Draft : September 2009

GEOLOGIC INVENTORY OF

NORTH ISLAND AGGREGATE RESOURCES:

Influences on Engineering Materials Properties.

DRAFT

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Research funded by FRST Contracts UoAX 402 and 407 :
Mineral Wealth of North Island

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INTRODUCTION

Aggregates are a non-renewable resource. There is an increasing imperative in legislation to mine and use aggregate in a way that recognises this fact. The Resource Management Act 1991 requires us to develop and manage the natural and built environment in a sustainable manner. High quality aggregate resources are very limited and many have already been exhausted. Further, increasing fuel costs are inhibiting transport of aggregate from distant sources to place of consumption.

The roading industry is a significant consumer of aggregate, and currently places around 24 million tonnes[1] per year of high quality material on New Zealand's public and private networks and on industrial pavements as base and surfacing material. The concrete industry also consumes a significant quantity of New Zealand's aggregate production.

In New Zealand, while most aggregates are sourced from greywacke and volcanic rocks, a range of different rock types can be recognised within these two large groupings. Each rock type produces aggregate with a matrix of properties which are determined by the nature of its mineral and other constituents and how these are arranged and held within the rock. Quarry operators are restricted in what they can produce by the nature and properties of the resource available to them.

Although a quarry may exploit a single geological rock type, the engineering properties of the material may change markedly at various locations within the quarry. These changes may simply be the result of a greater level of weathering near the top of the quarry face, grain size or compositional variations within the rock itself, local crushing caused by shear and fault zones cutting the rock, or varying degrees of thermo-chemical (hydro-thermal) alteration. Aggregate producers harvesting river gravels or other unconsolidated deposits face other problems with their resource which may be heterogeneous in terms of the rock types it contains and which may also have a restricted size range.

Rocks are processed to produce aggregate that meets the specifications of the consumer / contractor. In the roading industry a suite of material property criteria – crushing resistance, plasticity and weathering resistance, and the potential to result in a dense aggregate (as estimated by particle size grading and California Bearing Ratio) provide confidence, based on precedent and empirical testing, that the pavement structure can achieve a density which is permanent for a particular traffic loading and that the pavement will not fail before the design life has been achieved. Aggregates for use as sealing chips or in the manufacture of concrete are assessed using additional material property criteria that predict the aggregate's durability and performance in service. Those portions of the quarry output that do not comply with any one of the suite of material property criteria are termed 'marginal' aggregates.

In the case of quarries producing aggregate from gravel deposits, the small (< 20mm) river pebbles and "pea metal" are also regarded as 'marginal' although they may otherwise meet all the materials criteria of high quality aggregates. Thus, quarries produce marginal as well as high performing aggregates. In some quarries, because of the nature of the resource, more marginal aggregates tend to dominate the output, and much of this portion has been traditionally deemed unusable or limited to lower grade improvement material within a pavement structure.

There is a tendency for over - specification of aggregate intended for use in secondary and rural roading projects. Processing of material to meet unnecessarily high specifications has

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[1] 2007 data

the effect of relegating a larger proportion of the aggregate produced by a quarry into the 'marginal' category. Setting specifications on aggregate to levels appropriate for their intended use would increase the amount of quarried material that can be used and preserve high quality materials for future projects where very high performance is required. Increased use of marginal aggregates produced by quarries close to the point of consumption would also reduce transport costs.

The Geological Inventory of Aggregate Resources project is intended to enhance the industry's awareness of the availability of materials used as aggregates and to provide a matrix of their source and other properties. Individual quarries are not identified. Instead the regional distribution of different types of aggregates being produced in New Zealand is presented together with a review of what is known of their properties and performance.

Thanks to the generosity of many quarry operators, a considerable amount of data on aggregate source and production properties has been amassed. However it is difficult to compare this data because of the variety of ways that the aggregate has been processed and the different testing methods used. In some instances the tests have not been undertaken according to either NZS 4407: 1991 Methods of Sampling and Testing Road Aggregates or NZS 3111: 1986 Methods of Test for Water and Aggregate for Concrete, but to meet a local body or individual contractor's specification.

Aggregate processing methodology can vary significantly from operator to operator and may determine some of the properties of the aggregate. Aggregate produced by simple scalping, crushing and screening, often using mobile equipment, will be a different product to that prepared by a multistage processing circuit that uses several crusher types. If the quarry operator is prepared to bear the cost, and accept a substantial wastage, a high quality aggregate can be produced from what is overall a relatively low quality material. Nevertheless clear, although sometimes subtle, differences in aggregate properties do exist and are characteristic of the type of rock resource from which they have been produced. Some of these resources may, because of the inherent properties of the material, be incapable of producing top quality, high performance material appropriate for use in highly trafficked roads with a high component of heavy commercial vehicles or as structural concrete but may be perfectly adequate for other infrastructure projects.

The focus of this inventory is currently on determining what the differences are and why there are differences between aggregates. Thus the report is written in a two-part format. The first part surveys the relevant physical properties of rocks and minerals to demonstrate how these relate to standard aggregate property tests specified for aggregates used in road construction and structural concrete, and discusses what information they provide about their performance. The second part describes the main types of aggregate currently being quarried in the North Island, their general locations as well as their geological and some engineering properties. It also includes artificial materials used as aggregate in the roading industry. This approach provides a simple framework that will need little modification when South Island aggregates are incorporated.

All the photos of quarries, thin-section microphotographs and scanning electron microscope images of aggregate surfaces included in this report are from North Island aggregates. In almost all cases the quarries that produced the samples are currently producing aggregate.

This document, currently in draft form, should be regarded as a "living document". The expectation is that it will be updated within two years. At that time, South Island aggregate resources will be included. Additional information regarding engineering properties will also need to be provided for North Island aggregates.

GLOSSARY OF GEOLOGICAL TERMS

Acronyms :

BP	before present
Ka	thousand years
Ma	million years

APXX	premium graded aggregate all passing XXmm test sieve
GAPXX	general aggregate all passing XXmm test sieve.

Geological Terms :

Petrology : General term for the study of rocks

Mineralogy : General term for the study of minerals

Tectonic : A general term that describes both the forces which cause movements and deform or build structures in the earth's crust and the products of structural deformation.

Terrane : A slice of the earth's crust or a tract of rocks with a distinctive geological history and character.

Igneous rocks : Rocks formed by crystallisation or solidification of a melt. Igneous rocks are classified on the chemistry of the melt (see section 5).

Sedimentary rocks :Sedimentary rocks are classified into three intergradational groups :

1. Clastic sediments composed of discrete clasts (ie fragments or grains) of materials derived from the erosion of other rocks. The clasts may be mineral grains (eg quartz and feldspar and if these are the dominant grains then the rock is called quartzo feldspathic or arkosic if it is feldspar-rich) or rock fragments (eg volcanic rocks – in which case the sediment is called volcanoclastic). Greywackes are an example of a clastic sedimentary rock.
2. Chemical sediments which have formed from the chemical precipitation of minerals from solutions such as sea water which have become oversaturated with certain elements. Cherts are chemical sediments formed by the precipitation of silica in deep marine environments; some limestones are chemical precipitates of calcite and other carbonates in shallow water marine environments.
3. Bioclastic or organic sediments composed largely from the accumulation of the remains of organisms. For example limestone shell-beds.

Induration : The process of hardening of sediments through compaction and cementation by mineral matter deposited from pore solutions. It does not require heat although the baking process will also obviously harden rocks. Rocks that are hardened by these processes are described as indurated. While the process of induration is similar to that of lithification, use of the term "indurated" implies that the rock is tough and strong.

Lithification : The process of converting an unconsolidated sediment into a sedimentary rock. Essentially it is the process of porosity destruction through compaction and cementation of the sand grains into a compact solid (ie rock) but it does not imply that the rock thus formed is hard or strong.

Diagenesis : This is the term that describes the chemical and physical changes that a sediment (or volcanic rock) undergoes during and after its lithification (or solidification) but it excludes surface alteration (weathering) and metamorphism (which requires higher temperatures). Diagenesis changes the rock's original mineralogy and texture and requires relatively low temperatures (less than 150°C) and pressures. Diagenesis is transitional in its high temperature range with metamorphism.

Metamorphism : The process by which pre-existing rocks are mineralogically, chemically and texturally changed in the solid state by heat and/or pressure and to a lesser extent by the introduction of fluids. The temperature range for metamorphism is from the lower limit of c. 150°C, where it is transitional with diagenesis / cementation / lithification, to the temperature at which the rock melts (usually in excess of 700°C but dependant on the rock chemistry) and metamorphic processes are transitional with igneous processes.

Weathering : This is the surface alteration of rock. Weathering can be either a physical /mechanical process – that is the rocks are physically broken down – or a chemical process. In the climatic conditions that prevail over most of the North Island, chemical weathering dominates. Chemical weathering is the process of chemical leaching, hydrating, oxidising and altering of minerals in a rock. The ultimate product of chemical weathering of rocks is a soil that is largely composed of clay minerals.

PART I :

Properties and physical engineering tests of materials used as aggregates

This section reviews some of the properties of the minerals that constitute the rocks and other materials that are the resources for the aggregates industry. It also describes how these minerals influence the properties and performance of aggregates.

The tests that are used to specify aggregates are also reviewed. This is intended to provide an understanding of what physical and chemical properties of the materials the tests are actually measuring and to promote some discussion and additional research to improve their usefulness for predicting aggregate performance.

The writer acknowledges the large amount of useful critical comment and the many suggestions that have been made by the industry group that steered the aggregate inventory project and the production of this report :
David Hutchison (Downer EDI Works)
Allan Tuck (Higgins Group)
Allen Browne (Hiway Stabilizers NZ Ltd)
Jason Lowe (Winstone Aggregates)
Jayden Ellis (Stevenson Laboratory Ltd)
Thorsten Frobel (Fulton Hogan).

However, all errors and flaws in the report are the full responsibility of the writer.

1. PHYSICAL PROPERTIES OF ROCKS AND MINERALS : A REVIEW

Physical strength is probably the most important requirement for any material that is to be used as an aggregate.

Rock strength, hardness, or degree of lithification are terms used loosely and interchangeably by geologists to indicate the cohesiveness and density of a rock. In engineering practice rock strength is expressed quantitatively as the unconfined compressive fracture strength of the rock in megaPascals or kiloNewtons/metre^2. In the aggregate industry rock strength is provided by the Crushing Resistance test and expressed either as the percentage of fines produced by a specified load (usually either 130 or 230 kN – **NZS 4407: 1991**, depending on the end-purpose of the aggregate) or the load which produces 10% fines (**NZS 3111: 1986**).

1.1 Physical Properties of Minerals

1.1.1 Hardness

Geologists use the Mohs scale of hardness which ranks, on a 1 to 10 scale, the ability of one mineral to abrade or scratch another. The Mohs scale indicates relative rather than absolute hardness or abrasiveness.

Absolute hardness can be measured using the mineral’s resistance to indentation under a steadily applied stress (indentation or microhardness). However, most common rock-forming minerals are anisotropic, that is their physical properties, such as hardness, vary with the orientation of the mineral. Most common rock-forming minerals are also solid solutions, that is they have variable chemical compositions (although within the constraints of the mineral formula) and thus their physical properties also vary with their chemical composition.

Vickers (indentation) microhardness is commonly used in materials sciences and metallurgy. Recent advances in nanotechnology are also providing hardness data from depth sensing nanoindentation (DSI) experiments. Both methods provide absolute hardness values specific to the crystal plane measured. The relationship between Mohs scratch hardness number and absolute hardness is shown in Figure 1.1. Diamond (Mohs hardness 10), not shown on the figure, is in absolute hardness terms three times harder than corundum (Mohs hardness 9) and almost eight times harder than quartz (Mohs hardness 7).

Only a few of the minerals in Mohs scratch hardness scale are rock-forming and relevant to a study of aggregates. These are calcite, quartz, and corundum (= emery) which is the major component of calcined bauxite). However, it seems reasonable to generalize the data available for orthoclase to represent the feldspar group as a whole, which includes plagioclase which is a major mineral component in volcanic rocks, and albite, a common metamorphic mineral in greywackes.

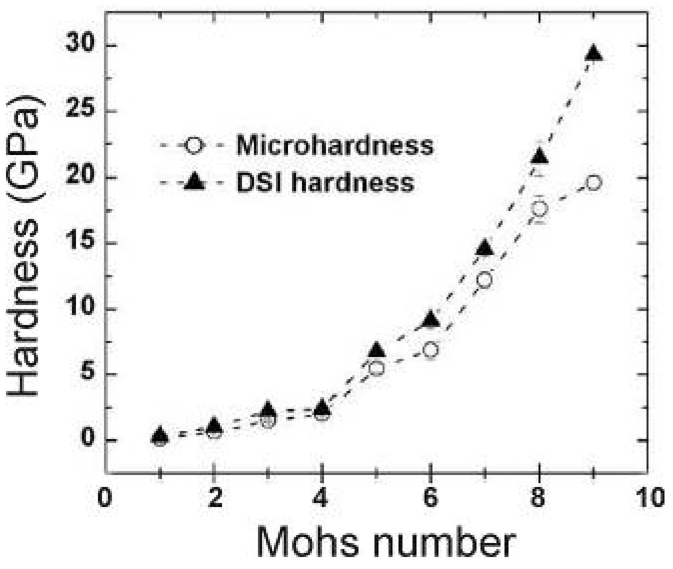

Figure 1.1 :

Relationship between Mohs number and absolute values of hardness as measured by the Vickers microhardness (indentation) and DSI methods.

Minerals representing the points on the Mohs scale are 1 = talc; 2 = gypsum; 3 = calcite; 4 = fluorite; 5 = apatite; 6 = orthoclase; 7 = quartz; 8 = topaz; 9 = corundum.

Figure from Bronz et al, (2006).

Vickers microhardness data measured at ambient and/or other temperatures exists for some other minerals that are major constituents of New Zealand aggregates. These data, shown in Table 1.1[2], demonstrate that in terms of absolute hardness quartz and olivine are 70% and 50% (respectively) harder than the hardest of the other common minerals (**Bronz et al, 2006**).

1.1.2 Mineral fracture behaviour and toughness

Mineral toughness is defined as a quantitative value that represents a mineral's resistance to fracture when subjected to high strain rate impact stress. Mineral toughness is different from mineral hardness.

Each mineral has a unique crystal structure with lattice planes which are held together by forces with variable strengths. Brittle minerals fail first along the planes of maximum weakness in the crystal structure (these planes are known as cleavages).

Geologists / mineralogists simply grade minerals with degrees of toughness as poor, fair, good, excellent, and exceptional. The fracture toughness of Mohs scale minerals has been measured by **Bronz, et al (2006)** but toughness data for common rock-forming minerals is very limited.

The available toughness data, relevant to aggregates are listed in Table 1.1 and for those minerals on which the Mohs hardness scale is based in Figure 1.2 where the nonlinear relationship between hardness and toughness is amply demonstrated.

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[2] Olivine with a composition very similar to that of olivine in basalts is listed in Evans and Goëtze, 1979. Data for diopside (a pyroxene very similar to augite) collected at 300°C (and 800°C) is from Dorner and Stöckhert, 2005; amphiboles of the type that occur in volcanic rocks, since they are structurally and chemically similar to diopside, could be expected to have similar hardness and toughness properties. Data for magnetite and spinels come from Wen and Liu, 1987, and Bhaduri and Bhaduri, 2002. Data for volcanic glasses from Ben Abdelounis et al, 2008.

Table 1.1: Summary of density, abrasion (Mohs) and indentation hardness, and toughness of minerals constituting materials used for aggregate production.

Mineral	Density	Mohs Hardness number	Vickers Hardness (in GPa)	Fracture properties	Toughness (in MPa /m^2)	Aggregate Occurrence
Corundum (emery)	4.0	9	19.6	No cleavage,	Excellent (2.38)	calcined bauxite
Spinel	3.6	7.5 - 8	12.7	No cleavages	Excellent (1.8)	melter slag
Quartz	2.65	7	12.2	Conchoidal fracture	Good (1.60)	greywacke
Olivine	3.3 – 3.6	7	10.3	Conchoidal fracture	good	basalt
K- feldspar Na- feldspar Ca-feldspar	2.56 2.62 2.73	6 – 6.5	6.9	Two sets of perfect to good cleavages	Poor (0.88)	basalt, dacite, andesite, and greywackes
Larnite and Ca$_2$SiO$_4$	3.3	6		One distinct cleavage	Poor to good	electric arc furnace slag
Magnetite	5.2	5.5 - 6	5.0	No cleavage	Excellent (1.42 ??)	basalt
Ilmenite	4.6 – 4.8	6		No cleavage	excellent	melter slag
Pyroxene	3.2 – 3.5	5 - 6	4.9 -est	Two sets of good cleavages	poor	basalt, andesite, and slags
Amphibole (hornblende)	3.0 – 3.4	5 - 6		Two sets of good cleavage	Poor – except when fibrous	Dacite, altered volcanics
Volcanic Glass	Variable 2.6 +/-	5.5	5.8 – 7.4	Conchoidal fracture	Poor to good (1.2 – 1.6)	Volcanic rocks
Laumontite	2.3	3.5 – 4.0		Two sets of cleavages; very brittle	poor	Some greywackes and altered volcanic rocks
Heulandite (other zeolites have similar properties)	2.2	3 – 3.5		Cleavage across length, very brittle	poor	Some greywackes and altered volcanic rocks
Calcite	2.7	3	1.5	Perfect cleavages	Poor to good	Greywackes, altered volcanics
Chlorite	2.6 – 3.4	2.5		Platy – perfect cleavage parallel to sheets	Poor to tough Flexible sheets	Greywackes, altered volcanics
Clay minerals		2 – 2.5		Platy – perfect cleavage parallel to sheets	Poor to tough Flexible sheets	Greywackes, altered / weathered rocks

Most silicate minerals will have toughness values less than 1.0 MPa/m^2. Oxides are much tougher than silicates and have toughness values slightly less than quartz. Notable is the toughness of volcanic glass, a noncrystalline isotropic substance (ie physical properties not affected by direction) comparable in toughness to quartz although its Mohs scratch hardness is only 5.5 (compared with 7 for quartz). Volcanic glass is physically the strongest phase in volcanic rocks but also chemically the weakest phase (see Section 7.1 p. 54).

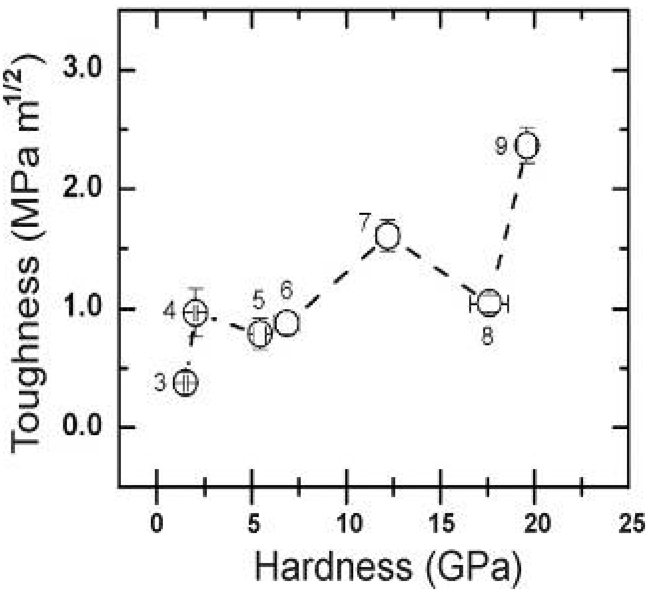


Figure 1.2 :

Graph showing the relationship between the absolute values of toughness and hardness. The numbers beside points indicate the Mohs numbers of minerals (given in Figure 1.1). The points (and minerals) that have relevance for rocks used as aggregates are : calcite (Mohs no 3); orthoclase (Mohs no 6); quartz (Mohs no 7) and corundum (Mohs no 9).

Diagram from Bronz et al (2006).

1.1.3 Summary

Mineral toughness is different from mineral hardness. Quartz is notably both harder and tougher than other common rock forming minerals.

Natural volcanic glass, although having Mohs hardness between 5 and 6 (depending on its composition) has brittle fracture properties similar to that of quartz and toughness values only slightly less than for quartz but notably higher than other silicate minerals in volcanic rocks. The layer silicates (clay minerals) are the softest and least competent components of rocks.

Most common volcanic rocks are composed of minerals with similar toughness and hardness properties but these values are considerably less than for quartz or glass.

Metasediments (ie greywackes) which contain quartz crystals as clastic grains and as a matrix / cementing mineral will always be harder and tougher than volcanic rocks.

1.2 Physical Properties of Rocks

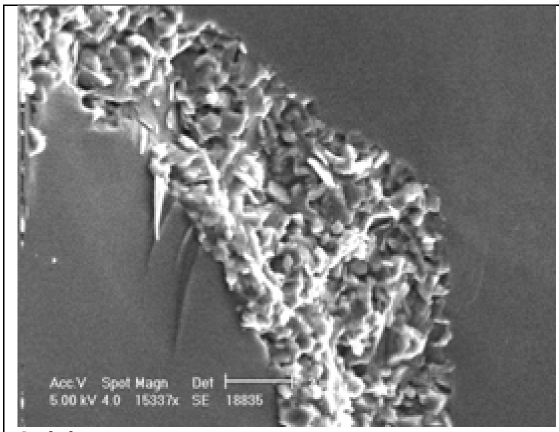
1.2.1 Rock Strength

There are a number of simple but universal materials principles that provide explanations for variations in rock strength. These relate largely to the surface area of grain to grain contacts as follows:

- The higher the surface area of grain to grain contacts the harder the rock .
- The surface area of irregularly shaped interlocking grains is greater than that of grains which either have good planar surfaces or are equidimensional
- Decreasing the size of mineral grains increases the surface area of grain contacts and rock hardness.
- Decreasing rock porosity increases the surface area and rock hardness.

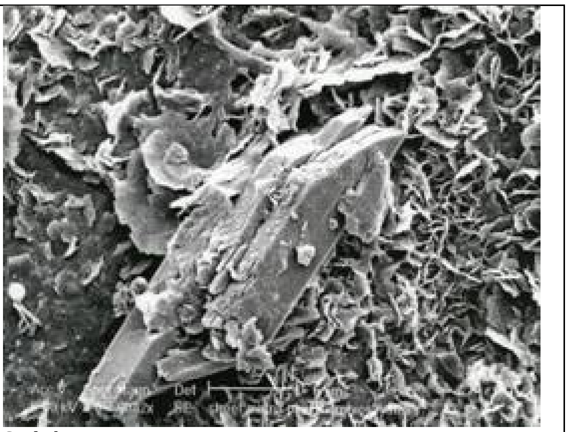
Rocks in which minerals are either segregated into layers or in which mineral grains have preferred orientation (foliation) will show pronounced direction-related variations in strength and will overall be less strong than those rocks that are equidimensional and unfoliated.

Induration of clastic sediments, such as greywacke sandstones, is caused by the compaction and consequent reduction in porosity of the rock and recrystallisation of its clayey matrix. In very weakly lithified sediments the matrix is held together largely by face to edge “bonding” (house of cards structure) of platy clay minerals and rock strength is low. New minerals, including grains of quartz and feldspar, grow in response to reactions caused by increasing temperature during progressive diagenesis and low grade metamorphism. These new minerals cement together “sand” grains and the clay-type minerals of the matrix. The photographs in Figures 1.3 (a) and (b) demonstrate the range in the nature and degree of cementation that can occur in greywackes and the importance of quartz and other minerals in “hardening” the rock.



Scale bar = 2μm

Figure 1.3 (a) – above: Scanning electron microscope image of strongly lithified greywacke sandstone showing a dense matte of granular quartz and feldspar, platy clays and other minerals which cement the matrix to the large detrital mineral grains.



Scale bar = 5μm

Figure 1.3 (b) – above: Scanning electron microscope image of weakly lithified sandstone (diagenetic alteration only) showing on right the typical “house of card” structures of clay minerals in the matrix and the weak support of the large mineral grain (centre).

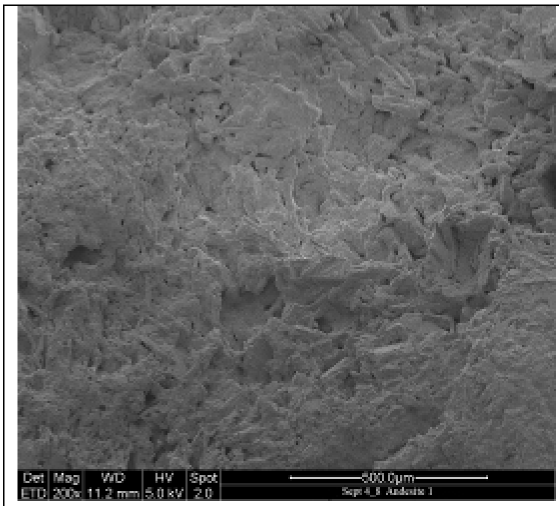


Figure 1.4 (a) – above: Scanning electron microscope image of surface of andesite showing abundant well formed feldspar crystals and rather porous overall texture.

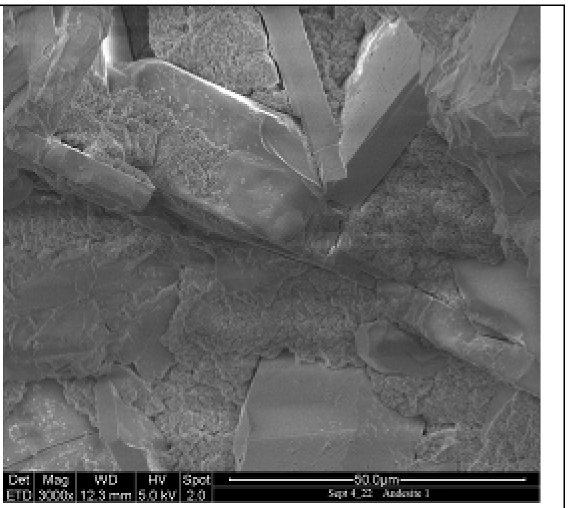


Figure 1.4 (b) – above: High resolution image of a more massive portion of the same andesite showing sharp straight faces of feldspar crystals in contact with slightly altered glass.

Igneous rocks are composed dominantly of feldspar and lesser amounts of pyroxene and/or amphibole and iron oxides. The toughness of these silicate minerals is rather similar and considerably less than of quartz. Oxides and volcanic glass both have higher toughness values than the silicate minerals but less than quartz.

