Weathering Characteristics of Modified Marginal Aggregates

Transfund New Zealand Research Report No. 216

Weathering Characteristics of Modified Marginal Aggregates

F.G. Bartley
Bartley Consultants Ltd
Auckland, New Zealand

Transfund New Zealand Research Report No. 216

ISBN 0-478-25074-6
ISSN 1174-0574

PO Box 2331, Lambton Quay, Wellington, New Zealand
Telephone 64-4-473 0220; Facsimile 64-4-499 0733

Bartley, F.G. 2001. Weathering characteristics of modified marginal aggregate. *Transfund New Zealand Research Report No. 216*. 37 pp.

Keywords: aggregate, clay minerals, marginal aggregate, modification, stabilisation, roads, weathering

An Important Note for the Reader

The research detailed in this report was commissioned by Transfund New Zealand.

Transfund New Zaland is a Crown entity established under the Transit New Zealand Act 1989. Its principal objective is to allocate resources to achieve a safe and efficient roading system. Each year, Transfund invests a portion of its funds on research that contributes to this objective.

While this report is believed to be correct at the time of its preparation, Transfund New Zealand, and its employees and agents involved in its preparation and publication, cannot accept any liability for its contents or for any consequences arising from its use. People using the contents of the document, whether directly or indirectly, should apply and rely on their own skill and judgement. They should not rely on its contents in isolation from other sources of advice and information. If necessary, they should seek appropriate legal or other expert advice in relation to their own circumstances, and to the use of this report.

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

Contents

Executive Summary

Introduction

Aggregates for road basecourses produced from quarries in some parts of New Zealand are not considered suitable for use on state highways and other heavily loaded pavements because they are unlikely to have the weathering characteristics necessary to comply with the Transit New Zealand (TNZ) M/4:1995 Specification for *Basecourse Aggregate*. Such an aggregate is often termed "marginal" because, although it may not comply, it may still be a useable material under certain circumstances. Modification of the material with lime or other appropriate additives, however, could improve its characteristics sufficiently to facilitate their compliance.

Transit New Zealand B/3:1999 Specification for the *Design and Construction of Performance-based Flexible Pavements* permits the use of stabilised marginal aggregate as a basecourse, provided it meets criteria similar to those specified in the TNZ M/4 Specification, *Basecourse Aggregate*.

Objectives

The objective of this project, carried out in 2000-2001, was to study the Weathering Quality Index (WQI), the measure used in the TNZ M/4 Specification, in order to determine what changes occur in the Index when a marginal aggregate is modified with lime. The Clay Index (CI) test was used to measure the changes that occurred in the quantity of swelling clay minerals present at each stage of the laboratory study.

The project involved a review of recent research into the weathering of rock and its relationship to aggregate used in the construction of unbound granular road pavements. This was followed by a series of laboratory tests carried out on a selection of aggregates obtained from quarries around the Auckland region.

Literature Review

From the literature review the process of weathering of rock is explained as the chemical or physical change that occurs when a rock is placed in an environment different from that existing at the time the rock was formed.

Swelling clay minerals, a common product of weathering of igneous rocks, may be contained within the structure of the rock, or within veins or fractures. They are found within the fines of an aggregate or are produced as rock particles degrade during compaction or possibly during trafficking of a pavement. A roading aggregate that contains excessive quantities of these minerals is potentially unstable.

Modification of aggregate using a chemical additive alters the molecular nature of the clay minerals and makes the aggregate less sensitive to water. Chemical modification also promotes the formation of inter-molecular bonds.

Physical weathering, i.e. the fragmentation of particles, occurs during compaction and may continue after the pavement is put into service. Little is known about the weathering conditions in the pavement but it is unlikely that they are neither aggressive enough, nor is the time period sufficient, to facilitate further chemical weathering.

Transit New Zealand uses NZS 4407 Test 3.11, *Weathering Quality Index*, as a measure of the weathering resistance of basecourse aggregate used on the State Highway (SH) network. This test has little or no relationship to the weathering conditions in the pavement nor has it been calibrated in terms of pavement performance.

Laboratory Study

The second phase of the project involved the selection of five aggregates for evaluation in the laboratory. During this phase changes in the WQI and the CI were monitored as each sample was treated with lime, and then passed through a laboratory crusher. The laboratory crushing process was intended to replicate the particle fragmentation that occurs during construction. Some additional experiments involving the use of proprietary additives based on lime-rich steel mill slag, were also included.

The WQI is the composite of two measures. The first records the breakdown of the larger particles that occurs during the test as the material is submitted to cycles of wetting, drying and rolling. The second measures the quantity of fine material that is produced from that process. The results of the test carried out on the five selected aggregates showed that the particle breakdown was relatively constant regardless of the amount and type of stabiliser used. The test also showed that the reduction in the quantity of fines produced when a stabiliser was added was, in most instances, insufficient to change the WQI. The conclusion is that the WQI is not an appropriate test for modified marginal aggregate.

The fragmentation of roading aggregate during compaction and trafficking is not a desirable characteristic but it is not serious provided the fines that are produced are non-plastic or only slightly plastic. The plastic nature of the fines can be monitored using the CI test. This study has shown that the CI is responsive to changes that occurred in the samples.

Conclusions

The changes that could occur during the construction and trafficking of a pavement built using modified marginal aggregate should be monitored using the CI test.

The WQI is not an appropriate test to use on modified marginal aggregate but the CI provides a good measure of the change in swelling clay minerals that occur during modification and during compaction.

Recommendations

The following recommendations are based on the results of this research project:

- To use the Clay Index test as a measure of the swelling clay minerals that could be liberated from a rock of marginal quality both during the manufacture of the aggregate and during the construction of the pavement;
- Further research is required to:
  - more closely define the weathering conditions within a pavement,
  - identify the reactions that occur between the rock minerals and the chemicals used to modify marginal aggregate,
  - establish the weathering potential of the clay minerals formed during the modification process, particularly that within the pavement environment,
  - determine the relationship between the Clay Index value of an aggregate and its ability to carry a range of traffic loadings.

Abstract

The objective of this project, carried out in 2000-2001, was to study the Weathering Quality Index (WQI), the measure used in the Transit New Zealand M/4:1999 Specification *Basecourse Aggregate*, in order to determine the changes occurring when a marginal aggregate is modified with lime. (A marginal aggregate is unlikely to have the weathering characteristics necessary to comply with TNZ M/4.) The Clay Index (CI) test was used to measure the changes that occurred in the quantity of swelling clay minerals present at each stage of the laboratory study.

The project involved a review of recent research into the weathering of rock and its relationship to aggregate used in the construction of unbound granular road pavements. This was followed by a series of laboratory tests carried out on a selection of aggregates obtained from quarries around the Auckland region.

The laboratory phase of the project involved measuring changes in the WQI and CI as the aggregate was being subjected to a number of processes including treatment with lime, curing, and then passing through a laboratory crusher to replicate the compaction and trafficking processes.

The results showed that the WQI was not sufficiently sensitive to the changes that were occurring in the aggregate, but that the CI provided a good measure. The report concludes that the potential effects of weathering should be monitored using the CI alone.

1. Introduction

1.1 General

Aggregates for road basecourses produced from quarries in some parts of New Zealand are not considered suitable for use on state highways and other heavily loaded pavements because they are unlikely to have the weathering characteristics necessary to comply with Transit New Zealand (TNZ) M/4:1995 Specification for *Basecourse Aggregate*. Such an aggregate is often termed "marginal" because, although it may not comply, it may still be a useable material under certain circumstances. Modification of the material with lime or other appropriate additives, however, could improve its characteristics sufficiently to facilitate their compliance. TNZ B/3:1999 Specification, *Performance-based Specification for Structural Design and Construction of Flexible Unbound Pavements,* does permit the use of a stabilised marginal aggregate, provided it complies with TNZ M/4:1995, TNZ M/3 (Notes) *Sub-base Aggregate,* or TNZ M/22 (Notes) *Notes for the Evaluation of Unbound Road Base and Sub-base Aggregates*. Another specification, TNZ M/5 *Regional Basecourse Aggregates,* describes the special requirements for basecourse aggregate in particular regions, e.g. Nelson.

