

Applications for asphalt millings on New Zealand roads

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Contents

Acknowledgements	4
Executive Summary	7
Abstract	10
1. Introduction	11
1.1 Objectives	11
1.2 Background information	11
1.3 Methodology	13
1.3.1 Literature review.....	13
1.3.2 Laboratory investigation.....	13
1.3.3 Field investigation	14
2. Literature review	15
2.1 General	15
2.2 Benefits of recycling.....	15
2.3 Detractions from RAP	16
2.4 Description of asphalt millings.....	17
2.5 Recycled hot mix	18
2.6 Other applications	18
2.7 Summary	21
3. Laboratory testing of asphalt millings	22
3.1 General	22
3.2 Sampling.....	22
3.3 Basic laboratory testing.....	23
3.3.1 Particle size distribution	23
3.3.2 Bitumen content	25
3.3.3 California Bearing Ratio and Clegg Impact Value tests	26
3.3.4 Plasticity Index and Clay Index	27
3.4 Repeated Load Triaxial testing	28
3.4.1 General.....	28
3.4.2 Resilient modulus.....	28
3.4.3 Permanent deformation	30
3.5 Interpretation of test data	31
4. Field investigation of asphalt millings	32
4.1 General	32
4.2 Investigation of base layers, Carbine Road	32
4.3 Trial of overlay on Great Barrier Island.....	34
4.4 Interpretation of field investigation data	39
5. Conclusions	40
5.1 Literature review	40
5.2 Laboratory investigation.....	40
5.3 Field investigation.....	41
6. Recommendations	42
7. References	43
Appendix: Laboratory test reports	45

Executive summary

General

This project involved an investigation carried out in 2004-05 into the mechanical properties of, and potential applications for, asphalt millings in the construction of New Zealand roads. The project involved three phases:

- review of the international technical literature;
- laboratory investigation; and
- field investigation.

Literature review

The literature review indicated that asphalt is the single most recycled product in the world and that the most cost-effective application for asphalt millings is generally considered to be in the production of recycled hot mix asphalt (HMA). The performance of recycled HMA is generally considered to be at least equal to that of asphalt produced from virgin aggregates.

Although the use of millings in road applications has very few detractors, some conjecture exists over the environmental soundness of millings. At least one agency in the United States (US) considers loose millings to pose a leaching risk.

The uses of millings varies significantly with some highway agencies allowing millings in sub-base applications under asphalt or concrete base layers, or as base layers in minor roads. Other agencies prefer to limit the use of millings to shoulders, medians or other non-structural applications. Millings combined with fresh bituminous binder have been used successfully in the upgrading of gravel roads.

The literature highlighted a small number of innovative applications for millings, e.g. millings combined with an orange peel-oil solvent have been used successfully as a pothole patching material.

Laboratory investigation

Six sources of millings were used in this investigation, including processed, unprocessed and surge materials.

The six samples had bitumen contents in the range of 4.1% to 5.9%. CBR (California Bearing Ratio) tests showed results ranging from 5 for the surge sample to 25 for processed millings. Unprocessed millings gave a CBR of approximately 10. Clegg Impact (CIV) tests indicated inferred CBR values in the range 45 to 80 for the same test specimens.

All millings samples were found to be non-plastic although they showed Clay Index values in the range 0.5 to 2.5. This may have been a result of minor contamination from basecourse materials.

Repeated load triaxial (RLT) tests were carried out on three millings specimens, i.e. two from processed samples and one from an unprocessed sample. In summary the RLT tests indicated that the millings possessed resilient modulus and permanent deformation properties that are generally acceptable for at least pavement sub-base applications. The unprocessed millings showed a reduced resistance to permanent deformation compared with the processed millings.

Field investigation

The field investigation showed that asphalt millings have been used successfully as a temporary base layer (approximately 200 mm thick) in a busy arterial pavement at Carbine Road, Auckland, New Zealand. The layer has been in service for approximately five years and continues to perform to a reasonable standard. FWD (Falling Weight Deflectometer) test data suggest that the millings layer had achieved at least a moderate degree of cohesion, although the material could not be recovered by coring.

Millings treated with slow-break emulsion have also been used with reasonable success in a trial section at Aotea Road, Great Barrier Island. The trial section has provided an appropriate level of service for the last four years. Although some distress has occurred, i.e. crocodile cracking, deformation, edge break and potholing, the material is generally considered to be superior to unbound aggregate.

Recommendations

The following recommendations have been drawn from the literature review, laboratory testing and field testing investigations:

- Processed millings are considered to be appropriate for sub-base (or lower level) applications for typical urban and rural road pavement applications.
- Processed millings treated with slow-break emulsion are a favourable alternative to unbound aggregates on unsealed roads.
- RLT tests should be used to verify that millings materials are appropriate for any given application. As a general guide, resilient modulus values of at least 200 MPa and stable permanent deformation behaviour under appropriate stress conditions should be attainable.
- Millings mixed with an organic solvent could provide a cost-effective and environmentally acceptable alternative to plant mix for minor pavement repairs.
- Pavement designers should consider the potential for reduced permeability in millings layers if the material achieves a reasonable degree of cohesion.

Abstract

This project has investigated the mechanical properties of, and potential applications for, asphalt millings in the construction of New Zealand roads. It involved a review of the international technical literature, laboratory investigation and field investigation. The project was carried out in 2004–05.

The literature review showed that the main use for asphalt millings is in the production of recycled hot mix asphalt. Other applications for millings include road sub-base layers, base layers on lightly trafficked roads, and in the production of bituminous patching mixes.

The laboratory investigation involved subjecting samples of processed and unprocessed millings to a range of basic characterisation and mechanical tests. Repeated load triaxial tests were used to evaluate resilient modulus and permanent deformation characteristics of three millings specimens. The test results showed that the properties of the millings were generally up to, or exceeded, those of conventional sub-base aggregates.

The field investigation involved a study of two sites in the Auckland region where millings had been used. The investigation showed that the millings had performed well in both applications.

1. Introduction

1.1 Objectives

The objectives of this project are to:

- establish the engineering properties of asphalt millings obtained from pavements undergoing resurfacing or rehabilitation; and
- identify appropriate applications for the use of asphalt millings.

The importance of recycling roading materials has been recognised by Transit New Zealand with their introduction of 'triple bottom line reporting' (Transit 2004). This is where both environmental and social impacts of all projects must be evaluated in parallel with economic considerations. The objectives of this project are therefore consistent with current Transit New Zealand policy.

1.2 Background information

A number of contractors have large stockpiles of millings that are often sold as a cheap aggregate for farm tracks or building-site hard fill, or it is waiting for suitable higher value applications. In the Auckland area alone the quantity of millings produced in a typical construction season is understood to be in excess of 30,000 tonnes (t). This represents a significant quantity of valuable material and an excellent opportunity to recycle and obtain both economic and environmental benefits.

One of the first tasks in the resurfacing or rehabilitation of pavements located in urban areas is to remove the existing surface materials. This task can provide a number of benefits, for example:

- The new surface material can be established on a sound platform, free of cracked, loose, or otherwise distressed material that could compromise the performance of the new surface.
- The new surface can be placed to the same level as the original surface, thus maintaining:
 - existing kerb and channel reveals;
 - crossing geometries;
 - overbridge clearances;
 - adjoining road levels;
 - barrier heights; and,
 - road furniture levels.
- The new surface can be effectively keyed-in to the pavement structure, thus reducing the risk of delamination; and
- The existing surface materials are available for recycling.

Where the existing surface comprises hot mix asphalt (HMA), surface removal is generally achieved using a milling machine. The millings typically comprise mineral aggregate, with 3% to 7% bitumen present in the form of a coating on the aggregate particles. The bitumen in the millings is typically somewhat harder than the fresh bitumen as a result of oxidation during the original mix production, transportation to site, laying and service life. However, if used appropriately, millings can be expected to provide superior performance in a number of roading applications compared with fresh aggregates.

The physical and mechanical properties of the millings are dependent upon a number of factors such as:

- pavement age;
- parent HMA bitumen grade and content;
- parent HMA aggregate quality and grading;
- milling machine characteristics; and
- clipping of underlying layers.

The main application for high quality millings is RHM (recycled hot mix) asphalt. This material is produced either in asphalt plants, or in hot (or warm) pavement recycling operations.

