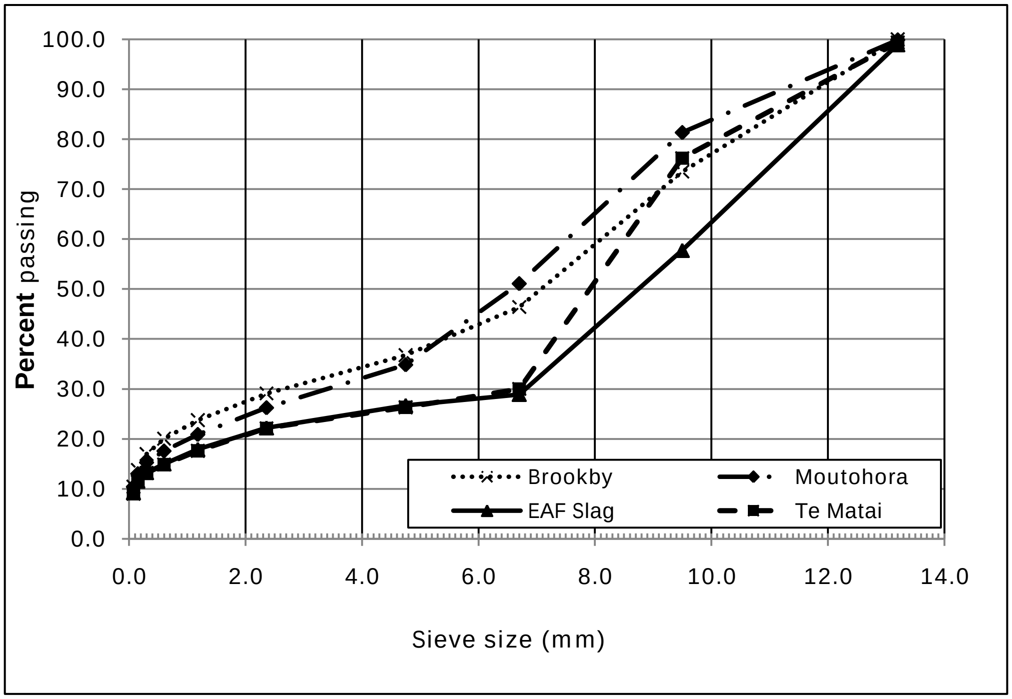


Figure 5.9 Degradation of sample aggregates caused by construction, measured as the difference between mean PSD for the production samples (PM) and post-compaction (PC)

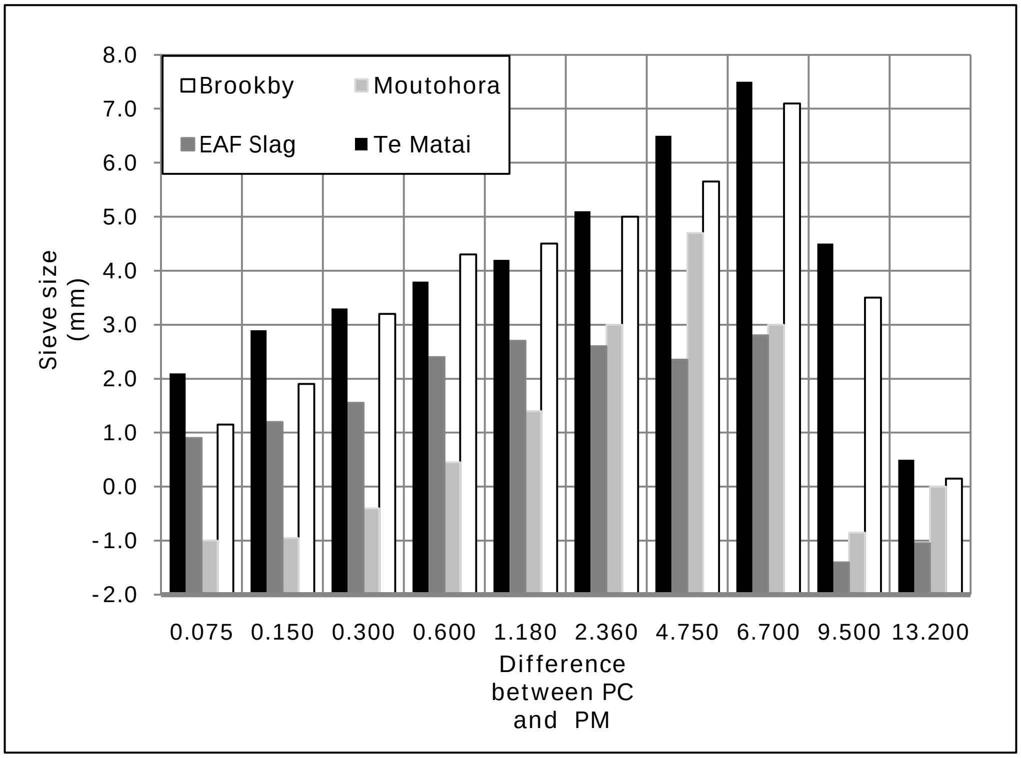


Figure 5.9, based on the difference in the percentage passing each sieve, shows that all of the aggregates suffered some breakdown, particularly in the larger size range. Most of the material that was generated was sand. The negative values, particularly in the larger stone sizes, may result from test error or the presence of elongated particles. Such values for the smaller sieve sizes could be a result of the production of more fines.