Basecourse aggregates that conform with the TNZ M/4 Specification will perform satisfactorily under all environmental conditions and not deteriorate within the design life of the pavement. The durability test in that specification is NZS 4407:1991, Test 3.11, *Weathering Quality Index* (WQI). Other tests include Proportion of Broken Faces, Crushing Resistance, Sand Equivalent, Atterburg Limits, Clay Index, and Particle Size Distribution.

TNZ M/22 (Notes) is a guide to be used in the assessment of marginal roading materials, and includes the ASTM D559-96 Standard Test Methods for *Wetting and Drying Compacted Soil-cement Mixtures* (ASTM 1996) as a measure of durability. However, ASTM D559-96 is only suitable for use with cemented materials.

Modifying a marginal aggregate with lime or a similar chemical additive is often preferable to treating it with cement. Many of the rock types found in New Zealand contain swelling clay minerals that respond well to lime (calcium hydroxide) modification. Calcium hydroxide changes the swelling clay mineral to a more stable form with a reduced affinity for water. It also promotes the formation of complex inter-molecular bonds that effectively increase the strength of the material.

1.2 Project Objectives

The objectives of this project, carried out in 2000-2001, were to investigate the weathering characteristics of chemically modified marginal aggregate to determine if the NZ Standard Weathering Quality Index test (WQI) is applicable.

The project was divided into a number of tasks including:

Task 1 Literature review
Task 2 Select aggregates for investigation
Task 3 Initial laboratory evaluation
Task 4 Field treatment
Task 5 Laboratory tests
Task 6 Analysis and draft report
Task 7 Peer review
Task 8 Finalise report
Task 9 Draft revision of M/22 (notes).

2. Weathering

2.1 The Process

The propensity for a rock to weather or degrade is dependent primarily on the extent that its current environment differs from that pertaining at the time the rock was formed.

Rocks are formed either under moderate to high pressures and temperatures or, in the case of volcanic rocks, under extremely high temperatures. As soon as they are exposed to the action of water, air, significant changes in temperature or stress, the rock minerals will start to change. This change is called weathering.

Weathering is a process that occurs in rock located at or near the earth's surface. During the process, the mineral constituents undergo chemical decay and physical fragmentation. Weathering is primarily a chemical reaction involving the minerals, water and air, complemented and reinforced by mechanical fragmentation. The rate of weathering is dependent on the rock type and the environment, and may occur in a short space of time (years) but more naturally over millions of years. The two principle types of weathering are:

- Physical weathering (more common in very cold climates) during which the rock structure is broken down without chemical change, and
- Chemical weathering (more common in hot, wet climates) which involves chemical decomposition of the constituent minerals.

Water is an important element in the weathering process. It can permeate the rock structure, it expands when it freezes, and it is a solvent for many natural materials. Air and temperature are other important factors.

The primary minerals formed at the time of deposition of sedimentary rocks or the solidification of magmatic liquid in volcanic rocks, react with weak acid solutions that are part of the ground and surface water. The reactions produce alteration products, such as secondary minerals and clays. In some rocks the chemical reaction is slowed because the alteration product effectively protects the fresh rock from further attack, but in others the rock is completely dissolved. Some rocks are transformed into more stable weather-resistant material, e.g. calcrete.

2.2 Products of Weathering

Weathering causes a reduction in the size of rock particles and a change in their composition. Most of the igneous and metamorphic rocks contain feldspar and other silicates that weather to form clays. Many sedimentary rocks consist of fragments developed from igneous and metamorphic rock types.

Clay minerals, such as kaolinite, smectite and illite, are the products of weathering of various minerals under different climatic conditions.

2.3 Resistance to Weathering

The less soluble the mineral the more resistant or stable it will be to weathering. Minerals can be ranked in terms of their stability, as summarised in Table 1. This ranking is related to the strength of both the chemical bonds and the crystal structure under different temperature and pressure conditions. It is approximately the reverse of the order of crystallisation that occurs as a rock cools from the molten state, so that the first mineral to crystallise is also the first to weather.

Table 1 Stability of common minerals under weathering conditions.

Most Stable	Iron oxides
	Aluminium oxides
	Quartz
	Clay Minerals
	Muscovite
	Potassium Feldspars
	Biotite
	Sodium Feldspars
	Amphibole
	Pyroxene
	Calcium Feldspars
Least Stable	Olivine

Note: Clays and oxides that are the products of weathering are included as they are among the most stable minerals to further weathering.

All clay minerals are made up of sheets of silicates, and the characteristics of a particular clay mineral depend on the molecular configuration and type of cation that occupies the space between the sheets. For example, smectite, a highly plastic mineral with a Plasticity Index (PI) of 600, has the structure and type of cations that gives it the ability to absorb large volumes of water. By comparison kaolinite, which has a more compact structure, is a much less plastic clay (PI 20).

3. Literature Review

3.1 Introduction

Research into the weathering characteristics of aggregates has primarily been carried out by two different groups, i.e. engineers and geologists. Each group has approached the problem from its own perspective. Geologists are interested in the impact of the environment on the characteristics of the rock structure and the constituent minerals. Engineers are more concerned about how the aggregate will perform as a building material, and have devised mechanical tests to reject the more troublesome rock types. In many instances there appears to have been little if any co-operation between the two groups. One paper (Buckle et al. 1987) berates the engineers in particular for ignoring capabilities of chemists, and emphasises the importance of chemistry in an understanding of the weathering process. Experience suggests that a joint effort involving engineers, geologists and chemists would improve the research into this topic.

3.1.1 Engineering Approach

The engineering characteristics of rock can be described in terms of its resistance to weathering. For example, durability is the quality of lasting without perishing or wearing out, and depends on the material's resistance to natural or imposed weathering processes, or to any other factor which can act to reduce its engineering life.

Engineers have developed simple mechanical tests to measure a particular characteristics of a rock, so that those that fail such tests will not be used in important structures such as buildings, dams, highways and the like. Examples of these tests are the Freeze Thaw, Crushing Resistance, Aggregate Impact Value, Los Angeles Abrasion, Washington Degradation tests, etc. Many of these tests were specifically designed to limit the use of aggregates known to have featured in structural failures.

3.1.2 Geological and Chemical Approaches

Trained geologists have a well developed knowledge of the origin and history of soil and rock. They apply a fundamental approach to the assessment of the likely performance characteristics of a particular rock. Their assessment will often be based on the results of petrographical examination which, along with X-ray defraction and electron microscopy, provide a detailed description of the main mineral composition of the rock. For example, the Methylene Blue Absorption (or Clay Index) test, used to determine the quantity of swelling clays present, is an important analytical test developed by geologists.

Chemists also concentrate on the physical nature of the rock and consider how the constituent minerals will react to the often significant change in the environment that occurs when a rock is quarried and put into a structure.

3.2 Weathering Processes

The proclivity for rock to weather or decay depends on the nature of the change in its environment. For example, the minerals in igneous rocks undergo chemical changes because of the large differences in the temperature and pressure at the earth's surface compared with those at the time of their formation. The weathering of sedimentary rocks is primarily caused by stresses generated by the removal of overburden or confinement, a change in water content, or the action of frost.

The two dominant processes, i.e. chemical weathering and physical weathering, seldom occur in isolation. Commonly one acts to enhance the other. Chemical weathering occurs primarily in hot, wet climates, whereas physical weathering is common in cold climates where cycles of freezing and thawing occur. In some climates both types occur. Significant weathering takes time and in many instances it evolves over thousands or millions of years.