RHM materials are used extensively overseas, but until recently it has not been used on a large scale in New Zealand. This can be attributed to a number of factors such as:

- asphalt plant emission controls;
- asphalt specification requirements; and
- the relatively small quantity of HMA pavements constructed in New Zealand.

The current New Zealand Specification for Asphaltic Concrete (M/10) (Transit 2005) allows up to 15% recycled asphalt pavement (RAP) material to be used in RHM asphalt mixes. The RAP percentage can be increased if additional testing on the material is carried out and specific approval is granted by Transit New Zealand.

Most millings that are collected in the Auckland region are processed by way of crushing to establish a particle size distribution that is conducive for re-use as RAP. In general, millings have a finer particle size distribution than the parent HMA because of breakdown under the action of the milling machine.

Clipping of the granular basecourse layer that underlies the asphalt surface layer may also influence the particle size distribution of the millings. It is noted that when thin HMA-surfaced pavements are milled for reconstruction using structural asphalt, as is often done in the Auckland City pavement rehabilitation contracts, quite significant quantities of unbound aggregate can be incorporated in the millings. These millings are generally dumped or used as uncontrolled hardfill as contractors generally do not have enough capacity to store materials other than premium quality aggregates. In addition, some road controlling authorities wish to retain ownership of millings, although in most instances, they too have issues regarding storage facilities.

1.3 Methodology

The methodology adopted for this project has been divided into the three main tasks of:

- Literature review;
- Laboratory investigation; and
- Field investigation.

1.3.1 Literature review

The local and international technical literature on the topic of characterisation and appropriate use of millings has been reviewed. The review has focused on issues including (but not limited to) the following:

- overseas studies of millings characteristics;
- accounts of millings performance in road construction applications;
- alternative applications for millings;
- environmental effects and issues;
- construction issues relating to the use of millings; and
- economic factors relating to millings.

1.3.2 Laboratory investigation

Sources of millings have been identified in the Auckland region and representative samples have been taken. Specimens have been subjected to a testing programme comprising:

- particle size distribution;
- bitumen content;
- compaction;
- California Bearing Ratio (CBR);
- Plasticity Index; and
- Clay Index.

These tests establish the fundamental characteristics of the millings in terms of their mechanical properties and variability with respect to road construction-related applications.

Selected specimens have also been subjected to repeated load triaxial (RLT) testing. This test procedure allows the resilient modulus and permanent deformation properties of the material to be evaluated under a range of stress conditions that are representative of in-situ pavement conditions.

1.3.3 Field investigation

A pavement rehabilitation site at Carbine Road (Mt Wellington, Auckland), where millings have been used as a temporary basecourse material, has been investigated by taking cores for visual inspection. In addition, Falling Weight Deflectometer (FWD) tests have been undertaken on this pavement to provide an assessment of the in-situ performance of the millings layer.

The performance of a pavement on Great Barrier Island where millings have been used in conjunction with bitumen emulsion has also been reviewed. This has involved a visual inspection and a review of the original design report.

2. Literature review

2.1 General

Most of the literature that is available on the topic of asphalt millings originates from overseas references. This is mainly attributable to the considerably higher proportion of structural asphalt pavements used in North America (Canada and US), Europe and the United Kingdom (UK) compared with New Zealand or Australia. Therefore, the findings of the literature review must be considered in the context of location, materials and environment in which the literature was developed.

A range of terminology is used in the literature that should be clarified.

Millings is a general term used to describe the material that is produced by the milling plant when it removes the existing pavement materials. In most instances the material being milled is asphaltic concrete, although instances could occur where the depth of milling penetrates through the asphalt surface to include an underlying basecourse layer. This could comprise unbound aggregate with no inherent bitumen or other binder. Where the millings originate from a mixture of asphalt and unbound aggregate the material is considered to be uncontrolled and is typically used in hard fill applications. This material is outside the scope of this study.

When the millings originate from asphalt materials only, the material is referred to as recycled (or reclaimed) asphalt pavement (RAP). The term *asphalt arisings* is often used to describe RAP in the UK literature and the term *grindings* is sometimes used in the Canadian and US literature.

When RAP is combined with fresh materials to produce an asphalt mix, the resulting product is often termed recycled hot mix (RHM) (Jové & De Bock 2002).

Most literature about millings is based on the design, production and construction of RHM pavements. This is because millings are considered to provide best value for money when used in RHM (InfraGuide 2005). InfraGuide reports that the use of asphalt millings as granular sub-base or shoulder construction material should be discouraged as it does not effectively utilise the bitumen that is inherent in the millings. In addition, such uses do not allow for recovery of the energy that was used to produce the original asphalt material. This is a view that appears to be consistent throughout the literature and consequently the literature on millings-related topics is minimal except for its use in RHM.

2.2 Benefits of recycling

One of the major advantages of using HMA in road pavements is the ability to recycle the material once the service life of the pavement has been consumed. Harrington (2005) reports that asphalt is the single most recycled material in the world. Recent data indicate that the annual production of RAP in the US alone amounted to approximately 41,000,000 tonnes and, of that, over 80% was re-used in pavement applications.

Recycling asphalt pavements provides a number of environmental, social and economic benefits by reducing:

- demand for aggregates;
- demand for bituminous binders; and,
- waste.

Reduced demand for aggregates. Aggregate resources are becoming more and more scarce, especially in urban areas where most heavily trafficked pavements are located. Quarries are not viable in urban areas where the land is of premium value and public resistance to any operations that create noise, dust or heavy vehicle movements is increasing. In addition, increasing fuel costs mean that transporting aggregates from remote quarries attracts high costs. Therefore, the ability to recycle aggregates and, in general, have them located close to the site where they will be re-used provides significant benefits.

Reduced demand for bituminous binders. The quantity of additional bitumen that is needed to produce RHM is reduced because the RAP already contains some bitumen. This provides benefits in terms of reduced cost and lower energy demands with respect to both the production and distribution of bituminous binders.

Reduced waste. Using RAP in pavement applications means that less waste material is going to landfills. This saves valuable space in landfills, thereby extending their lives and reducing the need for new landfills. This is an important factor considering the cost of establishing environmental compliance for new landfill operations. It also removes the disposal costs of cartage and dumping (InfraGuide 2004).

Reducing waste by recycling is a universal objective for government agencies around the world. The New Zealand Government has a Transport Strategy comprising five main objectives and one of those is to ensure environmental sustainability. This has accordingly been adopted into Transit New Zealand's strategic goals, i.e.

... to improve the contribution of state highways to the environmental and social well being of New Zealand ... (Transit 2004).

2.3 Detractions from RAP

There are few, if any, detractions from recycling asphalt. The only issues that have been found in the literature are the potential for fuming in the production of RHM and concerns over the possible leaching of carcinogens from the bituminous component of millings while the material is stockpiled or in service. The fuming issue can be allayed by the use of appropriate plant and procedures in the production of RHM.

The issue of leaching appears to have received relatively little attention in the literature, however most specifications for landfills consider asphalt waste to be clean or inert. In addition, Sadeci et al. (1996) tested leachate from a millings stockpile and found that the

concentration of polycyclic aromatic hydrocarbons (PAH) was near, or below, detectable limits.

The New Jersey Department of Environmental Protection Asphalt Millings Guidance Document (NJDEP 2001) reports that asphalt millings can have very high concentrations of PAHs and, when used in an unsealed road application, these toxic compounds can migrate from the road pavement and contaminate adjacent soils and/or water courses. Consequently, NJDEP (2001) states that asphalt millings can be used at the pavement surface only if the material is heated and rolled so that the loose particles are rebound. Vercoe (pers.comm. 2006) suggests that the release of toxic compounds from millings is very unlikely, unless the binder was comprised of coal tar. However, coal tar was used approximately 60 to 70 years ago, and therefore it is unlikely that this material would be recycled in significant volumes today.

2.4 Description of asphalt millings

Asphalt millings are generally defined as the fine particles (generally from dust to approximately 25 mm) of bitumen and inorganic material that are produced by the mechanical grinding of asphaltic concrete roading materials (NJDEP 2001).

Millings are generally sourced from road surface layers that are being removed to allow resurfacing to be carried out. This source of material is obtained from surfaces that are too high to accommodate an overlay, or deemed to be inappropriate, or not able to support the new surface layer, and therefore they have to be removed.

