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Initial Review of Aggregates with respect to Road Traffic Noise

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Abbreviations and Acronyms

AAV	Aggregate Abrasion Value
AC	Asphalt Concrete
AS	Australian Standard
ASTM	American Society for Testing and Materials
BS	British Standard
EMOGPA	Epoxy-Modified Open Graded Porous Asphalt
EN	European Standard
LAA	Los Angeles Abrasion
MD	Micro Deval
MPD	Mean Profile Depth
NM	Nordic Mill Test
NOC	Network Outcomes Contract (used herein as a region identifier)
NZ	New Zealand
NZS	New Zealand Standard
NZTA	Waka Kotahi New Zealand Transport Agency
OGPA	Open Graded Porous Asphalt
ORMD	Opus Research Modified-micro Deval
PSV	Polished Stone Value
RAMM	Road Asset Management and Maintenance Manual
WS	Wehner-Schulze test

1 Introduction

Waka Kotahi NZ Transport Agency, in the 2020 Road Surface Noise Research Programme, is investigating the role the road surface plays in the generation of road traffic noise. WSP Research and Innovation has been asked by the Agency to provide an overview of NZ road surfacing aggregates, in the context of tyre/road noise emissions, focusing on intrinsic properties of the aggregates rather than production properties such as chip size or quality of quarry operation.

1.1 Purpose

Road surfacing aggregates are drawn from a multitude of quarries around NZ, with each quarry typically supplying roading projects within its broad geographical vicinity. It follows that if aggregate properties have a non-negligible influence on tyre/road noise emission then differences between aggregates from different quarries could result in differences in tyre/road noise emissions between regions. That could have implications for the study, development, and applicability of road surface noise treatments. How aggregates differ between NZ quarries, and whether this could have an impact on road noise, has not previously been investigated.

1.2 Scope

This report is the result of a desktop review of literature, and is intended to collect relevant background information on NZ roading aggregates together in one place. It will consider the possible influence of aggregate properties on noise emission, including a quantitative study of aggregate and texture properties from the RAMM database, but these findings are intended to be indicative only, to inform the future road surface noise research strategy.

2 Acoustic Overview

2.1 Acoustic Effects

When discussing the possible acoustic ‘effect’ or ‘influence’ of aggregate properties in this report, we are generally considering those factors capable of increasing or decreasing the overall tyre/road noise emission level of a surface. While other influences on the sound emission spectra are also relevant (e.g. ‘tonality’), they sit at a level of detail beyond that required to initially assess whether there is a possible acoustic effect.

2.2 Aggregate Properties of Interest

NZ and overseas literature indicate that the physical properties of aggregate (as a final product appearing in the road surface) that are likely to be most relevant to the overall noise emission are as follows, in approximate decreasing order of importance:

2.2.1 Chip Size

The primary property of road surface aggregates that is known to influence tyre/road noise is the chip size. This strong interaction is seen across all surface types, including chipseals and asphalts (Sandberg and Ejsmont, 2002) and has been quantified for many NZ road surfaces (Dravitzki et al, 2002; Jackett, 2019). The overall chip size effect does not need to be revisited in this report, however, potential for size variation within a given grade[1] is of relevance. Aggregate chip size primarily affects the surface on the macrotexture scale (> 0.5 mm).

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[1] A designation given to the size of sealing chips, derived from NZTA Specification M/6 (e.g. Grades 1, 2, 3, 4, 5, 6)

2.2.2 Chip Shape

The shape of the aggregate particles, their cubicity or angularity, may be relevant to noise, particularly on surfaces where the aggregate forms a positive texture of chip “peaks” that the tyre contacts, such as chipseal. This would be realised as an effect on surface macrotexture. It may also be relevant to the noise emission of “negative texture” road surfaces like asphalts, for example OGPA, where the aggregate shape is a crucial element of the surface structure and therefore the porosity of the surface (NZTA, 2007).

2.2.3 Material Properties

It is possible that some surfacing materials could have material properties that would influence noise emission directly (e.g. extreme plasticity, compressibility, or porosity) or indirectly (e.g. susceptibility to breakdown, wear, reorientation, etc). In the context of traditional NZ aggregates, it is presumed that the indirect factors are of most relevance, though if more exotic materials are introduced (e.g. crumbed rubber, recycled polymers) then the direct factors may be of significance.