3.3 Weathering of Road Aggregate

Much is known about the natural rock weathering process but there is little reliable data to describe the relationship between the weathering characteristics of a particular rock and its performance in the pavement. One paper by Wu et al. (1999) points out that many tests have been developed to empirically characterise aggregate, even though no strong relationship has been established between the characteristics and the performance of products manufactured from the aggregates.

Fookes (1991) tabulated a number of failures that have occurred in roads over a 25-year period. This shows that the most troublesome aggregates were manufactured from igneous rocks and that the cause of degradation was either the presence of secondary minerals derived from alteration or weathering, or to the effects of active in-situ weathering.

The extraction and processing of rock can be expected to have a significant effect on the properties of roading aggregate (Fookes 1991). Shock waves from blasting may generate or enhance microfractures within the rock. These fractures may subsequently trigger further breakdown during the service life of the aggregate. Similarly crushing may induce or enhance development of intergranular, transgranular and grain contact flaws and weaknesses. Washing and screening aggregate to remove weaker material and dust add to degradation by virtue of the wetting and drying, abrasion and impact. Disintegration may also occur in the stockpile as a result of wetting, drying, freezing and thawing.

The construction processes of loading, spreading and compaction that combine the destructive forces of impact, abrasion and crushing, can cause a reduction in particle size. For example excessive rolling and watering of chlorite- and smectite-rich basalts can produce highly active slurries.

Chemical weathering within the pavement cannot be completely dismissed, particularly when the effects of size reduction are taken into account. Aggregate particles have large surface to volume ratios so that the potential for weathering within a short time frame is quite significant.

The effects of climate on the environment are important factors in the assessment of the likely changes that can occur. Weinert (1984) developed an index based on the climate in various parts of South Africa to facilitate the assessment of the performance characteristics of basic igneous rocks.

No evidence supports the concept that significant weathering occurs once the pavement is sealed and put into service. This is surprising given that most engineers believe it is possible. The failures reported by Fookes (1991) are in the main related to the release of swelling clay minerals (probably during compaction), and the subsequent loss in strength of the aggregate due to water. This emphasises the need to reduce the water content of the pavement before it is sealed, and to ensure that water cannot move back into the pavement once it is in service.

Observations of the changes in particle size distribution that occurred in test pavements located on a heavily loaded road south of Auckland were reported by Bartley (1981, 1984). He found that:

- hard aggregates suffered little or no degradation during construction;
- open-graded aggregate degraded more than fine graded material during compaction;
- some aggregates appeared to degrade during trafficking while others appeared to aggrade.

However, overall he concluded that any changes that may have occurred were masked by inaccuracies in the sampling and test procedures.

Chemical weathering appears to be the most dominant of the two possible processes which occur in nature, while mechanical degradation is by far the more significant in the road pavement environment.

3.4 Modification of Marginal Aggregates

3.4.1 Marginal Aggregate

In New Zealand roading terms, "marginal aggregates" are those that do not quite meet the TNZ M/4 Specification for *Basecourse Aggregate*. Usually a material fails in terms of plasticity (i.e. either Sand Equivalent (SE) <40, CI >3 or PI >5), Weathering Quality Index (WQI), 10% Fines Value, or a combination of these.

A marginal aggregate will quite possibly perform adequately in a pavement, but it is generally accepted that TNZ M/4-compliant materials carry a much lower risk of unsatisfactory performance. Therefore to show that, after modification, a material meets all the requirements of TNZ M/4 is an advantage.

Treating marginal aggregates with a chemical stabiliser is seen as a relatively cheap way to transform them into more durable products that comply with the TNZ M/4 Specification.

3.4.2 Modification

Chemical modification of aggregate involves alteration of swelling clay minerals to a more stable form. To some extent it is a reversal or, at least, a modification of the chemical weathering process. It is important that the new minerals formed by this process remain stable under the environment likely to prevail in the pavement. For this reason the environmental conditions need to be maintained in a non-aggressive condition throughout the life of the pavement.

The Western Australia experience with pedocretes (naturally weathered, re-cemented, materials) reported by Brice (1988), may well be relevant to a consideration of the weathering properties of modified aggregates.

3.4.3 Pedocretes

Brice's paper points out that the geology of Western Australia has been stable for a considerable period of time and as a consequence deep (>30m) weathering has occurred. This has resulted in the formation of pedocretes which are pre-existing soils, weathered material or rock, that have become cemented to varying degrees by natural processes. These processes cement or replace particles with iron oxide (ferricrete), silica (silcrete), carbonates (calcrete) or other compounds. The pedocretes are generally of two types:

- indurated or strongly cemented (hardpan and nodules), or
- non-indurated (soft powdery form).

Alluvium or colluvium eroded from the parent rock can also become cemented or partially cemented naturally. Transported material is generally more chemically stable than weathered in-situ rock. The stability depends on the distance transported and the amount of sorting that takes place. This is true of most if not all rocks. However, most of the overseas literature and standards for pedocretes refer to transported material, whereas roads in Western Australia are built predominantly from rock that has been weathered in-situ.

Attempts to apply standard geotechnical classification systems to pedocretes can be misleading because gradings and Atterberg Limits can depend on the method of extraction and processing, as well as on the method of testing. The geotechnical properties of pedocretes depend on three factors:

- texture and mineralogy of the host or parent material,
- stage of development i.e. extent to which it has been weathered, cemented or replaced, and
- nature of the cementing or replacing material.

For example the properties of calcareous soils are similar to those of the host soil whereas hardpan calcrete essentially behaves as a limestone rock.

The development of a pedocrete initially involves flocculation of clay and silt followed by cementation into larger silt- or gravel-sized complexes of varying strength and porosity.

Palygorskite, the dominant clay in calcrete, has approximately the same Plasticity Index as some smectites. However, it has a non-expansive lattice and a hollow needle-like particle shape that is typically matted into a haystack type structure, unlike the plate-like structure of most clays.

The characteristics of pedocrete are similar to those of lime-modified aggregate and should behave in a similar manner. Unfortunately, the paper does not provide an evaluation of the performance of pavements constructed using such materials.

3.4.4 Chemical Modification Process

The objective of chemical modification is to reduce the risk of unsatisfactory performance by changing the mineral composition and establishing inter-particle bonds. This form of treatment is an alternative to cement or bitumen stabilisation; processes that effectively cement or bind individual particles together to form a stiff layer.

Modification preserves the unbound nature of the material, even though there may be some weak bonds established during the process. Lime stabilisation, for example, results in the formation of complex silicate and aluminate hydrates which link the particles (Sameshima & Black 1982). The process of modification may also protect the aggregate from any further affects of weathering.

Lime, lime derivatives, or some other appropriate chemical agent should improve the plasticity and weathering characteristics of the aggregate.

3.5 Weathering Environment within the Pavement

3.5.1 Introduction

While particle degradation obviously occurs during compaction and that the environmental conditions change, there is little understanding of the weathering conditions that prevail within a pavement.

Generally some particle fragmentation is believed to occur during trafficking and that chemical weathering possibly continues once the pavement is sealed. However, while weathering of basecourse was believed to have been a factor in the failure of the Auckland Southern Motorway reported by Buckland (1967) and referred to in Fookes (1991), the evidence produced was not conclusive. Bartley's observations referred to in Section 3.3 of this report also indicated inconclusive evidence of degradation during trafficking.

Wu et al. (1999) state, in regard to aggregate used in asphaltic concrete, that:

> .....*a review of the literature and contacts with highway and transportation departments identified few if any performance problems related to aggregate degradation under in-service traffic loadings. Aggregate durability/soundness are occasionally directly related to pavement distress. Pop-outs, ravelling or potholes can develop in pavements if unsound or non-durable aggregate is used. Traffic certainly aggravates or accentuates these distresses, but they are primarily a manifestation of weathering.* (Note that the authors are referring to "weathering" as it relates to the weathered nature of the rock used, not to any change that may have occurred in the time the material has been in the pavement.)