Millings typically contain 5% to 7% bitumen (NJDEP). However the exact composition and properties of the material will be dependent on a number of variables, such as:

- age of the source asphalt mix;
- type of mix;
- properties of the bitumen used in the mix;
- properties of the aggregate used in the mix;
- configuration and performance of the milling plant; and
- clipping of underlying layers during the milling process.

Ageing of the asphalt results in the recovered RAP binder being significantly more viscous and having lower penetration values than the virgin bitumen (TFHRC 1997).

Contractors typically separate their stockpiles of millings from different sources to ensure that the variability of the material is minimised.

Most raw millings are subjected to a process of crushing and screening to achieve a particle size distribution that is conducive to use as RHM.

2.5 Recycled hot mix

As described earlier, RHM is generally considered to be the best value application for millings. However, RHM is outside the objectives of this study, except for a brief description presented in the following paragraphs.

RHM comprises a blend of RAP, virgin aggregate, bituminous binder and a rejuvenating agent to soften the existing binder. The ability to use RAP in RHM is dependent upon the consistency of the RAP and the design of the asphalt plant. The plant must be capable of accurately feeding the RAP and mitigating gaseous emissions. TFHRC (1997) reports that maximum RAP proportions of 50% and 70% are generally accepted for batch and drum asphalt plants respectively.

The performance of RHM is reported to be very satisfactory. Kandhal et al. (1995) carried out a detailed comparative study between RHM and new asphalt mixes and concluded that the RHM performed as well as the new mixes. The study included parameters such as a visual-based performance measure, percent air voids, resilient modulus, aged asphalt binder properties, stability and creep.

TFHRC (1997) goes further by reporting literature that stated that RHM shows a lower rate of hardening and reduced susceptibility to water compared with conventional mixes. Harrington (2005) also reports that asphalt mixes containing RAP often have better performance properties than mixes produced using all virgin aggregates. This is especially apparent when the virgin aggregates are relatively absorptive.

The amount of RAP that is allowed in an RHM is generally dependent on the application of the mix. Data from 1996 shows that, in the US, ten state roading authorities did not allow RAP in surface courses while all authorities allowed RAP in base and binder courses. States that allowed RAP in surface courses generally permitted from 10% to 30% RAP (TFHRC 1997). The allowable RAP contents in base and binder courses ranged from 10% to 70%.

Howard (2000) reported that the UK Highways Agency allows up to 30% RAP in asphalt, but only about 10% of asphalt millings are used in RHM. The remainder of the millings are used as fill material.

Transit New Zealand allows a maximum of 15% RAP in its M/10 (2005) Specification for Hot Mix Asphalt, although higher RAP percentages can be approved by Transit New Zealand on a case-by-case basis.

2.6 Other applications

While RHM is considered to be the most cost-effective application for millings, other roading applications are described in the literature. Such applications may be appropriate when the sources of millings are inconsistent and the cost of processing is considerable.

The UK Design Manual for Roads and Bridges (The Highways Agency (UK) 1995) allows bituminous millings to be used in the following applications providing the material complies with the applicable specification requirements:

- embankment and fill;
- capping; and
- cement-bound sub-base.

Asphalt millings are not allowed in the following applications;

- unbound sub-base;
- cement bound road base; and
- pavement quality concrete.

Steel et al. (2004) carried out an investigation into the use of asphalt millings in pavement sub-base layers in the UK. They reported that Type 4 asphalt millings sub-bases performed in a manner that was comparable to conventional Type 1 granular sub-bases, in which the Type 1 material was considered to be the highest quality sub-base aggregate. However, the authors warned that very thick layers of asphalt millings (750 mm plus) could be susceptible to excessive compressibility.

NJDEP (2001) reported the use of millings in a number of applications including:

- sub-base material beneath, and fully contained by, an asphalt or concrete pavement structure;
- surfacing material if an appropriate binder is applied to keep the millings in place;
- basecourse material for minor pavements, such as car parks, as long as the millings have sufficient viable asphalt and the material is laid and rolled in a hot condition;
- other beneficial applications subject to the approval of NJDEP.

Some roading authorities, e.g. Illinois Department of Transport (DOT) and Massachusetts DOT, use a significant proportion of millings in non-structural backfill situations and road shoulder mixes.

Trevino et al. (2003) reported that millings have been used with some success as a tack coat for new asphalt layers. Millings were evenly spread in the grooves left by the milling plant and the new asphalt layer was placed without applying a tack coat. The heat provided by the new asphalt mat was sufficient to mobilise the binder associated with the millings. This promoted a high level of cohesion between the two layers. Strength tests carried out on cores taken from trial pavements showed that failures generally occurred in the underlying material rather than at the interface between the old and the new asphalt layers.

The literature shows that asphalt millings have been used to construct secondary road pavements with mixed results. The City of Greeley, Colorado, US, reported that asphalt millings have been used to upgrade existing gravel roads. The millings were placed and compacted in a layer typically with a thickness of at least 150 mm. This treatment has proved to be successful in terms of reducing maintenance costs and dust complaints (City of Greeley, undated).

Koch Pavement Solutions (2002) reported that many of the highways in the state of New Mexico have been successfully rehabilitated using RAP that has been mixed with asphalt emulsion. The treated RAP forms the basecourse layer that is subsequently surfaced using a new HMA mat.

Russell (undated) described the rehabilitation of approximately 8 km of gravel roads in the state of Missouri using asphalt millings combined in situ with a bituminous binder. The key aspects of the construction were to achieve effective mixing of the millings and the binder, and for the work to be carried out on hot summer days so that adequate cohesion and compaction could be achieved. The resulting pavement structures were reported to be performing well and very cost-effective.

Westphal (2001) reported that a highway in Ventura, Albuquerque, that was rehabilitated using asphalt millings, failed prematurely by forming potholes and suffering from severe erosion. A second attempt to rehabilitate the pavement by heating the millings also failed because the millings were highly oxidised and the residual binder was not mobilised.

Roads & Bridges (2004) described pavement rehabilitation work carried out in Denver, Colorado. The City of Denver adopted a strategy of upgrading gravel roads by excavating 200 mm of the existing pavement and replacing it with compacted millings. The millings knitted together to form a uniform surface, effectively rebinding in the sun. The result was a firm surface that has performed well under residential traffic loads.

Huang & Shu (2005) investigated the performance of RAP in Portland cement concrete mixes. The authors tested mixes that had virgin aggregates substituted with either fine or coarse graded RAP materials. The investigation included workability, tensile strength, compressive strength, and toughness testing. The results showed that small quantities of RAP increased the slump of the concrete, thus increasing the workability of the mix. However, larger quantities of RAP tended to decrease the concrete slump significantly. The strength tests showed that increasing the proportion of RAP in the mix resulted in a decrease in tensile and compressive strength, regardless of the type of RAP. There was however a significant increase in the toughness of the mix with increasing RAP content. This could have practical importance for a number of civil engineering applications where structures are required to have a relatively high strength and yet be able to absorb repeated loading without suffering fatigue failure. These properties are required of road base and sub-base layers.

The City of St Joseph, Missouri (undated), reported the successful use of millings in an innovative approach to solving pothole problems. Potholes were traditionally repaired using cold-mix asphalt, however the material was found to be susceptible to water and it did not perform well. Other more technical asphalt materials were used, but the production cost was very high. The current strategy is to use asphalt millings combined with a small amount of solvent derived from orange peel oil as well as a small quantity of cutback bitumen. The orange peel oil appears to rejuvenate the residual binder in the millings and the additional bitumen provides extra adhesion. The mix is generally produced as required in a wheelbarrow and the cost is reported to be approximately half that of a conventional cold-mix asphalt.

2.7 Summary

It is universally recognised that an important benefit of asphalt as a pavement construction material is its ability to be recycled. This factor is becoming more and more relevant as the cost of winning and processing virgin aggregates increases, especially in urban areas. In addition, the political mileage that can be obtained by being seen to promote recycling is also considerable.

Most of the technical literature involves reports into the use of RAP in RHM or hot in-place recycling processes. These applications are considered to best utilise the residual binder contained on the millings.

Where the supply of millings is in excess, or the millings are considered to be inappropriate for use in RHM, alternative applications have been reported. These applications mainly involve pavement layers in low stress situations such as sub-base layers in highway pavements or as base/surface layers in secondary roads. Millings appear to be widely used in the conversion of gravel roads to sealed roads, generally to very good effect.