Feldspar minerals in volcanic rocks form elongated grains which have good planar surfaces. Grains are often ‘glued’ together by volcanic glass. Feldspars always show sharp clean crystal faces against the glass which provide sites of structural weakness for failure to occur. The importance of feldspar to the fabric and strength of volcanic rocks is demonstrated by scanning electron microscope photos in Figures 1.4 (a) and (b).

1.2.2 Rock abrasiveness

The free silica content is often regarded as the indicator of the abrasiveness of the rock because quartz (SiO_2) is the hardest mineral in most common rocks. Other silica minerals, cristobalite and tridymite, which crystallise in silica-rich volcanic rocks, have lower Mohs and indentation (Vickers) hardness numbers. A simplistic approach sometimes used to determine abrasiveness is to determine the percentage of individual constituent minerals, assign Mohs hardness values and then compute the composite hardness (abrasiveness) of the rock.

1. 3 Summary

The most important factors controlling variations in strength between rock types are :

- mineral content - ie the physical properties of the individual minerals that constitute the rock and the proportion of those minerals in the rock;
- the size, shape and orientation of the various mineral grains;
- the mechanism of cementing, and the type of cement that binds together the grains in the rock; and
- the porosity of the rock.

Rock abrasiveness is a function of the hardness of the minerals it contains.

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2. CLAY MINERALS : PHYSICAL/CHEMICAL PROPERTIES

The term “clay” has a variety of different meanings. It can mean a material that is plastic, or a material that has grain size of less than 2µm[3] irrespective of its plasticity. The term also often carries with it the presumption that clay minerals (ie a particular group of layer silicates) will be the dominant constituent of the clay size fraction of a rock (or natural soil) although rock flour is also a common constituent of the < 2µm fraction. Clay minerals have a unique mineral structure and many unique properties. Clay minerals and clay particle size should not be confused.

2.1 Clay mineral structures

All common clay minerals are layer silicates. The individual molecular layers of clay minerals are constructed from two structural units - an octahedral sheet with formula either $Al_2(OH)_6$ or $Mg_3(OH)_6$, which is charge neutral, and a sheet of silicon ions surrounded by four oxygens $[Si_2O_5]^{2-}$, called the tetrahedral sheet, which has a negative charge. The octahedral and tetrahedral sheets are combined via substitutions of OH^- for O^{2+} on the joining plane in such a way that the final clay mineral molecule achieves overall charge neutrality. In the 2 : 1 layer silicates the directions of the tetrahedral sheets in the layer are opposed. Individual types of the clay minerals are classified according to the ratio of tetrahedral to octahedral sheets in the molecular layer (see Figure 2.1 and Table 2.1).

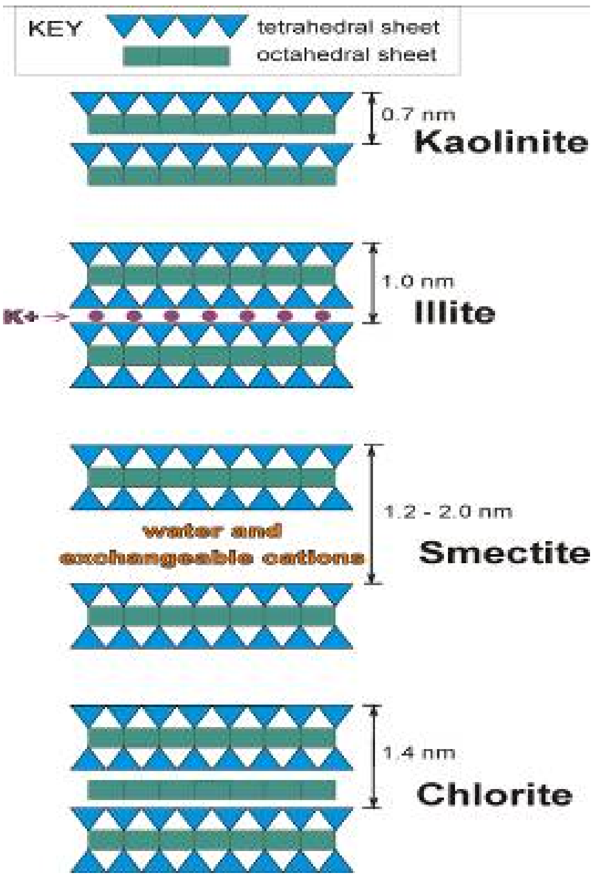

Figure 2.1 : Diagrammatic representation of the structures of common clay minerals.

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[3] Or less than 4 µm in some subdisciplines of Geology.

Clay mineral types differ in their chemical compositions and layer type, achieving charge neutrality with any one or more of the following chemical substitutions : Al^{3+} for Si^{4+} in the tetrahedral sheet, or trivalent ions (Fe^{3+} or Al^{3+}) for divalent (Fe^{2+} or Mg^{2+}) in the octahedral sheets and/or the addition of monovalent (K^+ or Na^+) or divalent (Mg^{2+} or Ca^{2+}) cations held between the layers. The interlayer cations may be held tightly (as in illite) or may be exchangeable (as in smectite).

2.2 Clay Mineral Properties

Clays, by virtue of their layer structure, have high specific surface areas but this and other physical properties, such as expansion and cation exchange (CEC) capabilities differ markedly between individual clay types. Table 2.1 (below) lists some of the important structural and physical properties of common clay mineral groups.

Table 2.1: Selected structural and physical properties of common clay minerals.

Clay Mineral Group	**Structure tetrahedral : octahedral ratio; swelling capacity; (layer thickness – air dried)**	**Interlayer condition / bonding**	**Swelling potential (and plasticity)**	**CEC [meq/100g]**	**Specific surface area [m^2/g]**
Kaolin	1 : 1 non-expanding (0.7 nm)	no interlayers, strong bonding	Almost none (plastic)	3 – 15	5 - 20
Illite (and micas)	2 : 1 non-expanding (1.0 nm)	partial loss of K = strong bonding	Low (mainly non plastic)[4]	10 - 40	50 - 100
Smectite	2 : 1 high expansion (1.0 – 2.0 nm)	very weak layer bonding	High/ very high (high plasticity)	80 – 150	700 - 800
Chlorite	2 : 1 : 1 non-expanding (1.4 nm)	moderate to strong bonding	Very low (non plastic)	10 - 40	< 80

The individual clay mineral molecular layers are stacked on top of each other (rather like the pages in a book) to form a thin plate-like mineral. Few clay minerals achieve anything other than small particle sizes, concentrating in the < 2 micron size fraction of rocks. Because the overall similarity of the horizontal dimension, as distinct from the thickness of the clay molecular layer, in weathering and sedimentary environments clay minerals are frequently mixed-layer crystals (eg smectite – illite or chlorite – illite). Two layer silicate groups (chlorites and micas) have a relatively large stability field and are the common minerals in many metamorphic rocks.

2.2.1 Mechanical / Deformation Properties

The strong layer structure of the clay mineral molecular units and the rather weak bonding between the molecular layers lead to very strong anisotropy in their physical properties and impart some unique physical properties to the clay and other layer silicate minerals. The molecular layers of these minerals are flexible and in the mica-type minerals are elastic.

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[4] Very fine-grained mica may be plastic – see Section 4.8.2, p.32.

While most other common rock-forming minerals are brittle the layer silicates deform as plastic (ductile) materials since relatively small shear stresses cause the individual molecular layers to glide /slip over each other, regardless of the orientation of the compressional axes. This property is also largely responsible for the plasticity characteristic of the layer silicates (see Section 2.2.6, p.14).

2.2.2 Expansion

Kaolinite, hydrous micas (illites), and chlorites are non-expanding; smectites[5] are expanding.

In kaolinite, when the layers are stacked on top of each other, the hydrogen ions of the hydroxyls in the octahedral sheet are attracted to the positively charged oxygens in the tetrahedral sheet, thus effectively tightly binding the individual molecular layers together. The relatively strong interlayer bonding of illite (hydrous mica) is mostly due to K^+ ions in the interlayer which neutralise the reduction in charge in the tetrahedral sheet due to substitution of Al^{3+} for Si^{4+}. Chlorite has a basic 2 : 1 layer structure similar to that of mica but instead of interlayer cations contains an additional stable, positively charged octahedral sheet in the interlayer space that neutralises the negative charge of the 2 : 1 sheets and inhibits expansion.

In smectites the force of the bonding between cations and the layers is not strong and depends on the amount of water present. The main expansion mechanism is localised on the sheet layer surfaces. In air-dried smectites the interlayer bonding force is relatively strong. However when water saturated, water is drawn into the interlayer space causing the clay to swell dramatically. The expansion is usually stepped, each increase being equivalent to the addition of a monolayer of water. The monolayer thickness ranges from 0.2 to about 0.3nm depending on the exchangeable cation. Individual molecular layers of the smectite minerals vary from 1.2 to 2.0 nm in thickness depending on the nature of the interlayer cation and its hydration state.

2.2.3 Specific Surface Area

The smaller the size of a fragment, the greater the ratio of its surface to volume (ie specific surface area). Clay minerals are always very small and have a thin platy shape and thus inherently have very high specific surface areas. The specific surface areas of kaolinite, illite and chlorites are low because they are non expanding. Smectites have very high surface areas because in addition to the outer surface of the mineral flake, the individual molecular layers are sufficiently distant from each other to expose the internal interplate surfaces thus very greatly increasing the surface area available for reactions and on which adsorbed water and ions can be accommodated. Many studies of soils have demonstrated the relationship between water absorption and surface area. Compared with the specific surface areas of clays (listed in Table 2.1) coarse sand has a specific surface area of about 0.01 m^2 /g, fine sand 0.1 m^2/g, and silt 0.1 - 1 m^2/g (**White, 1987**).

2.2.4 Cation Exchange Capacity

Cation exchange capacities (CEC) vary within and between the clay mineral groups. Kaolinites, illites, and chlorites have relatively low CECs while smectite has very high values.

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[5] Montmorillonite, which is often used in engineering practice as an example of swelling clay, is a species of smectite.

There are two mechanisms, both associated with the negative charges on the surfaces of silicate clays, which determine the CEC. The first involves unsatisfied valences at the broken edges of layers and the second is associated with the flat external surfaces of the mineral plate. Both these surfaces have some exposed oxygen and hydroxyl groups, all of which act as negatively charged sites which are balanced by cations adsorbed onto surfaces. The broken edges account for most of the charge of the 1 : 1 type (kaolin) minerals and up to 25% of that for 2 : 1 type minerals (specifically the hydrous mica-type and chlorites).

The cation exchange capacity of expanding 2 : 1 type clays such as smectite originates mainly from ionic substitution within the central octahedral sheet of the molecular layer. These internal negatively charged sites, sandwiched between the two tetrahedral sheets, are remote from the interlayer positions but constitute a permanent charge which is balanced by very loosely held hydrated interlayer cations.

2.2.5 Nature of exchangeable cations

In nature, H^+, Na^+, Ca^{2+} and Mg^{2+} are the exchangeable cations most commonly found in smectites but little is known of the nature of the exchangeable cations in New Zealand rocks used as aggregate. Direct chemical and X-ray diffraction methods (using the dimension of the basal layer spacing) suggest that the exchangeable cations in greywacke are dominantly Ca and Mg (**Sameshima, 1977**). A limited investigation based only on basal layer spacings has indicated that some altered volcanic rocks contain Na as the dominant exchangeable cation (**Bartley et al, 2007**).

The exchangeable cation has a major effect on the swelling capacity and some plastic properties of the smectite. Air dried Na-smectite has a single water layer while Ca and Mg exchanged smectites have two water layers, but at high humidities (and in wet samples) Na-smectite absorbs larger amounts of water than do the Ca-exchanged smectites (both expanding to have four water layers, ie from one for Na and two for Ca). Absorption of water ceases at approximately the liquid limit for Ca-smectites. However, when Na is the exchangeable cation water absorption continues beyond the liquid limit and if the smectite has a very fine particle size it may completely dissociate into molecular units.

All things being equal the higher the valency and/or the larger the size of the cation the greater its replacing power and the more difficult it is to replace. Ca^{2+} and Na^+ are larger than the other common exchangeable ions (magnesium, aluminium and hydrogen). Thus while Ca^{2+} and Na^+ have similar sizes, Ca^{2+} will more easily replace Na^+ than *visa versa*, but the order of replaceability is affected by concentration, the nature of anions, and pH.

The ease with which calcium exchanges into a clay system and the consequent mitigation of many of the undesirable properties of other clay minerals (swelling, plasticity etc) is the basis of lime stabilisation of aggregates. When the lime medium is Portland cement there is also a longer term cementing process during which new mineral phases grow to physically cement the particles together.

2.2.6 Plasticity

The layer silicates have plasticity because their individual molecular layers have the capacity to slip over each other. The kaolin and smectite minerals are plastic while the layer silicates which have closely bound molecular layers (illite / micas and chlorite) have limited or no plasticity.

However, plasticity is greatly affected by the grain size, how the minerals are aggregated together, and chemical factors.[6] Some very fine-grained illites can have plasticity intermediate between that of kaolin and smectite and some macro-grained (ie sand-sized grains) of detrital chlorite and mica can become plastic when the large crystals are ground into small particles.

2.2.7 Water content and water absorption capacity

The common clay minerals are all hydrous and contain a considerable amount of water that can be driven off (and largely resorbed) by oven drying at 110°C. Kaolin minerals when oven dried loose 13 – 15 weight percent of water and chlorites 10 – 14 weight percent. Illites are much less hydrous containing only 5 to 6 weight percent water.[7] While these minerals tend to dehydrate in a continuous fashion up to 110°C the minerals of the smectite group have a very high and very variable water content which is lost in a stepped fashion and can be resorbed completely on cooling.

2.2.8 Flocculation and dispersion

Flocculation is the process by which individual particles of clay are coagulated to form aggregates. The degree and permanence of flocculation depends on the nature of the ions present. Dispersion is the process by which the individual clay particles are kept separate from one another. Calcium (and hydrogen) ions cause flocculation, while potassium and sodium ions keep the clay minerals dispersed. Thus, depending upon the cations saturating pore waters or exchanged into the clay mineral structure the clay may be either in a flocculated (aggregated) or a dispersed state. Low pH favours a flocculated structure while a high pH and a high percentage of monvalent cations favours a dispersed structure.

Clays in the dispersed state in high moisture / water logged environments (soils and granular materials) become distributed through all the pores in the material clogging them up and converting the material into a massive (unworkable) state.

2.3 Clay Formation and Clay Mineral Occurrence in Rocks

2.3.1 Clay Minerals in the Weathering Environment

Rocks in the weathering environment are chemically and physically changed by the weathering process. They are physically broken down, elements are leached from the minerals in the rock by weak acid solutions[8]. Minerals are hydrated and new minerals are precipitated in the rock.

The most soluble elements in rocks are alkalies (sodium and potassium) and calcium which are all readily dissolved out of minerals and carried away by ground and surface waters. Among the first weathering products of many common rocks are the smectite clay minerals (hydrated iron – magnesium aluminium silicates). Continued weathering also removes iron and magnesium leaving only the least soluble elements in the rock (aluminium and silica). Thus prolonged weathering / leaching, produces kaolin group clay minerals irrespective of the parent rock type. However even kaolinites will ultimately decompose, the silica released from

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[6] Chemistry in this context refers to the elements within the sheets forming the molecular layers and not the elements in the interlayer (exchangeable) positions.

[7] Newman, 1997, Chapter 5.

[8] Carbon dioxide is soluble in water and forms the weak acid solutions that leach rocks.

it is carried away in ground and surface waters, and the aluminium transforms to hydrous oxides, usually gibbsite [$Al(OH)_3$].[9] These minerals tend to persist as the final products of long and intense silicate mineral weathering.

The stages of weathering are time-related functions, whereas the rate of weathering depends primarily on the climatic factors (temperature, precipitation). Silicate mineral weathering and clay synthesis are limited under either dry or cold conditions, but they proceed rapidly under hot, wet conditions, as in tropical regions. The time span required for a full weathering cycle is several tens of thousands of years.

2.3.2 Clays in clastic sediments (greywackes).

Clay minerals are transported together with other weathering products and deposited to form sediments. Kaolin, however, is unstable in the marine environment and converts to those clay minerals that are stable – mainly illites and smectites. Smectites can precipitate directly from solutions rich in silica and magnesium and also commonly form from the alteration of detritial fragments containing volcanic glass. The clays form flocks and house of card structures which collapse under the overlying sediment load and transform with increasing temperature and pressure into nonexpanding minerals such as chlorite and illite.

In greywackes clay minerals form in the matrix of the rock and/or are concentrated in argillite layers interbedded with the sandstones. The natural sedimentary processes and also the loading that occurs in huge sediment piles causes the clay minerals to both deposit and grow with preferred orientation. Deleterious clay minerals are also deposited on the surfaces of joints andin shear zones.

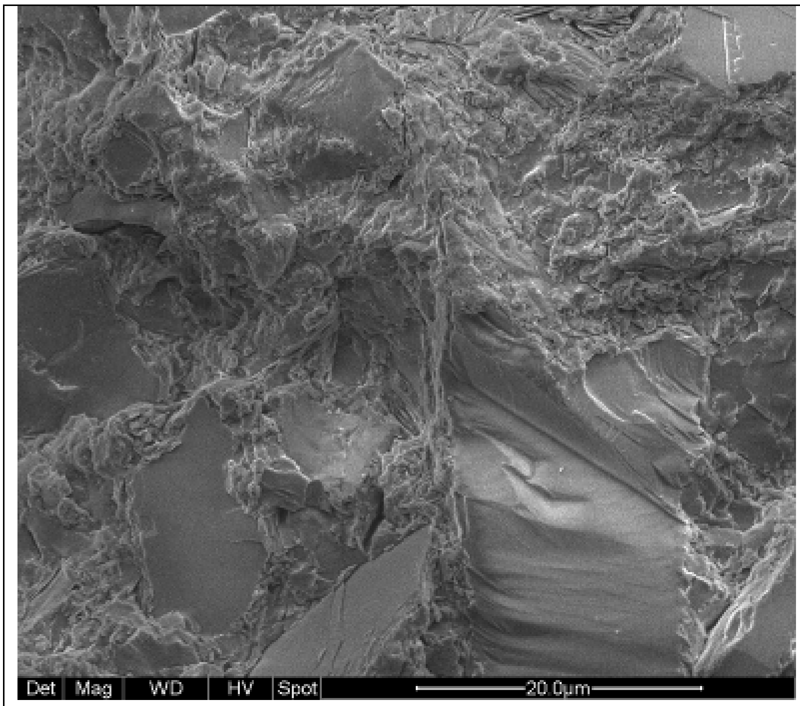

Figure 2.3 : Scanning electron microscope photo of clay-rich matrix of Murihiku-type greywacke. Judging from the presence of Ca-rich zeolites in this particular aggregate the clays may have originally been flocculated.

Clay platelets have collapsed under the sedimentary load although a rosette of clay plates can be seen above a detrital grain immediately right of centre.

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[9] This is the process that produces bauxite deposits.

2.3.3 Clays in hydrothermally altered rocks

Heated ground or marine waters are potent leaching agents which are particularly effective if the rock being hydrothermally altered is volcanic. Volcanic glass is chemically unstable and readily alters to form the clay mineral smectite. Alkalis, particularly sodium, are major constituents of volcanic glass and readily go into solution. Thus the alteration of glass and feldspars ready provides the environment for the formation of smectite (and zeolites) which precipitate directly from the hydrothermal solution as dispersed well-formed platy crystals.

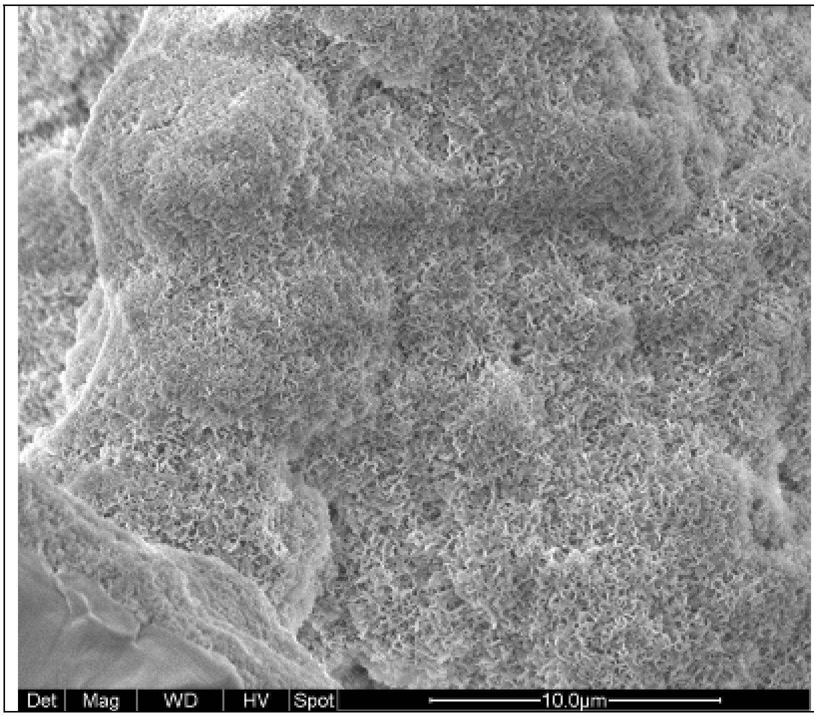

Figure 2.4 :

Scanning electon microscope photo of surface of altered andesite showing a deposit of Na-smectite plates.

Dispersed plates such as these are typical of clay minerals that have precipitated from solutions.

2.4 Summary and Relevance of Clays to Aggregates

Clay minerals are the weakest components of rocks. They are concentrated in the matrix of sedimentary rocks and are a component of all weathered and altered rocks used as aggregates in New Zealand. The nature and physical / chemical properties of clay minerals have a profound effect on the properties and performance of many aggregates.

The swelling capacity of the smectite minerals, and their consequent ability to reversibly absorb large amounts of water are the properties of overriding importance to the aggregate industry and the consumers of aggregates because of their affect on the durability and water absorbing properties of aggregates.

The potential effect of the expansion of smectite to the physical strength of a rock is illustrated in Figure 2.5. The smectite in the image is in a collapsed 1.2nm form.[10] In the natural environment, saturating the rock with water will expand the mineral layers to a thickness of at least 1.8nm (assuming it is a Ca-smectite) creating internal strains that will cause the rock to physically disintegrate.

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[10] Electron microscopy is carried out in a high vacuum which strips out any adsorbed water.

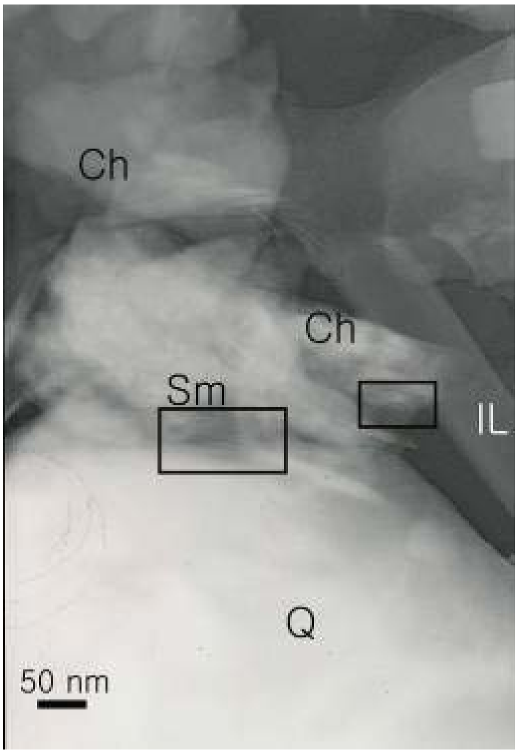


Figure 2.5 (a) (above): Transmission electron microscope image of portion of an Auckland area greywacke showing the location of photos b and c.
Photo b - area between Ch and IL.
Photo c – area labelled Sm.

Q is a detrital quartz crystal
Ch = chlorite and IL = illite crystals.

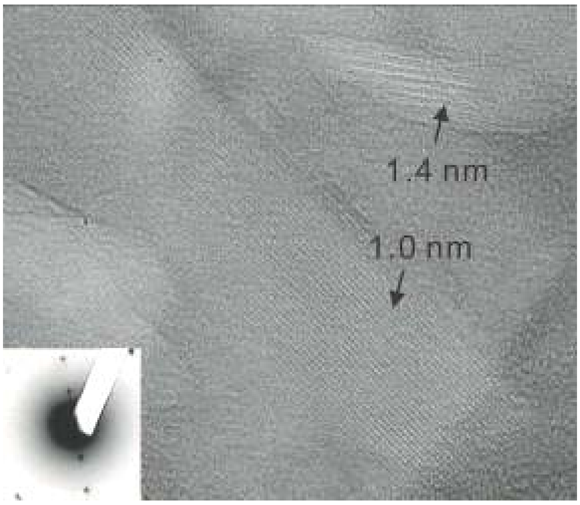
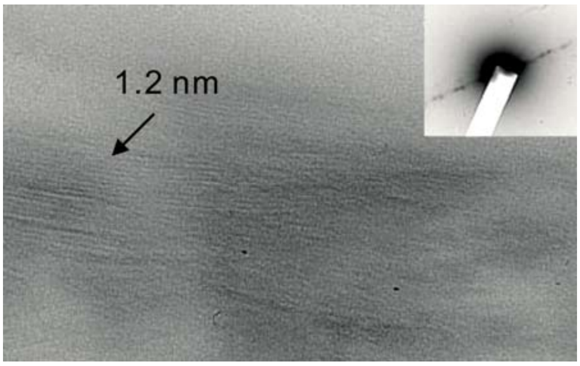


Figure 2.5 (b) (above): shows layers of illite and chlorite 1.0 nm and 1.4 nm thick respectively
Figure 2.5 (c) (below): showing 1.2nm thick smectite layers at the boundary between quartz and chlorite grains.
Arrows point to layers of indicated thickness.



The exchangeable cation has a major effect on the swelling capacity of a smectite. H^+, Na^+, Ca^{2+}, and Mg^{2+} are the dominant exchangeable cations in nature; of these Na^+ exchanged smectites are the highest swelling and Ca^{2+} the lowest. The capacity of the Ca^{2+} ion to readily preferentially exchange for Na^+ (and other ions) thus reducing the swelling capacity and plasticity of aggregates is the basis of the lime stabilisation of aggregate.

Current knowledge of the cations exchanged into smectites in North Island greywackes indicates that they are naturally Ca-rich. Some types of oceanic basalts contain smectites that are already Ca-saturated.[11] Thus further addition of lime may have little effect on the swelling capacity of these smectites. Since the most common lime compound used in lime stabilisation is Portland cement, the stabilising process may be largely one of cementation.