Fookes (1991) on the other hand points out that the reliability of engineering materials used in the construction industry is too often taken for granted. He tabulates seventeen reported cases of deterioration of geological materials in a pavement, including two from New Zealand. Interestingly of the seventeen listed, fifteen involve rocks of volcanic origin, one is non-specific and only one (Auckland Southern Motorway) relates to a metamorphic rock (indurated argillite).

Wylde (1979) reports that the deterioration of crushed rock used in pavements is a significant problem in Australia. The aggregates with poor performance histories were predominantly basic volcanic and intrusive rocks. Granitic rocks were not a problem.

Little information supports a concern that aggregate is subject to change under trafficking. Fookes (1991) and Wylde (1979) give a number of examples of failures that primarily involve the release of swelling clay minerals from aggregate of volcanic origin. These could be explained by breakdown of the aggregate during the placing and compaction stages of construction rather than by any change that might have occurred subsequently.

3.5.2 Changes in Temperature and Water Content

Foley (2000) summarised information provided by other researchers to show, for instance, that in Rhode Island in the USA, the temperature and water content in a thick asphalt pavement, and up to 1m below subgrade level, varied quite widely from summer to winter. For example the temperature records showed:

- an annual (winter to summer) variation of 30°C at the surface;
- a variation of 23°C at subgrade level;
- a variation of 17°C at 1m below subgrade level; and
- maximum temperature at the surface was 29°C at which time the temperature at depth was 19°C.

Data for water content showed:

- an annual variation in the asphalt of 8%;
- variation of 7% at subgrade level; and
- variation of 2.5% at 1m below subgrade level.

The data also showed that in February and March (northern winter) the water content was uniformly high over the full depth of the pavement, and that by August (northern summer) it was at its lowest. However in August the water content in the subgrade was still near the maximum.

These results could represent the conditions in similar pavements in similar climate circumstances anywhere in the world. However, the only data available for New Zealand pavements relates to surface temperature.

3.5.3 Changes in Stress

The very high stresses imposed during the winning, processing, placing and compaction of the aggregate are the most severe mechanical processes likely to be imposed throughout the life of the pavement. They cause significant degradation of particles and an increase in the volume of fines. Fragmentation of some rocks will also result in the release of clay minerals.

The removal of overburden and the processes of blasting and crushing weaken the structure of the rock. Joints and shear planes tend to open and provide access for water to intrude. Screening, placing and compaction are all processes that abrade the rock particles, remove sharp corners and produce fines. As well compaction causes fragmentation and the release of fines.

Water contained within the pores and cracks in rock particles will freeze in low temperatures and cause fragmentation and the release of fines. This applies particularly to stockpiles of aggregate in very frosty regions.

The breakdown of particles into fragments, including very fine particles, is not in itself a major problem. The release of moisture-sensitive fines within an aggregate placed in a wet pavement environment could be expected to have a disastrous effect on strength and stability.

Stress changes in the pavement and within particles also occur during trafficking. The basecourse layer has to carry the applied stress (which is close to the usual tyre pressure of 750kPa) without significant strain. However, in situations near the surface and where the area of particle contact is small, the inter-particle stresses may be many times the tyre pressure. Particle fragmentation can occur at points of extreme stress resulting in a release of fine material.

3.5.4 Weathering Experiments

Wetting and drying, and hydrothermal alteration experiments were carried out by Professor Sameshima at Auckland University, New Zealand (Sameshima 1977). He used samples of aggregate from six greywacke quarries in the Auckland–Northland regions. The experiments were designed to simulate the type of weathering that could be expected in stockpiles and in the road environment.

Each complete cycle of wetting and drying took one hour and the samples were subjected to 1700 cycles. A month-long series of cycles produced no discernible disintegration of the rock chips. Similar samples were soaked in rainwater and/or distilled water, and placed in an incubator at 50°C for one month. The results were inconclusive.

In the hydrochemical experiments the samples were covered with distilled water, or rainwater, or dilute hydrochloric acid, and observed for 6 months. The results indicated a gradual increase in montmorillonite and kaolinite for all three solutions, although the magnitude of the increase varied from sample to sample. The formation of montmorillonite appeared to be controlled by chemical characteristics of the rock, and the pH and grain size.

These experiments, while being quite simple in arrangement, were relatively fleeting in terms of the natural weathering period. However, they showed that some greywacke aggregates could produce deleterious minerals at least while they are exposed in the stockpile. Whether the weathering conditions in the road are as severe as those used by Sameshima is not known.

3.5.5 Summary

Little is known about the weathering conditions within a pavement. Physical weathering leading to the fragmentation of particles occurs during construction and may continue to an unquantified degree after the pavement is put into service.

While significant changes in the applied stresses, water content, and temperature are quite likely to occur, no evidence shows that the conditions are severe enough to cause chemical weathering. In terms of natural weathering the period of exposure is nowhere near long enough.

3.6 Aggregate Quality Tests

3.6.1 Introduction

The literature studied contained references to a wide range of engineering tests used worldwide to determine the weathering quality of roading aggregate. As far as can be established they are all empirically based and aimed more at separating altered rock from fresh rock, rather than at providing an absolute guide to performance of a material in the pavement.

A summary of a commentary by Fookes (1991) on the significance of these tests is as follows:

- *Strength Tests:*

  Specific gravity and water absorption are both useful indicators of rock quality. Point Load Strength and Schmidt Hammer Rebound tests can be used to detect weathered and altered rocks. Tensile strength can be used to determine the sensitivity of a rock to degradation by crystallisation processes.

- *Hardness Tests:*
  Aggregate Impact and Aggregate Crushing tests indicate the durability under production, construction and in-service dynamic loads. The Ten Percent Fines test has replaced the Aggregate Crushing test in the UK.

  Failure in this test is due to flexural stressing at the ends of rock prisms, a mechanism comparable with the degradation process. In some cases the test should be performed under wet conditions to more closely reflect the in-service environment.

- *Freeze/Thaw Tests:*
  The Freeze/Thaw test measures the resistance of a rock to the cycle of crystallisation pressures set up during the freezing of water. It is more applicable to material with large pore spaces and to highly absorptive materials. The long time required to perform the test is a problem when it is required for quality control purposes.

- *Chemical Soundness Tests*
  The Magnesium Sulphate Soundness test is useful in distinguishing sound and unsound aggregates as it also gives an indication of the water absorption capability, tensile strength and resistance to freeze/thaw. The result is sensitive to particle size and shape and cannot be used with carbonated rocks because of the chemical reaction between the carbonate and the sulphate in the solution.

3.6.2 TNZ M/4 Requirements

The tests provided in TNZ M/4 Specification *Basecourse Aggregate* to assess the quality of the rock at source are the Crushing Resistance (CR), Weathering Quality Index (WQI), and California Bearing Ratio (CBR) tests. TNZ M/4 also has a set of product quality tests including the Clay Index (CI) Test as a measure of the quality of the fines.

The CR and WQI are used to assess the strength and durability of the parent rock in common with similar tests used overseas. It is a difficult to see how the CBR test contributes to those criteria as the test is sensitive to particle size distribution, compactive effort and water content. These are properties related to production and construction rather than to the characteristics of the source rock.

3.6.2.1 *Crushing Resistance*

The Crushing Resistance (NZS 4407:1991 Test 3.10), is the percentage of fines generated when a sample of 9.5 - 13.2mm size particles, placed to a depth of 100mm inside a 150mm diameter steel cylinder, is crushed using a 150mm diameter steel plunger. The load on the plunger is increased at a uniform rate to a maximum specified value over a period of 10 minutes. The crushed sample is then sieved on a 2.36mm sieve and the mass passing the sieve is expressed as a percentage of the total specimen. The test is repeated until the load that is required to generate 10% of material finer than 2.36mm is established.