An innovative use for millings has been reported which involves adding small quantities of orange peel-based solvent and additional cutback bitumen to a batch of millings to produce a cost-effective and well-performed pothole patching mix.

3. Laboratory testing of asphalt millings

3.1 General

The fundamental properties of asphalt millings that were identified as being of interest in the pavement engineering context were:

- particle size distribution;
- bitumen content;
- compaction;
- CBR;
- Plasticity Index; and
- Clay Index.

The material's response under repeated loading was also assessed using the Repeated Load Triaxial (RLT) apparatus. This test approximates in-service pavement stress conditions and provides information on both the elastic modulus and the permanent deformation characteristics of the material. An important benefit of the RLT test is that the stress dependence of the specimen response can be investigated. Test sheets for all tests are presented in the Appendix to this report.

3.2 Sampling

Four major contractors in the Auckland roading market were approached to gauge their interest in supporting this project. All four companies were very supportive and offered access to their millings stockpiles. They were:

- Higgins Contractors Ltd;
- Fulton Hogan Ltd (FH);
- Works Infrastructure Ltd (Works); and
- Blacktop Construction Ltd.

All four companies provided samples of processed millings. In addition, Blacktop provided samples of unprocessed millings and Works Infrastructure provided samples of surge material. *Surge* is the term given to excess HMA that is removed from the asphalt plant between changes in mix production.

Civil Lab Ltd was engaged to obtain two 25 kg samples of each type of material. This size sample was sufficient to undertake duplicate tests for the basic testing programme and single tests for the binder extraction and RLT tests.

3.3 Basic laboratory testing

3.3.1 Particle size distribution

The particle size distribution of each source of millings was determined using two procedures:

- sieving of the samples as-received; and,
- sieving of samples following binder extraction.

The dry sieve testing was carried out by Civil Lab Ltd and Pavement & Bitumen Ltd during the period January to March 2005.

The results of the particle size distribution tests are presented in Tables 3.1 and 3.2, and Figure 3.1. Figure 3.1 also shows the Transit New Zealand M/4 grading envelope for AP20 aggregates.

Table 3.1 Particle size distribution results for as-received samples.

Sieve size (mm)	% passing					
	Higgins millings	FH millings	Works millings		Blacktop millings	
			Processed	Surge	Processed	Unproc.
63.0	100	100	100	100	100	100
37.5	100	100	100	99	100	97
26.5	100	100	100	99	100	94.5
19.0	99.5	100	100	99	95.5	89
13.2	95.5	100	99.5	96	85.5	78.5
9.5	81.5	100	90.5	88	74	63
4.75	32.5	74.5	40.5	58.5	41	38
3.35	26	60.5	32.5	44	33	31
2.36	19.5	46.5	25.5	30.5	24	23.5
2.00	17	41.5	23.5	26.5	21.5	21
1.18	11	28.5	17	12.5	14.5	13
0.50	6.5	17	11.5	3	9	6.5
0.425	5	12.5	9	1	6.5	5
0.300	3.5	9.5	7	0.7	4.5	3.5
0.212	2.5	6	5	0.35	3.5	3
0.151	2	4	3.5	0.25	2	2
0.090	1.5	2	1.5	0.20	1	1
0.075	1	2	1.5	0.16	1	1
0.063	1	1.5	1	0.16	1	1

Table 3.2 Particle size distribution results for post binder extraction.

Sieve size (mm)	% passing					
	Higgins millings	FH millings	Works millings		Blacktop millings	
			Processed	Surge	Processed	Unproc.
26.5	100	100	100	100	100	100
19.0	100	100	100	99	98	99
13.2	99	100	100	98	97	94
9.5	86	100	96	90	93	87
6.7	57	96	76	83	87	82
4.75	36	78	51	75	77	73
2.36	25	54	33	53	56	55
1.18	18	39	25	38	42	40
0.60	14	30	20	27	32	30
0.30	11	22	16	17	22	20
0.15	8	16	11	10	14	13
0.075	5	11	7	7	9	9

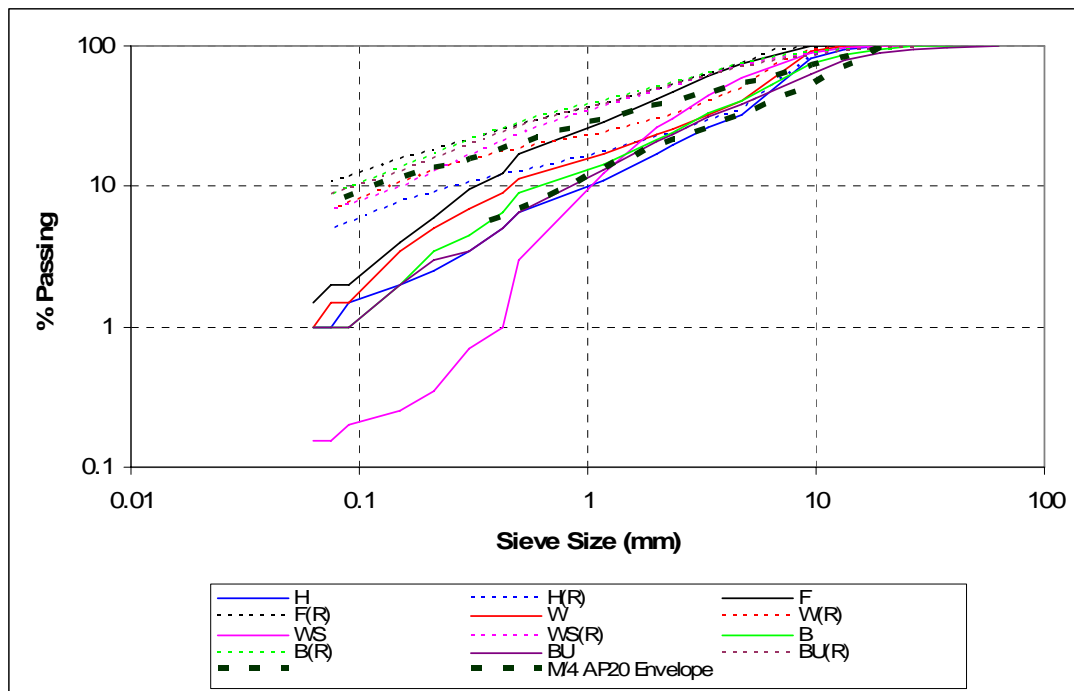


Figure 3.1 Test results for particle size distribution compared to TNZ M/4 AP20 standard.

Samples: Solid lines = as-received samples
 Dotted lines = residual samples (R) post-binder extraction
 Heavy dashed lines = the M/4 AP20 envelope

Sample origins: H = Higgins, F = Fulton Hogan, W = Works Infrastructure,
 WS = Works Surge, B = Blacktop, BU = Blacktop Unprocessed

Figure 3.1 shows that the as-received millings samples were somewhat coarser than the samples that had been subjected to binder extraction. This is reasonable considering that a reasonable proportion of the as-received samples were bound with bitumen, irrespective of the pulverising action of the milling plant.

It is difficult to make any conclusive comments regarding the particle size distribution as the result will be highly dependent upon the type and age of the material being milled, the inclusion of any underlying aggregates, and the characteristics and operation of the milling equipment.

As a general observation, the as-received samples plotted outside, or close to, the fine side of the TNZ M/4 AP20 envelope for the fraction over about 10 mm. However, the converse was observed for the fraction below approximately 10 mm, with the exception of the Fulton Hogan sample. The generally low proportion of particles in the fine fraction suggests that the material would be reasonably free-draining, although it may suffer from a lack of stability if fine particles are insufficient to 'lock-up' the interstices between the larger particles. This may also make the material somewhat 'lively' and consequently difficult to place and compact.

Figure 3.1 also shows that, after binder extraction, the samples generally plotted as a straight line on the log-log particle size distribution plot. The majority of these samples plotted close to, or above, the fine side of the TNZ M/4 AP20 envelope.

3.3.2 Bitumen content

Bitumen & Pavement Ltd carried out bitumen content tests on all samples using the WCS AL 4.02/15a:1990 test procedure. The test results are presented in Table 3.3.

Table 3.3 Bitumen content test results.