Figure 5.10 Degradation of sample aggregates caused by trafficking, measured as the difference between the mean PSD post-compaction (PC) and after trafficking (AT)

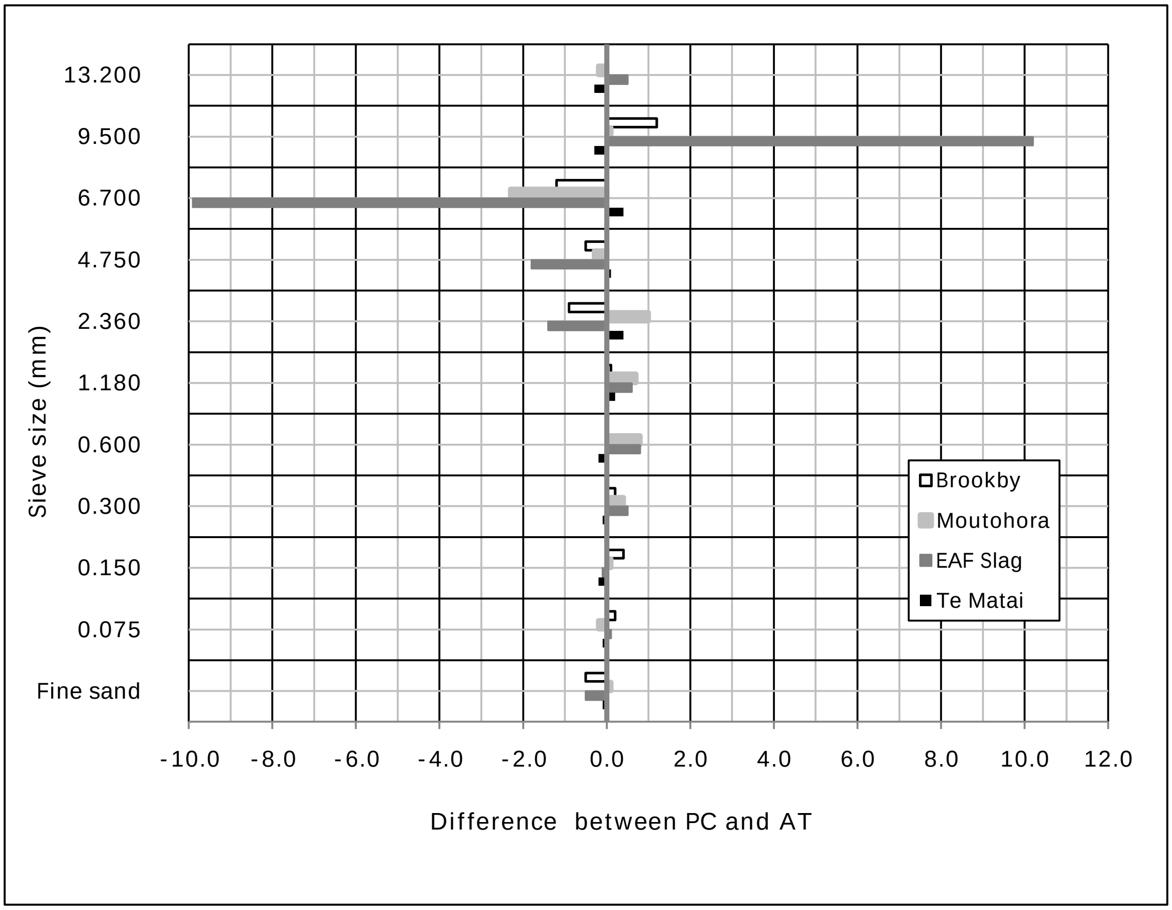


Figure 5.10 shows that little or no change was caused by traffic. Note that the extreme positive value for EAF slag could be an anomaly in the AT sample or may result from a collapse of particles during trafficking.

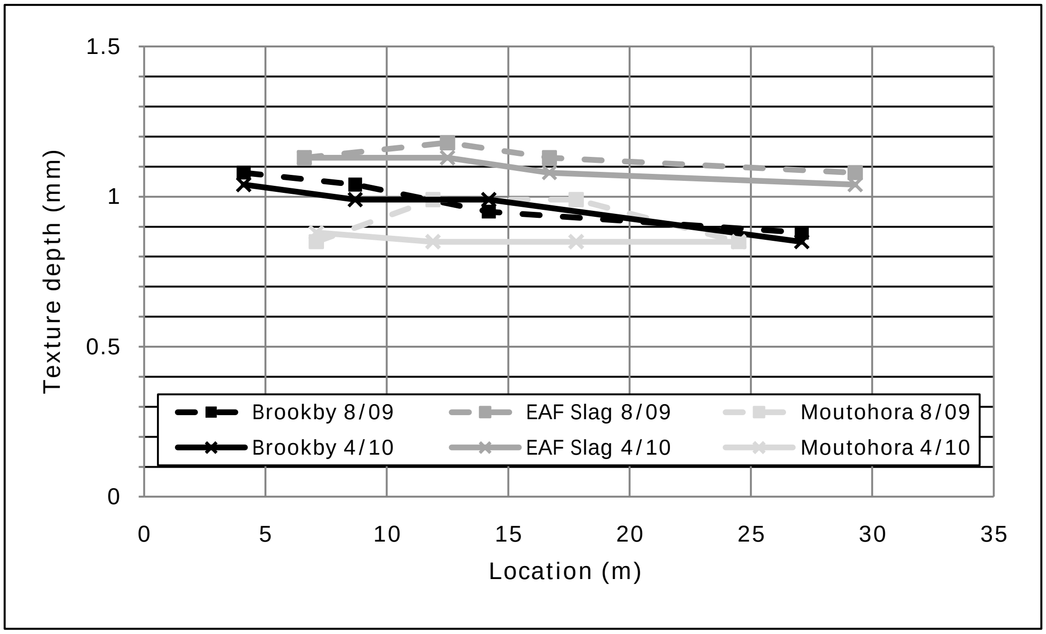
The traffic loading was primarily created by truck and trailer units delivering aggregate to the plant stockpiles but was applied over a relatively short period of time. The units generally carried 29–30 tonne payloads and were estimated to apply a loading to the pavement equivalent to four standard 18kN axle loads (ie four equivalent standard axles (ESA) per truck and trailer unit). The units travelled over different paths as they were manoeuvred into position to unload (refer to figure 5.1) and, as a consequence, the estimated wear on each test section can only be a 'best guess'. However, it is possible that the most frequently loaded section (probably at the east end) carried something in the order of 20,000ESA over the period.

It should be noted that other investigations similar in nature to this project have shown that degradation can occur during trafficking.

5.3.2.3 Surface texture

The texture of the surface of each section was measured immediately after construction using the standard sand circle test. A second set of measurements was taken in April 2010.

The results are set out in table B1 in appendix B and summarised in the graph shown as figure 5.11. The comparative texture at the time of construction is illustrated in figure 5.12.