The test used in TNZ M/4 is a modification of this standard test. For TNZ M/4 the applied load is fixed and the amount of fines produced from one application of the load is recorded. It requires that not more than 10% fines be generated by a load of 130kN. This modification is often referred to as the Ten Percent Fines Value.

3.6.2.2 *Weathering Quality Index Test*

Transit New Zealand adopted WQI (NZS 4407:1991 Test 3.11) as the measure of the weathering characteristics of rock used in basecourse aggregate. The Index is based on the results of a wetting and drying test and the Cleanness Value for Coarse Aggregate (NZS 4407:1991 Test 3.9).

WQI is determined on a sample of crushed rock all passing 19mm and comprising 2kg of material retained on the 9.5mm sieve, and 3kg of material retained on the 4.75mm sieve.

The sample is placed on a 350mm square tray, covered with water and allowed to soak for approximately 18 hours. The water is then drained off and the tray is placed in a drying oven for 4 hours after which it is cooled for one hour. A 75mm diameter steel roller weighing 6kg is then used to roll the aggregate for 100 cycles. The whole process of wetting, drying and rolling is repeated ten times using the same water each time. The sample is then boiled for 1 hour, allowed to cool before being agitated 50 times, and finally sieved over a 4.75mm sieve. The material and liquid passing the 4.75mm sieve is then sieved on a 75 micron sieve. The slurry passing the 75 micron sieve is poured into a Sand Equivalent (SE) measuring cylinder to give a liquid depth of 400mm and allowed to settle for 20 minutes. The depth of sediment determines the Cleanness Value, so that a depth of 0mm gives a value of 100, and a depth of 400mm gives a value of zero.

The weight of material retained on the 4.75mm sieve is expressed as a percentage of the 5kg sample used in the test. The WQI is determined in reference to a chart provided with the test method. A summary of the values is given in Table 2.

Table 2 Weathering Quality Index values.

Cleanness Value	Percent Retained on 4.75 sieve	Weathering Quality Index
100 – 90	100 – 95	AA
	95 – 90	BA
	90 – 60	CA
90 – 70	100 - 95	AB
	95 – 90	BB
	90 – 60	CB
70 – 50	100 – 95	AC
	95 – 90	BC
	90 – 60	CC

TNZ M/4 states that basecourse has to be manufactured from rock that has a WQI of AA, AB, AC, BA, BB or CA (Table 2).

The WQI was first included in TNZ M/4 in 1973 at the same time that the Los Angeles Abrasion test was replaced by the CR Test. Note that none of these tests have been calibrated to the performance of an aggregate in the road. Rather they have been devised as approximate, albeit conservative, models of the weathering conditions believed to occur in the road. In fact, the WQI test was devised to reject material known to break down in the stockpile of concrete aggregate on a North Island hydro-electric dam site. However, the test does model processes used during the manufacture of aggregate and the construction of a road, and rocks with excessively high concentrations of swelling clay minerals are likely to break down during the test. To that extent the test tends to reject all but the best quality aggregates.

3.6.2.3 *Clay Index Test*

The plasticity of a roading aggregate is an important aspect. Originally TNZ M/4 relied on the Atterburg Limit test with the PI limited to a maximum of 5%. Problems with laboratory aspects of this test resulted in it being replaced by the Sand Equivalent (SE) test. Some useful aggregates could not meet the SE value of 40 (minimum) required by TNZ M/4 and a provision was adopted that allowed the fines to meet one of the following three tests, Atterburg Limits, Sand Equivalent, and Clay Index.

The Clay Index (CI) test uses methylene blue dye as an indicator. Overseas this test is called the Methylene Blue Absorption test. TNZ M/4 specifies that the material passing the 75 micron sieve must have CI value not greater than 3.

Sameshima (1977) suggested an empirical relationship between CI values and pavement performance. Pavements constructed using a basecourse with a CI value not greater than 3 were stable, while those for which the CI value was greater than 3 were potentially unstable.

The NZS 4407:Test 3.5 provides for the test to be carried out on naturally occurring fines or on fines crushed from clean rock. In both instances a sample all passing 75 microns is boiled in a solution of hydrogen peroxide and sulphuric acid for five minutes. This solution is then titrated with methylene blue solution. A drop of the clay solution, extracted as each 1ml of dye is added, is transferred to filter paper using a glass rod. The formation of a light blue halo around the blue centre of dyed clay marks the end point of the titration.

3.7 Summary

The following summarises the important aspects identified during the literature review.

- Weathering is a chemical or physical change or a combination of both.
- Weathering occurs when the rock is placed in an environment different to that pertaining at the time the rock was formed.

- Swelling clay minerals are contained within the rock mass and may be released during mechanical weathering, or are produced as a result of chemical weathering.
- Modification of an aggregate with a chemical additive, such as lime, changes the chemistry of the environment and promotes the formation of new minerals and inter-particle bonds.
- Modified aggregate should not deteriorate significantly, provided the pavement environment is not chemically aggressive.
- The potential for chemical weathering within a pavement is not known but is believed to be insignificant once the pavement has been sealed.
- The use of established aggregate quality tests, such as those quoted in the TNZ M/4 Specification, should provide a more than adequate guide to performance. However, no known relationship exists between these tests and pavement performance.
- Material that does not meet TNZ M/4 after modification may still provide an adequate level of service.
- The Clay Index Test provides a good measure of the swelling clay mineral content in an aggregate.

Overall, a need remains for a better understanding of the various factors that influence the weathering of aggregate, and the effect they have on particular types of rock. Further research is necessary including:

- An investigation of the environmental conditions within the pavement, and
- A study of the changes that could occur to the chemistry of the minerals, the likely products, and the time required for significant changes to occur.

4. Laboratory Study

4.1 Introduction

This project was designed to compare the weathering properties of marginal roading aggregate before and after modification. The intention was to establish whether or not the Weathering Quality Index is a suitable test for modified aggregates. In addition the Clay Index values were used to quantify changes in the swelling clay content.

Aggregates from five different quarries in Auckland – Northland regions were tested, and a brief description of each material is set out in Table 3.

Samples of aggregate were obtained from:

- three roading projects being carried out in the Rodney District;
- one sample from a stockpile of aggregate stored in the Drury Quarry; and
- one sample was taken from a stockpile of GAP40 aggregate from Omaha Quarry.

All the samples were modified with lime, but similar material was also treated with KOBM (lime-rich steel mill waste) and cement, or with Durabind, a proprietary product manufactured from KOBM.

Table 3 Description of marginal aggregates used for laboratory study.

Quarry	Rock Type	Roading Project	Sample from
Mt Braine	Basaltic Andesite	Wharf Street	Behind hoe
Flat Top	Basaltic Andesite	Lonely Track Road	Behind hoe
Waitakere	Andesite	Taupaki Road	Behind hoe
Drury	Greywacke	SH22 Wesley Bends	Quarry stockpile
Omaha	Greywacke	Not Applicable	Quarry stockpile

While the objective of this project was to examine weathering properties of aggregate and the tests required to measure such properties, all the aggregates tested have been used previously on the region's roads in their modified form and have performed quite satisfactorily for a number of years.

4.2 Test Programme

4.2.1 Untreated Aggregate (A Samples)

The Weathering Quality Index and the Clay Index were determined for samples of untreated aggregate. These tests were used to establish the durability and plasticity in terms of TNZ M/4 Specification. They were also used to compare the changes that occurred after the aggregate had been modified and compacted. These samples were referenced "A" samples.