In altered andesites and basalts the exchangeable cation is variable. Those that have been altered in the low temperature marine environment commonly have sodium as the

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[11] See Section 7.3, p.59.

exchangeable cation. Sodium exchanged smectites usually exist in the dispersed form. Aggregates that have abundant dispersed sodic smectite are difficult to work in wet environments because smectite becomes dispersed throughout the pores, clogs them and densifies the material. Thus addition of lime is needed to flocculate the clay minerals (by cation exchange) to make them sufficiently workable for cement to be added.

All layer silicates, are difficult to crush because of the toughness of the silicate sheet in the molecular layer, but since clay minerals are usually only a few microns in diameter they will in any event be concentrated in the fines by the screening process. It is the layer silicates (irrespective of their swelling capability) that impart plastic properties to aggregate fines.

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3. ZEOLITES: PHYSICAL/CHEMICAL PROPERTIES

3.1 Introduction

Zeolites are an important constituent of some volcanic rocks and types of greywackes used as aggregate in New Zealand. Zeolites have some characteristics that may influence the properties and performance of aggregates; in particular their strong capacity for cation exchange imparts pozzolanic properties to materials containing them and their ability to reversibly dehydrate and rehydrate affects the aggregate's water absorption properties.

3.2 Structure of Zeolites

The basic feature of all zeolite structures is an open aluminosilicate framework composed of $(SiO_4)^{4-}$ and $(AlO_4)^{5-}$ tetrahedra linked by sharing oxygens to form structurally stable low density networks of interconnecting loops (distorted rings), closed cages and open channels. The channels are continuous through the mineral structure.

The net negative charge on the tetrahedral framework is balanced by adsorption of exchangeable cations (Ca^{2+}, Na^+ or K^+ and less frequently Li^+, Mg^{2+}, Sr^{2+} and Ba^{2+}) onto the aluminosilicate framework surfaces. Water (and other molecules) and the exchangeable cations are contained in the channels that run through the framework.

The zeolite group is large. Approximately 50 natural zeolites are known.[12] These are generally divided into families according to the arrangement and number of the silica and alumina tetrahedral in the silicate loops, cages and channels.

Individual mineral species are characterised by their Si : Al ratio and the nature of their exchangeable cations. Because a large proportion (approximately 25 – 33%) of their molecular structure is voids all natural zeolites have densities in the 2.1 to 2.3 range which is very low compared with the densities of quartz : D=2.6; feldspars : D=2.55 - 2.75; and layer silicates (clay minerals): D= 2.6 – 2.8.

The structures of the two Zeolites commonly found in New Zealand aggregates are shown in Figure 3.1 (a) and (b).

Figure 3.1 (a) shows the heulandite – clinoptilolite group of zeolites to be built of 4, 5, 8 and 10 member (tetrahedra) loops. The cage-like framework enclosing the channels is composed of sets of 4- and 5-member rings of SiO_4 and AlO_4 tetrahedra linked to form puckered sheets that run across the page in this diagram (ie parallel to the xz plane). The sheets are combined to form two large 8-member and 10-member channels that run in parallel (parallel to the z axis) through the structure.[13]

Laumontite $Ca_4Al_8Si_{16}O_{48}.16H_2O$ has a structure [shown in Figure 3.1 (b)] that consists of 4- and 6-membered aluminosilicate loops linked together to form a 10-member channel which is oval in cross section.

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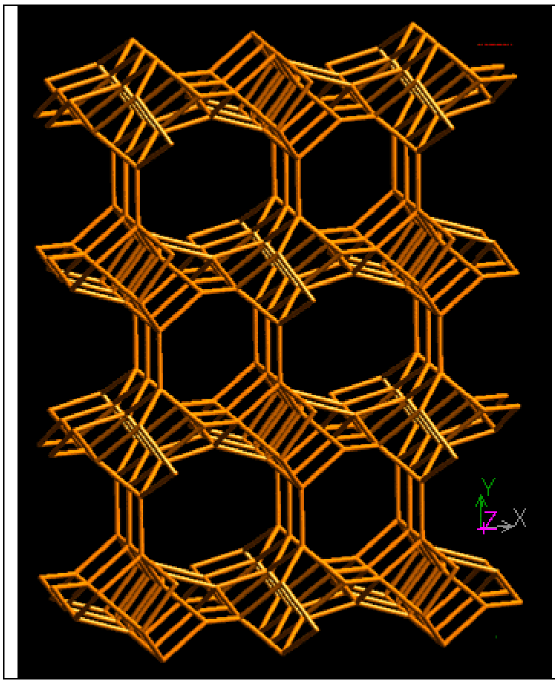
[12] An additional approximately 150 zeolite species have been synthesized for specific uses such as industrial catalysts, molecular sieves in the petroleum industry, and absorbent or dispersion applications.

[13] A third smaller channel runs through the structure parallel to the horizontal plane (= x axis) of the diagram intersecting the two large channels.



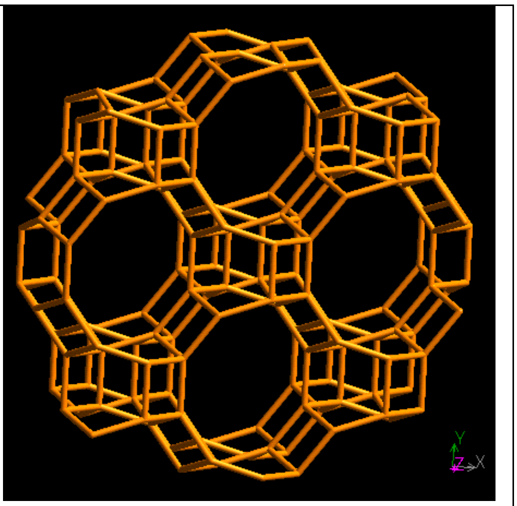


Figure 3.1(a) (left): heulandite structure showing 4, 5, 8 and 10 tetrahedra loops
Figure 3,1b (above): laumontite showing 4, 6 and 10 tetrahedra loops.[14]

3.3 Water Absorption and Thermal Properties of Zeolites

The number of water molecules that can be absorbed into a zeolite is largely related to the dimensions of its channels. Some of the water molecules are independent of the nature or number of the exchangeable cations, but other water molecules form hydration spheres around exchangeable cations. The absorbed water can be driven off by heating to 300 - 400°C without affecting the zeolite structure which will usually reabsorb all the water on cooling. At ambient temperatures the amount of water held in cavities is dependent on humidity.

The dehydration / rehydration of zeolites is very complex and not well understood. Some zeolites show no dimensional change with dehydration / rehydration even when heated to more than 300°C; others show significant volume change. The amount of volume change appears to be related to the nature of the exchangeable cations. Fortunately, in most natural zeolites the reversable water loss steps that cause volume change occur at temperatures significantly above 100°C.

Unfortunately, one of the few zeolites that does show volume changes below 100°C is laumontite, a zeolite widespread in diagenetically altered greywacke-type sediments and volcanic rocks. Laumontite partly dehydrates, loosing two of its sixteen water molecules at ambient temperatures when the humidity drops below about 60% and then rehydrates back to the $16H_2O$ form when saturated with water. This reversible hydration associated with wetting and drying is accompanied by a small (about 2.4%) volume change which is sufficient to cause expansion effects in structures. Very laumontite-rich rocks when exposed to the atmosphere, and consequent wetting and drying, usually develop a surface coating of fine white powder which is physically decomposed laumontite.

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[14] In these "stick diagrams" each "stick" represents a line joining the centres of adjacent (linked) tetrahedra. The diagrams are sourced from International Zeolite Association Structural Commission data base : 2008.

Laumontite, is known to cause deterioration (ie pop-outs, cracking and exfoliation) of concrete surfaces exposed to the atmosphere and thus subject to wetting and drying (**Wakizaka et al, 2001; Wakizaka and Anan, 2003**). Figure 3.2 shows these surface affects in a concrete manufactured using a laumontite – rich North Island greywacke aggregate.

Figure 3.2: Pop-out effects on concrete surface adjacent to laumontite-bearing greywacke aggregate chips.

3.4 Cation Exchange Capacity of Zeolites

The cation exchange capacity of zeolites is significant and of a similar order to that of clay minerals. Data for zeolites known to exist in New Zealand aggregates are listed in Table 3.1 below.

Table 3.1: Cation exchange capacity of natural zeolites occurring in New Zealand aggregates. (Data from Pabalan and Bertelli, 2001).

Zeolite name	**Formula**	**Occurrence** **G = greywacke ; V= volcanic**	**CEC** **(meq/100g)**
Analcime	$Na_{16}(Al_{16}Si_{32}O_{96}) . 16H_2O$	G, V	450
Chabazite	$Ca_2(Al_4Si_8O_{24}) . 12H_2O$	V	390
Clinoptilolite	$(Na,K)_6 Si_{30} Al_6 O_{72} . 20H_2O$	G,V	220
Heulandite	$(Ca)_4 (Si_{28} Al_8 O_{72}) . 24H_2O$	G,V	320
Laumontite	$Ca_4(Al_8Si_{16}O_{48}). 16H_2O$	G,V	430
Natrolite	$Na_{16} (Al_{16} Si_{24} O_{80}) . 16H_2O$	V	530
Mordenite	$Na_2KCa_2(Al_8Si_{40}O_{96}). 28H_2O$	V	220
Phillipsite	$K_2(Ca_{0.5} Na)_4(Al_6Si_{10}O_{32}). 12H_2O$	V	450

3.5 Occurrence of Zeolites

Natural zeolites commonly form as the result of low temperature devitification of volcanic glass which breaks down in contact with sea or fresh water, including groundwater, to form smectite–type clays plus zeolite. Thus zeolites are frequently found in volcanic rocks, particularly those erupted into the marine environment. Zeolites are also amongst the most common products of the chemical interaction between ground waters and volcaniclastic and/or feldspar-rich sediments during their diagenesis and low-grade metamorphism (Coombs et al, 1959). Zeolites formed at low temperatures (up to c. 100°C) are usually K, Na – rich species; Zeolites formed at higher temperatures (150 - 200°C) are Ca-rich.

Members of the heulandite - clinoptilolite series are the most widespread and abundant zeolites produced by the low-temperature hydration and of plagioclase feldspars and volcanic glass and these minerals are also found in low grade diagenetically altered greywackes.[15] In the Murihiku – and Eastern North Island – type greywackes, zeolites may be a significant component of the cementing matrix and zeolites, either heulandite-clinoptilolite or laumontite, depending on degree of diagenesis (ie Temperature), are a major component of altered tuff horizons.

Zeolites, are occasionally found as thin late-stage veins cutting Waipapa and Torlesse - type greywackes, but very rarely occur in sufficient amounts to have a deleterious effect on the performance of these greywacke aggregates.

3.6 Summary and Relevance of Zeolites to Aggregates

Zeolites have high cation exchange capacities and the ability to reversibly hydrate / dehydrate. They can, therefore, have an adverse effect on the water absorbing capacity of aggregates. When present in an aggregate, they contribute to any aggregate property test that measures cation exchange capacity (eg Clay Index). Zeolites do not have plastic properties and, with one exception, are non-swelling at temperatures below 100°C.

Zeolite-rich tuff horizons are common in some greywacke types. These rocks are harder than normal, have low densities, and are often white or buff-coloured. Thus, they are easily recognised in a quarry face (see Figure 6.6 (a)) so selective quarrying will remove the chance of incorporating them in aggregate products.[16]

Zeolitised volcanic rocks often have large (several meter scale) irregular light coloured areas or have cavities and vesicles in the rock filled with clear glassy minerals (zeolites).

Laumontite, is the only zeolite that has a swelling capacity. Laumontite can observed as white platey minerals on joints and in veins that break down forming a powdery material when exposed to air. The surfaces of very laumontite-rich rocks are often covered with a white powdery bloom.

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[15] See sections 6.2 to 6.5.

[16] See Figure 5.6(a) p

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4. AGGREGATE PROPERTY TESTS

4.1 Introduction

The testing of aggregate properties, using standardised procedures, is undertaken to classify and compare aggregates, facilitate prediction of the aggregate's performance, and to ensure it is fit for purpose.

Most of the aggregate property tests used in New Zealand have been developed either in Europe (including the UK), or North America to help predict the performance of those countries' aggregates (and / or soils) and have been adopted, with minor modifications, to suit New Zealand conditions. However, aggregate source rocks of old continental countries are very different to those in New Zealand. In the USA 69% of aggregate (crushed stone) produced is carbonate (limestone and dolomite), approximately 16% is from intrusive igneous rocks (granites and gabbros) and only about 3% is sandstone, slate and quartzite.[17] In Canada more than 70% of all crushed stone production originates from carbonates, the next most common aggregate sources are plutonic rocks (granites, diabases), followed by metamorphic rocks.[18] The UK production of aggregate is 60% carbonate, the remainder derived from plutonic and metamorphic rocks.[19] Greywackes (and other lithified sandstones) are a very small proportion of the aggregate production in Europe, North America, South Africa and Australia and their sandstones usually contain physically and chemically stable debris that has been through several cycles of sedimentation; many are quartz-rich.

In contrast, more than 70% of all aggregates produced in New Zealand are greywacke, the remainder largely derived from young volcanic rocks. **Mackechnie (2006)** has pointed out that New Zealand greywackes have high moisture absorption values and intrinsic shrinkage[20]; all features commonly associated with swelling clay minerals. Many of the volcanic rocks used as aggregate sources in New Zealand are young, erupted in the marine environment, and typically contain zeolite and swelling clays. Thus there are fundamental differences in the nature and properties of rock formed in young active geological environments and the aggregate source rocks of old continental environments. It follows that tests developed for continental source rocks may not be an effective predictive tool for New Zealand aggregates.

4.2 Source versus Production Properties

The New Zealand Transport Authority (NZTA), formerly Transit New Zealand (TNZ), specifications for roading aggregates (base course and sealing chip) distinguish between source and production properties.[21]

There is no indication of the philosophy or criteria which underlies this distinction other than the clear implication, from the different frequency specified for testing source versus production properties, that source properties of aggregates produced from a quarry should not

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[17] US Geological Survey 2007 Minerals Yearbook : 'Stone, crushed'. 2007 [Advance Release]. US Department of the Interior 2009.

[18] Statistics Canada. 'General Review of the Mineral Industries. Mines quarries and sand pits', 2006 Annual census of Mines. Also Panagapko, D. 'Stone', Canadian Minerals Yearbook, 2006.

[19] British Geological Survey. 'Mineral Profile Building and Roofing Stone', November 2005, also Scottish Government. 'Geology and Mineral Planning factsheets for Scotland', 2007.

[20] Water absorption is the weight percent of water that can be driven from an air dried sample at temperatures in excess of 100°C.

[21] Specifications for aggregates to be used in concrete use the same categorisation.

change significantly with time, while production properties do change and are strongly processing influenced.[22]

Sets of data and information have been accumulated by this writer for a range of aggregate products processed from essentially the same rock[23] but with different levels of processing ranging from simple scalping plus primary jaw crushing and screening (ie GAP products), to more sophisticated processing involving, for example, successive scalping, primary jaw crushing, secondary cone crushing, and tertiary Barmac. These reveal that test results for the aggregate products vary significantly according to the nature of their processing. A large part of a quarry operators' work is directed to improving, by judicious use of processing the quality and the physical properties of the rock material that presents in the quarry face.

Material such as GAP products which would not meet the strength and weathering quality standards required for use in regional low-traffic volume roading can, by multiple recycling through the crushing and screening plant, concentrate high crushing strength material (although in doing so discarding large volumes of material) from which aggregate can be produced that meets all TNZ M/4: AP40 specifications. Aggregate chips produced from low quality material are routinely shaped by processing and the quality of the fines improved by washing to meet the higher specifications required for concrete and sealing chips.

Some standard test data does cluster according to aggregate (rock) type, thus clearly indicating that those specific properties are true aggregate source properties. However every one of the standard aggregate property tests is influenced to some degree by production methodology. If it is felt that there is an advantage in retaining a distinction between source and production properties it would be better to use the term source property for those properties that address aggregate durability and the presence of deleterious minerals[24] since these properties are least affected / altered by processing methodology.

4. 3 Tests of Rock Strength

4.3.1 Crushing Resistance [25]

In the aggregate industry an assessment of rock strength (ie the stress at which the material begins to fail) is provided by the Crushing Resistance (CR) test. Rocks are heterogeneous materials and thus different components will fail at different stress levels. Most common rock-forming minerals are brittle; the exceptions are the layer silicates which are semi-elastic and undergo plastic deformation. Crushing resistance results are expressed as the percentage of fines produced by a specified load which is either 130 or 230 kN (**NZS 4407: 1991**) for aggregate to be used as base course or sealing chip respectively, or if aggregate for concrete the number of kiloNewtons which create 10% fines (**NZS 3111: 1986**).

The toughness of the individual mineral constituents and the cohesiveness of the rock (actually how the mineral grains are held together either by grain boundary interlocking or mineral cement) are the most important controls on rock strength – and it follows the aggregate's crushing resistance. The fine fraction produced by the test will contain those

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[22] 'Source property testing shall be performed at periods not exceeding two years (provided production method has not changed) at least one sample every 10,000m^3 while production tests must be performed every 1000m^3.' (TNZ M/4: 2006 specification of basecourse aggregate).

[23] That is sourced from the same quarry/operator and produced over a relatively short time period.

[24] Source properties are defined in this manner in US useage – see Prowell et al, 2005, p. 7.

[25] Overseas this test is commonly known as Aggregate Crushing Value.

brittle components that are least tough (in sedimentary and volcanic rocks), and/or least well held together (sedimentary rocks).

Unsurprisingly, crushing resistance is strongly dependant on aggregate type. All the most abundant mineral components of fresh volcanic rocks have similar toughness and all fail in a brittle manner. In greywackes the sand grains are tough, hard and brittle. In contrast the greywacke matrix, although also containing many brittle minerals, is the locus of the clay minerals that deform as plastic materials. Greywacke types that have quartz-cemented matrices are notably stronger than any igneous rock.

4.3.2 California Bearing Ratio

The California Bearing Ratio (CBR) is a simple strength test developed by the California Division of Highways about 80 years ago and subsequently widely adopted in the US and elsewhere to provide measure of the load-bearing capacity of base course (and soils). The advantage of the test is that it can be carried out either in the laboratory or in situ. The test measures the load required to penetrate the compacted sample with a plunger of standard area (ie force per unit area) and compares it with the load required to penetrate a standard compacted crushed rock to the same depth (although in practice the apparatus is calibrated to associate the standard with a specific load value). Thus, a high quality aggregate with the same load-bearing capacity as the standard material will have a CBR of 100.

The CBR is generally carried out on the sample in the “as received” moisture state which is normally slightly less than the optimum moisture content which is specified. Variations in moisture content have been shown to have a significant effect on the result (eg **Berthelot, et al 2004**). The CBR for aggregates derived from greywackes, which have abundant hydrous layer silicates, will be more affected by moisture variations than will test data obtained from unaltered or weakly altered volcanic rocks.

4.4 Tests for Stiffness of Compacted Aggregate

4.4.1 Triaxial load testing

The stiffness of a compacted aggregate is determined by simultaneously collecting axial stress and strain data while the confined compacted aggregate sample is being loaded. The stress-strain relationship below the material’s failure point enables prediction of how well the material is able to return to its original shape and size after being stressed, or conversely and more practically, the likelihood of permanent deformation (rutting) occurring in what should have been a flexible pavement.

In the case of samples being loaded slowly, the stress – strain relationship is initially linear and consequently the material is elastic and will return to its original shape when the stress / load is removed. In the linear area the stress/strain ratio is constant for the particular material and known as its **modulus of elasticity.** Beyond the elastic limit the material deforms and when the load is removed some strain is permanently retained in the material.

When loads are applied rapidly the stress - strain relationship is non linear thus changes in stress have a substantial effect on the elasticity /displacement /deformation of the material. The **resilient modulus** is the average slope of the stress - strain curve which takes into account the cumulative permanent deformation that has been generated. It provides an estimate of the likelyhood of the material returning to its original shape after the stress has been removed. These “estimates” can be made either empirically by collecting field deflection data or, more commonly, via a triaxial resilient modulus test in which a repeated axial cyclic stress of fixed magnitude, load and cyclic duration is applied to a cylindrical test specimen. The ratio of the applied load per sample cross section area to the measured total resilient (recoverable) axial deformation response of the specimen is the resilient modulus.

Repeat load triaxial testing subjects a confined compacted aggregate sample to rapidly repeated (cyclic) stress of fixed magnitude and load. The test replicates the stress levels experienced by the aggregate at various points in the in-service environment (such as in the basecourse of a pavement). After a set number of load cycles the micro-strain is measured. The load cycle / strain measurement sequence is repeated thus establishing a relationship between cumulative permanent strain and the number of load cycles. This can be used to model the critical value beyond which any deformation of the material is permanent. The aim of the test is to classify aggregates into performance bands.

The method itself is not excessively complex, although the data processing is, and the test can be undertaken in a range of moisture conditions from dry to saturated. Factors that need to be considered in interpreting the results are that: rocks are heterogeneous materials and some minerals (particularly in greywackes) do not deform in a brittle fashion; and fatigue failure can occur at considerably lower loads than will occur under a static load when material is subjected to cyclic stresses. The results are also likely to be affected by particle size distribution, the shape of the aggregate chips, and the aggregate's crushing resistance – all of which are determined by the nature and type of aggregate ie volcanic rock versus greywacke, and the type of greywacke.

4.5 Tests for Durability and Soundness [26]

4.5.1 Weathering Quality Index (WQI)

This test essentially takes a sized sample (19.0mm to 4.75mm size range) and subjects it to cycles of wetting, drying and rolling (abrasion under a light applied load) followed by boiling, drying and weighing to determine the percentage reduction in size (ie the weight of material which as a result of the test passes the 4.75 sieve).

The test is using the rolling force and the expansion / contraction forces of existing clays to physically disaggregate the aggregate thus is really a measure of the degree of lithification of the material and the nature of its matrix. Weathering is the process of hydration and leaching of existing minerals – a time dependant process requiring a minimum time scale at least several orders of magnitude greater than that involved in the testing.

The WQI test is designated as a source property - which implies that it is intended to be a measure of the original source rock's degree of weathering.[27] However, some greywackes which are in geological terms totally fresh, ie completely unweathered, will always have WQIs in the CA – CC range because they are poorly lithified / cemented, or have rcok matrices that in the fresh state normally contain clay minerals. Further, the WQI of a rock can be changed from BC or CB to AA or AB by multistage processing designed to select into the product the tougher, high crushing resistance, more durable parts of the rock!

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[26] Resistance to wear (mechanical breakdown) and to physical-chemical changes (weathering).

[27] although the same test is designated "Method for determining weathering resistance of coarse aggregate" in tests specified by the concrete industry (NZS 3111: 1986).

The WQI has nothing to do with the degree of weathering of sedimentary source rocks, and also provides a poor prediction of the likelyhood of the aggregate weathering in service. The most important control on the WQI for greywackes is the level of processing.

In the case of volcanic rocks where swelling clays are associated with weathering and/or alteration there is a reasonable correlation between the rock's level of weathering/alteration and its WQI but processing can also significantly change the WQI value.

4.5.2 Sulphate soundness tests [28]

This test provides an estimate of an aggregate's resistance to the volume changes caused by water freezing in those aggregate pores that are accessible to water. The aggregate is soaked in either sodium or magnesium sulphate solutions and then dried to allow the crystallisation of the salts. There are a number of reasons why this test is not favoured, even in those countries which have to deal with the annual effects of freeze / thaw and frost heave etc. Salts formed by evaporation have several hydration states (and volumes) so the stresses produced are often much higher than with the volume changes associated with the freezing of water. There is also relatively low precision in the testing. Studies comparing sulphate soundness with Micro-Deval test results show good correlation but the Micro-Deval test offers better precision.

4.5.3 Los Angeles Abrasion test

This is a standard test in the EU and in North America and is included in NZS 4407: 1991. It provides an evaluation of the toughness of coarse aggregate and its potential to degrade in dry conditions. The test basically consists of placing a graded (sized) sample of dried aggregate and steel balls in a rotating drum. The drum has an internal shelf which, with each rotation, lifts and drops the steel balls onto the aggregate. After the test the sample is screened and the increase in the amount of fine material produced is measured.

This test is exposing the aggregate firstly, to the abrasive effect of aggregate grains tumbling against and abrading each other and secondly the aggregate's resistance to the impact of the steel balls falling on them. The hardness of the minerals contained in the aggregate determine its abrasiveness. Toughness controls resistance to impact. Some sources suggest that the effect of impact is greater than that of abrasion (eg **Smith and Collis, 2001**).

Tests used to predict aggregate durability can reasonably be carried out on dry aggregate in continental countries where very few aggregates contain clay minerals (unless they are weathered). But for New Zealand aggregates dry-testing for durability / soundness has the disadvantage that it thus does not accommodate the expansive effect of swelling clays.

Some degradation tests used overseas do test the aggregate under wet conditions. Two tests incorporated in the ASTM testing system are the Micro-Deval test and the California Durability Index.

4.5.4 Micro-Deval test

This test, originally developed in France has been adopted throughout the EU, and North America, for fine (ie sand) as well as coarse aggregate. Essentially the aggregate is tumbled in a container with water and some with hard steel balls under standardised conditions and for a defined number of revolutions. Any increase in the amount of fines is measured. The

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[28] sometimes also known as Aggregate Durability test.

tumbling action produces aggregate grain on grain, and grain on metal abrasion, physically breaking down low strength particles by both abrasion and, if the material contains expanding clay minerals, the physical effect of their swelling.

4.5.5 California Durability Index

This is the simplest of the durability tests. It was developed to provide an estimate of the amount of degradation that occurs during the mixing of sand and aggregate in, for example, concrete production. The wet aggregate charge is mixed with an impeller. The increase in fines measured after the test will include the products of grain on grain abrasion and any breakdown of material caused by expansion of existing clays.

4.6 Tests to Assess Compaction Capability

4.6.1 Particle Size Distribution [29]

The particle size distribution is a simple wet or dry sieving test which provides an assessment of how the material might mix and compact and in doing so provide strength for roading subbase and concrete. The cumulative weights of material passing the standard set of sieves (all < 75.0mm) are recorded and displayed on a grain size versus percentage passing graph. The tested aggregate's cumulative particle size curve must fit within a defined particle size distribution envelope.

Particle size distribution is very closely related to both the crushing regime and the strength of the material. Crushed volcanic rocks consistently fall within the allowable particle size distribution envelope while many types of greywacke have difficulty doing so.