Numbers indicate month and year of measurement

Figure 5.12 Comparative texture of the three sections laid in Auckland

Figure 5.12 shows the difference in the texture of each section immediately after laying and after eight months' trafficking. The EAF slag, being the aggregate with the coarsest grading, has the deepest texture. Initially, the texture of the Brookby and Moutohora aggregates was similar, although the Moutohora aggregate showed a greater variation. After trafficking, the texture of the Brookby and EAF slag sections showed little change but the surface of the Moutohora aggregate became almost uniform throughout its length. However, the change is in the order of 0.1mm, which is probably within the tolerance for this type of test.

5.3.3 Ranking and predictability

One of the objectives of this research was to review the current source property tests and acceptance criteria to assess whether they are appropriate for durable stone-on-stone mixes.

The aggregates used in this project have been ranked in terms of the performance of each in the various source property tests. This is shown in table 5.2

Table 5.2 Ranking in terms of the results for source and similar tests

Aggregate	PSV	Crushing resistance	Weathering quality index		Abrasion resistance (%)		Wet/drystrength	Dynamic compactor
			Cleanness value	$R_{4.75}$	LA	Micro-deval		
Moutohora	1	4	4	4	4	4	?	4
EAF slag	2	3	1=	2=	2=	1	1	1
Te Matai	3	1	1=	2=	2=	2	3	2
Brookby	4	2	3	1	1	3	2	3

The ranking indicates that the Moutohora aggregate, which has the best PSV, scored poorly in the tests that indicate durability. The EAF slag, which also has good skid resistance qualities, has better strength and durability characteristics. It has poor crushing resistance properties, but scored well in the micro-deval and dynamic compactor tests. The other two greywacke aggregates from Brookby and Te Matai have similar all-round source characteristics.

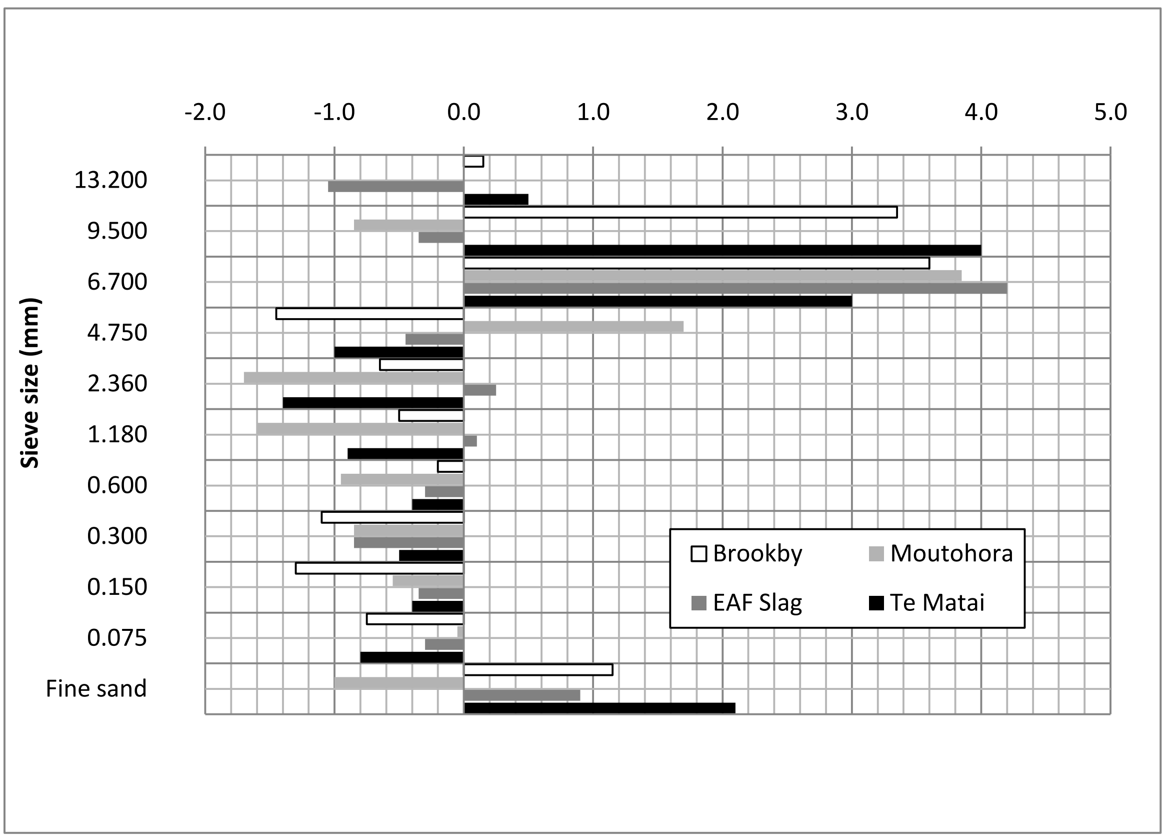
The properties that were predicted by the geological assessment are generally borne out by the results of the tests. The results of the LA and micro-deval abrasion tests do not appear to be greatly different. The micro-deval test ranked the aggregates in the same sequence as the dynamic compactor.

5.4 Degradation

5.4.1 Results

The research carried out during this project shows that the coarser particles of aggregate used in SMA degrade during compaction. Most of the breakdown occurs in the larger particles, which can be described as small to medium gravel. As these particles wear, they produce predominantly fine sand. This is illustrated in figure 5.13.

Figure 5.13 Degradation caused by construction (based on material retained on each sieve), defined as the difference between the mean PSD of the production samples (PM) and the post-conduction means (PC)



It is therefore concluded that the degradation process involves the removal of sharp corners and edges of the larger particles when one large particle moves against another as the mix consolidates under the action of the steel-wheeled rollers.

5.4.2 Measurement of degradation

Degradation is usually assessed on the basis of the change in the PSD. Most researchers select the change on one of the coarse sieve sizes (eg 4.75mm) as the correct measure. However, comparison of individual PSD values is fraught with difficulty. Obviously, the larger particles are reduced in size during the compaction process and move from one sieve size down to the sieve with the next smallest aperture, while the debris may fall down a number of sizes. Figure 5.13 indicates that major changes occurred on two or three of the larger sieves, with varying amounts of sand accumulating on the smaller sieves.