Source	Recovered bitumen content (%)
Higgins	5.0
Fulton Hogan	4.1
Works	5.3
Works Surge	4.9
Blacktop	4.5
Blacktop Unprocessed	5.9

The bitumen content values presented in Table 3.3 represent recovered bitumen content, which is the combination of the effective bitumen content and some of the bitumen absorbed by the aggregate.

The values obtained appear to be reasonable considering that most surfacing mixes would typically have effective binder contents of 4% to 7% with up to an additional 1% expected for absorption.

3.3.3 California Bearing Ratio and Clegg Impact Value tests

California Bearing Capacity (CBR) tests were carried out on the millings samples by Civil Lab Ltd. The tests were performed under the following conditions:

- duplicate tests carried out for all specimens;
- test specimens comprised particles passing the 19 mm sieve;
- NZ standard compaction was used to prepare the specimens;
- test specimens were soaked for 5 days before testing;
- a 4 kg surcharge was used for all tests; and
- optimum moisture content for compaction was estimated.

Clegg Impact Value (CIV) tests were also carried out on the CBR specimens.

The test results are presented in Table 3.4.

Table 3.4 CBR and Clegg Impact Hammer test results on duplicate samples.

Millings	Compacted dry density (t/m ³)	Water content (%)	CBR	CIV
Higgins	1.90	7.2	11	28
	1.90	7.7	10	30
Fulton Hogan	2.10	7.7	25	34
	2.12	8.1	25	33
Works	1.86	7.5	20	28
	1.86	6.9	17	28
Works Surge	1.66	4.3	5	28
	1.68	4.9	5	30
Blacktop	1.88	5.5	11	29
	1.88	5.5	12	29
Blacktop Unprocessed	1.90	5.8	12	30
	1.86	5.8	10	25

The CBR test represents a miniature bearing capacity test. The results are expressed as a percentage of the value that would be expected from a high quality crushed rock aggregate.

The CBR results presented in Table 3.4 indicate that the bearing capacity of the millings specimens ranged from 5 for the Works Surge, to about 20 to 25 for the Works and Fulton Hogan specimens. The low result for the surge can be attributed to the material being comprised of fresh binder, and subject to creep under the slow rate of loading used in the CBR test.

The remaining test results are also relatively low, which is most likely attributable to the relatively low dry density of the test specimens. The specimens were prepared using NZ standard compaction conditions as we envisaged that pavement applications using millings would be confined to low levels in the pavement structure where compaction conditions are generally difficult. Another contributing factor is that the particle size

distributions of the Fulton Hogan and Works specimens are considered to be more stable than those for the other specimens.

The CIV results are reasonably uniform for all of the specimens. The CIVs do not necessarily reflect the CBR results, mainly because of the nature of the impact loading relative to the slow loading associated with the CBR test. The low rate of loading associated with the CBR test allows the sample to undergo creep deformation.

Converting CIVs to equivalent CBR values using the published relationship, which is:

$$\text{CBR} = 0.07(\text{CIV})^2$$

results in equivalent CBR values in the range approximately 45 to 80, i.e. significantly higher than the CBR results that were measured directly.

3.3.4 Plasticity Index and Clay Index

Civil Lab Ltd was engaged to carry out Plasticity Index and Clay Index tests on duplicate samples. The Clay Index results are presented in Table 3.5, but all specimens were found to be non-plastic.

Table 3.5 Clay Index test results on duplicate samples.

Millings	Clay Index
Higgins	2.5
	2.5
Fulton Hogan	0.5
	0.5
Works	0.6
	1.1
Works Surge	0.5
	0.5
Blacktop	0.8
	0.8
Blacktop Unprocessed	0.7
	0.7

As expected, the Clay Index results shown in Table 3.5 are generally low. However, the value of 2.5 obtained for the Higgins specimen is approaching the maximum value that is generally considered to be acceptable for a roading aggregate, i.e. 3.0.

The Clay Index is an indicator of the presence of swelling clay minerals in the aggregate. Sources of such material could include:

- contamination from underlying soil or aggregate; or
- clay minerals liberated from the fabric of the aggregate as a result of particle breakdown during the milling process.

3.4 Repeated Load Triaxial testing

3.4.1 General

The Repeated Load Triaxial (RLT) test attempts to simulate the stress conditions that occur in a pavement layer as a wheel load passes a point on the pavement surface. While the simulation of stresses is reasonable, the apparatus cannot however model the rotation of principal stresses that occurs in the field.

The RLT tests were carried out by Opus International Consultants Central Laboratories in March 2005. The following test conditions were adopted:

- specimens prepared to 100% NZ standard compaction (NZS4402:1986 Test 4.1.1);
- specimens prepared at optimum water content;
- specimen dimensions of 295 mm height by 150 mm diameter;
- tests carried out using consolidated, drained conditions;
- loading pulses applied as per the AS1289.6.8.1:1985 test specification;
- three loading stages per sample, 10,000 load cycles per stage;
- confining pressure constant at 50 kPa; and
- maximum deviator stresses of 150, 250 and 350 kPa for each stage respectively.

Considering that millings would generally be appropriate for use in pavement applications under relatively low traffic volumes, the RLT tests were carried out using stress conditions that are specified for sub-base layers. This factor was also taken into consideration when adopting the NZ Standard level of compaction for the preparation of the test specimens.

The tests were carried out using three millings samples as described in Table 3.6.

Table 3.6 RLT test specimen details.

Specimen	Dry density (t/m ³)	Water content (%)
Works Infrastructure (Processed)	1.91	4.0
Fulton Hogan (Processed)	2.11	9.0
Blacktop (Unprocessed)	1.88	5.5

The RLT test results are presented in Figures 3.2, 3.3 and 3.4 for the three specimens respectively. Test result sheets are included in the Appendix.

3.4.2 Resilient modulus

The test results show that, for each source of millings, the specimens achieved a relatively constant resilient modulus (right axes on Figures 3.2–3.4) after approximately 200 to 1,000 load cycles irrespective of the level of deviator stress.

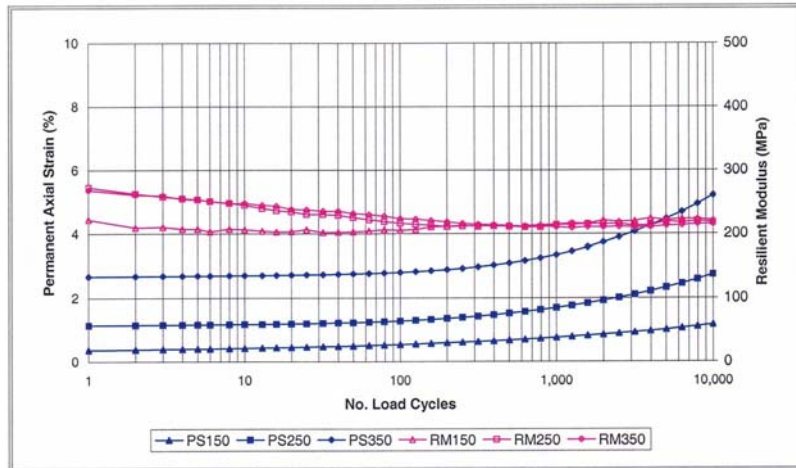


Figure 3.2 RLT test results for the Works millings sample.

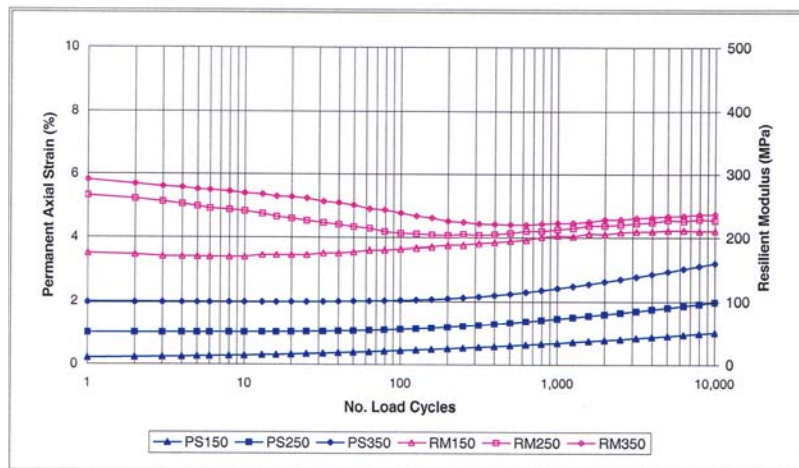


Figure 3.3 RLT test results for the Fulton Hogan millings sample.