The **Fineness modulus** of an aggregate is the cumulated percentage of material retained on the 9.50mm sieve.

4.7 Tests for Aggregate Cleanness

4.7.1 Sand Equivalent (SE)

This test was developed in 1953 in the USA and adopted in the UK in 1962 as a "rapid method for detecting the presence or absence of detrimental fines or clay-like materials in soils and mineral aggregates."[30]

The underlying concept, as stated in **ASTM D7419-02**, is that "The 'sand equivalent' expresses the concept that most …. fine aggregates are mixtures of desirable coarse particles, sand, and generally undesirable clay or plastic fines and dust." A representative sample passing the 4.75 mm sieve is dispersed with a flocculant in a measuring cylinder and after 20 minutes the heights of the sand and sand plus clay columns are measured. The sand equivalent is the ratio of the height of the sand column to the height of the sand plus dispersed clay material expressed as a percentage.

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[29] Known as Aggregate Grading overseas.

[30] Highway Research Board Proceedings v 32, 238 -250, 1953 National Academy of Sciences Washington DC.

There are a number of problems with the Sand Equivalent (SE) test.

The first relate to the crushing regime which can affect the percent passing the 4.75mm sieve and also the shape of the "sand" particles. The height of the sand column will be affected by the shape of the "sand" particles since shape to a large extent determines sediment packing and thus the volume (height) of the accumulated "sand" column.

The settling velocity of sediment in a static environment (like that of the test cylinder) is simplistically related to the density, size and shape of the sediment particles. Clay minerals, which have a platy shape and a very small grain size will settle very slowly in spite of their relatively high density (comparable with that of rock flour composed of quartz and feldspar at c.2.6) and need to be flocculated to increase their settling velocity.

However other minerals which are relatively common in some types of aggregate have very low densities (in the 2.2 range) and also very small grain size – these are zeolites (in altered volcanic rocks and some types of greywacke) and the two silica-minerals tridymite and cristobalite (common in silica-rich volcanics which are/were very glassy). These minerals can not be flocculated and rock flour containing them may stay in suspension for long periods and will therefore be included in the "clay column" thus lowering the sand equivalent value. Since neither the density of the suspended material nor the composition of the material in the suspension is known the SE test provides no information about percentage of the clay size fraction or the presence or proportion of clay minerals in it.

4.7.2 Cleanness Value

The preamble to **NZS 4407: 1991 test 3.9** states – 'the "cleanness value" .. is a function of the amount, fineness, and character of the clay-like material present, with or on the coarse aggregate particles.' A relatively large amount (2500 +/- 125gm) of moist, as received sample less than 26.5mm in size is washed with wash water containing a flocculant, and sieved to retain < 75 µm fraction within the wash water. The wash water is made up to 1 litre then shaken to disperse the material in the wash water, poured into a 400mm cylinder and allowed to settle for 20 minutes. The height of the column of sediment is measured and the cleanliness value (on a 0 to 100 scale) read from a provided table.

The cleanness test suffers from most of the same shortcomings as the Sand Equivalent test – although not claiming as much. However, since the cleanness test involves shaking of the water – aggregate sample any fine material that has been hammered into pores and cavities by the processing of the aggregate will be more likely to be released than in the SE test.

4.8 Properties of Clay Size Fraction

4.8.1 Clay Index (CI)

This test is actually measuring the surface area of the fine fraction of the aggregate using a titration method to determine how much methylene blue can be adsorbed on the surface of the aggregate fines. Since a characteristic of clay minerals is their high surface area, and of these minerals smectite has an order of magnitude higher surface area than other clays, the clay index is generally considered to be a measure of the material's smectite (swelling clay) content (eg **Higgs, 1988**).

However the actual process of adsorption of the methylene blue is one of cation exchange (**Kahr and Madsen, 1995**). Individual clay species have different cation exchange capacities and the nature of the exchangeable cation in the smectite also affects absorption of methylene blue and hence the clay index (**Hang and Brindley 1970; Chen et al 1999**). The nature of the interlayer (exchangeable) cation depends largely on the chemistry of the water-rock system (ie simplistically the rock type). An identical amount of a smectite in the same rock type but with different exchangeable cations will produce significantly different clay index values.

Finally, clay minerals are not the only common rock-forming minerals with high surface areas and cation exchange capacities. Zeolites have a very large open silicate framework structure on the surface of which water and exchangable cations are adsorbed and these can easily be replaced with methylene blue. Natural zeolites similar to those associated with altered volcanic rocks and tuffs have specific surface areas of 500 to 600 m^2/g. and CEC 200 to 400 meq/100gm.[31] However, almost all zeolites are nonexpanding. The exception is the zeolite laumontite which reversibly hydrates and dehydrates. Zeolites are a common constituent of a number of rock types used as aggregate in New Zealand – specifically some types of greywackes in which zeolites are common matrix constituents, and in oceanic basalts, and some andesites where zeolites may occur as alteration minerals.[32]

4.8.2 Plasticity Index (PI) and Plastic Limits

The Plasticity Index is the numerical difference between the plastic and liquid (Atterberg) limits for the material smaller than 425μm contained in the aggregate. The determination of the liquid and plastic limits is rather subjective and dependent on the experience of the tester. As a consequence there has been criticism of the Plasticity Index test.[33]

Many individual studies have shown that no characteristic value for either plastic or liquid limits can be associated with any individual clay (layer silicate) mineral although in general the plastic limits of the common clay minerals decrease in the order smectite, illite, kaolinite (see for example **White, 1949** and a general summary in **Bell, 2000**). In the case of smectites plasticity is strongly determined by the nature of the exchangeable cation; Na- exchanged smectites have the highest plastic and liquid limits (and therefore Clay Indices).

Clay mineral particle size is an important control on plasticity as is crystallinity (ie the degree of order in the stacking of molecular layers to form the individual mineral). Very fine grained illite and kaolinite crystals are strongly plastic while larger grain sizes generally have very low plasticity. Clay-sized platelets formed by the crushing of large (sand size) non-plastic mica and chlorite crystals are also often plastic (**Guggenheim and Martin, 1995**). Mechanical crushing of layer silicates is a well known way of destroying the crystallinity of clay minerals.

Note that the Plasticity Index is not a test for the presence of swelling clay minerals as nonswelling layer silicates (eg kaolinite and illite) may be strongly plastic. Large grains of non plastic mica, may when crushed provide small grains with relatively high plasticity index accompanied by a very low or negligible Clay Index.

Zeolites, which have some properties similar to clay minerals (CEC and high surface area), are not plastic and therefore their presence has no influence on plasticity index.

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[31] Zeolites of the clinoptilolite – mordenite – heulandite group. See Table 3.1, p.22 and the specific surface data for these minerals given in Englert and Rubio (2005) listed in references to Section 3.

[32] Refer to Sections 5.3 and 5.4.

[33] For example in Prowell et al 2005.

4.9 Density, Water Absorption and Shrinkage

Density, ie mass per unit volume, is one of a material's fundamental physical properties but it is difficult to measure precisely and it is also temperature dependant. In the aggregate industry relative density (Specific Gravity) and bulk density are the properties usually measured.

The relative bulk density is measured via a series of weighings of the sample in various conditions: in water (to provide an equivalent weight of the volume of water displaced); then in air but water saturated, surface-dried, and oven-dried to over 100°C. Formulae using these weights provide relative density, that is Specific Gravity of the aggregate, its water absorption (% dry mass); and the percentage of voids in the sample. Apparent density can be reported in the air-dried or oven-dried state. Bulk density is the weight of compacted material in a unit volume.

The difficulty with the determination of apparent density is that the basic data used in the calculations are dependant on the material's permeability. Continuity between the voids in the sample is needed to ensure that all the pores (voids) can be filled with water.

There is no standard method for measuring the expansion or shrinkage of aggregate due to the presence of swelling clays. Those researchers that have published data on aggregate shrinkage have attached strain gauges to aggregate chips embedded in an inert epoxy resin and measured intrinsic shrinkage strain.[34]

4.10 Shape of Aggregate Chips

The shape of aggregate particles affects packing (compaction), porosity and permeability, and mechanical stability of unbound material. Shape, flakiness and elongation of fine aggregate can also affect workability of the material. There are many implications of variations in shape, size and surface properties of coarse and fine aggregate used in the concrete industry.[35] The shape test involves manual checking and sorting of a sufficient number of particles for shape, elongation, rounding, surface smoothness and number and size of broken faces to provide statistically valid data.

Some source rocks, such as foliated metamorphic rocks and flow-banded volcanic rocks, will naturally produce elongated or flaky rock chips. Argillites and fine siltstones, that is rocks with a dominance of layer silicates which during sedimention and/or growth will always align themselves parallel to the depositional surface or perpendicular to the stress direction respectively. Very strong and fine-grained brittle rocks tend to produce very angular chips. Weaker and coarser-grained rocks tend to produce more equidimensional chips (and more fines). However natural variations in shape are greatly affected by the type of crusher used, and the size and volume of feed going into the crusher.[36]

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[34] Mackechnie, 2006; Fujiwara, 2008; and Asamoto et al 2008.

[35] For example summarised in Quiroga et al 2003.

[36] For example as summarised in Smith and Collis, 2001, pp 173-7; also Prowell et al, 2005, pp 55-58.

4.11 Surface Properties of Aggregate

4.11.1 Polished Stone Value (PSV)

This test was developed to compare an aggregate’s propensity for polishing under standard conditions and thus is undertaken to facilitate prediction of the exposed aggregate’s resistance to polishing by vehicle tyres while in service. The state of polish of the exposed surface is a major factor affecting skid resistance of the pavement surface. The level of polish and time taken to achieve it is determined by the inherent properties of the rock and its consequent ability to maintain its surface microtexture, and the amount and type of traffic.

In general there seem to be a number of simple rules relating to rock polishing :

- Rocks composed of minerals with a wide range of hardness are more resistant to surface polishing than rocks of similar hardness.
- The rate of polishing is related to variation in grainsize of the minerals.
- Rocks composed of minerals with similar hardness and uniform grainsize will polish quickly while those with a wide variation in grainsize will polish more slowly.
- Large grains will take longer to polish than the smaller grains and will stand proud above the general surface and retain the surface microtexture for longer.

Some of these “maxims” are illustrated in Figure 4.1 below. The minerals (mainly feldspars and pyroxenes) forming the andesite rock matrix polish uniformly while larger crystals of the same minerals stand proud. Mineral constituents of andesites have similar hardness / toughness values thus released mineral fragments provide little potential for reviving the aggregate surface.

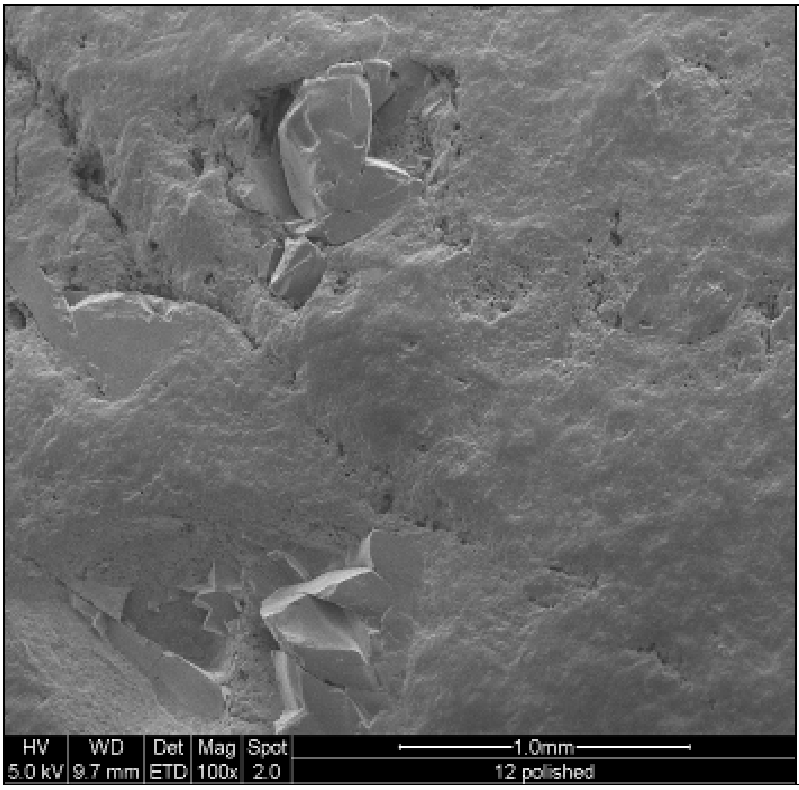

Figure 4.1 :

Scanning electron microscope photo of polished surface of and andesite aggregate chip.

Note the uniform polishing of the fine grained matrix surface while large crystals of the same minerals (feldspar and pyroxene) are standing proud, and breaking up. The fragments of the large crystals will ultimately drop out of the rock.

In the case of clastic sediments, such as greywacke, the degree of induration, level of diagenesis /metamorphism, and the nature of the rock matrix, are important. All greywackes contain fragments of quartz, a hard, tough mineral, and also physically strong grains of sand. During diagenesis it is usual for clay minerals, such as smectites, to wrap around the clastic grains (Figure 4.2 below). Since many of these clays are swelling, wetting and drying of the rock will expand the clays and release the clastic grains to scratch (revive) the surface.

Weathering, a process which in its early stages produces smectite clays, will weaken the matrix minerals in greywackes allowing the hard sand and mineral grains to drop out and revive the polished surface (**Wilson and Black, 2009**).

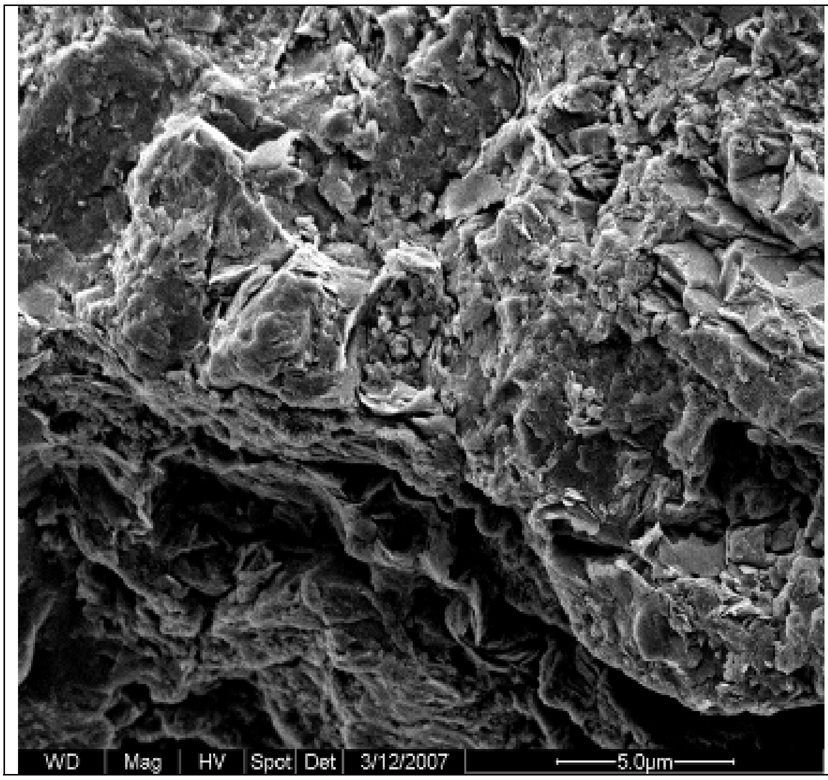

Figure 4.2 :

Scanning electron microscope photo of weakly lithified greywacke sandstone showing clay mineral plates wrapping around small detrital grains (centre).

The large area of clay mineral flakes (lower left corner) is most probably the clay rind enclosing a larger grain.

Many greywacke quarries produce high PSV aggregates described as either being slightly brown (oxidized) or moderately weathered and having lower CR values than the lower PSV value material produced from fresh rocks in the quarry. Aggregates that rely on weathering to achieve high PSV values probably have questionable long-term soundness.

4.12 Summary and Comment

All aggregate properties are dependant on the processing methodology used to produce them. This writer concludes that many of the tests included in the suite of aggregate property tests specified by NZTA (formerly TNZ) and other agencies will not adequately inform the engineer about fitness for purpose, or the likelihood of the aggregate remaining sound to the end of the design life, if the aggregate processing methodology is not incorporated in the test report.

Some aggregate properties are strongly affected by aggregate type (ie greywacke versus volcanic rock, or greywackes with different levels of induration and metamorphism).

Since all greywackes and altered volcanic rocks contain clay (layer silicate) minerals, many of which have the ability to adsorb water and swell, dry testing of material will not provide an adequate assessment of an aggregate's soundness. Thus it is important that all durability tests be undertaken on wet samples.

Most standard aggregate test procedures are measuring or displaying a combination of several physical properties at the one time. Without an independent control on any one of the properties being measured it is difficult to interpret the results.

In the evaluation of source and production property tests and what they mean in terms of fundamental rock materials properties, the importance of one aggregate property - its physical strength (ie crushing resistance) - is striking. This property, because rock strength determines the amount of fines produced has a profound affect on whether or not the material can comply with the prescribed particle size distribution envelope, and a flow - on effect on other source property tests that are carried out on sized material (for example weathering quality index, and sand equivalent values). Rock strength is also a property that is reflected in the shape of crushed aggregate particles.

In terms of the properties of aggregate fines, the TNZ M/4 flow chart for basecourse aggregate requires that an aggregate failing the sand equivalent test (that is having a sand equivalent of less than 40%) must undergo either a clay index test or plasticity index test. However, comparative studies of the relationship between the three tests and for a wide range of aggregates suggest that there is no significant correlation either between the three tests or their ability to determine the presence of moisture sensitive fines.[37] This is not surprising since these three tests are 'measuring' different and not necessarily related physical properties. In the sand equivalent test it is the settling velocity (density, grain size and shape related) which is the dominant control on the result and zeolite and silica minerals (cristobalite and tridymite) will be included in the clay-size fraction "measured". The clay index is a measure of high surface area and cation exchange capacity of the sample; these properties are characteristic of smectite (swelling) clays and zeolites. Plasticity is a function of the total layer-silicate mineral content (ie includes kaolinite and illite and may also include a contribution from micas and chlorite).

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PART II :
Geological Inventory of North Island Aggregates

The objective of the Geological Inventory of North Island aggregates is to :

- survey and to classify the aggregate resources of the North Island in terms of their "source properties" and in doing so
- provide understanding of the causes of aggregate property and performance variations.

The two most important properties of any material being considered for use as an aggregate are its strength and durability. Of course aggregates have many other properties that are important to the engineer and to others who can be regarded as consumers of aggregate, but if an aggregate is not both strong and durable it will find little acceptance. For this reason the main criteria that have been used in developing this classification / inventory of North Island aggregates are those tests which are measures of strength (determined in this case by the aggregate's crushing resistance) and durability. The most commonly used tests to predict the durability of both fine and coarse aggregate are sand equivalent (SE) and clay index (CI) values, that is the amount and nature of the aggregate fines (clay–sized particles). These criteria are not the same as those used by geologists who usually associate rocks according to their stratigraphic position (age), and/or geochemical affinities and tectonic association. Thus this classification, which is focused on the nature of the aggregates produced from different types of rocks, does not necessarily coincide with geological classifications / associations.

The caveats to any classification of aggregates are:

- Aggregate is a processed material – rock is scalped, crushed, screened, shaped and washed to produce a material that meets the specifications of clients.
- The processing methodology used to produce an aggregate determines many of its properties.
- Rocks – whether volcanic or sedimentary - are intrinsically variable in nature. Thus there is a continuum in properties between different types of sedimentary rock such as greywacke; and also between different types of volcanic rock.

However, in spite of these caveats the different types of rock resources used to produce aggregates in the North Island can be classified into categories on the basis of clear, although sometimes subtle, differences in their engineering (physical) properties.

The following sections, and indeed the whole inventory, would not have been possible without the cooperation and support of the aggregate and quarry industry.

The writer is indebted to the many quarry operators who provided information about their resource and were unfailing generous in providing samples, production data and other information about the aggregates they produce.

5. GREYWACKES AS AGGREGATE RESOURCES

5.1 Introduction

Approximately 25% of the exposed rocks of the New Zealand landmass are greywackes. Greywacke is the source rock for close to 75% of aggregates produced in New Zealand.

Geologists consider that the greywackes forming the basement of New Zealand can be allocated to one of six terranes. These basement greywackes range in age from Permian to earliest Cretaceous (roughly from 330 to 120 MaBP). Each terrane has had a unique geological history (including age range) and its constituent greywackes have characteristic chemical and mineralogical compositions which reflect the source and nature of the sediment (that is the sand and silt grains) contained in them.

The geographic distribution of these terranes in New Zealand is shown in Figure 5.1. Four of the six greywacke terranes (Murihiku, Caples, the Torlesse - Rakaia and Torlesse – Pahau terranes) are found in the North and South Islands; the remaining two, Waipapa and Waipa, outcrop only in the northern North Island. Quarries are producing greywacke aggregate from all six terranes. Gravels derived from the erosion of the greywacke uplands that are the spine of the New Zealand landmass are the major source of aggregate for large parts of the country.

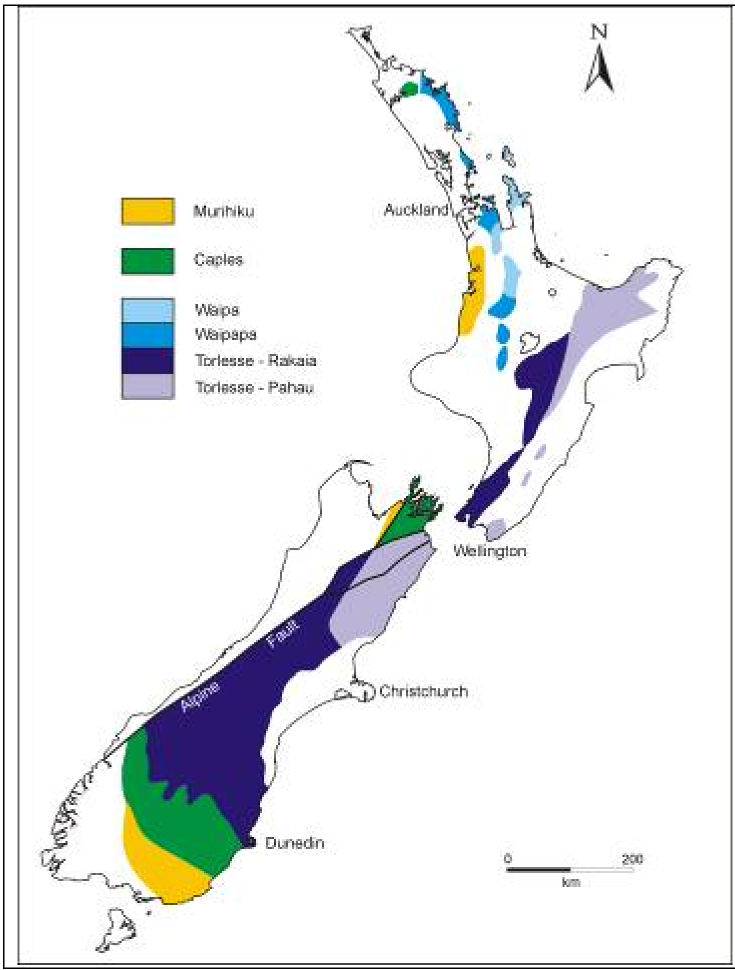

Figure 5.1 :

Map showing the outcrops of pre-Tertiary greywacke basement terranes. These rocks are the major aggregate resource for New Zealand.

The term “greywacke” as used in New Zealand encompasses a wide range of sedimentary rock types and grain sizes, from argillite (originally mudstone), through siltstone and sandstone to conglomerate. Because they are clastic sediments, the nature of the debris (sand grains etc) in the individual greywacke sandstone beds, and the proportion of grains to matrix in the sediment may vary significantly from bed to bed and consequently may have a profound effect on the rock properties. Thus greywackes are intrinsically heterogeneous and may show a range of properties on the quarry scale.

Locally some greywacke sequences are very siliceous and chert horizons are relatively common in the greywackes from Auckland to the Bay of Islands and in the Wellington area.

Greywacke terranes are bounded and juxtaposed by major fault systems. Near these bounding faults the rocks may be extensively sheared. The individual terranes themselves are also dislocated by major mid Tertiary (less than 20 Ma BP) fault systems. Almost all greywacke quarries will contain one or more shear zones or faults but those that are located close to the major fault systems that disrupt tracts of greywacke in the North or to the terrane boundary zones will be more deformed, sheared and veined and thus tend to contain more alteration minerals than greywackes located in the interior of fault blocks.

Some of the greywackes have been intensively internally deformed on a regional scale and have developed a tectonic overprint known as foliation or, in its more intense form, as schistosity.

In classifying / inventorising North Island greywackes as **aggregate resources**, the criteria that must be paramount are the source rock’s strength and durability. These are not the criteria that are used by geologists to assign greywackes to terranes so there is no reason why terrane boundaries and aggregate type boundaries should coincide. But since the properties of sedimentary rocks are in large part determined by the geological /mineralogical attributes of the source rock, including factors such as the temperature conditions of their diagenesis / metamorphism which largely affects the rock matrix and also determines their degree of lithification (ie hardness / toughness), these features should be reflected in the aggregate classification. Penetrative deformation of the rock leading to the development of schistocity will also affect the rock properties.

Where there is a coincidence of aggregate type with a geological terrane, the terrane name is retained for the aggregate type; this is the case in the North Island for Murihiku and Caples terrane rocks.

In the Waikato Valley, Waipapa and Waipa terrane greywackes have rather similar geological and other attributes, including the properties of the aggregates produced from them. They are combined into Waipapa-type aggregates. However, the Waipa terrane greywackes on Coromandel Peninsula are lower in metamorphic grade and thus have different materials and aggregate properties. Accordingly they are placed in a different greywacke type.

The greywackes of the Torlesse (sometimes called Torlesse-Rakaia) terrane, which is quartz- and feldspar- rich and probably derived from a granitic or mature continental source, are quite different from the Waipapa type (including Waipa terrane) volcanoclastic greywackes. While some of the physical /engineering properties and geological characteristics of these two greywacke types are similar, the difference in the nature of the sand grains contained in the sediments is reflected in their chemical composition (Figure 5.2) and thus in their different matrix clay mineral assemblages.