Two of the samples were taken direct from quarry stockpiles, and the Mount Brame, Flat Top and Waitakere aggregates were sampled after they had been spread on the road, compacted and hoed. These samples would be expected to have higher CI values than those taken from the quarry stockpiles.

4.2.2 Modified Aggregate (B Samples)

4.2.2.1 *In-situ Stabilisation*

Samples of modified aggregate treated in-situ, were obtained from three roading projects located in the Rodney District. On these projects the aggregate was spread on an existing road, then shaped and rolled to form the basecourse layer. The lime or other additive was spread, water was added, and the layer hoed to mix in the additive and water. The layer was then compacted. The concentration of additive was varied as considered appropriate for the particular aggregate. One sample of each material was collected after the modified aggregate had been hoed, watered and compacted. Each of these samples, referenced "B", was subsequently delivered to the laboratory.

The three rock types sampled were originally sourced from the Flat Top, Waitakere and Mt Brame quarries. The first two were treated with 1% lime, while the third had 1.5% lime added.

4.2.2.2 *Laboratory Mixed Aggregate*

The B samples of modified Drury WSS65 Greywacke and Omaha GAP40 Greywacke were manufactured in the laboratory. To prepare these, a sample of aggregate obtained from the quarry stockpile, was crushed in the laboratory crusher to replicate the stabilisation process, after which lime and water were added and mixed into the sample. The sample was then bagged and cured for 28 days. This sample also differs from those described in Section 4.2.2.1 in that it was not compacted after stabilisation.

The rock types treated using this method were greywacke rocks sourced from the Drury and Omaha quarries. Both samples were treated initially with 1% lime.

4.2.3 Modified Aggregate (C Samples)

A second sample of modified aggregate was collected from each source (or manufactured in the case of the Drury and Omaha samples) and referenced "C" for testing in the laboratory.

4.2.4 Other Modifying Additives (D Samples)

Two other types of additive were used on the Rodney District road projects. At Wharf Street, where the aggregate from Mt Brame was used, a section of the road was treated with KOBM (5%) and cement (1%). Similarly at Lonely Track Road, where aggregate from Flat Top Quarry was used, and at Taupaki Road where aggregate from the Waitakere Quarry was used, a section of each of these roads was treated with Durabind (3%).

In the case of the Omaha sample, the Durabind (4%) was added in the laboratory. These samples which had been treated generally, as described in Section 4.2.2, were referenced "D".

4.3 Laboratory Tests

The test programme was primarily designed to identify changes that were expected to occur in the Weathering Quality Index due to modification and later breakdown of the aggregate. The Clay Index test was used to monitor changes in the concentration of swelling clay minerals.

The test programme was as follows:

1. Untreated A samples were tested on return to the laboratory.
2. Each modified B sample was split into two sub-samples, referenced B_1 and B_2.
   Samples B_1 were tested following a 28-day maturing period.
   Samples B_2 were passed through a laboratory crusher to generate some breakdown and then cured for 28 days.
3. An extra 1% lime was added to each C sample on its return to the laboratory to provide a surplus to modify any swelling clay minerals present. Each sample was then split into two sub-samples, referenced C_1 and C_2.
   Samples C_1 were tested after a 28-day maturing period.
   Samples C_2 were passed through a laboratory crusher to generate some breakdown and then cured for 28 days.
4. D samples modified with other additives were treated in a manner similar to the B samples.

Note that the choice of laboratory crushing process to replicate breakdown during stabilisation was quite arbitrary, being based on convenience and availability. The change in grading was not recorded. Table 4 provides a summary of the results of the test programme.

4.4 Discussion of Results

4.4.1 Percentage retained on 4.75mm Sieve

Little change was recorded in the percentage retained on the 4.75mm sieve for each type of treatment. This result is determined primarily by the properties of the rock and is not greatly influenced by the modification process. The small variation that does occur may have more to do with repeatablity of the test than with actual changes in the sample.

4.4.2 Cleanness Value

The changes that occur in the Cleanness Value (CV) reflect the concentration of fine particles in the sample. A CV of 0 indicates that the fine material completely fills the measuring cylinder used in the test, while a value of 100 indicates little or no sediment settled out in a period of 20 minutes.

Table 4 Laboratory test results.

Quarry	Test	Samples						
		A	B_1	B_2	C_1	C_2	D_1	D_2
Mt Brame	% retained 4.75mm	83	86	83	84	83	84	84
	CV	57	63	58	63	56	60	64
	WQI	CC	CC	CC	CC	CC	CC	CC
	CI	4.9	3.2	3.2	2.2	2.2	1.6	1.4
Flat Top	% retained 4.75mm	90	90	90	91	90	91	89
	CV	3(1)	31	52	36	38	48	14
	WQI	CC	CC	CC	BC	CC	BC	CC
	CI	6.7	1.2	1.1	0.8	1.0	1.5	3.2
Waitakere	% retained 4.75mm	95	94	95	94	96	95	93
	CV	89	89	89	89	89	89	85
	WQI	BB	BB	BB	BB	AB	BB	BB
	CI	4.3	3.0	3.1	0.9	1.7	3.8	3.1
Drury(2)	% retained 4.75mm	97	97	97	97	97	97	96
	CV	93	98	98	95	95	85	80
	WQI	AA	AA	AA	AA	AA	AB	AB
	CI	2.7	0.6	0.6	0.3	0.3	0.9	0.9
Omaha(2)	% retained 4.75mm	94	93	95	93	93	93	94
	CV	85	75	77	63	72	77	71
	WQI	BB	BB	BB	BC	BB	BB	BB
	CI	5.4	3.2	3.5	1.8	1.7	3.7	3.4

(1) This Cleanness Value (CV) of 3 was confirmed by the laboratory. It is possible that the chemical relationship between the rock and the flocculent used in the test influenced the result.
(2) Unlike the other three samples, the B samples from Drury and Omaha were not crushed either in the field during compaction or in the laboratory.

A samples – untreated
B samples – treated with 1% lime — B_2 – re-crushed in laboratory
C samples – treated with an additional 1% lime — C_2 – re-crushed in laboratory
D samples – treated with other types of additive — D_2 – re-crushed in laboratory

It had been thought that significant agglomeration of particles would occur as a result of the modification process, and that the Cleanness Value would have increased to give a more favourable WQI. However any agglomeration that may have occurred has not been sufficient to change the CV.

The CV for Mt Brame samples is improved only marginally by the addition of lime, and KOBM + cement. The addition of 1% lime (i.e. C samples) made no difference but a slight decrease occurred to both the B_2 and C_2 samples when they were crushed, and the CV for the D_2 sample increased slightly. Generally the changes that occurred were small and not sufficient to make any improvement in the WQI.

The significant improvement in the CV for Flat Top aggregate was a result of the first lime modification, with a further improvement when the additional 1% was added. Durabind (D sample) had an even stronger effect. Crushing the lime-treated samples further improved the CV, but a significant decrease occurred when the Durabind sample was crushed. While the changes in CV were quite pronounced they were not sufficient to improve the WQI sufficiently to meet TNZ M/4 requirements. The decrease that occurred when the Durabind-treated sample was crushed is of concern.

Little or no change was recorded in the CV for the Waitakere aggregate, except for a slight decrease when the Durabind-treated sample was crushed. All the samples met TNZ M/4 WQI requirements.

The untreated Drury aggregate met TNZ M/4 WQI requirements and only a small improvement occurred when it was treated with lime. It showed a slight decrease in CV when the extra lime was added.

The CV of the Omaha sample was decreased by the addition of lime and Durabind. Crushing the samples actually improved the CV for the lime-treated samples but made it worse for the sample treated with Durabind.

These results show a range of responses to the modification process and little change for most of the aggregates. Therefore this test is unlikely to be sufficiently sensitive enough to be adopted as a durability test for marginal aggregates.