For comparing the aggregates, the change on the 6.7mm sieve appears to be the more consistent and will be used in this instance. The material from Te Matai suffered the least change (3%), while the Brookby, Moutohora and EAF slag aggregates suffered the greatest change (3.6–4.2%).

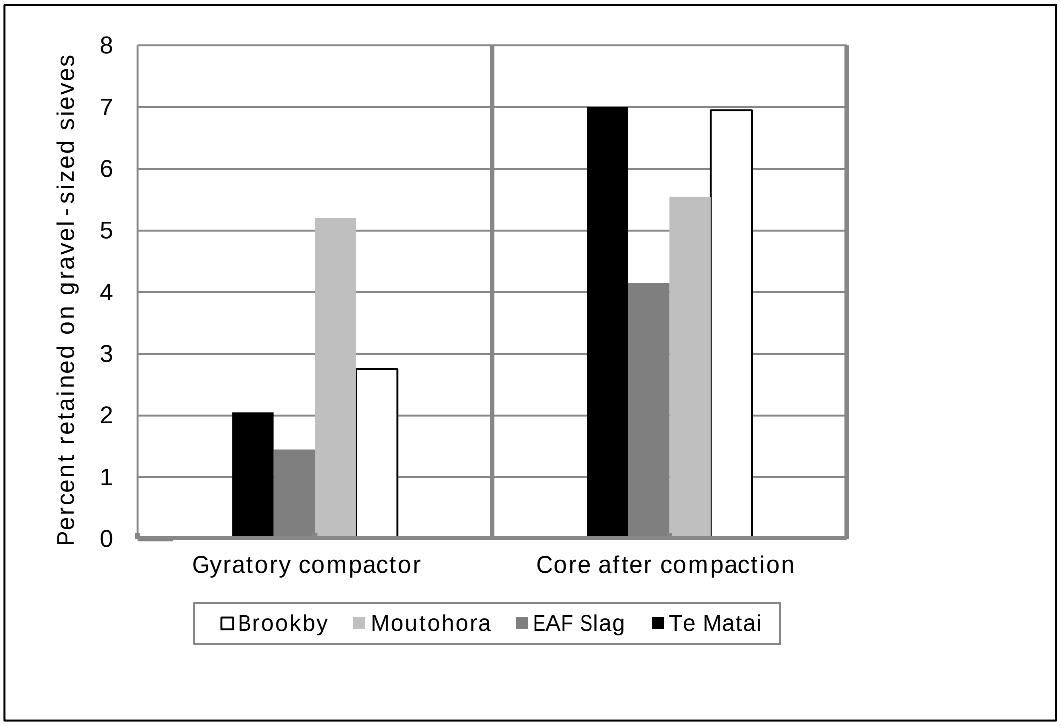
It was not possible to detect any degradation after seven months of traffic wear. However, the loading period was quite short, and the movement of the truck and trailer units over the test sections was not restricted to one path (as it would be on a highway).

5.5 Prediction of degradation

The gyratory compactor test provides a reasonably accurate model of the conditions in the SMA layer during compaction. It was therefore expected that the results of that test would provide a good indication of the degradation that occurred in the test sections.

A comparison of the degradation generated during the compaction of the test sections and that generated during 350 revolutions of the gyratory compactor is shown in Figure 5.14. This graph is based on the sum of the material retained on the larger sized sieves rather than on one particular sieve.

Figure 5.14 Degradation of test sections versus laboratory results



This figure indicates that the gyratory compactor could be used to provide a reasonably accurate indication of the breakdown (30–40% at 350 revolutions) for some (but not all) rock types.

For the Moutohora aggregate, the gyratory compactor measurement was virtually equal to the field measurement. It was noted earlier that this rock type was more weathered than the others and it may have broken down more easily in the compactor than the others.

The micro-deval test was more accurate in predicting the degradation generated by the gyratory compactor test but the other source property tests were of little value in this regard.

6 Conclusions

6.1 Introduction

The objective of this project was to investigate the durability and mechanical integrity of high PSV (>60) aggregates for HMA, particularly chips or coarse aggregates in stone-on-stone mixes such as SMA and OGPA.

The methodology used was changed from that originally intended (for the reasons explained earlier) and, as a consequence, the aggregates evaluated cover a much wider range of PSV values than would have been originally possible.

One of the unsatisfactory characteristics of the stone-on-stone mixes is the potential for degradation, which could lead to ravelling, rutting and flushing. Degradation can result from the removal of the sharp corners as one large particle moves against another.

This project has explored some of the possible factors related to the breakdown of aggregate such as the crushing strength and abrasion resistance, but a number of other factors, such as particle shape, have not been evaluated.

6.2 Geology

The geological evaluation provided a good assessment of the different characteristics and potential performance of the four types of aggregate used. It identified the properties that determine the skid resistance and the durability of the chips, properties that are not mutually exclusive. The predictions made from the geological assessment are generally borne out by the results of the engineering tests.

6.3 Source properties

Most of the properties determined using the source property tests had no particular relevance in terms of the ability of the aggregate to withstand the construction process. The Moutohora aggregate had by far the worst crushing resistance, weathering quality index and LA abrasion results, but did not degrade as much in the test sections as would have been expected from the results of the source property tests.

The micro-deval test provided a reasonably accurate prediction of the degradation generated by the gyratory compactor test but not the breakdown in the test sections.

6.4 The gyratory compaction test

The load applied in the gyratory compaction test on three of the four aggregates did not cause the level of breakdown that occurred in the test sections. The one exception was the Moutohora aggregate. It is worth noting that the test was based on the Australian standard (Standards Australia 1995b), which differs from the American Superpave protocol in that the applied load is 40% of the Superpave requirement, while the angle of gyration is 3° rather than 1.25°. This suggests that each country has adapted the test to suit the characteristics of the aggregate most commonly used, and it may be appropriate for New Zealand to adopt the same approach.

6.5 Test sections

The three test sections in Auckland and the one in Taupo provided a useful source of test data for this project. A good set of start data has been established and is recorded in the appendices. However, more information is required about the breakdown of aggregate under traffic loading. It would therefore be appropriate to monitor the condition of these pavements on an annual basis for a year or two to record what changes occur.

6.6 Air voids and surface texture

The air voids and the surface texture in the test sections decreased but no apparent change in the performance of the test sections was noted.