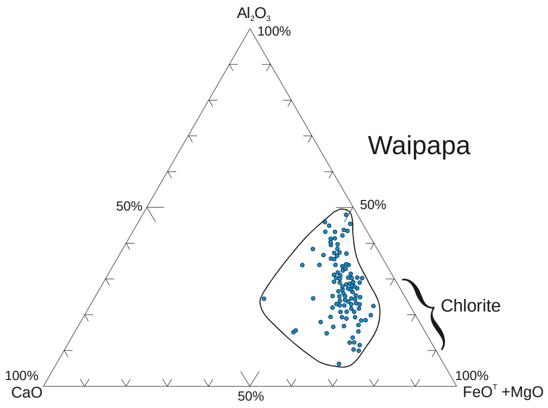

Figure 5.2 (a) : Chemical composition of the Waipapa type greywackes. Molecular proportions of Al2O3, (total iron as FeO + MgO), and CaO.

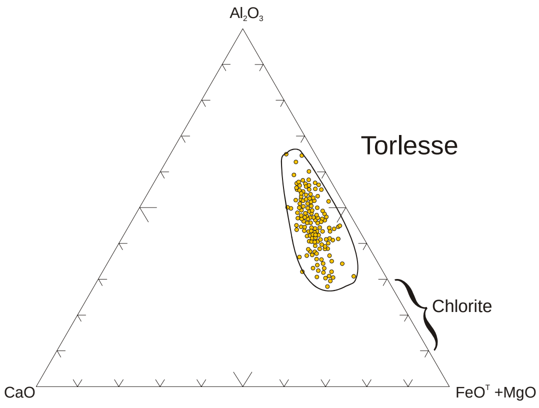

Figure 5.2 (b) : Chemical compositions of Torlesse type greywackes; same diagram as (a) but note that the Torlesse greywackes contain proportionally more Al2O3 and less (FeO + MgO) than Waipapa greywackes.

The greywackes in the eastern North Island were the most problematic since few quarries exist and very little is known of the basement greywackes in the Gisborne – East Cape area where they are variously placed either in the Torlesse-Pahau or the Waipa terrrane (eg **Mortimer 2004** and also in the ***Bateman New Zealand Encyclopedia*, 2005**). The clustering together of greywackes of the Coromandel Peninsula and the Whakatane – Gisborne/Napier areas, as Eastern North Island type greywacke is based (i) on observations and samples collected during visits to all the active greywacke quarries in the Coromandel, Whakatane and Gisborne areas (ii) examination of samples of greywackes from these areas held in the University of Auckland collections, (iii) collection and examination of new material particularly from the Waioeka Gorge area and (iv) published work on the petrology of greywackes in the Kaweka – Kaimanawa – Napier area (**Baker and Staverley-Parker, 1989**).

In the North Island the distribution of the five greywacke types is shown in Figure 5.3. Their distinguishing geological features and generalised engineering properties are listed below :

Murihiku - type greywacke:

- Broad regional folding; bedding and other sedimentary features clearly recognisable
- Rocks largely volcaniclastic; tuff (volcanic ash) horizons relatively common
- Zeolite zone diagenesis alteration : zeolites common in the matrix of sediments
- Clay minerals – chlorite, smectite, illite and kaolin; mixed layered clay minerals common; ie may have significant CI values and low cleanness values.
- Veining: zeolites, calcite and quartz
- Crushing resistance – medium range.

Caples - type greywacke :

- Penetrative deformation – semischistose
- Rock composition originally volcaniclastic
- Mineral composition – quartz, albite, actinolite, pumpellite, epidote
- Clay minerals – chlorite, illite; ie have low / insignificant CI and PI values
- Crushing resistance – medium.

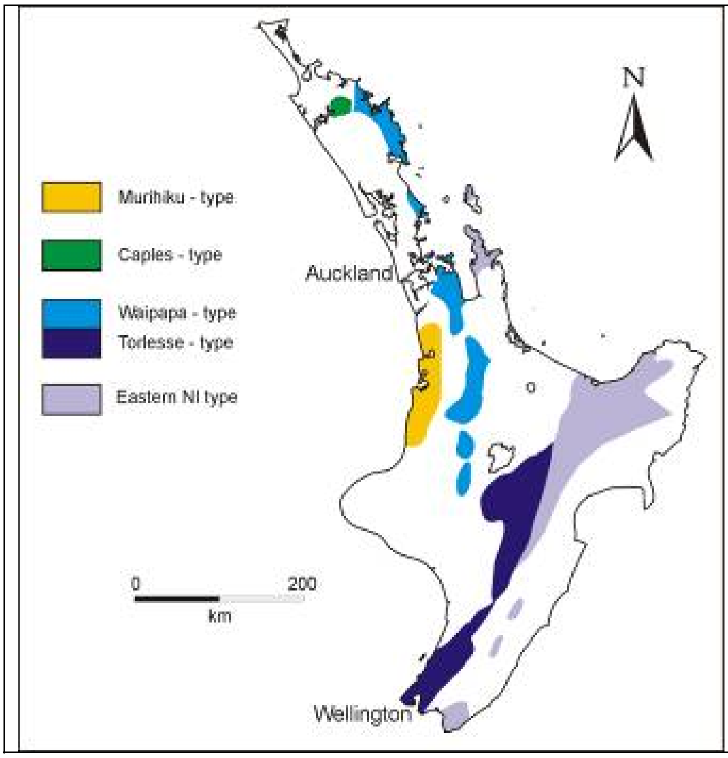

Figure 5.3 :

Map showing the outcrops of the different North Island greywacke types classified according to their aggregate properties.

Waipapa - type greywacke :

- Local intense brittle deformation (shearing and fracturing) and faulting common.
- Rock composition volcaniclastic.
- Strongly lithified by very low grade metamorphism (anchizone)
- Widespread prehnite + quartz veining; chlorite and smectite on shear zone surfaces
- Clay minerals chlorite, illite and minor smectite.
- Crushing resistance – high range

Torlesse - type greywacke :

- Local intense brittle deformation (shearing and fracturing) and faulting common.
- Rock composition quartzofeldspathic
- Strongly lithified by very low grade metamorphism (anchizone)
- Widespread quartz veining; chlorite and smectite can appear on shear zone surfaces
- Clay mineral assemblage dominated by illite; chlorite is minor and smectite rare. Crushing resistance – high range, tend to have slightly higher crushing resistance than Waipapa – type greywackes.

Eastern North Island - type greywacke:

- Well bedded relatively undeformed sedimentary sequence
- Rock composition variable from volcaniclastic to quartzofeldspathic
- Moderately lithified to a level intermediate between anchizone and zeolite zone diagenesis. The zeolite laumontite is relatively common in the matrices of many of these greywackes.
- Veining uncommon but veins usually contain only quartz, calcite or laumontite.
- Clay mineral assemblage : illite, smectite, chlorite; smectite often interlayered with chlorite or illite; high clay index
- Crushing resistance – medium to high range.

The differences in mineral content (particularly in the amount of quartz and feldspar clasts) between the volcaniclastic and quartzofeldspathic greywackes and the textural differences between foliated (Caples-type) and the unfoliated greywackes are illustrated in the microphotographs below.

	
Figure 5.4 (a) – above: Microphotograph of Auckland area Waipapa - type greywacke which contains considerably less quartz and feldspar and more detrital pyroxene and hornblende(olive green) and dark rock fragments (mainly volcanic) than the Torlesse sandstone. Scale bar = 0.5mm.	**Figure 5.4 (b) – above: Microphotograph of Wellington area Torlesse - type greywacke showing the abundance of quartz (white) and feldspar (grey) and a general lack of lithic clastic material. Same scale as (a).**
	
Figure 5.4 (c) – above: Microphotograph of Eastern North island greywacke showing lithic volcanic debris and angular quartz and feldspar grains. The olive brown material in the matrix and some grains is smectite. Same scale as (a).	**Figure 5.4 (d) – above: Microphotograph of Caples terrane greywacke showing strong foliation of the rock (oriented NE – SW in the microphoto) and lack of any obvious detrital texture. Same scale as (a).**

The nature of the minerals forming the matrix of a greywacke has an important effect on the hardness-toughness of the aggregate (eg crushing resistance) and some of its other fundamental properties (such as rock density). With the exception of the clay / sheet silicate minerals (illite-muscovite, chlorite and smectite), which when deformed slip parallel to their silicate sheet or even fold (illite / muscovite has elastic properties) rather than break, all the other minerals are brittle and most fracture along well defined cleavage planes in the crystal.

5.2 Murihiku – type Greywackes

There are at least seven working quarries in Murihiku-type greywackes in the North Island. The greywackes worked are mainly fine sandstones and siltstones. Zeolitised tuff horizons are common in these greywackes, thus selected quarrying is necessary to avoid producing zeolite-rich aggregates which can cause in-service problems particularly if the zeolite is laumontite.[38]

Figure 5.6 (a) :

Murihiku greywacke quarry showing white zeolitised tuff horizon.

Figure 5.6 (b) :

Microphotograph of zeolitised tuff in Murihiku greywacke; the cream coloured very irregular shaped material is zeolite. (crossed polars - field of view is 2mm).

The clay content in the matrices of the Murihiku sediments is complex. All rocks examined have contained mixtures of illite, chlorite, kaolin and smectite. The evidence from X-ray diffractograms indicate smectite is often interlayered with other clay minerals. Expansion and contraction of smectite may cause fritting (breakdown) of the more argillaceous aggregate chips.

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[38] See Section 3. 3 p. 21.

Murihiku - type greywacke aggregate properties:

Data from AP and GAP products from four Murihiku greywacke quarries and produced using simple processing methodologies, give crushing resistance values ranges from 4 to 8% fines at 130kN. High level multistage processing and scalping can produce an aggregate product for which the CR test will produce less than 2% fines at 130kN.

SE : Range from 27 to 55 for all products but the majority in the 30-40 range
CI : variable ranging from 2 to 6.
Plasticity Index (PI) : from 7-21 in simply processed GAP or AP aggregate but with judicious processing these indices can be reduced to CI < 3 and PI < 10.

5.3 Waipapa – type Greywackes

This greywacke type is the major aggregate resource for the northern half of the North Island from Kaeo (Northland) to the area immediately south-west of Lake Taupo.

The Waipapa-type greywackes are volcaniclastic and strongly lithified. Almost all the Waipapa -type rocks quarried are sandstones and siltstones. The degree of metamorphism of the Waipapa-type rocks vary, although they can all be considered as prehnite – pumpellyite facies; the highest metamorphic grade rocks are found in the Hunua Ranges. Chlorite dominates the clay mineral assemblage of Waipapa greywackes with minor associated illite and lesser amounts of smectite. Kaolin occurs only in weathering zones.

A characteristic of the Waipapa-type greywackes in the Northland/Auckland area (Kaeo to the Hunua Ranges) is their imbricated nature and the shearing into them of slices of basalt and chert and more rarely limestones. In the Waikato area the Waipapa-type rocks lack the sliced-in basalts and cherts, and the sediments tend to be coarser grained with more obvious bedding structures.

On a quarry scale, most of the Waipapa-type greywacke sequences are locally disrupted by major faults and shear zones. Fault and shear surfaces are usually coated with smectite and / or chlorite. Influx of water along these zones usually causes weathering, discolouration and sometimes hydrothermal alteration of the adjacent rocks.

Waipapa – type greywacke aggregate properties:

CR : Waipapa – type greywackes, produced using multist processing, provide 10% fines at around 330 kNs. The levels of fines are produced when GAP products are tested.

SE : variable although > 25 in GAP products and 40 - 60 in TNZ M/4 AP40 products.
CI : usually around 3 – 5 in GAP products and 2 - 3 in TNZ M/4 AP40 products
PI variable in GAP products but usually <10 in TNZ M/4 AP40 products.
PSV: usually 50 - 55.

5.4 Torlesse – type Greywackes

Torlesse greywackes have many geological properties similar to the Waipapa–type greywackes. In the Wellington region the Torlesse greywackes are locally strongly imbricated and sometimes include slices of basalts and cherts. Torlesse sediments are quartzofeldspathic and thus contain abundant detrital grains of quartz and feldspar and micas. The rock matrices are illite-rich and contain much less chlorite and smectite than do the Waipapa greywackes.

Due to the abundance of quartz as detrital grains and as matrix cement in Torlesse sandstones aggregates produced from them have slightly higher crushing resistance values and SE values than do Waipapa type aggregates. Torlesse greywackes usually have low CI values, but because the sediments may locally contain abundant detrital micas, which contribute to plasticity, some may have plastic fines.

Torlesse – type greywacke aggregate properties:

These aggregates tend to have a very high crushing resistance :

CR: 2% at 130 kN and for GAP 65 products tested at 100 kN.
2.5% @ 230kN in TNZ M/4 AP 40 products
Some aggregates may require loads of more than 400kN to produce 10% fines.

SE : in the 60 – 65% range
CI : varies but usually in the 2 – 4 range
PI : variable and may be high in GAP products
PSVs of sealing chips may exceed 55.

5.5 Eastern North Island - type Greywackes

This greywacke type provides aggregate in the Coromandel Peninsula and for the area from Whakatane to Napier (Figure 5.3).

In the Coromandel Peninsula these rocks are strongly indurated and volcaniclastic but zeolite facies in terms of their metamorphism. Locally they have been intensely hydrothermally altered. In the Whakatane – Gisborne area the rocks are more quarto-feldspathic, locally conglomeratic, and may be intensely sheared but the majority of greywackes in this region are indurated alternating sandstone / argillite sequences. There are few quarries in these greywackes. The quarries that do exist are located in the conglomeratic horizons or in parts of the sequence where sandstones dominate.

Chlorite, illite and smectite are the common clay minerals. Smectite is often interlayered with the chlorite and illite as well as occurring as discrete minerals.

Eastern North Island - type greywacke aggregate properties:

The aggregate properties are highly variable but in general :

CR: around 6 % fines are produced at 130 kN, which is slightly higher than for Murihiku-type greywacke aggregates which are less indurated tha the Eastern North Island greywackes.

CI: can be very high. CI = 13 to 14 in the argillite sequences but processing (and high wastage) will produce an aggregate with much lower CI values.

5.6 Caples – type Greywackes

There is currently one quarry in Northland exploiting Caples - type greywacke. Other quarries have existed in the past but most of the outcrops of this greywacke-type are now encompassed within the boundaries of forest parks.

The Caples – type greywackes are volcaniclastic sediments that have been penetratively deformed and metamorphosed to the extent that they are now semischistose. While there are variations in mineral proportions and grainsize in the rock, there is no major post-metamorphic shearing, deformation or veining with accompanying alteration. Chlorite and illite are the only clay minerals that have been detected.

Caples - type greywacke aggregate properties[39]

Crushing Resistance on GAP 65 (3 samples) 8.6 – 10.7% fines at 130 kN.

No Clay Index or Plasticity Index data is available but since this greywacke has been metamorphosed at temperatures above the stability range of smectites, and no swelling clays have been detected in fresh samples, CI values will be minimal.

5.7 Greywacke Gravels

Gravels derived from the Torlesse-type greywackes forming the axial ranges of the North Island are the major aggregate resource for the Hawkes Bay, Manawatu, Wairarapa, and Wanganui and Wellington districts. Since greywackes, even of the one type, have variations in properties and large areas of greywacke are being eroded to shed material into the river systems, the individual pebbles / boulders show a range of grain sizes and colours although all appear to be Torlesse-type. Very small amounts of chocolate or reddish coloured chert and igneous pebbles (both found in Torlesse – terrane greywacke sequences) can appear in some gravels.

Natural sorting and abrasion during river transport has eliminated all the weaker rocks and generally provide a very clean resource which produces aggregate with properties in the high end of Torlesse-type greywackes.

River systems in the Gisborne - Napier area are sourcing material which may be derived from outcrops of Eastern North Island–type greywackes, and / or Torlesse-type greywackes.

Greywacke gravels being harvested from coastal terraces on the west side of the Hauraki Gulf, and are sourced from Waipapa-type greywackes.

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[39] Caples terrane rocks are widespread in the South Island (See Figure 5.1) and it is expected that more information will become available when this project is extended to he South Island.

5.8 Summary and Comment

Greywacke aggregates have very variable properties but five types can be recognised each with a distinctive matrix of engineering properties.

Two of the greywacke types (Waipapa and Torlesse –type) have very high crushing resistance values. The low contents of fines produced can mean that these aggregates sometimes have difficulties with achieving particle size distributions within the TNZ M/4 prescribed envelope.

Two other types of aggregate (Murihiku and the Eastern North Island types) have less strength and lower durability mainly because of the occurrence in their source rocks of swelling clays and zeolites.

A fifth greywacke type (Caples - type) is semischistose and relatively coarse grained. Chlorite is the main clay-type mineral and sweeling clays are absent in this greywacke type.

With the exception of the Torlesse – type, the greywackes are volcaniclastic. Such greywackes all contain the minerals chlorite, and in greywackes that are only diagenetically altered, smectite. Since clay minerals are concentrated in the matrix of the sandstones, in argillites, and also on joint and shear surfaces, the clay content of the aggregate can be reduced by washing and screening out of fines.

While quartz is abundant in all the greywackes, strained quartz grains and clasts of multicrystalline or fibrous quartz are very rare. Other silica minerals that are cited as causing issues with alkali aggregate reactivity in aggregates to be used in concrete, and which are common in volcanic rocks (tridymite and cristobalite), do not survive the process of sedimentation and diagenesis and are absent in greywacke aggregates.

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6. CHERTS AND SILICA - RICH ROCKS

Most physically hard and inert rocks have at one time or other been quarried. Cherts and silica-rich rocks are exceptionally hard and inert.

Red cherts that locally form thick sequences in the Waipapa-type rocks are being quarried on islands in the Hauraki Gulf largely to provide aggregate for decorative purposes. Similar cherts are found in the Torlesse greywackes in the Wellington region. Red-brown and chocolate coloured chert pebbles are relatively common in gravels derived from the Torlesse-type greywackes of the axial ranges in the Wairarapa, Manawatu and Wellington areas.

The oldest rocks in the Waipapa sequence, found in the Whangaroa/Kaeo area, are very siliceous and chert-like. Other silicified rocks are also being quarried in parts of Northland.

These rocks generally lack a clay mineral assemblage. Very minor illite has been recorded in some cherts. Sulphides occur in some types of siliceous rocks.

Source properties :

Available data for crushing resistance is c.2% fines at 230kN.

These rocks produce non plastic fines and have minimal clay index values.

7. IGNEOUS ROCKS AS AGGREGATE RESOURCES

7.1 Introduction

Igneous rocks, mainly volcanics, are the major resource for the production of aggregates in much of Northland, the Bay of Plenty, and the Taranaki region. In the national context approximately 25% of all aggregates produced are sourced from igneous rocks.

Igneous rocks are formed from melts (called magmas) which originate deep in the interior of the earth. The processes by which magmas are formed and evolve during their ascent through the earth's crust are very complex and as a result there are a wide range of igneous rock types. The simplest way of explaining the occurrence and type of volcanic rocks is to associate them according to their position with respect to the crustal plates of different types that constitute Earth's surface.

For most of its geologically short life New Zealand has been on a plate boundary where oceanic crust has been pushed (subducted) under continental crust. Melting at various levels along the subduction zone produces chains of volcanoes (volcanic arcs) that parallel the plate boundary (Figure 7.1). Arc volcanism is very complex. There may be parallel sets of volcanic arcs each with different chemical signatures. Some volcanic arcs also show chemical variations along the arc. These along- and cross-arc differences can be very significant, as can be changes in the nature of the rocks erupted with time as the arc system evolves.[40]

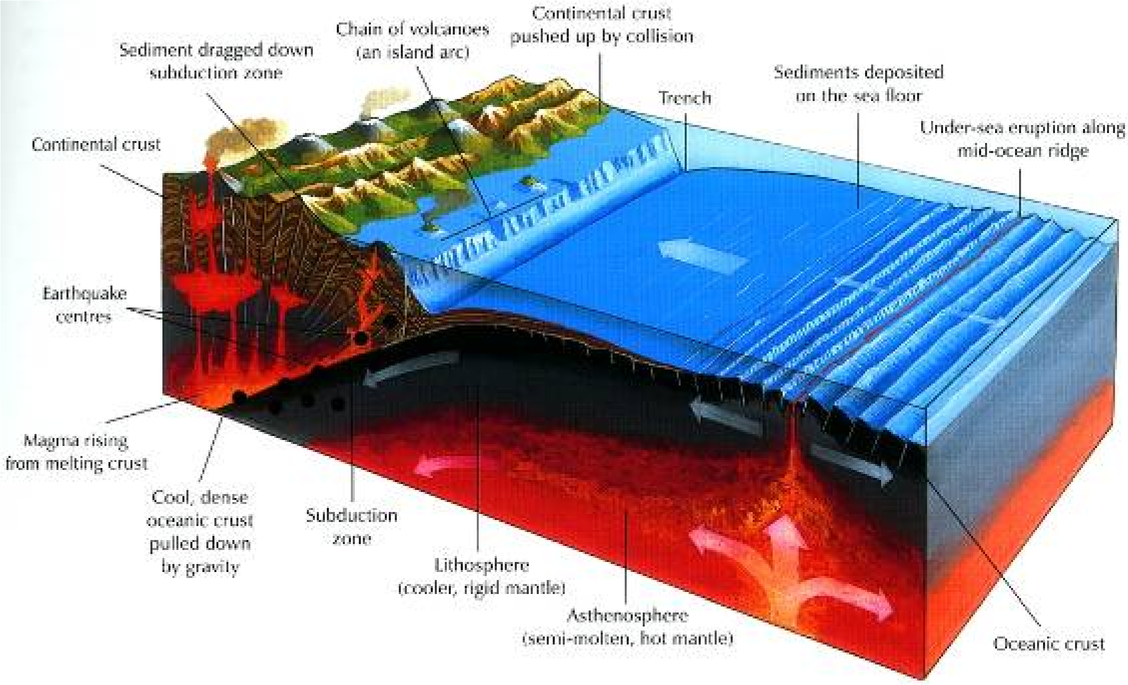

Figure 7.1 (above) : Diagram showing causal relationship of different magma types to geological tectonic environment.

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[40] The volcanic arc system that erupted in the northern and central North Island from 25 Ma to the present shows such variations, changing in composition with time and also across the arc; see Sections 7.3 and 7.4.

Earth’s interior is not uniform. Local “hot spots” in the mantle cause melting and production of basalt magma which will leak upwards towards Earth’s surface. The resulting volcanic fields, which are unrelated to subduction and often far from any plate boundary, are known as intraplate or “hot spot”; they occur in oceanic and terrestrial crustal environments.

In the oceanic environment where crust is being rifted apart, basalt magma generated in the hot mantle erupts forming new ocean floor crust (sometimes called ophiolite).

The classification (naming) of igneous rocks is largely based on the silica content (weight percent of SiO_2) of their parent magma. Silica content determines to a considerable extent the nature of the minerals in the rocks as well as many important physical properties of the magma. The chemical silica content of the rock is not the same as the amount of silica minerals crystallising in the rock. Most rock-forming minerals are silicates, that is they are composed of silicate tetrahedra linked together in combination with other elements, and they are often hydrous. Silica minerals, of which quartz is the best known, are essentially pure SiO_2. Only volcanic rocks which have chemical compositions of more than approximately 65% SiO_2 can contain a silica mineral,[41] thus silica minerals are very rare in basalts and andesites. In dacites and rhyolites the most abundant silica mineral is usually tridymite although lesser amounts of cristobalite also occur. In rhyolites these minerals may constitute close to 50% of the volume of the rock. In silica-rich andesites, dacites and rhyolites, the minerals tridymite and cristobalite most commonly form as devitrification products of volcanic glass.

If the magma has a low (chemical) silica content, it will be very fluid and may take only a few days to a week to rise from its source at depths in excess of 100km to erupt as lava on the Earth’s surface. As the melt rises through Earth’s crust it cools and the minerals characteristic of igneous rocks (olivines, pyroxenes, plagioclase feldspars, hornblende, and iron oxides) begin to crystallise and can grow to form relatively large crystals before reaching the surface. When the lava is erupted on the earth’s surface, it chills and crystallises rapidly forming many small crystals. That part of the lava which is still liquid when it is erupted may also freeze to form glass. The texture of large crystals (phenocrysts) that grew while the magma was still in the crust, enclosed in a finer grained crystalline and/or glassy matrix (also known as groundmass) that formed after the lava was erupted is typical of volcanic rocks (a texture known as porphyritc).

Often the lava chills so quickly that all the volcanic gases rising to the surface of the lava flow cannot escape before the lava solidifies trapping the gas bubbles in the lava. The resulting rock contains many semispherical cavities or vesicles (texture known as vesicular). Vesicular rock is usually found close to the surface of the flow.

The tops and ottoms of lava flows, where lava has chilled against air and earth respectively, will be fine grained or glassy. Most basalt lavas also have columnar joint systems perpendicular to the cooling surfaces. If the lava has flowed extensively those minerals (usually feldspars) that had crystallised in the lava before it was extruded will orient parallel to flow direction and the rock will be platey.

Very fluid basalts and basic (i.e. silica-poor) andesite erupting on land produce thin lava flows that may be quite extensive. If the lava erupts under pressure molten material is “fire fountained” into the air. Lava spatter dropping back and accumulating around the vent builds scoria cones; scoria cones may lack flows or only have very small flows associated with them.

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[41] There are at least six polymorphs (ie minerals with the same chemical composition but different crystal structures) of SiO_2.

Basalt lavas erupted in relatively deep water marine environments are restrained by the overlying mass of water from fire fountaining. Hot lava quickly chills against the cold water forming globular masses of molten basalt enclosed within a chilled glassy rim (selvage); these are known as pillow lavas. The continuing eruptions from the vent disrupt the pillow pile causing the glassy selvages to break, allowing the lava to flow out and chill again against the sea water. Thus pillow lavas are usually associated with masses of broken glassy material called hyaloclastites (Figure 7.2).

Figure 7.2 :

Pillow lavas of basalt with hyaloclastite (bottom left corner).

Photo by D. L. Homer from 'Geology of the Kaitaia area' IGNS 1: 250 000 geological map 1, (1996).

In contrast to basalts and most andesites, the silica-rich dacite and rhyolite lavas are very viscous. They extrude slowly, the lava accumulating above the vent in thick piles known as dome complexes. Very silica–rich lavas also have difficulty crystallising so form glassy flows that contain the volcanic gasses trapped within them. These gasses either extensively alter the rock as it cools and/or if they develop sufficient pressure, blow apart the semi-solid lava converting it into a shower of ash, glass shards and crystal fragments that blanket the countryside leaving a large explosion crater at the vent site (Figure 7.3).