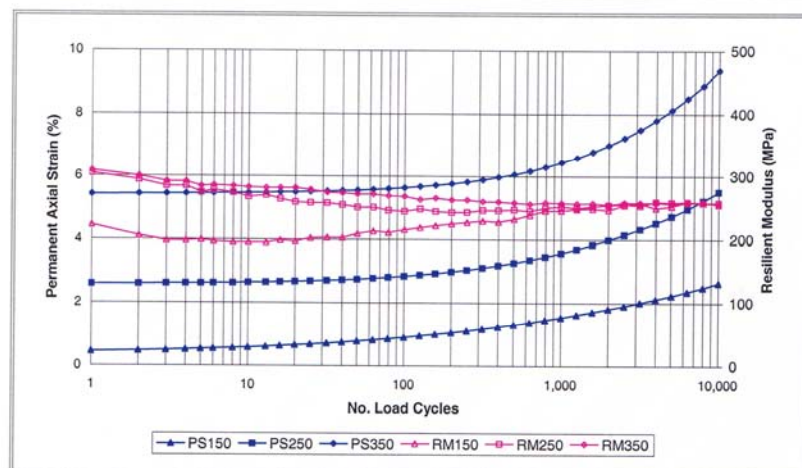


Figure 3.4 RLT test results for the Blacktop (unprocessed) millings sample.

Note: permanent deformation (%) and resilient modulus (MPa) are the left and right axes respectively.

Constant resilient modulus values of approximately 220 MPa were obtained for the Works Infrastructure and Fulton Hogan specimens while the Blacktop specimen achieved a slightly higher value of 260 MPa. However, for practical purposes it is reasonable to conclude that all three specimens produced a consistent resilient modulus response.

Somewhat surprisingly the resilient modulus response was constant for all three levels of repeated deviator stress, as granular materials generally show a non-linear stress versus strain response.

The test results indicate that the millings produce an approximately linear resilient modulus response after approximately 1,000 load cycles and for the test conditions adopted in this study.

The values of the resilient modulus obtained in the tests, i.e. 220 to 260 MPa, are consistent with what would be expected from an unbound, sub-base type aggregate. The Austroads Pavement Design Guide (2004) suggests presumptive sub-base modulus values in the range 150 to 400 MPa with a typical vertical modulus of 250 MPa.

3.4.3 Permanent deformation

Figures 3.2 to 3.4 show the progression of permanent deformation for each specimen and each loading stage. The permanent deformation results are summarised in Table 3.7.

Table 3.7 Summary of permanent deformation test results.

Specimen	Deviator Stress (kPa)	Permanent Strain Over 10 ⁴ Loading Cycles (%)
Works Infrastructure	150	0.82
	250	1.51
	350	2.50
Fulton Hogan	150	0.80
	250	0.98
	350	1.25
Blacktop (Unprocessed)	150	2.17
	250	2.78
	350	3.98

Table 3.7 shows that the Fulton Hogan millings specimen provided the greatest resistance to permanent deformation, followed by the Works Infrastructure millings. The unprocessed Blacktop millings showed significantly less resistance to permanent deformation compared with the other two (processed) materials.

The superior permanent deformation resistance of the processed specimens is most likely attributable to their particle size distributions forming a relatively dense structure compared with the unprocessed sample. This is reflected to some extent by the (NZ Standard) maximum dry density values for each material. The Fulton Hogan, Works Infrastructure and Blacktop (unprocessed) materials had maximum dry density values of 2.11 t/m³, 1.91 t/m³ and 1.88 t/m³ respectively.

In general, an unbound material is considered to perform satisfactorily in terms of permanent deformation if it exhibits stable behaviour. Stable behaviour is where the material shows a decreasing rate of accumulation of permanent strain on a plot of permanent strain versus number of load cycles. All three specimens show stable behaviour when plotted on linear scales, at least over the 10,000 load cycles used in the RLT tests.

3.5 Interpretation of test data

The basic test data indicate that, as expected, the millings samples were reasonably uniform in terms of bitumen content. However some variation was shown in particle size distribution, CBR and Clay Index. The variation in particle size distribution is not surprising, given that the nature of the millings would be dependent on a number of factors including: the nature of the original material, the characteristics and operation of the milling plant, and the amount of underlying material that may have been clipped during the milling process.

There was no evidence that the residual binder had any significant influence on the performance of the millings specimens, except for the surge material. This material was observed to have re-adhered itself in the sample bag.

The CBR tests showed reasonably good responses for the Works Infrastructure and Fulton Hogan specimens with CBR values in the range 20 to 25. While still being somewhat less than would be required for a pavement sub-base aggregate, it should be recognised that a relatively low level of compaction has been applied (i.e. NZ standard compaction). The Blacktop and Higgins specimens showed somewhat lower CBR values but that may have been a result of a less favourable particle size distribution for those materials.

The RLT tests provide the most informative results as they utilise the most appropriate stress conditions for simulated pavement applications. The tests showed that both the processed and unprocessed samples provided resilient modulus values that were comparable to those of conventional aggregates used in sub-base applications, i.e. E_R in the range 220 to 260 MPa. The permanent deformation component of the RLT tests showed that the processed millings provided superior rut resistance compared with that of the unprocessed millings. However, both the processed and unprocessed samples showed stable permanent deformation resistance performance, and therefore would be deemed acceptable, at least for pavement sub-base applications in relatively low risk projects.

4. Field investigation of asphalt millings

4.1 General

At least two pavement rehabilitation applications in the Auckland region have utilised millings in the recent past. The Carbine Road (Mt Wellington) and Aotea Road (Great Barrier Island) pavement rehabilitation sites have been investigated as part of this project.

A visual inspection of both sites was carried out as well as performing coring and Falling Weight Deflectometer (FWD) tests on the Carbine Road site.

4.2 Investigation of base layers, Carbine Road

Carbine Road is a heavily trafficked arterial road located in an industrial part of Mt Wellington, Auckland. The section of Carbine Road immediately south of the Bowden Road intersection was scheduled for rehabilitation in 1999. The original pavement conditions were somewhat complex and included various overlays and widenings. A site location plan is shown in Figure 4.1.



Figure 4.1 Location map of rehabilitation site on Carbine Road, Auckland City.

Upon excavation of the southbound right lane and the northbound right-turn lane, the original pavement conditions were discovered to differ significantly from what had been adopted in the design. Given the volume of traffic that uses the area, the decision was to implement a temporary solution to enable the road to be re-opened to traffic on the same day. The solution that was adopted was to backfill the excavation with approximately 200 mm of millings and to apply a thin dense asphalt surface course.

The area in question comprised approximately 100 m in length by 7 m in width. This is a very high demand site with an AADT in excess of 10,000 vehicles per day, of which heavy vehicles are a relatively large proportion. In addition, the subgrade conditions are generally poor and therefore it is difficult to achieve a high level of pavement performance. The proportion of vehicles using the two lanes in question is estimated to be of the order of 25% to 30% of the AADT.

Three test pits were excavated in July 2003 in the area that was backfilled with millings. All three pits indicated that the millings layer had become bound. However, none of the eight 95 mm-diameter cores that were drilled in the area provided intact cores of millings. This suggests that the millings layer was not heavily bound.

FWD tests were carried out on the temporary repair in November 2004, in both wheel paths of the lanes that contained millings in the base layer. A plot of the inferred base layer modulus values versus distance is presented in Figure 4.2.