4.4.3 Weathering Quality Index

Little change was recorded in the WQI throughout the testing processes because only insignificant changes occurred in the Percentage retained on the 4.75mm sieve, and in the CV. The small improvements that were reported were mainly caused by a one percentage-point shift, e.g. 95% to 96%, of aggregate retained on the 4.75mm sieve. A decrease in the CV for the Omaha C_1 was sufficient to put it outside the TNZ M/4 requirement.

The Waitakere, Drury and Omaha aggregates have WQI values that meet TNZ M/4 basecourse specification requirements without the need of modification. The other two aggregates have values that place them well below those required for premium aggregate. In both cases the improvement from modification was not sufficient to change that situation.

Overall only small changes occurred in the WQI suggesting that the test is not sufficiently sensitive to changes that the CI showed was occurring in the aggregate.

4.4.4 Clay Index

The CI results exhibit the largest change reflecting the alteration of the swelling clay minerals at each stage of the process. All the aggregates show a significant decrease in CI value as a result of the addition of a stabiliser, regardless of stabiliser type (Figures 1 and 2).

Some, but not all, show an increase following crushing and others exhibit different levels of reaction to different stabilisers. Note that results within 0.1 or 0.2 of each other are within the range of accuracy of the test.

Figure 1 Effect of lime at different concentrations on CI value for the 5 aggregate types.

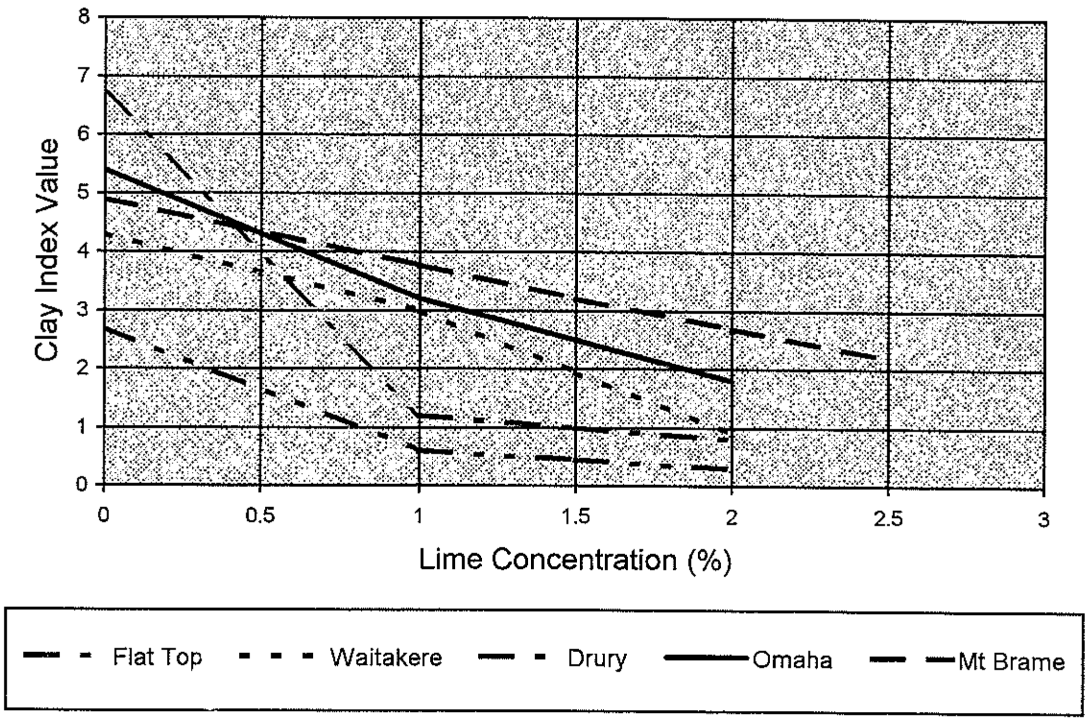
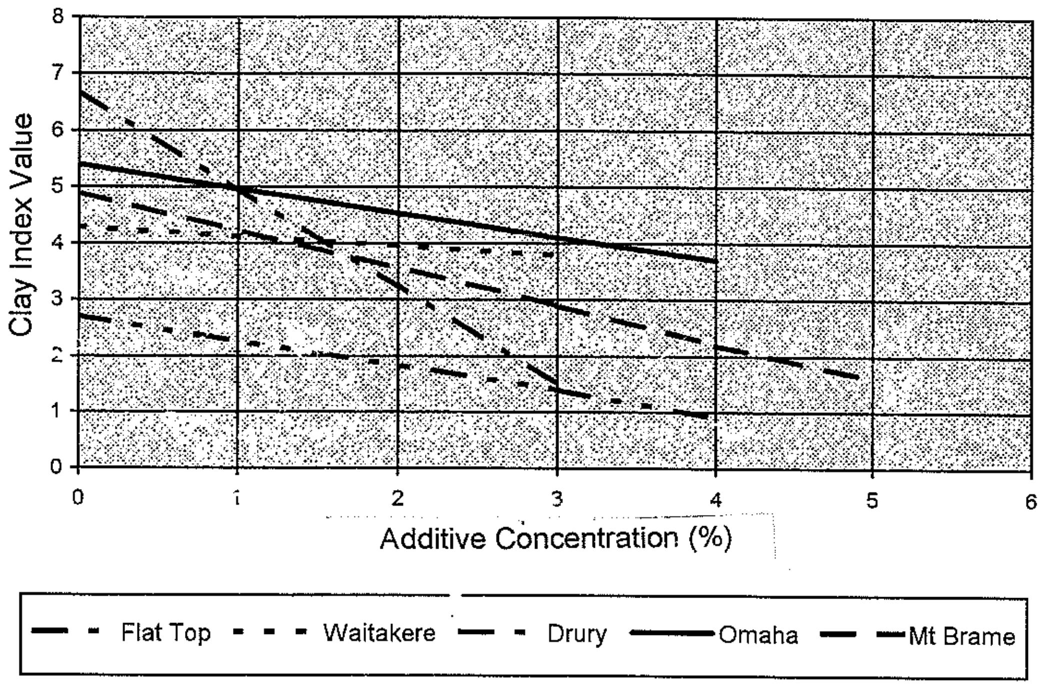


Figure 2 Effect of other additives at different concentrations on CI value for the 5 aggregate types.



A CI value of 3 is the upper limit specified in TNZ M/4 but it is known that some aggregates with higher CI values have performed satisfactorily for more than 15 years. The CI values using other additives (or binders) are shown in Figure 2. Note that the Mt Brame aggregate was treated with 5% KOBM plus 1% cement.

The increase in CI value following crushing indicates that swelling clay minerals were released as the larger pieces of rock were broken down. The apparent decrease where it has occurred following crushing is believed to reflect experimental error.

The CI value for the Mt Brame sample followed the expected pattern because the swelling clay mineral content was reduced by the addition of the binder. However, it did not change when each treated sample was crushed. This suggests that the swelling clays were concentrated in the original fines rather than being incorporated within the mineral structure of the rock. That is to say, the swelling clays were the alteration products of natural weathering of the basaltic andesite.

The lime-treated Flat Top sample showed a significant improvement over the untreated sample and was hardly changed at all by the crushing process. However, the sample treated with Durabind showed a substantial change. This suggests that the modification process for this aggregate using Durabind is different from that using lime.

5. Conclusions

5.1 Introduction

The laboratory study carried out during this project has provided useful information about the changes that occur when aggregate is treated with lime and similar stabilisers. It has also shown that the Weathering Quality Index test is not sufficiently sensitive to detect neither the changes caused by chemical modification of marginal aggregates, nor those caused by particle breakdown.