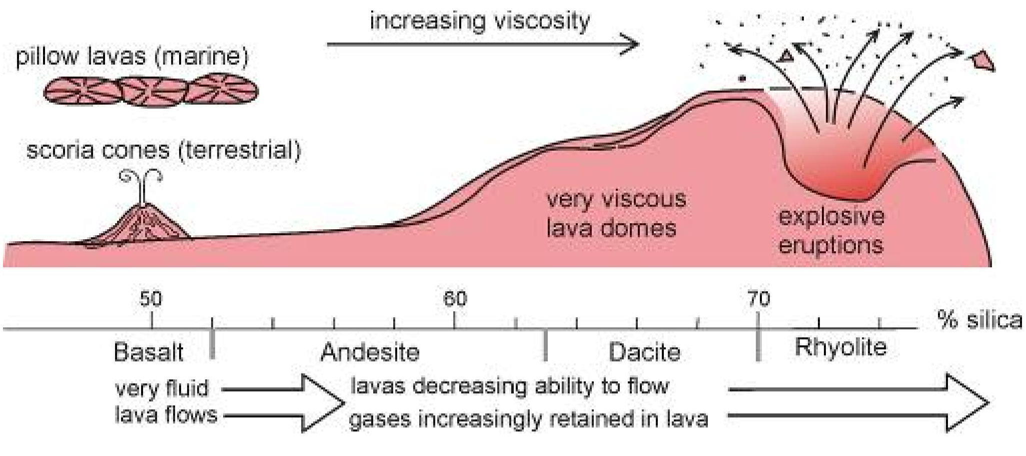


Figure 7.3 : Diagram showing relationship between silica content, fluidity of lavas and the lava / eruptive type. Volcanic rock names are also assigned according to the silica (ie SiO2) content of the lava.

The nature of minerals in igneous rocks also depends on the chemistry of the magma. Igneous rocks with low silica contents (ie less than 52% SiO_2), and consequently high amounts of aluminium, iron, magnesium and calcium (ie basalts, and their plutonic equivalents dolerites and gabbros) contain combinations of olivine, augite (calcium-rich pyroxene), plagioclase (calcium–rich feldspar) and iron oxides. Volcanic rocks with high (ie > 63%) chemical silica contents (dacites and rhyolites) are composed of hypersthene (Fe-Mg pyroxene), hornblende, biotite, alkali and plagioclase feldspars, and quartz or other silica minerals. Intermediate silica content igneous rocks (andesites and diorites) are dominantly composed of augite and/or hypersthene, hornblende, plagioclase feldspar, and iron oxides. Figures 7.4 (a) to (d) show most of these minerals in volcanic rocks.

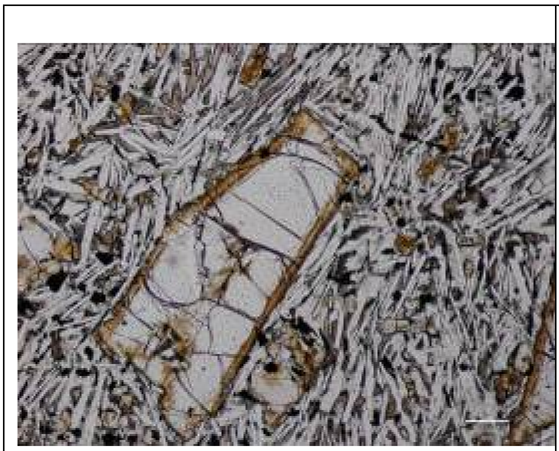
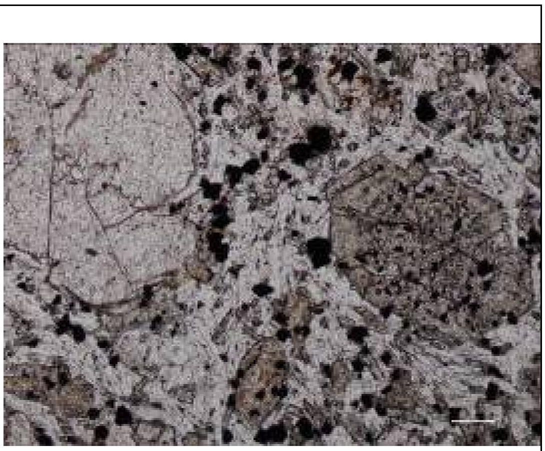
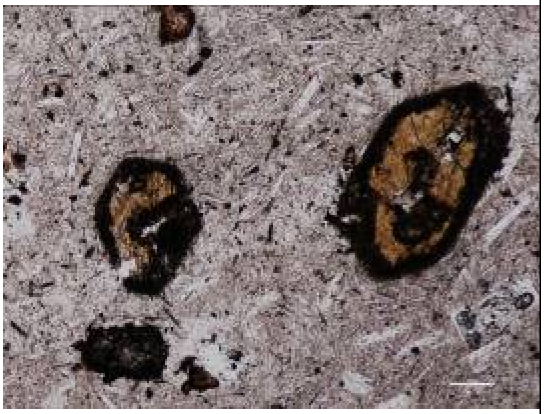
	

Figure 7.4 (a) – above: Microphotograph of olivine basalt . The large colourless olivine phenocryst (centre) has oxidised (brown) rims). Note the flow orientation of the colourless feldspar needles in the matrix. Plane polarised light. Scale bar = 0.1mm.	**Figure 7.4 (b) – above: Microphotograph of phenocrysts of augite (a calcic pyroxene – center right) and olivine (colourless crystal top left) in olivine basalt. Black minerals are iron oxides; white needles are feldspars. Plane polarised light Scale bar 0.1mm.**
	
Figure 7.4 (c) – above: Microphotograph of two pyroxene andesite: phenocrysts of pyroxenes and plagioclase feldspar in very fine grained glassy matrix; brown material lower centre is glass. Plane polarised light. Scale bar 0.5mm	**Figure 7.4 (d) – above: Microphotograph of hornblende dacite. The brown hornblende is showing oxidation and alteration effects on its rims. The pale brown matrix is intergrowths of feldspar and silica minerals. Scale bar 0.1mm.**

In the types of volcanic rocks that occur in the North Island, feldspar is always a major constituent, and particularly dominates in the matrix of the rock, except in the case of lava that has been very quickly chilled and instead contains abundant glass. All the most common minerals in volcanic rocks are brittle low-toughness minerals. Consequently volcanic rocks can not achieve the CR of greywackes such as the Waipapa– or Torlesse-type greywackes. Volcanic rocks also have higher SE values. Volcanic rocks that have not been subject to post depositional alteration will have low CI values and be non plastic.

While fresh volcanic glass is physically one of the strongest components of volcanic rocks, it is chemically the weakest component. Glass is a metastable material, that is the liquid has chilled / solidified too quickly for the ions in it to organize themselves into crystalline structures (minerals). Glass is very reactive and with time (geological rather than human time scale) it will devitrify and crystallize. The addition of water accelerates devitrification of volcanic glass and to some extent also controls the new minerals that will crystallize. Volcanic glasses devitrify and hydrate at rates determined by the chemistry of the glass and the temperature at which the alteration occurs.

All the first-crystallising (high temperature) silicate and oxide minerals in volcanic rocks are rich in so-called refractory elements (aluminium, magnesium and iron) and calcium. The alkalies (sodium and potassium) are concentrated in the glassy groundmass of the rock.

Basaltic glasses contain in the range 45-52% silica (and abundant aluminum, iron and magnesium). Basaltic glass in contact with sea water rapidly hydrates and is extensively leached of all elements (except Fe and Ti) to form a gel-like substance called palagonite. The palagonite then reacts with silica –rich solutions and converts to smectite (Stroncik and Schmincke, 2001). Alkalies leached out of the glass may, under certain conditions, combine with silica and crystallize as zeolites.

Silica – rich volcanic glasses, such as are formed by chilling dacite and rhyolite lavas, will have SiO_2 contents in the range 68 – 78% SiO_2 and high total alkali contents. High temperature devitrification of these glasses will result in the crystallisation of spherules composed of fibrous forms of feldspars and the silica mineral tridymite.[42] When devitification/hydration of silica-rich glass occurs at low temperature, alkalies diffuse out of the glass simultaneously with the hydration (diffusion of water into the glass) thus the hydrated glass is enriched in silica which then converts directly to tridymite and sometimes also to cristobalite (**O'Keefe, 1984**). Minor amounts of smectite may accompany the formation of the tridymite and cristobalite.

Volcanic rocks are a major resource for production of aggregates in the North Island. The quality and nature of the aggregate resource is a function of the rock type (ie its chemistry and mineral content), and the environment in which it was erupted. A basalt or an andesite lava that has been erupted on land (terrestrial environment) and has not subsequently been either weathered or hydrothermally altered will be a very different material to the same rock type that has been erupted in the marine (oceanic) environment.

In the following sections the volcanic rocks used as aggregates in the North Island are described broadly according to rock type, but also clustered to provide an understanding of regional variations which are related to geological environments.

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[42] Tridymite and cristobalite are low density forms of SiO_2. Compared with quartz, which has a relatively dense structure consisting of a framework of joined SiO_4 tetrahedra and is thus unable to include many impurities, tridymite and cristobalite have open networks of six sided rings and can accommodate roughly ten times more impurities than can quartz in its structural cavities, these impurities are usually alkalies and/ or water. Cristobalite will only crystallise at low temperatures when water is present (Heaney, 1994, p6).

7.2 Young Intraplate Basalts

Very small basaltic intraplate or “hot spot” volcanoes cluster in geographically discrete centres from the Kaikohe/ Bay of Islands area to west Waikato (Figure 7.5). Each of the individual centres has a slightly different age. The oldest is in the Bay of Islands but volcanism has continued in Northland until relatively recently. The youngest is the Auckland volcanic field which is considered to be still active.

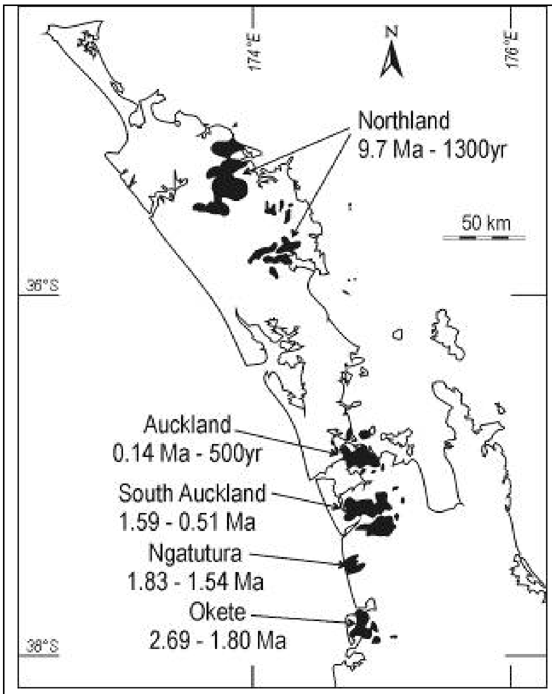

Figure 7.5 :

Map showing the location and age of the young intraplate (“hot spot”) basalt centres of the North Island.

Each lava flow is a unique pulse of highly fluid magma; generally only one eruption occurs at each site. There are slight chemical compositional differences, reflected in different mineral composition and texture, between centres and between individual lava flows. Some of the basalts are slightly alkaline in their chemistry.[43]

All of these basalts have been erupted on a land surface with significant topography which will control flow direction. Lava flows are frequently ponded and thickened behind surface topographic highs. Since most of these basalt flows are relatively small it is rare to have more than one quarry working a lava flow. Many of the flows have been quarried in the past although urban expansion (particularly in the Auckland area) now limits or prohibits further quarrying activities. Currently there are active quarries in basalt flows in the Bay of Islands - Kaikohe area and in South Auckland; additionally there are scoria quarries on many cones, including in the Auckland field. In the Waikato district the Ngatutura and Okete centres have been quarried, but to the writers knowledge there are no active quarries.

Individual flows, although mineralogically uniform, show variations in rock texture, grain size and in vesicularity which are related to position in the flow. Basalt close to flow cooling surfaces is finer grained and more vesicular than basalt in the centre of the flow.

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[43] That is they have higher than normal contents of alkalies, generally contain abundant olivine, and sometimes very small amounts of nepheline (a sodium- rich and silica- poor minerals). Other basalts are “tholeiitic”, that is contain less alkalies and olivine and more abundant feldspars.

Examples of the range in mineralogical and textural variations found in these young “hot spot” basalts are shown in Figure 7.6.

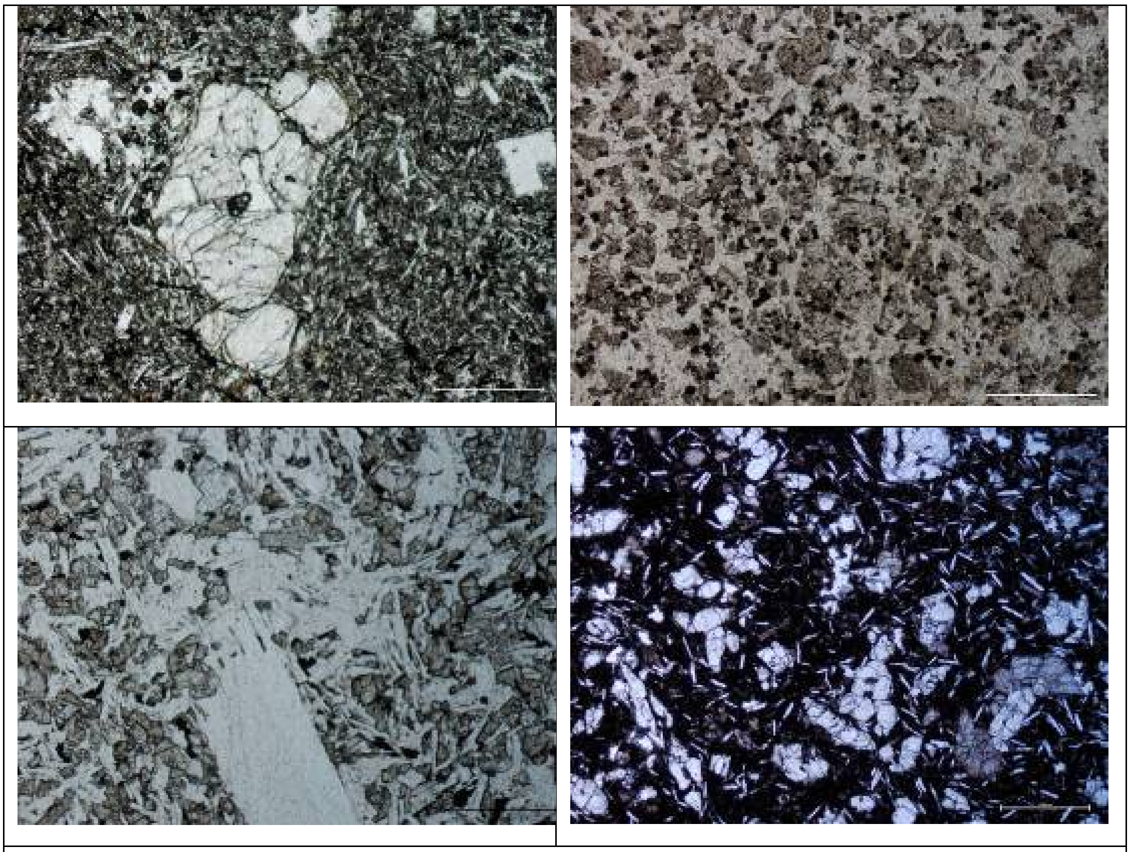

Figure 7.6 : Microphotos showing the considerable variations in nature of young “hot spot” basalts quarried for aggregate in the Northland/Auckland region. From top left clockwise : porphyritic olivine basalt; crystalline equidimensional olivine – augite basalt; fine-grained very glassy olivine basalt; completely crystalline feldspathic basalt (bottom left). All photos in plane polarised light; Scale bars in all photos = 0.1mm.

The young intraplate basalts produce very high quality aggregates. Vesicles may occasionally contain siderite (iron carbonate) or opaline silica. These basalts are not veined and joint systems are not usually coated with secondary minerals. Smectite is the common weathering product of basalts but because these basalts are young, few flows have been affected by even mild weathering.

<u>Intraplate Basalt Aggregate Properties:</u>

The basalts do not have very high CR values unless they are very glassy. The crushing resistance (range) is:

3 – 4 % fines at 130kN (base course)
5 - 6 % fines at 230kN (sealing chip)
10% fines produced in the 260-290 kN range (ie at less than 300 kN)

SE : high even in GAP 40/65 products where SE is generally in the range 50 – 75.
PI : non plastic
CI : negligible
Cleanness values are very high.
PSV : usually in the 52 – 55 range.

7.3 Ophiolitic Basalts : Tangihua and Matakaoa Volcanics

The ophiolitic basalts are slices of Cretaceous/early Tertiary ocean floor material that have been emplaced on Northland and East Cape areas enclosed within large debris flows known as the Northland and East Coast Allochthons (Figure 7.7). The volcanic rocks, known as Tangihua (Northland) and Matakaoa (East Coast) Volcanics are augite - plagioclase basalts. Unlike most other New Zealand basalts, they do not usually contain olivine.

Quarries in the Tangihua Volcanics are the major aggregate resource in Northland (north of Hokianga Harbour) and in the Far North. Many of the ophiolite massifs in central Northland have also been quarried in the recent past. There is one large active quarry in these rocks in the South Kaipara. To the writer's knowledge no quarries currently operate in Matakaoa Volcanics although river gravels derived from them are harvested in the East Cape region.

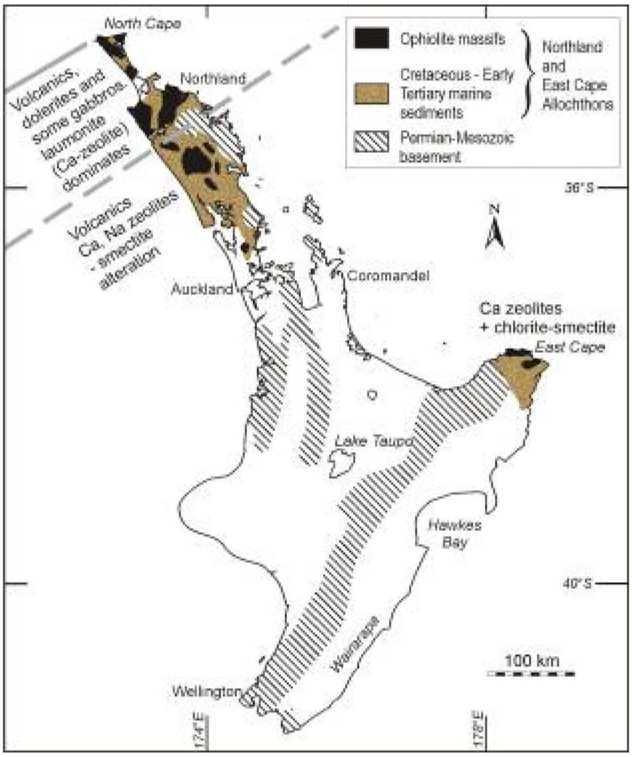

Figure 7.7 :

Distribution of ophiolitic basalts in the North Island and their alteration zones.

In the aggregate and quarry industries the ophiolitic basalts are often (incorrectly) called andesites, probably because in Northland there are also quarries exploiting young terrestrial basalts and these two types of basalt look and present very differently in quarries and their aggregates. Nevertheless the ophiolitic basalts are by any definition of the term true basalts. Their different appearance and properties, compared with the intraplate basalts, reflect the fact that they have been erupted in an oceanic environment and the ophiolites have also been transported long distances in huge debris flows which have mixed up different types of rocks and are also locally very deformed. Pillow lavas, dolerites and slices of reddish coloured cherts and deep water marine argillite can occur in a single quarry face (Figure 7.8).

Figure 7.8 : Ophiolitic (Tangihua) basalt quarry : note dark grey lensoid pillow forms (eg top centre). The almost vertical bands of light coloured rock are dykes of dolerite (left of centre) and the red-brown and buff-coloured rocks are ocean floor sediment sheared into the volcanics.

Ophiolite complexes, like those in Northland, are composed of layers of different types of basaltic rocks.[44] Enormous piles of pillow lava basalts and associated hyaloclastites form over and around the eruptive vents on the sea floor. Silica liberated by the volcanism and accompanying devitrification of glass encourages "blooms" of organisms (radiolarian) that built their skeletons of silica which post-mortem accumulate on the sea floor as siliceous sediments (cherts). Later lavas intruded into the thick pillow piles are insulated from contact with sea water and cool slowly forming coarse-grained dolerites and gabbros.

Ocean floor volcanism heats sea water. When the lavas cool, they contract and fracture allowing the hot sea water to circulate through the lava pile. Volcanic glass reacts with sea water, forming smectite-type minerals and zeolites which often fill veins and coat joints. Zeolites also form as alteration products of feldspars within the rock.

There is a well described depth-related pattern of rock types and their temperature-related alteration related to the rock sequence (pillow lavas at the top, and dykes of dolerites and the gabbros at the bottom of the succession) which also depends on the temperature (ie depth) that the hot sea water water penetrates into the volcanic pile, "fixing"[45] some elements into the rocks and leaching other elements out of them (**Bednarz and Schminke, 1989; Leverne et al, 2001**). The top to bottom rock and alteration pattern of ophiolites can be summarised as (see also Figure 7.10) :

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[44] There are many descriptions of ophiolite sequences in the international literature. The North Island ophiolite sequence has been described by Brothers and Delaloye (1982).

[45] That is the cations are held in the material in sites that are non-exchangeable or difficult to exchange. – usually clay minerals that are weakly expanding and zeolites.

Layer 1 (L1) = fine grained deep sea sediments (cherts and argillites), breccias composed of broken pillow lava material and volcanic glass. Cold water alteration of the glassy material “fixes” K and Mg into the rocks as Mg-smectite and K, Na Zeolites.

Layer 2 (L2) = pillow lava material and dolerite dikes. Warm water alteration of volcanic glass and feldspars leaches K and fixes Na and Ca into smectite and zeolites.

Layer 3 (L3) = dolerites and gabbros deeper in the ophiolite pile; alteration occurs at relatively high temperature (> 200°C). K and Na are leached from the rock and Ca is fixed into the rock as exchangeable cations in smectite and Ca-rich zeolites such as laumontite.

The textures, grain size of minerals and degree of alteration in the ophiolite basalts are very variable. Some of these are illustrated in Figure 7.9 (a) to (d).

Figure 7.9 (a) above : Thinsection microphoto of breccia composed of angular fragments of fine grained but altered pillow basalt material. On this scale individual crystals within the fragments are barely visible. Scale bar = 1mm

Figure 7.9 (b) above : Thinsection microphoto of slightly altered oceanic basalt showing needles of feldspar (white), pyroxene (pale brown), iron oxides (black) and altered matrix material. Scale bar = 1mm.

Figure 7.9 (c) below : Thinsection microphoto of oceanic basalt showing typical texture of altered feldspar (white), pyroxene (pale brown) and iron oxides (black). Veins of zeolite cut the rock. Scale bar = 1mm

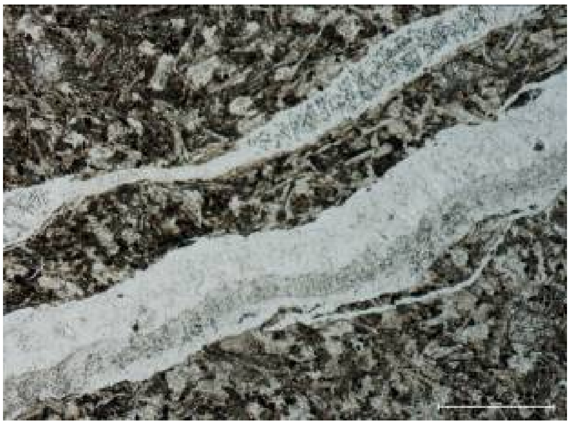
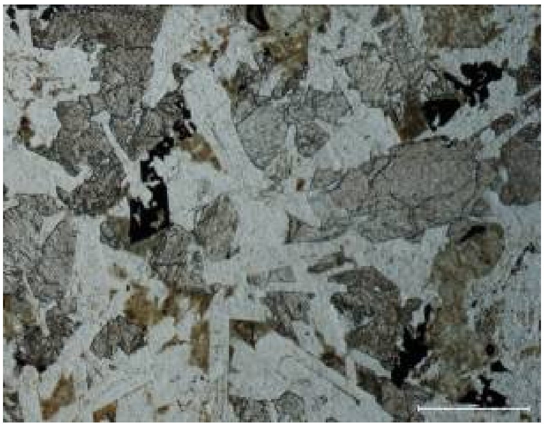


Figure 7.9 (d) below : Thinsection microphoto of dolerite showing large interlocking crystals of feldspar (white), grey pyroxene, iron oxides (black) with brown alteration material. Scale bar = 1mm



When the ocean floor material was tipped onto the submerged mass now known as Northland (and East Cape), the different layers in the ophiolite pile delaminated. The top layer and the overlying marine sediments being shed first to travel down Northland towards Auckland followed by progressively deeper layers in the volcanic pile (Figure 7.9) each of which travelled progressively lesser distances down Northland (**Brothers and Delaloye, 1982**).

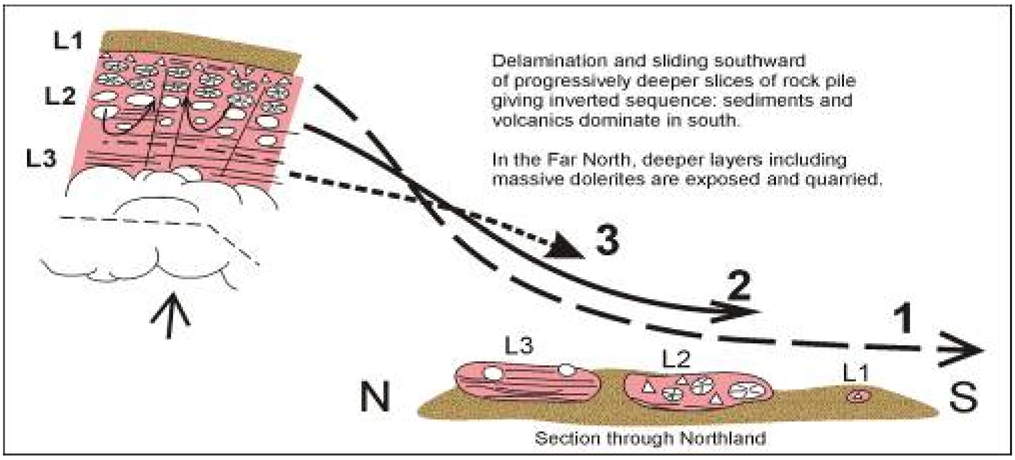


Figure 7.10 : Diagram showing delamination of the ophiolite complex and the resulting geographic distribution of the various layers down Northland. See also Figure 7.7.