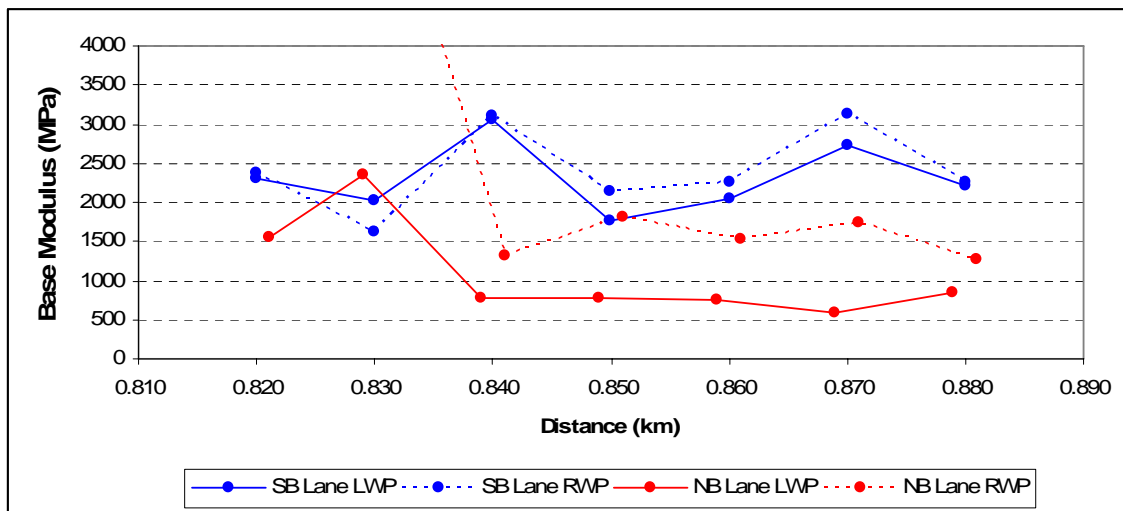


Figure 4.2 Elastic modulus values inferred by FWD for base layers of the lanes containing the millings.

The results shown in Figure 4.2 suggest that the modulus of the millings layer ranged from approximately 700 MPa to more than 3,000 MPa. The higher values of modulus are typical of the results that could be expected for asphalt materials, whereas the moduli below about 1,000–1,500 MPa are typical of modified basecourse modulus values.

The Carbine Road pavement was inspected in August 2005. The inspection showed that the area containing millings was performing reasonably well considering the demanding nature of the site. The asphalt surface showed some cracking and permanent deformation, but the distress was relatively minor. Personal communications with the designers of the Carbine Road rehabilitation confirmed that the millings have performed very well, at least as a temporary repair measure. The traffic loading that has been applied since the repair was carried out is estimated to be up to 0.5×10^6 ESA.

A photograph of the pavement is presented in Figure 4.3. Note that the area containing millings comprises the second and third lanes from the camera.

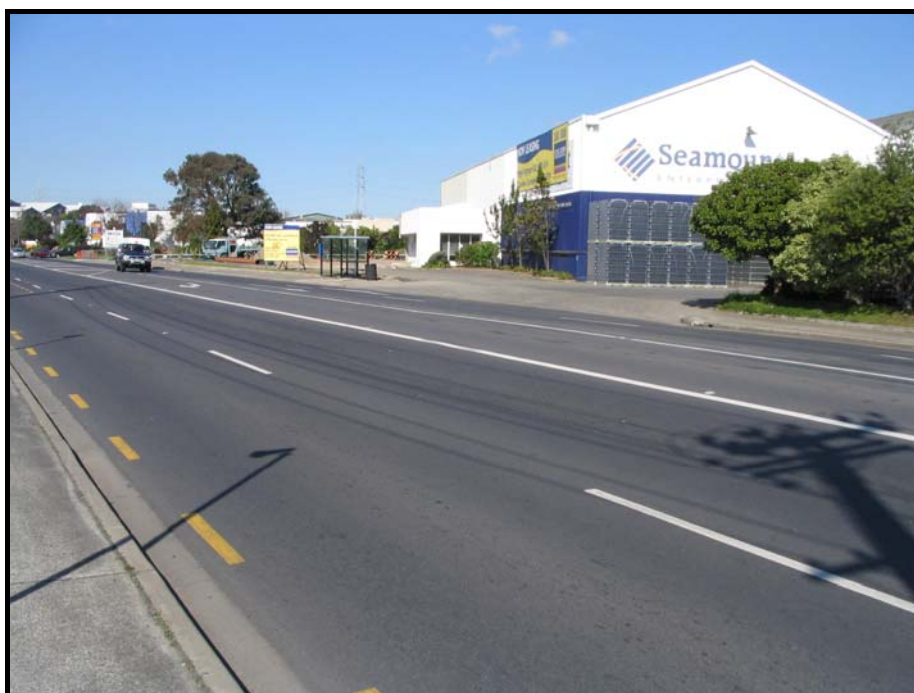


Figure 4.3 View of the Carbine Road rehabilitation site.
The second and third lanes from the camera have base layers with asphalt millings.

4.3 Trial of overlay, Great Barrier Island

The Great Barrier Island road network consists of approximately 78 km of unsealed roads and approximately 30 km of sealed roads. The very high rainfall and mountainous terrain results in significant erosion of the unsealed component of the road network.

In 2001, City Design Ltd carried out a literature review on the topic of utilising RAP to upgrade unsealed roads. A methodology was selected and a trial section (about 500 m long) was constructed on Aotea Road (Okiwi, Great Barrier Island, Figure 4.4) in October 2001. The trial section treatment comprised the following:

- a slow-break emulsion was sprayed onto the surface of the unsealed road;
- millings were spread into a 150 mm-thick layer;
- further slow-break emulsion was sprayed onto the millings; and
- the layer was compacted using a drum roller.

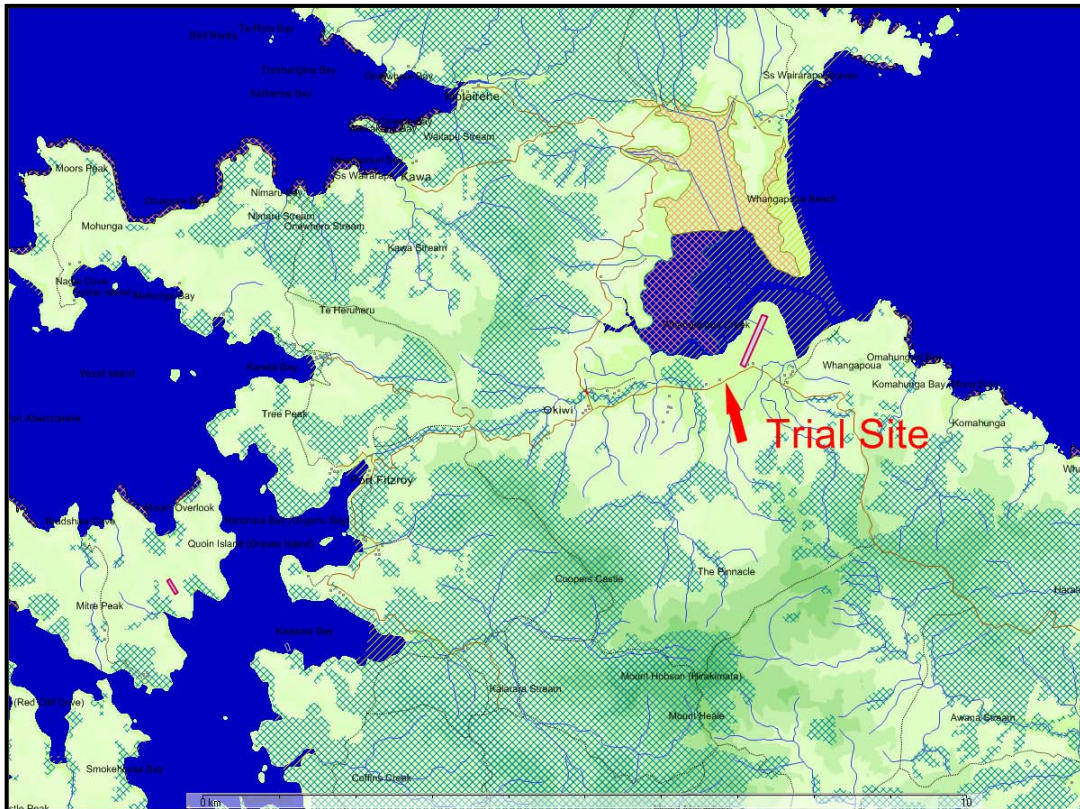


Figure 4.4 Location map of overlay trial site on Great Barrier Island.

As of October 2002 the trial section was performing relatively well in terms of smoothness and skid resistance, however areas were showing cracking, shearing, potholing, edge break and some scouring of the surface. The anticipated upgrade would involve scarifying the existing pavement surface and placing further millings. However, we understand that no major upgrading has been carried out to date.