6.7 Degradation

All the aggregates in the test sections suffered degradation during compaction but to varying degrees. The coarser gravel-sized particles degraded to release mainly fine sand particles.

Opinion differs regarding the measurement of degradation. Some prefer the change on one sieve size, but others consider the change on a range of sieves may be a better measure. The volume of sand produced could also be used.

6.8 Degradation from traffic

The PSD of the aggregates in the test sections in Auckland changed little during the seven-month trafficking period, even though the trucks that used the test area were heavily loaded (4ESA per unit). This result was different to that experienced in Grafton Gully (described in section 1.4). One reason could be the short period of time but it may also be caused by the different loading conditions between the test sections and the motorway in Grafton Gully.

At Higgins' yard, the trucks delivering aggregate to the stockpiles were virtually unrestrained except that most crossed the test sections at the east end. On a motorway, the traffic is virtually confined so that the wheels travel down two paths, each approximately 700mm wide. So while the loading applied by each truck and trailer unit delivering aggregate to the yard was relatively high, the number of passes over one particular area varied and was probably comparatively low.

7 Recommendations

It is recommended that monitoring of the changes in the surface texture and the PSD of the test sections be continued for at least two years.

It is also recommended that various types of specification for the use of the gyratory compactor should be evaluated to establish the most suitable protocol for New Zealand aggregates.

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Appendix A Abbreviations and acronyms

AAPA: Australian Asphalt Pavement Association

EAF: electric arc furnace

ESA: equivalent standard axles

HMA: hot mix asphalt

LA: Los Angeles

NAS: National asphalt specification

NZTA: NZ Transport Agency

OGPA: open graded porous asphalt

PSD: particle size distribution

PSV: polished stone value

SH: State Highway

SHRP: Strategic Highway Research Programme

SMA: stone mastic asphalts

TNZ: Transit New Zealand

US: United States

Appendix B Geological aspects of stone polishing

B1 Introduction

The association between the inherent properties of the rock and its resistance to polishing under traffic is based on grain size and the hardness of the minerals. In general, the following tend to hold:

- Rocks composed of minerals with similar hardness polish uniformly.
- The rate of polishing is related to the hardness of the minerals and the variation in grain size of the minerals.
- Large grains take longer to polish than smaller grains, and will stand proud above the general surface of the rock and retain the microtexture of the surface for longer.
- Rocks with fine grain sizes polish more quickly than those with coarse grains.
- Rocks comprised of minerals with a wide range of hardness are more resistant to polishing.

The sand grains in greywacke rocks are chemically and physically the strongest components of the rock. All greywackes contain fragments of quartz (a hard, tough mineral) and physically strong grains of sand. The size, angular shape and the degree of grain size sorting may vary throughout the deposit so that a variation in the ease of polishing could be expected. The sand grains are held in a matrix of clay and other cementing minerals (zeolites, quartz and calcite). In the case of clastic sediments, such as the greywackes, the degree of induration and the level of diagenesis/metamorphism, which determines the level of cementation, is important.

Diagenesis is any chemical, physical or biological change undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surface alteration (weathering) and metamorphism. After deposition, sediments are compacted as they are buried beneath successive layers of material and eventually become cemented by minerals that precipitate from a solution. These changes happen at relatively low temperatures and pressures, and result in changes to the rock's original mineralogy and texture. Grains of sediment, rock fragments and fossils can be replaced by other minerals during diagenesis. The boundary between diagenesis and metamorphism, which occurs under conditions of higher temperature and pressure, is gradational.

During diagenesis, it is usual for clay minerals to wrap around the detrital fragments. Many of the clay minerals within the rock absorb water and swell. As a consequence, the cement holding the matrix together will weaken when exposed to the weather so that the harder grains can be dislodged. This process will revive the skid-resistant qualities of rock chips exposed on the surface of a road. For example, the matrix holding partially polished grains in sealing chip can be removed by traffic to expose fresh unpolished grains. Hence the long-term durability and skid resistance of sealing chip is related to the weathering characteristics of the rock.

While most of the chips studied during this project were produced from sedimentary rocks, chips produced from igneous rock types or from slag produced during the manufacture of steel may have similar characteristics depending on the chemical composition and the mode of formation. For example, the EAF slag used in this project has a surface roughness because of the vesicles formed during manufacture. In addition, the presence of larnite and wustite minerals make it a very hard, durable material.

The skid resistant properties of aggregate result from the presence of hard rock fragments contained within a softer matrix. The action of rubber tyres then polishes the hard rock fragments and also erodes the matrix. Eventually, a polished fragment is dislodged and the matrix is removed to expose other sharp fragments in the layer below.

Many greywacke quarries produce high PSV aggregate described as being either slightly brown (oxidised) or moderately weathered. This material will have a lower crushing resistance value than fresh rock from the same quarry, but the fresh rock will probably have a lower PSV. However, the durability of the partially weathered rock, particularly in wet situations, is likely to be in doubt.

The grains of EAF slag are welded together at high temperatures and rock has vesicles through which gas has escaped during manufacture. The surface of the aggregate formed from the slag is therefore highly irregular and sharp. It also contains large crystals of larnite (dicalcium silicate), which has an inherent toughness that is considered to be good. Wustite, the other mineral in the slag, also has a high degree of toughness. While dicalcium silicates commonly carbonate when exposed to the atmosphere, this does not apparently affect the hardness.

B2 Hardness

Most common rock-forming minerals are solid solutions with a chemical composition that varies within the constraints of the mineral formula. Their physical properties vary with the chemical composition. Most are anisotropic so that the physical properties, such as hardness, vary with the orientation of the mineral.

The relative hardness of minerals can be assessed using the Mohs scale, which ranks the ability of one mineral to abrade or scratch another. The Mohs scale has a range of 1 to 10, with talc having a value of 1 while diamond has a value of 10. Absolute hardness can be assessed using the Vickers microhardness test that measures the mineral's resistance to indentation under a steadily applied stress. This is termed indentation hardness or microhardness. Recent advances in nanotechnology provides hardness data from Depth Sensing Nanoindentation experiments. Both tests provide absolute hardness data relative to the crystal plane measured.