This has implications for the nature of the material quarried and the properties of the aggregate produced. In the Far North, where the material is closest to source, large coherent doleritic and gabbroic bodies are exposed and exploited in several quarries. Quarries south of Hokianga are largely composed of the basalt lava and pillow lava material although lenses of dolerite may be exposed from time to time.

Ophiolite Basalt Aggregate Properties :

The properties of aggregates produced from ophiolite basalts will vary considerably depending on whether massive dolerite or a pillow lava sequence is being quarried.

Aggregate from quarries in the massive dolerite/gabbro sequences have
Crushing resistance in the range of
2-3% fines at 130 kN.
c. 5% fines at 230 kN
Good quality sealing chip with a relatively high PSV (55-59) and crushing resistance (10% fines at c.400kN) can be produced from some of these coarse grained rocks.

PI and CI values are variable
CI : values which will include the presence of zeolite are generally less than 9.
PI : in the 5 – 9 range.

Quarries in the pillow lava sequences have much lower crushing resistance, ie >5% fines at 130 kN. GAP products produce 5 – 7% fines at 110 kN
CI : values generally less than 10
PI : 10 - 15

It should be noted that some of these aggregates (particularly in northern Northland) are saturated with (exchangeable) calcium while others (in central and southern Northland) will have high contents of exchangeable sodium and potassium. This will have an effect on their reaction to lime stabilisation.

7.4 Arc-related Basalts and Basaltic (basic) Andesites

Geologists recognise arc basalts by their characteristic trace element and other geochemical properties which distinguish them from intraplate basalts, although in terms of their eruptive style, and mineralogical composition they are very similar. Arc basalts and basaltic andesites[46] are included together in this inventory because they have very similar materials properties and they have been erupted in similar environments.

Unlike the ophiolitic basalts, the arc basalts rocks are “rooted” into the underlying rocks by feeder dykes and their flows can often be followed back to the feeder vent. The arc basalts and basic andesites show all the primary features of lava flows. They are relatively undeformed and generally lack veins and/or shear zones filled with secondary smectite–type minerals. Quarries in the arc rocks usually produce from single flows.

Arc (ie subduction zone) volcanism began in the northern part of the North Island about 25 million years ago. In the North Cape – Cape Reinga area it is difficult to distinguish arc basalts from the ophiolite type basalts as they both form pillow lavas and marine flows. However definite Miocene arc basalts and basaltic andesites are exposed as small intrusions, submarine flows, and the eroded remnants of large volcanic centers along the western side of the Northland Peninsula, from the south Hokianga (Waipoua – Maunganui Bluff centre), Dargaville - Hukatere Peninsula (North Kaipara centre) and the Waitakere Ranges as shown in Figure 7.11.

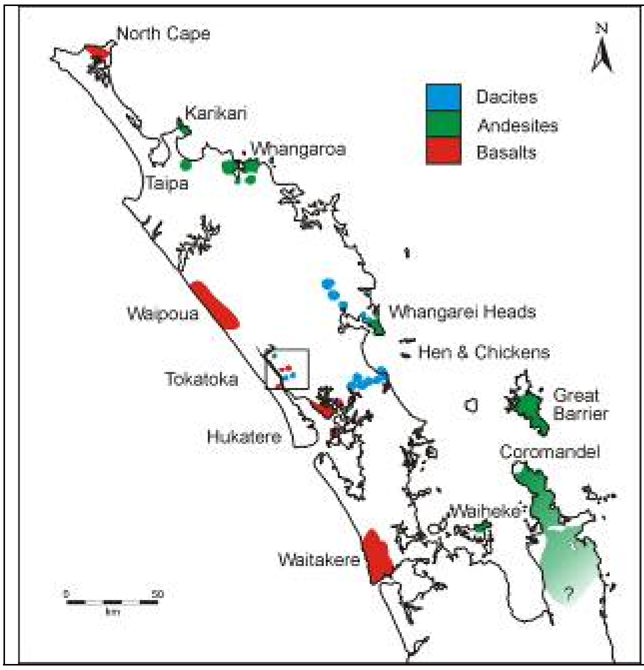


Figure 7.11 :

Map of the Auckland – Northland area showing location of arc volcanics older than 15 Ma. Note basaltic andesites are included with basalt.

Many of the Miocene basaltic rocks were erupted in the marine environment and consequently contain smectite and zeolite. The dyke rocks also tend to show some, although minor alteration affects [Figure 7.12 (a) and (b)]. Most of the basalt or basic andesite lava flows and dykes suitable for aggregate in Northland have been quarried at some time in the past but the majority have now either been exhausted or are in areas designated as reserves Nevertheless there are active quarries in basalts in each of the three main volcanic centres.

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[46] Basaltic andesites have silica contents less than 54% SiO_2 and, like basalts are composed of augite, plagioclase, iron oxides and variable amounts of olivine.

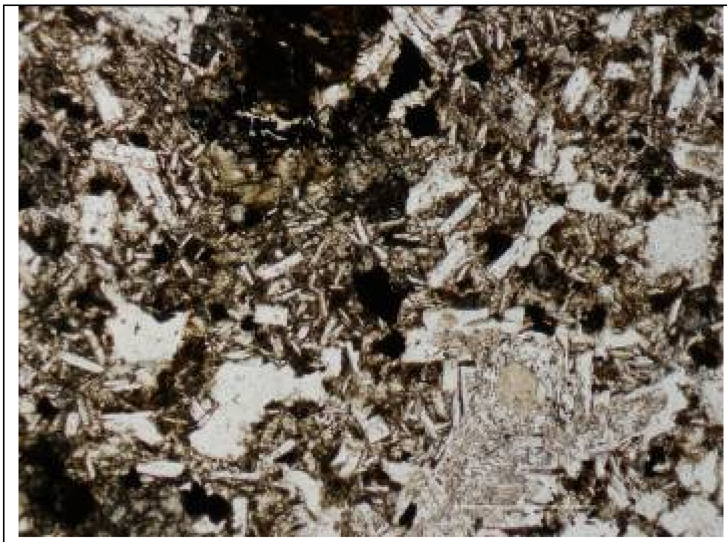

Figure 7.12 (a) left : Microphoto of Northland Miocene basaltic andesite (marine lava flow) showing zeolitised feldspar (pinkish buff coloured mineral in centre of feldspar, bottom right) and extensive alteration of glassy matrix of the rock to smectite (olive green colour).
Plane polarised light. Scale bar 0.5mm.

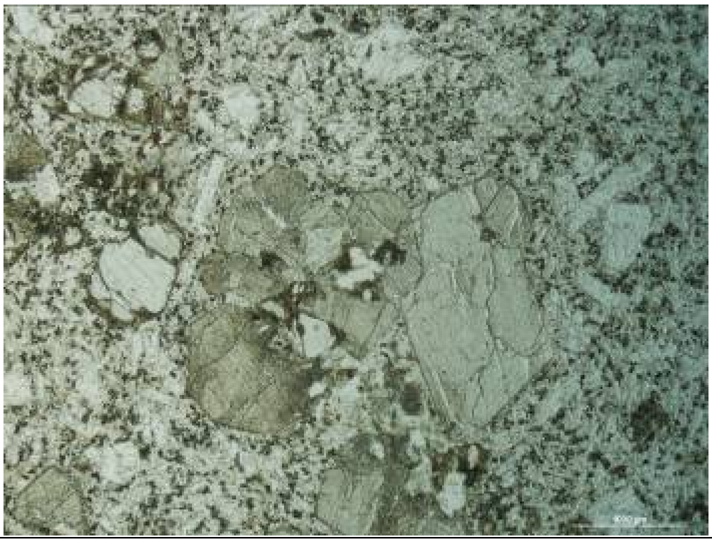

Figure 7.12 (b) left : Microphoto of relatively unaltered Northland late Miocene basalt (dyke rock) showing augite (centre) and slightly altered olivine (top and centre left).
Plane polarised light. Scale bar 1mm.

After 15 Ma the focus of arc volcanic activity largely shifted to the Coromandel Peninsula. The nature of the arc volcanism also changed. Arc basalt and basic andesite rocks became relatively rare in the north and central North Island region.

Nevertheless small amounts of basalt continued to erupt. About 10 MaBP there was a small pulse of arc–related basaltic magmatism in Northland focused on the Matakana / Leigh area. There are also small basalt fields on Coromandel Peninsula, in the eastern Waikato, and the central North Island (see Figure 7.13). Basalts, of approximately 10 – 5 Ma age, occur in the Mercury Islands and on the mainland north of Whitianga (Kuaotunu Peninsula). Deposits of basaltic material occur in the Okataina and Kapenga (Rotorua) areas but most of them are very small. Basalts also outcrop at Ongaroto and in the area immediately north of Lake Taupo where they are quarried for aggregate and scoria.[47] In almost all cases these basalt lavas have been erupted on land and form small scoria cones and lava flows. They are a small resource and most accessible lava flows have been exploited although many are now either worked out or have been abandoned because such small resources are now uneconomic.

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[47] See Hiess, et al 2007 for the localities of basalts in the Rotorua – Taupo volcanic zone.

Arc – related basalt and basaltic andesite aggregate properties

Fresh arc-related basalts and basaltic andesites have similar materials properties to the intraplate basalts.

Basalts erupted in the marine environment have zeolites and smectite thus relatively high CI (less than 10), and low plasticity indices. Little data is currently available for these basalts and basaltic andesites.

7.5 Arc Andesites

Arc andesites are largely augite-hypersthene (ie two-pyroxene) and pyroxene - hornblende andesites. In Northland these andesitic volcanics are a small aggregate resource and most accessible lava flows and dykes have been exploited although many are now worked out.

Two - pyroxene andesites, the remnants of old andesitic volcanoes outcrop along the eastern margin of Northland and extensive deposits of similar andesites are found in northern Coromandel and on Great Barrier where andesitic arc volcanism began about 18 MaBP then continued along the Coromandel Peninsula. A notable feature of the arc volcanism in the Coromandel Peninsula, in comparison to the slightly older arc rocks of Northland is the clear migration of volcanism down the peninsula as indicated by the time lines for the start of volcanism shown in Figure 7.10. (but note that once volcanism was initiated it continued behind the migrating volcanic front). The first lavas as the volcanic front rolls down the peninsula, are always two - pyroxene andesites. The volcanism behind the moving front is generally more complex and may include hornblende-bearing andesites and dacites.

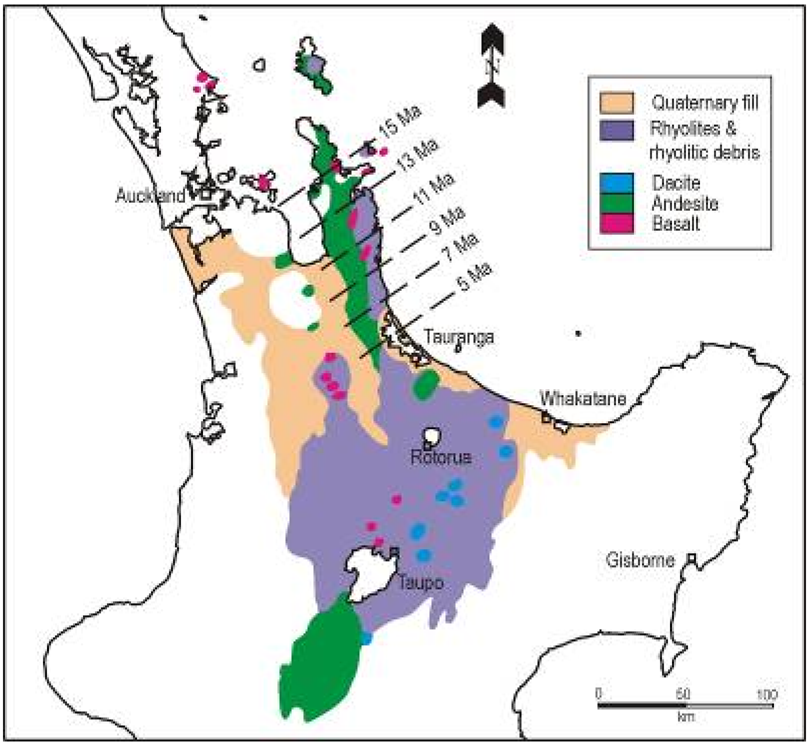

Figure 7.13 :

Simplified map of Coromandel and Rotorua - Taupo areas showing location of the younger than 15 Ma arc volcanics. The lines indicate the age of first volcanic activity (after Kear 2004). Volcanism in the Rotorua – Taupo area is younger than 2 Ma.

The major aggregate resource of the Coromandel – Tauranga area is two-pyroxene andesites. The volcanism shows a generally similar spatial distribution to that seen in Northland with some basaltic rocks and andesites on the west, and rhyolites mainly dispersed along the eastern side of Coromandel Peninsula. The andesites generally lack major deformation; joint systems are open and uncoated with secondary minerals.

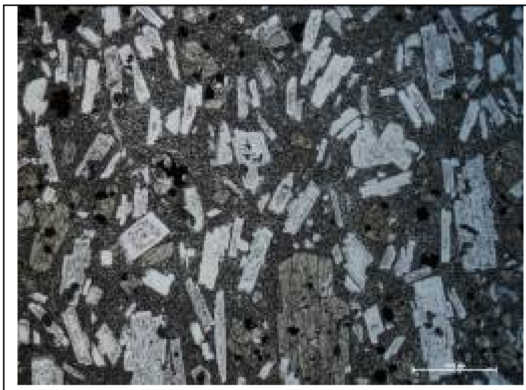	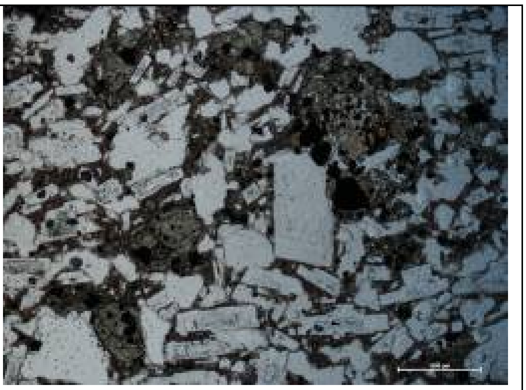
Figure 7.14 (a) : microphoto of augite – hypersthene andesite showing flow alignment of plagioclase and pyroxene phenocrysts, and fine-grained glassy matrix. Plane polarised light. Scale bar 1mm.	**Figure 7.14 (b): microphoto of Taranaki andesite showing abundant plagioclase phenocrysts and lesser amounts of pyroxene. Plane polarised light. Scale bar 1mm.**

The Coromandel Peninsula is noted for gold and other mineralization. The volcanism is the heat source for the hydrothermal alteration that produced the mineralisation. Although there are several stages of mineralisation on the peninsula, the last and the major one (located in the Waitekauri – Karangahaki region) occurred about 7 Ma BP. Consequently many andesites older than 7 Ma tend to be rather extensively hydrothermally altered. The younger than 7 Ma andesite flows, particularly on the western side of the Kaimai Ranges, are very fresh but all others show some degree of alteration which has produced smectite. In the Bay of Plenty where andesites are covered by younger rhyolite flows (which act as heat sources) the andesite lavas are usually hydrothermally altered and may contain troublesome Na- smectite.

The focus of arc volcanism for the past 2 Ma BP has been the Rotorua – Taupo zone. The first eruptions were andesitic and then, at about 1.6 Ma BP, volcanism became largely rhyolitic.[48] The young volcanism (0.34 Ma BP) to the south of Lake Taupo is andesitic. Geothermal activity has extensively altered many andesitic flows in thr Rotorua - Taupo region making them unsuitable as aggregate.

Arc Andesite Aggregate Properties:

Aggregate properties vary depending on the level of alteration in the andesite.
Fresh andesites have crushing resistance :

c. 3% fines at 130 kN
5-8% fines at 230 kN
10% fines at c. 280 kN (ie < 300kN)

SE : 50 – 70 for fresh glassy andesites but around 40 for altered andesites.
CI : Fresh andesites have negligible CI values; more altered andesites CI 4-5.
PI : Usually zero in fresh rocks with a maximum of around 5 in altered rocks

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[48] Wilson et al, 1995. See also Hiess et al, 2007.

7.6 Taranaki Andesites

Mt Egmont (Taranaki), and the volcanic centres (Pirongia and Karioi) in the west Waikato area are regarded by geologists as back arc volcanoes.[49] These centres all erupted basalt, basaltic andesite and andesite lavas and explosive volcanic debris and they all have associated breccias and conglomerate deposits. None of the volcanic cones in the Waikato region are currently being quarried but in Taranaki, where there is a dearth of other quality source rocks, material originating from Mt Egmont forms the region's major aggregate resource.

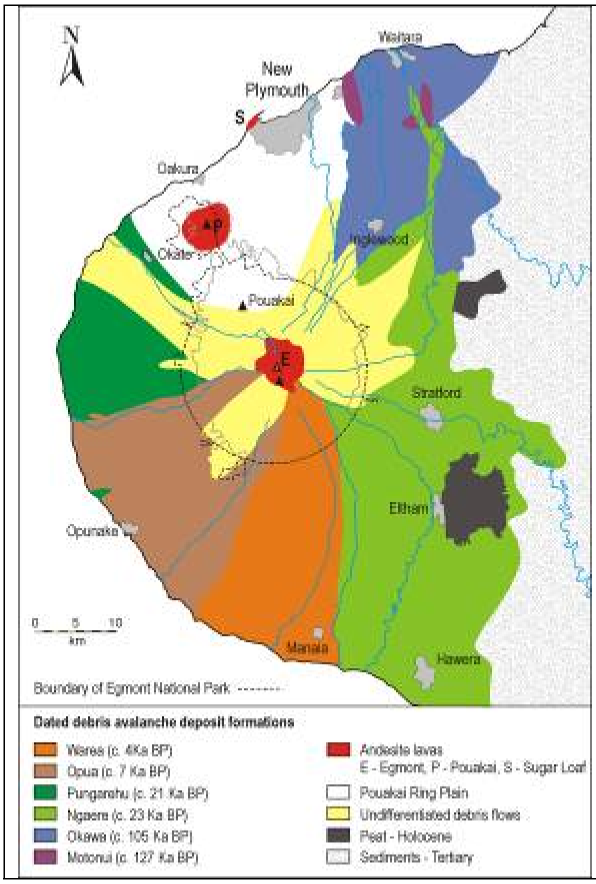

Figure 7.15 :

Above – typical nature of Taranaki laha deposits. Rounded – subangular andesite boulders are separated from the finer grained mud matrix for crushing.

Left - Map showing Quaternary Geology of Taranaki – adapted from Neall (1974) and Alloway et al (2005).

Mt Egmont (Taranaki) first erupted about 70,000 years ago and has erupted at least eight times in the last 6,000 years. The cone is surrounded by an extensive ring plane of debris avalanche deposits, lahars, and fluvial material (Figure 7.15). These debris deposits are the resource for at least fourteen active quarries. Unlike other regions where andesite aggregates are produced from a single flow the Taranaki andesite resource is an unsorted mix of many different types of andesitic rock. The larger (meter scale) blocks are usually considered to be the remnants of lava flows that have been disrupted and transported by one or other of the numerous cone collapses that have occurred. The smaller (cm to half meter scale), and often very vesicular blocks, are believed to be explosive debris and lava bombs. Selective quarrying, ie separating out the large blocks and processing them, can provide good quality aggregate from this resource.

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[49] This includes the Kakepuku and Te Kawa centres near Te Awamutu.

The Taranaki andesites are chemically distinct from the other North Island arc andesites. Taranaki andesites notably and consistently contain more alkalies (both potassium and sodium) than do the andesites from the Coromandel and Taupo regions (Figure 7.16.). These alkalies can only be accommodated in feldspars and volcanic glass. The Taranaki andesites are not unusually glassy, and the composition of the glass is andesitic,[50] but they do appear to be very feldspathic [see Figure 7.14 (b)].

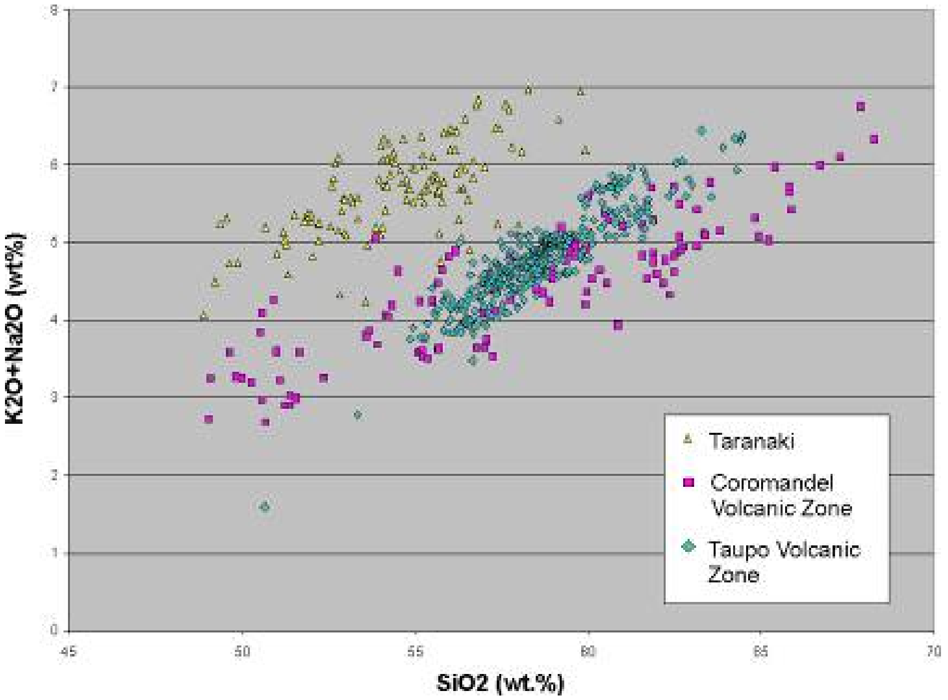

Figure 7.16 : comparison of the chemical composition of volcanic rocks from the Coromandel and Taupo volcanic zones with Taranaki andesites.

Taranaki Andesite Aggregate Properties

Crushing resistance data indicates the Taranaki andesite aggregates characteristically produce 10% fines at loads below 130kN. However selective quarrying of the large hard blocks can achieve 9% fines at 180 kN. The abundance of feldspar in Taranaki andesites is probably the cause of their relatively low strength compared with other andesites.[51]

Most of Taranaki andesites that this writer has examined lack smectite and zeolites, and consequently they have low CI values (<2), are non plastic, and have good cleanness values.

The Taranaki andesites have a propensity for alkali aggregate cement reaction and are thus regarded as being generally unsuitable for use as concrete aggregate (**Freitag et al, 2003**). The alkali reactivity of Taranaki andesites is related to their intrinsically high alkali content (held in glass and feldspars) compared to other similar North island andesites (Figure 7.16).

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[50] 65% SiO_2 according to Katayama et al, 1989.

[51] See sections 1.1 and 1.2 in Part 1 for data about the relative toughness of minerals.

7.7 Dacites and Rhyolites

Dacites and rhyolites associated with arc volcanism in the northern and central North Island form dome complexes. While many of these dacites have been quarried in the past, there are now few quarries producing aggregate from them. Most quarries in rhyolites are being worked to provide fill.

Chains of dacite domes were erupted during the time period 23 to 20 Ma BP in the Whangarei area and along the southern side of the Brynderwyn Hills from west of Riwaka to Mangawai Heads (see Figure 7.11). These old Northland dacites are totally crystalline and composed largely of feldspar with some biotite and minor quartz and mica-type minerals [Figure 7.18 (a)].

Dacites in the Coromandel Peninsula and Rotorua/Taupo area are all hypersthene and occasionally hornblende and biotite bearing. They are largely crystalline and show some similarities to the silica rich andesites of the area. The young (less than 2 million years old) dacite and rhyolite domes in the Rotorua - Taupo area contain hypersthene, hornblende and plagioclase phenocrysts in a very glass-rich groundmass, although most of the groundmass glass has devitrified to tridymite and cristobalite [Figure 7.18 (b)]. Some of the more crystalline lavas in these domes are being quarried for aggregate.

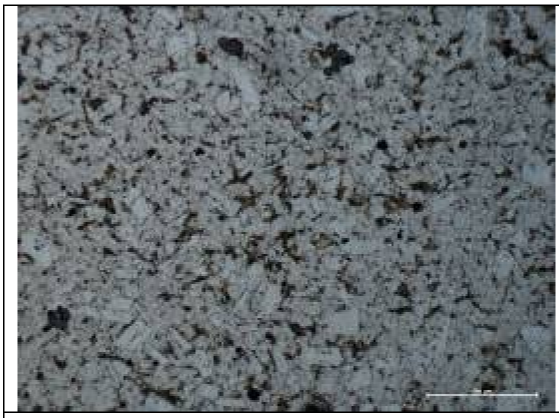	
Figure 7.18 (a) : Northland arc dacite – lacking phenocrysts but completely crystalline. Largely composed of feldspar with minor brown clay / mica minerals and quartz. Plane polarised light. Scale bar 500µm	**Figure 7.18 (b): Rotorua area dacite strongly porphyritic with phenocrysts of plagioclase and pyroxene in devitrified glass matrix of tridymite and cristobalite. Plane polarised light. Scale bar 100 µm**

<u>Dacite and rhyolite aggregate properties :</u>

There is little data available for these aggregates.

The dacite aggregates are all light grey coloured, and as such, have some thermal properties that are valuable in surface chips. A feldspar-rich Northland dacite has been used successfully as sealing chip.

The glassy dacites of the central North Island contain considerable amounts of tridymite and cristobalite and thus are undesirable aggregates for concrete. They also have lower crushing resistance than andesites.

7.8 Summary and Comment

A variety of volcanic rocks are used as aggregate in the North Island.

Three different types of basaltic aggregate sources are recognised : young intraplate basalts extending from Bay of Islands to South Auckland and west Waikato; ophiolitic basalts (Northland and East Cape); and arc-related basalts (includes basaltic andesites) in Northland, Coromandel Peninsula and the Rotorua Taupo Volcanic zone.

Augite-hypersthene arc andesites are being quarried throughout the northern North Island from Northland to the Taupo region. These andesites are the major aggregate resource for the Coromandel Bay of Plenty region and when fresh produce a high qualityaggregate.

Dacites have been erupted as part of the arc-related volcanism along the eastern side of Northland and in the Taupo area. Some of these are being quarried for roading aggregate.