The conclusions of the City Design report into the trial section stated that, while the trial section showed superior performance compared with the adjacent unsealed road sections, further research was needed to establish the best methods for construction using millings.

An engineer from Bartley Consultants inspected the site in September 2005. The inspection confirmed that the site was demanding in terms of alignment and terrain, although the traffic loading was very low.

The surface of the trial section appeared to be bound and very hard, to the point where a car key would not penetrate the surface (see Figure 4.5). The surface showed large stone particles mixed in with the millings, most likely caused by contamination of the original material with basecourse. There was also evidence of flushing in isolated areas.

Significant areas of crocodile cracking that were not confined to the wheel paths were obvious (see Figures 4.6 and 4.7). This suggests that the material has suffered fatigue failure, and therefore it may have behaved like a low-grade asphalt. Because the cracking was widespread across the carriageway suggests that the traffic wanders significantly, which is quite likely given the carriageway dimensions, or the cracking may include an

environmental mechanism. The depth of cracking appeared to be somewhat variable with evidence of delamination of the upper materials, leaving the lower materials in an unbound state. The lower materials would therefore be highly susceptible to shearing.

The widespread cracking, with subsequent water ingress, would certainly contribute to the pavement distress such as the significant areas of edge break, deformation (with heaving) and potholing (see Figures 4.6 to 4.9). Edge break may have been exacerbated by the improved stormwater run-off performance of the road surface. It may also have been aggravated by tracking off the edge of the pavement, given the minimal carriageway width.

The Great Barrier Island road maintenance contractor indicated that the trial section had performed significantly better than the previous loose metal road, even though the millings pavement still required a reasonably high level of maintenance. By all accounts the local residents are generally pleased with the performance of the trial section.



Figure 4.5 Bound surface of trial section on Aotea Road.



Figure 4.6 Crocodile-cracked surface.



Figure 4.7 Detailed view of crocodile-cracked surface.



Figure 4.8 Example of edge break.



Figure 4.9 Potholing in the surface of the trial section.

4.4 Interpretation of field investigation data

The field investigations showed two successful applications for millings in contrasting locations. The Carbine Road site showed that millings could be used as a temporary base layer in heavily loaded pavements. The five (plus) years of service would almost certainly have exceeded the expectations of the pavement designer and the local authority asset manager. The Great Barrier Island site also showed that improved performance was achieved by using emulsion-treated millings compared with that of a conventional unsealed road surface. While the surface had suffered significant cracking and other forms of distress, the road users appear to be happy with the performance. A slightly higher emulsion application may have further improved the performance of the material.

The millings layers at both sites appear to have attained some level of cohesion based on the evidence of the in-situ test data and visual inspections.

On the basis of the field investigation the conclusion is that millings could be appropriate in (at least) the following applications:

- Base layers for:
 - temporary road repairs;
 - haul roads;
- Integral base and surface layers for lightly trafficked roads (when combined with bitumen emulsion);
- Sub-base or subgrade improvement layers in most highway applications;

5. Conclusions

The main conclusions that have been drawn from the literature review, laboratory investigation and field investigation are as follows:

5.1 Literature review

- Asphalt is the single most recycled product in the world.
- The most cost-effective application for asphalt millings is generally considered to be in the production of recycled hot mix asphalt. This is to ensure that the bitumen present in the millings is used in the most efficient way. The literature indicates that the performance of recycled HMA is at least equal to that of asphalt produced from virgin aggregates.
- The use of millings in road applications has very few detractors. However there is some conjecture over the environmental soundness of millings. At least one agency in the US considers loose millings to pose a leaching risk.
- The uses of millings varies significantly with some highway agencies allowing millings in sub-base applications under asphalt or concrete base layers, or as base layers in minor roads. Other agencies prefer to limit the use of millings to shoulders, medians or other non-structural applications.
- Millings combined with fresh bituminous binder have been used successfully in the upgrading of gravel roads.
- A small quantity of millings incorporated in concrete mixes increases the workability and toughness of the mix without significantly compromising the strength.
- Millings combined with an orange-peel oil solvent have been used successfully as a pothole patching material.

5.2 Laboratory investigation

- The six sources of millings used in this investigation had bitumen contents in the range of 4.1% to 5.9%.
- CBR tests showed results ranging from 5 for the surge sample to 25 for processed millings. Unprocessed millings gave a CBR of approximately 10. These results are somewhat lower than expected but could be attributable to the relatively low (NZ Standard) compactive effort used in preparing the test specimens.
- Clegg Impact tests indicated inferred CBR values in the range 45 to 80.
- All millings samples were found to be non-plastic although they showed Clay Index values in the range 0.5 to 2.5. This may have been a result of minor contamination from basecourse materials.

- RLT tests were carried out on three specimens, i.e. two from processed samples and one from an unprocessed sample. Three stages of loading were applied with a constant confining pressure of 50 kPa and maximum deviator stresses of 150, 250 and 350 kPa respectively.
- The RLT results showed constant resilient modulus responses of approximately 220 MPa from about load cycle number 1,000 to the end of the test (10,000 load cycles) for all three samples. The resilient modulus was found to be independent of the deviator stress.
- The permanent deformation component of the RLT test indicated that all three specimens showed stable permanent deformation performance up to 10,000 load cycles. However, the two processed specimens showed superior performance to that of the unprocessed specimen. This is most likely attributable to the superior particle size distribution of the processed specimens.
- The overall findings of the laboratory investigation are that the processed millings generally show a soaked CBR of up to 25, the resilient modulus is of the order of 200 MPa and is not influenced by deviator stress, and the permanent deformation properties are generally acceptable for pavement applications. The unprocessed millings show generally lower CBR values and a greater degree of permanent deformation.

5.3 Field investigation

- Millings have been used successfully as a temporary base layer (approximately 200 mm thick) in a busy arterial pavement at Carbine Road, Auckland.
- The layer has been in service for approximately five years and continues to perform to a reasonable standard.
- FWD test data suggests that the millings layer achieved at least a moderate degree of cohesion although the material was not recoverable by coring.
- Millings treated with slow-break emulsion have been used with reasonable success in a trial section at Aotea Road, Great Barrier Island.
- The trial section has provided an appropriate level of service for the last four years. Although some distress, i.e. crocodile cracking, deformation, edge break and potholing, has occurred, the material is generally considered to be superior to unbound aggregate.

6. Recommendations

The following recommendations have been drawn from the research carried out in this project:

- Processed millings are considered to be appropriate for sub-base (or lower level) applications for typical urban and rural road pavement applications.
- Processed millings treated with slow-break emulsion can be a favourable alternative to unbound aggregates on unsealed roads.
- RLT tests should be used to verify that millings materials are appropriate for any given application. As a general guide, resilient modulus values of at least 200 MPa and stable permanent deformation behaviour under appropriate stress conditions should be attainable.
- Millings mixed with an organic solvent could provide a cost-effective and environmentally friendly alternative to plant mix for minor pavement repairs.
- Pavement designers should consider the potential for reduced permeability in millings layers if the material achieves a reasonable degree of cohesion.

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Appendix Laboratory test reports

**Laboratory test reports for material sampled from Higgins Yard,
carried out by Civil Lab:**

Standard compaction
Particle size distribution
California Bearing Ratio test
Clay Index
Plasticity Index

**Laboratory test reports for material sampled from Blacktop Yard,
carried out by Civil Lab:**

Standard compaction

Particle size distribution

California Bearing Ratio test

Clay Index

Plasticity Index

**Laboratory test reports for material sampled from Fulton Hogan,
carried out by Civil Lab:**

Standard compaction curve
Particle size distribution
California Bearing Ratio test
Clay Index
Plasticity Index

Laboratory test reports for material sampled from Works Lunn Avenue Yard, carried out by Civil Lab:

Standard compaction curve
Particle size distribution
California Bearing Ratio test
Clay Index
Plasticity Index

**Laboratory test reports for samples from Works, Fulton Hogan,
Higgins and Blacktop, carried out by Bitumen & Pavement Ltd:**

Binder content

Aggregate grading

**Laboratory test reports for Repeated Load Triaxial
permanent strain test**

**for Works processed samples,
Fulton Hogan processed samples,
Blacktop unprocessed samples,**

**carried out by Opus International Consultants Ltd,
Central Laboratories**