Only a few of the minerals in the Mohs hardness scale form rocks and are relevant to a study of aggregates. These are calcite, quartz and corundum. Table B1 contains comparative data for a range of minerals found in New Zealand aggregates.

Table B1 Summary of properties of minerals found in New Zealand rocks

Mineral	Density	Hardness scale		Fracture properties	Toughness	Found in
		Mohs	Vickers*			
Quartz	2.65	7	12.2	Conchoidal fracture	Good (1.60)	Greywacke
Olivine	3.3–3.6	7	10.3	Conchoidal fracture	Good	Basalt
K-feldspar	2.56	6–6.5	6.9	Two sets of perfect to good cleavages	Poor (0.88)	Basalt, dacite, andesite and greywacke
Na-feldspar	2.62					
Ca-feldspar	2.73					
Larnite and Ca_2SiO_4	3.3	6	–	One distinct cleavage	Good	EAF slag
Magnetite	5.2	5.5–6	5.0	No cleavage	Excellent (1.42?)	Basalt
Pyroxene	3.2–3.5	5–6	4.9 (Est)	Two sets of good cleavage	Poor	Volcanic rocks and detrital grains in many greywackes
Amphibole (hornblende)	3.0–3.4	5–6	–	Two sets of good cleavage	Poor, except when fibrous	
Laumontite	2.3	3–4	–	Two sets of cleavages; very brittle	Poor	Greywackes as veins and in the matrix of some rocks
Calcite	2.7	3	1.5	Perfect cleavages	Poor to good	Greywackes
Chlorite	2.6–3.4	2.5	–	Platy: perfect cleavage	Poor to tough. Flexible sheets	Greywackes
Clay minerals	–	2–2.5	–	Platy: perfect cleavage parallel to sheets	Poor to tough. Flexible sheets	Greywackes, altered/ weathered rocks

* In GPa

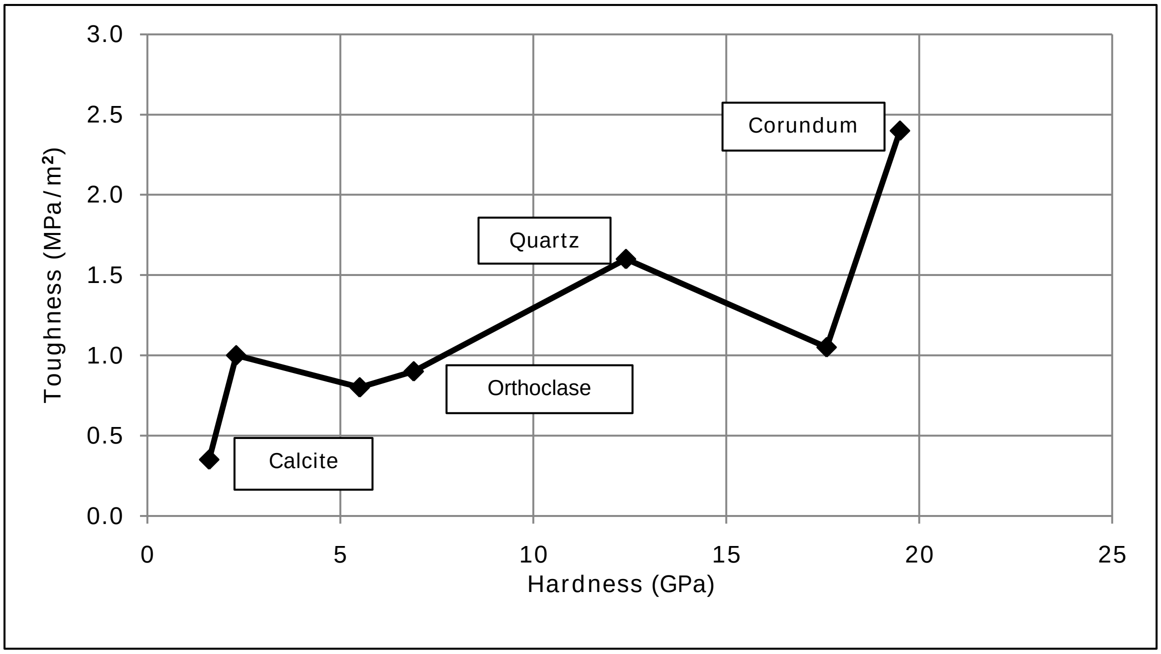
B3 Mineral fracture behaviour and toughness

Toughness is the resistance of a mineral to fracture when subjected to impact stress from a high strain rate. Mineral toughness is different from mineral hardness.

Each mineral has a unique crystal structure with lattice planes that are held together by forces with variable strengths. Brittle minerals fail first along planes of minimum strength in the crystal structure. These planes are called cleavages. In geological terms, the toughness of a mineral is graded as poor, fair, good, excellent or exceptional. Data for the toughness of rock-forming minerals is very limited. The data that is available for minerals relevant to aggregates is listed in table B1. The nonlinear relationship between hardness and toughness is illustrated in figure B1.

Natural volcanic glass has a Mohs value between 5 and 6, and has brittle fracture properties similar to that of quartz but notably higher than other silicate minerals in volcanic rocks. The layer silicates (clay minerals) are the softest and least competent components of rocks.

Figure B1 Mineral toughness and hardness of rock-forming materials



Appendix C Source properties of aggregates

The following information (tables C1–C6) is based on quality assurance test results provided by Higgins Contractors and/or their suppliers, except when stated otherwise.