Aggregates derived from volcanic rocks all have moderate crushing resistance (10% fines produced at < 300kN), high cleanness and SE values. Other properties of volcanic aggregates depend on the source rock type and to a considerable extent on whether they have been erupted in a terrestrial or marine environment.

Basalts and andesites erupted on land, provided they have not been hydrothermally altered, have negligible Clay and Plasticity Indices. Weathering of volcanic rocks produces some smectite and ultimately kaolin clay.

Eruption of basalts in a marine environment (ophiolite basalts and some arc-related basalts) will result in reactions between heated sea water and volcanic glass. The glass hydrates and devitrifies, initially forming a gel like material (palagonite) which then reacts to form smectite and zeolite. High temperature reactions between sea water and volcanic glass result in Ca-enriched clay minerals and zeolites. Low temperature rection with sea water results in clays and zeolites that have mixed and usually rather alkali- rich exchangeable cations.

Hydrothermal alteration, causes devitrification of volcanic glass and alteration of other minerals in volcanic rocks resulting in the crystallisation of a variety of secondry clay minerals including some smectite, but only rarely zeolite. Some hydrothermally altered andesites contain high sodium-smectite.

Most alteration of volcanic rocks is associated with the devitrification of glass and alteration of the iron magnesium silicates, particularly of hypersthene or olivine. Since the alteration minerals are disseminated through the rock they are an inherent part of the aggregate chips and little can be removed by washing and screening. Only in the ophiolite basalts, which have been intensively deformed during their emplacement process will clay minerals and chlorite coat shear and joint surfaces, thus allowing for the possibility of some reduction in these minerals.

Ophiolitic basalts quarried in northern Northland appear, on the evidence of the zeolites and clay minerals they contain, to be saturated with calcium while those from central and southern Northland have more Na-rich zeolites. Most of the aggregates produced from these quarries for use in roading are routinely lime stabilised. In the case of the aggregates produced in northern Northland, already containing calcium-saturated clays and zeolites, the lime stabilisation is mainly a cementing process.

The devitrification of high silica glass in very silica-rich andesites, dacites and rhyolites produces the silica minerals tridymite and cristobalite which are deleterious in aggregates that are to be used in the making of concrete because of the potential for alkali-aggregate reaction.

Alkali-aggregate reactions in concrete occur as the result of reaction between alkaline pore solutions in the cement and silica minerals[52] which are soluble in alkaline solutions; this reaction produces hydrous gels. Freitag et al (2003) attribute the reaction between alkali pore solution and silica minerals and silica-rich volcanic glass as the major cause of alkali aggregate reaction. However, some silicate minerals that occur in volcanic rocks, particularly alkali-rich feldspathoids and feldspars are also known to be able to release alkalis into the concrete.[53] It seems probable that the alkali reactivity of the Taranaki andesites is the result of the high alkali content of their parent magmas and the consequent high and slightly alkali-enriched feldspar content of these volcanic rocks.

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[52] All silica minerals have some degree of solubility in water. Quartz is the most stable (ie least soluble); cristobalite twice as soluble and tridymite almost three times as soluble in water the other silica minerals (Dove and Rimstidt, 1994).

[53] Bérubé, et al. 2002. In particular the sodium feldspathoid, nepheline, is noted for releasing sodium; but feldspathoidal rocks are very rare in New Zealand.

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8 : GRAVELS AND CONGLOMERATES

8.1 Introduction

Conglomerates and gravels share a common origin as sediments composed of pebble to boulder size fragments of rock. Gravels essentially represent material still in the transport stage, that is they are uncemented and are harvested either from river systems or beach deposits. Conglomerates have ceased being transported. The spaces between the pebbles have been filled with sand, silt-sized material, clay and other cementing minerals which have converted the sediment into a sedimentary rock.

The nature of the pebbles contained within gravels and conglomerate deposits is determined by the source / hinterland being eroded. The eroded fragments are abraded and sorted by the transport processes. Initially transport may be down slope under the force of gravity but ultimately all long distance transport is by river systems. Only the strong stable fragments survive transport and since a river's capacity to carry load is determined by the velocity / stream bed grade, the boulders being carried in a general sense become smaller and more rounded the further they are carried from their source.

In most cases the source of the pebbles / cobbles in the deposit is near at hand and obvious, but for many conglomerates in Tertiary sedimentary sequences the original source rocks are either no longer exposed or have been completely destroyed by erosion.

8.2 Mixed source-rock gravels.

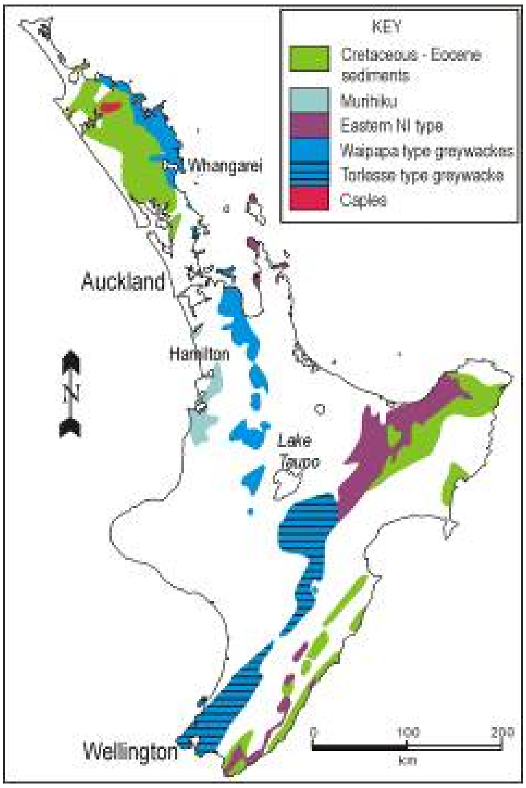
Gravels composed almost entirely of greywacke pebbles are harvested from river systems that transport material eroded almost entirely from the Permian – Mesozoic greywacke terranes of the axial ranges of the North Island and have been covered earlier (in Section 5.7).

Most Tertiary sedimentary rocks are either weakly consolidated or do not survive long transport in river systems. Debris from igneous rocks of all ages and siliceous material in the Cretaceous early Tertiary sedimentary sequences are the major constituents of mixed-source gravels.

In Northland gravels and conglomerates formed by marine erosion of the Waipoua (Miocene arc) basalt in the coastal south Hokianga region are being exploited on the coast south of the Hokianga harbour and several small gravel pits are sited in rivers in central Northland where river gravels are derived from mixed sources (ophiolitic basalts, Miocene arc basalts, and conglomerate horizons in Cretaceous sediments).

River gravels harvested in the Bay of Plenty area contain a variety of volcanic rocks and greywacke material.

River systems in the East Coast - Gisborne area are sourcing material which is largely derived either from outcrops of Eastern North Island–type greywackes, or from cherts and conglomerate horizons in the Cretaceous sediments; many of these conglomerates contain igneous pebbles. In the East Cape area, Matakaoa ophiolitic basalt boulders are a major component of some river gravels.



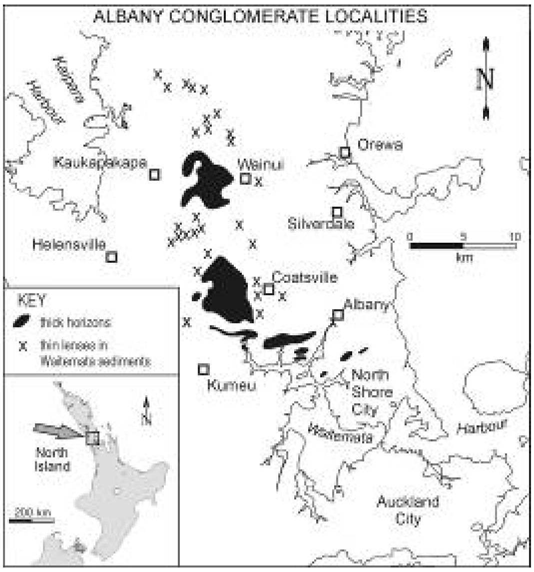


Figure 8.1 (a) left : Map of North Island showing the distribution of the basement sediments which contribute to gravel deposits. Figure 8.1 (b) right (above): Map showing outcrops of Albany Conglomerate.

8.3 Albany Conglomerate

In the area immediately north west of North Shore City deposits of conglomerates provide an important resource of aggregate which, although not currently quarried, has been worked by a number of operators in the past.

There are two main lenses of the conglomerate, one in the Wainui/Kaukapaka area, the other west of Coatsville [Figure 8.1 (b)]. The main conglomerate lenses may locally be up to 200m thick. Other thin lenses (several meters thick) of conglomerate occur to the north and west of Wainui and in the south in the Albany area.

The Albany Conglomerate contains pebbles of a large variety of sedimentary, igneous and metamorphic rocks but the major rock type in the pebbles is metamorphosed igneous rock (greenschists and amphibolite) most of which do not contain swelling clay minerals. The pebbles in the conglomerate are supported by a clay-rich sandy matrix which is cemented by calcite, clay (dominated by smectite) and zeolite.

Examples of the nature of the pebbles and their relationship to the matrix of the conglomerate lenses are shown in the microphotographs in Figure 8.2. The age and origin of the majority of the igneous and metamorphic pebbles is unknown as there is no known presently exposed source for them.

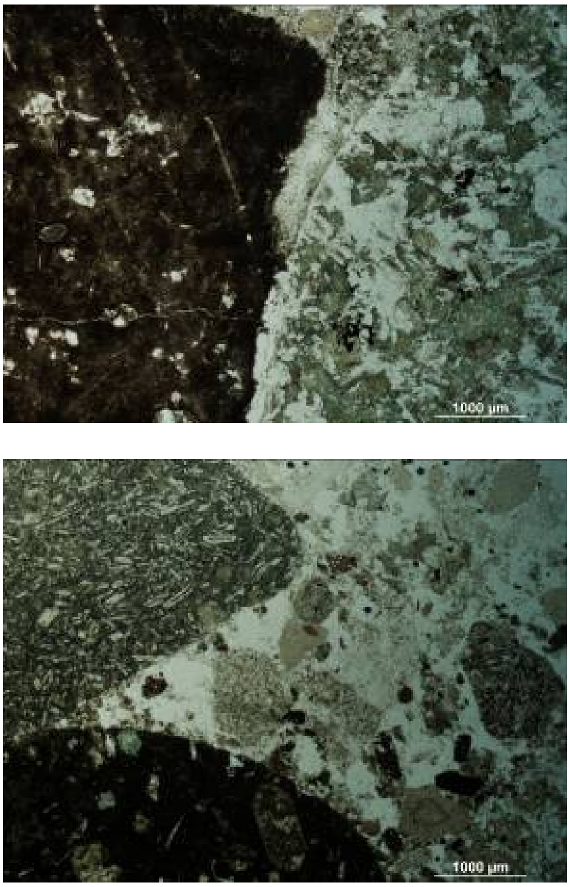


Figure 8.2 Albany Conglomerate.

Photograph top left shows the nature of the resource. Scale is in mm.

Microphotographs on right show the mixed nature of pebbles and their variable shape although most have small surfaces indicating water transport. Chert and amphibolite pebbles are shown in the photograph top right. Volcanic rock pebbles and the constituents of the matrix are shown in the photograph bottom left.

Quarrying of conglomerates is a multistage process, requiring separation of pebbles from the sand and matrix followed by crushing of the pebbles.

There is no modern data available for the aggregate that was produced from the Albany conglomerates.

9. ARTIFICIAL AGGREGATES

The artificial aggregates used in New Zealand are largely slags formed as by-products of iron- and steel-making processes, and imported calcined bauxites. The Huntly power station, which burns Waikato sub-bituminous (and currently also imported Indonesian) coals, produces a high-lime fly ash with good pozzolanic properties.

These materials are usable in many applications more commonly satisfied with natural rock aggregates; fly ash and high-lime basic slags may be used as aggregate modifiers.

9.1 Slags

The basic iron and steel-making process involves the melting of a charge of impure raw material (either iron-rich oxide minerals or scrap iron) in a reducing environment to convert it to metallic iron. Limestone is added as a flux to lower the melting temperature and also to provide an agent to combine with impurities in the charge. The resultant lime-rich, low density slag accumulates above the molten metal, is poured from the furnace, and air cooled. All slags are dominated by lime-rich minerals.

Once the slag has been cooled it is crushed, any pieces of metal caught up in the material being magnetically removed, and the slag is then processed and sized in the same manner as any other aggregate.

9.1.1 New Zealand Steel (Glenbrook) slags

The raw material for the steel-making process used at the Glenbrook steel mill is an iron-rich titanomagnetite sand concentrated from the company's Waikato North Head sand mine. The making of steel is a two-stage process, both of which produce slags, but the chemical and hence the mineralogical composition of the two slag types is very different.

In the iron-making stage the titanomagnetite charge is mixed with Huntly coal and limestone, then heated to drive off the volatiles in the coal, before being fed into reduction kilns, from which the charge passes to melters. In the melters the bulk of the impurities combine with lime to form a molten titanium and lime-rich slag which floats above the molten iron. The molten impurities are poured off and air-cooled to form **melter slag**.

In the steel-making stage scrap steel is added to the molten iron and they are, together with limestone, melted and transferred into a continuous oxygen blowing converter vessel (KOBM). The remaining impurities and some iron are oxidised, foam to the top of the vessel and are poured from the molten steel as **KOBM slag** (also called **basic slag**).

Melter slag

The New Zealand Steel melter slags are rich in elements derived from the titanomagnetite and sand impurities in the charge: titanium, aluminium, silica, and magnesium. The melter slag on average contains around 15% CaO and the sum of CaO, silica and alumina is approximately 50%.

The major mineral constituents of the melter slag can be divided into three types :
(i) complex titanium oxides which have a needle-like form:

ilmenite	$(Fe,Mg)\,Ti\,O$
rutile	$Ti\,O_2$
armalcolite	$(Mg,Fe)\,Ti_2\,O_5$

(ii) spinels and similar metal oxides which have a rather equidimensional shape :

spinel	$(Mg,Fe)\ Al_2O_4$
ulvospinel	$(Fe,Mg)_2\ TiO_4$
magnesiowustite	$(Mg,Fe)\ O$

(iii) calcium bearing oxides and silicates :

Perovskite	$CaTiO_3$
Pyroxene	$Ca\ (Mg,Fe)\ Si_2O_6$
Monticellite	$Ca\ (Fe,Mg)\ SiO_4$
Melilite	$Ca_2\ (Fe,Mg,Al\ Si)_3\ O_7$
Rhönite	$Ca_2\ (Fe,Mg,Ti,Al)_6\ O_{20}$

Titanium has two common oxidation states (as also does iron). The melter slag is chilled and crystallises at high temperatures where the titanium and iron contained in the slag minerals are often in the reduced state. However, as the slag cools to ambient temperatures these minerals oxidise, a process that changes the minerals' "electronic" stability causing them to break down into two or more intergrown, and usually more oxidised, low-temperature mineral phases. Thus the mineral assemblage of the melter slags may be very complex and minor amounts of many different mineral phases have been recorded in them (Hitching, 1981).

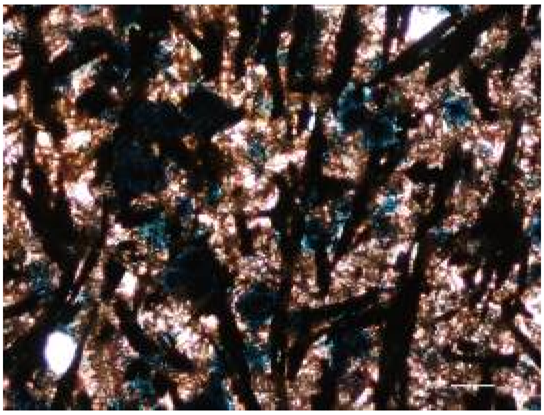


Figure 9.1(a) – above. Microphoto of Melter Slag; plane polarised light. The black needles are various titanium oxides; the blue areas spinels; the remainder largely perovskite and pyroxene. Scale bar 0.1mm

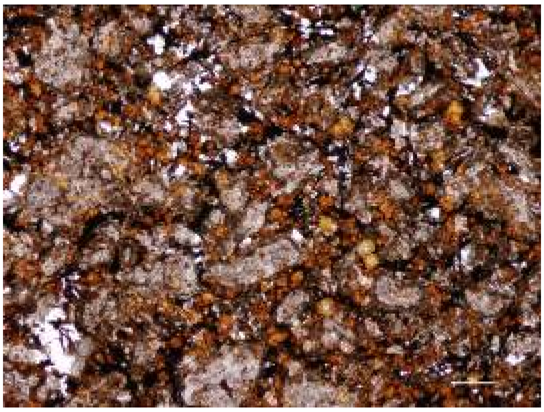


Figure 9.1 (b) – above. Microphoto of Basic Slag (KOBM); plane polarised light. The large crystals are larnite, the orange-brown crystals are dicalcium ferrite; and the black crystals are wustite. Scale bar 0.1mm

The interlocking needles of titanium oxide minerals in the melter slags (black minerals in Figure 9.1(a)) provide strength to the material and a high degree of roughness to the slag surfaces. Aggregates produced from these slags generally have crushing resistance values of <10% fines at 110 kN, and are non expansive. Melter slags also tend to have high PSV values and have been trialled and used as asphalt and sealing chips.

Basic or KOBM slag

The basic or KOBM slag contains more than 50% CaO and less than 30% silica plus alumina. It is composed of a number of very calcium-rich minerals dominated by larnite (β- Ca_2SiO_4) and dicalcium ferrite ($2CaO.Fe_2O_3$), with lesser amounts of gehlinite $Ca_2\ Al\ [Al\ Si\ O_7]$ and usually contain some free lime which hydrates to portlandite $Ca(OH)_2$. Wustite (FeO) is also a major component of this slag. (Figure 9.1(b). The KOBM slag, because of its high lime content is used as a soil conditioner, and to modify / stabilise aggregates.

9.1.2 Pacific Steel Electric Arc Furnace slags

The Pacific Steel process uses a 100% scrap metal feedstock melted in an electric arc furnace. Pulverised coal and lime are added to react with any impurities present and to form slag. Pulverised coal is lanced into the surface layer of the slag where it combusts to form carbon monoxide gas that causes the slag to foam on top of the molten steel from where it is poured off and collected.

The mineral phases in the electric arc furnace slag may show very minor variations according to the nature of the scrap material used, but all samples that the writer has looked at show the "unweathered" slag to be dominated by wustite (FeO) and dicalcium silicate in the β form known as larnite (Figure 9.2(a)). Another dicalcium silicate, the impure form called bredigite (α - Ca_2SiO_4), occasionally forms instead of larnite. Other very minor phases that occur in the electric arc furnace slags are : gehlinite Ca_2 Al [Al Si O_7], and rankinite (Ca_3 Si_2 O_7).

Exposure of the slag to atmospheric CO_2 and H_2O, ie weathering, causes carbonation of the dicalcium silicate minerals which react with water hydrating to $3CaO.2SiO_2.3H_2O$. Spurrite Ca_5 $(SiO_4)_2$ (CO_3) has been found in some weathered electric arc furnace slags; lime liberated by the carbonation of the calcium silicates converts to portlandite Ca $(OH)_2$ or calcite ($CaCO_3$) and thin films of calcite may rim cavities and coat the surface of weathered slags.

The electric arc furnace slag has, from data thus far available, a greater strength than that of the melter slag (crushing resistance <10% fines at 230 kN). Sealing chips have high PSV values (>60).

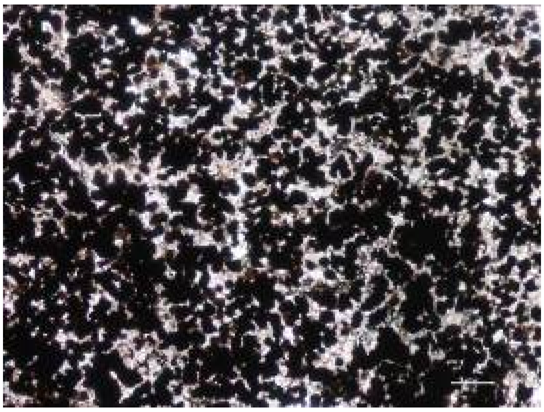
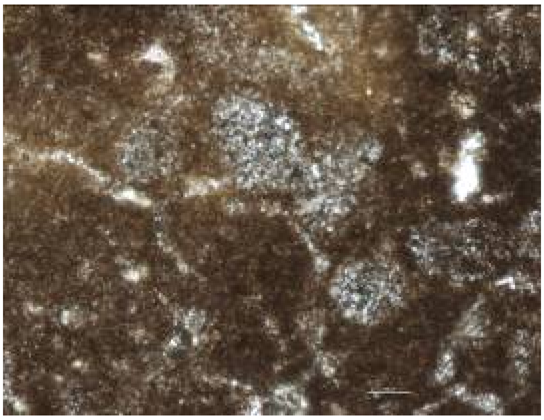
	

Figure 9.2 (a) – above. Microphoto of Electric Arc Furnace slag. The black minerals are wustite and the colourless minerals dicalcium silicates. Scale bar 0.1mm.	**Figure 9.2 (b) – above. Microphoto of calcined bauxite. Brownish granular material is corundum [Al_2O_3]; the grey mineral mullite. Scale bar 0.1mm.**

9.2 Calcined Bauxite

Calcined bauxite, commonly imported into New Zealand from either China or Guyana, has high strength and very high PSV values (>70) and is increasingly being used as sealing chip on high (skid) risk road surfaces.

The primary raw material, bauxite, is composed of hydrated aluminium oxide minerals. In the case of Chinese bauxite the raw material is monohydrate type – composed mainly of diaspore [AlO(OH)] while the Guyanan bauxite is largely composed of gibbsite [$Al(OH)_3$]. Both types also contain minor kaolinite [$Al_2SiO_5(OH)_4$] and trace amounts of iron oxides (Hill and Sehnke, 2006).

The bauxite is high temperature treated (calcined) at about 1,100°C which converts the material to a granular aggregate of corundum (Al_2O_3) crystals with some mullite ($Al_6Si_2O_{13}$). Many calcined bauxites also contain small amounts of hematite which is largely responsible for the buff colour variants of the material.

9.3 Fly Ash

New Zealand fly ash derived from burning low-ash, low-sulphur sub bituminous Waikato coal is ASTM type C fly ash. Chemically it contains approximately 25% CaO and has a SiO_2 plus Al_2O_3 content in excess of 50%. At the present time Indonesian sub bituminous coal is also being burned in the Huntly power station; while the exact chemical composition of this coal fly ash is unknown it is unlikely to be very significantly different, at least in terms of major elements, to that produced by Waikato coals.

The fly ashes are largely silicate glass spheres but high temperature calcium silicates which are generally similar to those found in basic slags, and minerals such as mullite (derived from kaolinitic clay minerals in the coals) and high temperature quartz have also been recorded.

References for Section 9

Vincent G. Hill and Errol D. Sehnke, Bauxite *In Industrial Minerals and Rocks. Commodities, markets and uses. 7th Edition*, J E Kogel et al Eds. Society for Mining, Metallurgy and Exploration Inc : Colorado USA. (2006) pp 227 – 261.

Keith D Hitching, *Investigations into NZ Steel Slags*. PhD thesis University of Auckland Library (1981).

PART I I I :

10. SUMMARY COMMENTS AND RECOMMENDATIONS

There is a fundamental difference in the materials properties of sedimentary rocks and volcanic rocks. These differences are reflected in the aggregate properties and particularly in rock strength (ie crushing resistance) and related properties.

In sedimentary rocks (ie greywackes) the clastic grains are mechanically and chemically the strongest parts of the rock; the weakest part of the rock is the matrix. The deleterious minerals (specifically clay minerals but also zeolites) are contained in the matrix of the sediment. The sand and silt grains in the North Island greywackes are very variable in nature but quartz (the toughest mineral constituent) dominates in clastic grains and also, with increasing temperature (ie degree of metamorphism), as cement in the matrix of the rocks.

Clay (and other layer silicates) which are major constituents of greywacke matrix are the softest and weakest components of the rock. They also fail under stress in a semi-ductile fashion (ie slip / glide along the layer planes of the mineral).

There are regional differences in the nature and level of diagenesis / low grade metamorphism in North Island greywackes which are reflected in the properties of aggregates produced from them. Five different types of greywacke, each with a characteristic matrix of properties, are recognised in the North Island.

Volcanic rocks are largely composed of brittle, low toughness minerals. These minerals occur as large grains (phenocrysts) and also in the matrix of volcanic rocks.

Volcanic glass, which is the “cement” of most volcanic rocks, although physically strong, is chemically the weakest component of the rocks.

Whether the lava has been erupted in a marine or terrestrial environment is an important control on the presence of smectite (swelling clays) and zeolites, both of which are products of alteration of volcanic glass.

While volcanic rocks can be subdivided on their chemistry and mineral content into basalts, andesites and dacites there are regional differences in the nature and properties of volcanic rocks of similar rock type.

Aggregate property tests used by engineers to specify aggregate for use in roading, or in concrete manufacture, or for other construction purposes, are all strongly determined by processing methodology. Information about the methods used to prepare the aggregate tested should be included with aggregate property test data.

Because of the strong influence of production methods on all the properties of aggregates the distinction between source properties and production properties should be abandoned.

Since many greywacke and volcanic rocks contain clay minerals (layer silicates) and zeolites, which absorb water and/or swell, it is unwise to use any tests for aggregate durability that are carried out in the dry state.

There is a need for a better understanding among the producers and consumers of aggregates of what individual aggregate property tests are actually measuring and the relationship between test results and the important and desirable physical properties of aggregate.

There is currently a tendency to overspecify aggregate for many uses. Quarry operators process their resource to produce aggregate that meets the consumers' requirements. Thus processing of the aggregate to meet unnecessarily high specifications relegates more of the material produced by a quarry into the marginal category.

In the interests of "sustainability" and "value for money" (two current mandates from Government that are likely to remain with us), use has to be made of more of the marginalised aggregate resource in the construction and maintenance of New Zealand's public road network.

There is therefore a need for judiciously widening specification requirements, and in further developing skills in the roading industry in making optimum use of marginal product.

The engineering perspective (physical test results) needs to be more strongly complemented by geological considerations in order to reliably identify and put to use these materials.

Part of the solution lies in stabilising crushed aggregate with appropriate added reagent (lime, cement etc), but further progress will need to be made in strengthening the association of pavement types (traffic demand), pavement stratum (base course, subbase, subgrade improvement) with locally available currently marginalised materials, and in selection of the aggregate product most suited for its planned use.