5.2 Literature Review

The literature review provided a guide to the process of weathering of roading aggregates. Important aspects that were noted included:

- Weathering is a chemical or physical change or a combination of both, that occurs when rock is placed in an environment different to that pertaining at the time it was formed. Swelling clay minerals may be contained within the structure of the rock and may be released when particle breakdown occurs, or they may be the product of chemical weathering.
- Modification of an aggregate with a chemical such as lime, changes the chemistry of the environment and promotes the formation of new minerals and inter-particle bonds. A modified roading aggregate should not weather unless the pavement environment becomes aggressive.
- The weathering potential within a pavement is not known but is believed to be relatively benign once the pavement is sealed.
- The use of established aggregate quality tests such as those quoted in TNZ M/4 specification provide a guide to performance, but a material that does not meet TNZ M/4 may, after modification, provide an adequate level of service.
- The Clay Index test provides a sensitive measure of the swelling clay mineral content in an aggregate.

5.3 Laboratory Study

5.3.1 Weathering Quality Index

It had been assumed that some significant agglomeration of particles would occur as a result of the modification process and that, as a result, the Cleanness Value would increase. However even though a substantial change occurred in some samples, this was not reflected in the WQI. Hence this study has shown that the WQI is not sufficiently sensitive to important changes that occur when an aggregate of marginal quality is modified with lime.

5.3.2 Clay Index Test

The literature review showed that an important product of weathering was the release of swelling clay minerals. Modification of aggregate with chemicals such as lime, changes the chemical environment and promotes the formation of more stable forms of the minerals within the aggregate. In particular, lime changes the swelling clay mineral to a more stable form by cation exchange, and also promotes the formation of chemical bonds.

The methylene blue dye used in the CI test is absorbed by the swelling clay minerals present in the aggregate, and therefore provides a measure of the quantity of such minerals present.

5.3.3 Conclusion

The results of the laboratory tests carried out during this project show that the CI test is sensitive to the changes that occur during modification with lime and similar chemicals, and also when the aggregate is crushed. The overall test procedure, i.e. monitoring the changes that occur with the CI test as the raw material is modified and then crushed, provides a good indication of how a particular aggregate would perform in the pavement. It can also be used to determine the type and quantity of chemical that should be used to control swelling clay minerals in marginal aggregates.

6. Recommendations

The following recommendations are based on the results of this research project:

- To use the Clay Index test as a measure of the swelling clay minerals that could be liberated from a rock of marginal quality both during the manufacture of the aggregate and during the construction of the pavement;
- Further research is required to:
  - more closely define the weathering conditions within a pavement;
  - identify the reactions that occur between the rock minerals and the chemicals used to modify marginal aggregate;
  - establish the weathering potential of the clay minerals formed during the modification process, particularly that within the pavement environment;
  - determine the relationship between the Clay Index value of an aggregate, and its ability to carry a range of traffic loadings.

7. Bibliography

ASTM. 1996. Test methods for wetting and drying compacted soil-cement mixtures. *ASTM D559-96.* American Society for Testing & Materials, Pennsylvania, USA.

Bjarnason, G., Petursson, P., Erlingsson, S. 2000. Aggregates resistance to fragmentation, weathering and abrasion. *Unbound Aggregates in Road Construction 5th UNBAR Conference: 3-11.*

Bartley, F.G. 1981. Test sections at Quarry Road. *National Roads Board, Road Research Unit Project BC 16B.*

Bartley, F.G. 1984. Test sections at Quarry Road. *National Roads Board, Road Research Unit Project BC 16C.*

Boumezbeur, A., Ramsay, D.M. 1998. Rock strength: the interrelationship between strength indices from crushed rock aggregate and intact rock. *Quarry Management 25(7):* 41-45.

Brice, S.J. 1988. Some aspects of the use of products of rock weathering as road materials in Western Australia. *Proceedings of 26th ARRB Regional Symposium:* 13-22.

Buckland, A.H. 1967. The degradation of roading aggregate. *Proceedings of New Zealand Roading Symposium 2:* 692-715.

Buckle, L.J., Netterberg, F., Oberholster, R.E. 1987. Some chemical aspects of road building materials. *Proceedings of the Annual Transportation Convention 4A:* IV1-VI42.

Cawsey, D.C., Massey, S.W. 1988. In-service deterioration of bituminous highway wearing courses due to moisture-susceptible aggregates. *Engineering Geology 26:* 89-99.

Davidson, W.H. 1972. The influence of constitution on the engineering properties of crushed volcanic breccias. *Proceedings of 6th Australian Road Research Board Conference 6(5):* 71-90.

Foley, G. 2000. Effect of design, construction and environmental factors for long-term performance of stabilised materials *ARRB Transport Report RC91022 (1 Draft).*

Fookes, P.G., Gourley, C.S., Ohikere, C. 1988. Rock weathering in engineering time. *Quarterly Journal of Engineering Geology 21:* 33-57.

Fookes, P.G. 1991. Geomaterials. *Geological Society Quarterly Journal of Engineering Geology 24(01):* 3-15.

Nunes, W.P., Ceratti, J.A., Arnold, G.P. 2000. Weathered basalts, alternative aggregates for thin pavement bases. *Unbound Aggregates in Road Construction 5th UNBAR Conference:* 117-124

Sameshima, T. 1977. Hydrothermal degradation of basecourse aggregate. *National Roads Board, Road Research Unit Project BC 21.*

Sameshima, T., Black, P.M. 1982. Stabilisation of aggregates with additives and their effects on fines. *National Roads Board, Road Research Unit Project BC 39.*

Sandy, M.J., Cole, W.F. 1982. The influence of the degree of weathering of hornfels on its physical properties and durability. *Proceedings 11th Australian Road Research Board Conference 11(3):* 80-89.

Standards Association of New Zealand (SANZ). 1991. Methods of sampling and testing road aggregates. *NZS 4407:1991.*
Test 3.5 The clay index.
Test 3.9 The cleanness value of coarse aggregate.
Test 3.10 The crushing resistance of coarse aggregate under a specific load.
Test 3.11 The weathering quality index of coarse aggregate.

Sueoka, T. 1988. Identification and classification of granitic residual soils using chemical weathering index. *Proceedings of Second International Conference on Geomechanics in Tropical Soils 1:* 55-61.

Transit New Zealand. 1984. Notes: Regional basecourse aggregates (Nelson addition). *TNZ M/5:1984 (Notes)*. Transit New Zealand, Wellington, New Zealand.

Transit New Zealand. 1986. Notes: Specification for sub-base aggregate. *TNZ M/3:1986 (Notes)*. Transit New Zealand, Wellington, New Zealand.

Transit New Zealand. 1995. Specification for basecourse aggregate. *TNZ M/4:1995.* Transit New Zealand, Wellington, New Zealand.

Transit New Zealand. 1999. Performance-based specification for structural design and construction of flexible unbound pavement. *TNZ B/3:1999.* Transit New Zealand, Wellington, New Zealand.

Transit New Zealand 1999. Draft notes for the evaluation of unbound road base and sub-base aggregates. *TNZ M/22 (Notes)*. Unpublished. Transit New Zealand, Wellington, New Zealand.

Weinert, H.H. 1984. Climate and durability of South African road aggregates. *Bulletin of the International Association of Engineering Geology 29:* 463-466.

Woodside, A.R., Woodward, W.D.H. 1989. Assessing basalt durability – rapid alternative techniques. *Unbound Aggregates in Roads 3rd UNBAR Conference:* 178-187.

Wu, Y., Parker, F., Kandhal, P.S. 1999. Evaluation of tests for toughness/abrasion resistance and durability/soundness of coarse aggregates. *American Society for Testing Materials Cement, Concrete and Aggregates 1999/06. 21(1):* 12-22.

Wylde, L.J. 1979. Marginal quality aggregates used in Australia. *ARRB Research Report No. 97.*