Table C1 Crushing resistance properties of the aggregates in this research (NZS 4407 test 3.10 (Standards New Zealand 1991a)) – percent loss for a load of 230kN

Aggregate	Date sampled		No. of results	Range of results		
	Earliest	Latest		Lowest	Mean	Highest
Brookby	Oct 2000	Oct 2009	10	2.9	4.1	7.2
Moutohora	Sep 2002	Aug 2005	7	5.1	7.4	9.1
EAF slag	Sep 2006	Dec 2009	6	4.7	7.2	9.5
Te Matai	Aug 1998	Dec 2009	9	2.4	3.3	4.6

Table C2 Weathering quality index properties of the aggregates in this research (NZS 4407 test 3.11 (Standards New Zealand 1991b))

Aggregate	Date sampled		No. of results	Range of results					
	Earliest	Latest		Lowest		Mean		Highest	
				CV*	$R_{4.75}$**	CV	$R_{4.75}$	CV	$R_{4.75}$
Brookby	Oct 2000	Oct 2009	11	91	98	95	99	98	99
Moutohora	Oct 2002	Aug 2005	6	78	86	87	94	93	97
EAF slag	Oct 2006	Aug 2009	4	95	94	97	98	98	100
Te Matai	Aug 1998	Dec 2009	8	96	92	97	98	98	100

* CV = cleanness value

** $R_{4.75}$ = percent retained on 4.75mm sieve

Table C3 PSV properties of the aggregates in this research (BS 1097 part 8 (British Standards Institution 2000)

Aggregate	Date sampled		No. of results	Range of results		
	Earliest	Latest		Lowest	Mean	Highest
Brookby	Dec 2000	Oct 2008	8	55	56	58
Moutohora	Oct 2002	Aug 2003	2	65	66	66
EAF slag	Sep 2006	Aug 2009	6	63	65	67
Te Matai	Nov 1997	Jun 2009	12	57	58	60

Table C4 LA abrasion test results for the aggregates in this research (AS 1141.23 (Standards Australia 1995a))

Aggregate	Date sampled		No. of results	Range of results		
	Earliest	Latest		Lowest	Mean	Highest
Brookby	Oct 2000	Dec 2008	10	9	11	14
Moutohora	Nov 2003	Nov 2003	2	25	26	27
EAF slag	Oct 2007	Oct 2007	1	–	13	–
Te Matai	Dec 2009	Dec 2009	2	11	13	15

Table C5 Micro-deval abrasion (ASTM 6928-03 (ASTM International 2003) provided by Fulton Hogan (Hamilton)

Aggregate	Date sampled		No. of results	Test result (%)
	Earliest	Latest		
Brookby	Mar 2010	Mar 2010	1	5.9
Moutohora	Mar 2010	Mar 2010	1	15.2
EAF slag	Mar 2010	Mar 2010	1	3.4
Te Matai	Mar 2010	Mar 2010	1	5.7

Table C6 Wet/dry strength (AS 1141.22 (Standards Australia 1996)

Aggregate	Date sampled		No. of results	Range of results		
	Earliest	Latest		Lowest	Mean	Highest
Brookby	Oct 2000	Dec 2008	4	9	20	29
Moutohora	–	–	Nil	–	–	–
EAF slag	Oct 2007	Aug 2008	2	2	13	23
Te Matai	Dec 2009	Dec 2009	1	–	24	–

Appendix D Production properties of mixes

D1 Particle size analysis

D1.1 EAF slag

- Micro-deval abrasion loss: 3.4%.
- Calibration aggregate loss: 8.1%.
- Size of fraction tested: 12.5–4.75mm.

Table D1 Particle size analysis gradation of EAF slag (% passing)

Test		Sample #	Sieve size (mm)											
			13.2	11.2[b]	9.5	8[b]	6.7	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Lab-based	Servopac Austroads gyratory compaction 150mm diameter moulds at 25°C.[a]	#24839 (0 cycles)	99.4	77.4	41.4	24.1	22.8	22.5	20	17	15.1	13.8	12.5	10.2
		#24842 (0 cycles)	99.4	74.7	42.1	25.2	22.8	22.6	20.4	17.5	15.4	14.1	12.7	10.5
		#24840 (80 cycles)	98.3	72.1	41.1	25.3	23.4	23.1	20.2	17	15.1	13.9	12.7	10.7
		# 24841 (80 cycles)	99.2	74	42.6	25.2	23.4	23.1	20.5	17.5	15.6	14.2	12.9	10.6
		#24843 (350 cycles)	99.5	76.3	43.5	26.4	24.2	23.6	20.9	18.2	16.3	15	13.7	11.2
		#24844 (350 cycles)	98.9	73.5	42.5	25.7	24	23.4	21	17.9	15.9	14.6	13.3	11.1
Production	Brew blend	11/08/09	99.7	–	55.2	–	24.2	23.6	20.8	17.0	14.4	12.7	11.3	8.8
	Post-mixing	#7215	100.0	–	54.4	–	26.0	25.0	20.7	16.0	13.0	11.9	10.6	8.7
		#8306	99.5	–	53.2	–	25.4	24.7	20.9	16.2	13.2	12.0	10.6	8.5
	Post-compaction[c]	#7316	98.7	–	52.4	–	28.5	27.2	23.4	18.8	15.5	13.5	11.8	9.5
	Post-trafficking	#8291	99.2	–	63.1	–	29.3	26.2	21.0	17.0	14.5	13.0	11.2	9.0

Notes to table D1:

a Bitumen was replaced with glycerine.

b Sieves used in design, not production.

c Two cores combined.

D1.2 Brookby aggregate

- Micro-deval abrasion loss: 5.9%.
- Calibration aggregate loss: 8.1%.
- Size of fraction tested: 12.5–4.75m

Table D2 Particle size analysis gradation (% passing) of Brookby aggregate

Test		Sample #	Sieve size (mm)											
			13.2	11.2[b]	9.5	8[b]	6.7	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Lab-based	Servopac Austroads gyratory compaction 150mm diameter moulds at 25°C.[a]	#24509 (0 cycles)	100	95.5	63	40.9	33.4	26.4	21.1	17.5	15	13.4	11.8	9.4
		#24676 (0 cycles)	100	95.1	60.5	40.8	32.7	26.2	20.3	16.6	14.4	13	11.7	9.5
		#24757 (80 cycles)	100	95.9	63.4	41.7	34.1	27.1	21.9	18.2	15.5	13.6	11.9	9.6
		#24756 (80 cycles)	100	96	63.3	41.6	33.9	26.3	21	17.1	14.6	13	11.6	9.4
		#24758 (350 cycles)	100	94.7	60	42.3	34.3	27.1	21.5	17.8	15.5	13.9	12.6	10.5
		#24759 (350 cycles)	100	93.9	60.1	41.1	33.9	27.1	21.4	17.7	15.4	13.9	12.5	10.3
Production	Brew blend	10/08/09	99.7	–	64.8	–	35.2	25.8	20.8	17.6	15.3	13.8	12.4	9.6
	Post-mixing	#7214	100	–	69.0	–	38.5	31.1	24.5	19.5	16.0	13.9	11.7	9.1
		#8305	99.7	–	69.8	–	40.1	31.6	25.1	20.3	16.8	14.7	12.7	10.0
	Post-compaction[c]	#7315	100	–	72.9	–	46.4	37.0	29.8	24.4	20.7	17.5	14.1	10.7
	Post-trafficking	#8290	100	–	74.1	–	46.4	36.5	28.4	23.1	19.4	16.4	13.4	10.2

Notes to table D2:

a Bitumen was replaced with glycerine.

b Sieves used in design, not production.

c Two cores combined.

D1.3 Moutohora aggregate

- Micro-deval abrasion loss: 15.2%.
- Calibration aggregate loss: 8.1%.
- Size of fraction tested: 12.5–4.75mm.

Table D3 Particle size analysis gradation of Moutohora aggregate (% passing)

Test		Sample #	Sieve size (mm)											
			13.2	11.2[b]	9.5	8[b]	6.7	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Lab-based	Servopac Austroads gyratory compaction 150mm diameter moulds at 25°C.[a]	#24679 (0 cycles)	99.6	89.4	71.6	57.3	45.8	29.1	22.5	18.7	16.3	14.6	13.2	11.3
		#24764 (0 cycles)	99.2	87.5	70.2	57.6	45.9	28.6	21.8	17.8	15.4	14.0	12.8	10.9
		#24760 (80 cycles)	99.5	90.7	74.0	60.4	50.0	34.1	24.4	19.9	17.3	15.6	14.0	11.6
		# 24761 (80 cycles)	99.6	90.3	74.7	60.5	49.1	32.9	23.9	19.7	17.0	15.3	13.8	11.3
		#24762 (350 cycles)	99.6	90.0	76.3	61.9	49.0	34.0	25.8	21.3	18.4	16.5	14.7	12.4
		#24763 (350 cycles)	99.5	88.5	71.4	58.8	49.9	34.3	24.9	20.5	17.9	16.1	14.6	12.3
Production	Brew blend	10/08/09	99.6	–	74.5	–	46.5	28.1	22.2	18.6	15.9	14.4	13.0	10.2
	Post-mixing	#7216	100	–	81.6	–	47.6	30.6	23.4	19.6	16.9	15.3	13.5	11.1
		#8307	100	–	82.9	–	51.0	32.4	24.8	20.4	17.6	15.9	14.2	11.7
	Post-compaction[c]	#7317	100	–	81.4	–	52.3	36.2	27.1	21.4	17.7	15.2	12.9	10.4
	Post-trafficking	#8292	98.2	–	81.3	–	49.9	33.5	25.4	20.7	17.5	15.4	13.2	10.5

Notes to table D3:

a Bitumen was replaced with glycerine.

b Sieves used in design, not production.

c Two cores combined.

D1.4 Te Matai aggregate

- Micro-deval abrasion loss: 5.7%.
- Calibration aggregate loss: 8.1%.
- Size of fraction tested: 12.5–4.75mm

Table D4 Particle size analysis gradation of Te Matai aggregate (% passing)

Test		Sample #	Sieve size (mm)											
			13.2	11.2[b]	9.5	8[b]	6.7	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Lab-based	Servopac Austroads gyratory compaction 150mm diameter moulds at 25°C.[a]	#24931 (0 cycles)	98.5	94.2	83.1	55.1	29.3	24.3	21.4	17.6	15.5	14.2	12.9	10.6
		#24932 (0 cycles)	98.6	91.6	80.4	52.8	28.3	24.1	21.1	17.5	15.4	14.1	12.8	10.2
		#24933 (80 cycles)	99.4	94.5	83	56	30.6	25.7	21.8	18.3	16.2	14.8	13.4	11
		# 24934 (80 cycles)	99.5	94.5	83	56.1	30.6	25.5	21.9	18.4	16.5	15.1	13.7	11.2
		#24935 (350 cycles)	99	93.4	82.6	55.5	31.1	26	22.3	18.6	16.6	15.2	13.9	11.8
		#24936 (350 cycles)	99.6	93.5	81.9	56.1	31.6	25.8	22.5	18.9	16.9	15.9	14.2	11.9
Production	Brew blend	09/02/10	98.3	–	78.2	–	32.8	29.6	25.6	20.8	18.1	16.3	14.3	11.3
	Post-mixing	#7945	99.2	–	74.1	–	26.3	23.1	19.5	15.4	12.9	11.5	10.1	8.0
		Only one post-mixing sample was taken for this aggregate												
	Post-compaction[c]	#8295	99.7	–	78.6	–	33.8	29.6	24.6	19.6	16.7	14.8	13.0	10.1
	Post-trafficking	#8346	99.4	–	78.0	–	33.6	29.5	24.9	20.1	17.0	15.0	13.0	10.0

Notes to table D4:

a Bitumen was replaced with glycerine.

b Sieves used in design, not production.

c Two cores combined.

D2 Air voids and texture depth

Table D5 Air voids (%) post-compaction and post-trafficking

Aggregate source	Post-compaction		Post-trafficking	
	Sample #	%	Sample #	%
EAF slag	7312	9.2	8280	5.5
		7.4		7.0
		7.2		6.1
		8.7		7.0
Brookby	7311	5.7	2879	3.1
		3.6		1.8
		2.7		1.7
		2.6		2.5
Moutohora	7313	3.2	8281	2.7
		6.1		3.3
		4.3		3.3
		3.2		2.8
Te Matai	7951	2.0	8345	2.9
		1.5		1.6
		2.7		1.9

Table D6 Texture depth of aggregates post-compaction and post-trafficking

Aggregate source	Post-compaction		Post-trafficking	
	Date	mm	Date	mm
EAF slag	21/08/09	1.3	13/04/10	1.13
		1.18		1.13
		1.13		1.08
		1.08		1.04
Brookby	21/08/09	1.08	13/04/10	1.04
		1.04		0.99
		0.95		0.99
		0.88		0.85
Moutohora	21/08/09	0.85	13/04/10	0.88
		0.99		0.85
		0.99		0.85
		0.85		0.85
Te Matai	Not done		25/05/10	0.7
				0.5
				0.7