2.2.4 Chip Microtexture

The properties of individual surfaces (faces) of the aggregate particle are generally related to its microtexture (< 0.5 mm), which is of much lower relevance to noise emission than the macrotexture (Sandberg and Ejsmont, 2002; Wei et al, 2018).

3 New Zealand Aggregates

3.1 Engineering Properties

Road surfacing aggregates are subject to substantial stresses from the time they are quarried, and throughout the time they are employed in road pavements and road surfacings. In general, the aggregates used in road surfacings need to be sufficiently hard to resist high rates of micro-wear, but not so hard that they polish rapidly and lose skid resistance (Waters, Pidwerbesky, Rainsford, 2012). Simultaneously, the same aggregates need to be sufficiently tough to resist fracturing and breakdown degradation.

When used in chipseals, individual aggregate particles are in direct, or near direct, contact with the traffic above, the basecourse or previous chipseal layers below, and adjacent chip particles in the chipseal.

In asphalts, aggregate particles and the bituminous binder carry and distribute the traffic loading. Dense graded or continuous graded asphalts are made with a mix of larger chips to successively smaller chips. The larger chips are supported in a packed mix of smaller chips and bitumen. Open graded or gap-graded asphalts have only larger chips and load is transferred by chip-on-chip contact. Tougher aggregates are required in these open graded mixes to withstand the high contact stresses. Open graded asphalts have greater surface texture than dense graded asphalts, potentially increasing exposure to traffic-induced surface stresses particularly where there is braking and turning traffic.

This leaves both chipseal and OGPA aggregates subject to high vertical and lateral compression stresses, and high abrasion stresses. Resistance to degradation therefore becomes a very important issue for surfacing aggregates, and it is possible that this property is important in noise production over the life of a surface. By contrast, it is assumed that, due to the different structure of the material, noise emission from dense asphalts would be comparatively less sensitive to physical aggregate properties.

Previous work has indicated that the in-service stresses encountered by the chipsealing aggregate indeed appear to be high enough to cause fracture degradation if the aggregate is susceptible to fracturing. While high resistance to abrasion can result in polishing which can lead to chipseal failure due to a loss of skid resistance, aggregates that are insufficiently tough and susceptible to fracturing breakdown during service, impact on the chip density and the chipseal void contents and are thereby implicated in the chipseal flushing failure mechanism (Herrington et al, 2015; Bagshaw, Cook 2018).

Many sources of degradation arise from many of the activities associated with the production and the use of the aggregates. It is these degradation routes that lead to changes in size, shape, macrotexture and microtexture, all of which may impact on the noise that is produced by any given aggregate when applied in a road surface (section 2.2). Sources of degradation include quarrying, crushing, transporting, stockpiling, placing, and in-service (trafficking and weathering). The type and amount of degradation that occurs will depend strongly on the source properties of the particular material. Ultimately however, it is the condition of the aggregate once it is in the road surface, and the degradation/weathering that occurs thereafter, that are most important.

3.1.1 Implications for Tyre/Road Noise

Aggregate hardness is expected to predominantly affect surface microtexture (via polishing). The influence of the microtexture of the road surface on noise has been shown by Sandberg & Ejsmont (2002) to be very minor, and it therefore seems unlikely that hardness alone would cause acoustic differences between aggregates.

On the other hand, aggregate toughness has been linked with fracturing and breakdown, and subsequently surface flushing of chipseals. These surface defects may influence the road surface macrotexture, which is a primary driver of tyre/road noise emission (Sandberg & Ejsmont, 2002; Jackett, 2019), and therefore the noise emission may change over time.

Due to the physical structure of the surfaces, chipseals are generally the most sensitive to the physical properties of their constituent aggregates, followed by OGPA, and with dense asphalts least sensitive. If noise emission is subsequently linked to the physical properties of aggregate, it might be expected to apply in the same order of significance.

3.2 Aggregate Geology

Several wide-reaching studies have been undertaken that have examined and catalogued the New Zealand industrial aggregate landscape, their geologies, source properties and applications (Black, 2010; Black 2014). Much of the recent work, which has built upon much earlier work from NZ Universities and the DSIR, has been undertaken by the Geology and the Engineering Departments of University of Auckland with Professors P. Black and D. Wilson the principal investigators. These reports allow the identification of New Zealand aggregates and provide preliminary understanding of the likely source properties of aggregates from any given source location (Bartley, 2001; Bartley et al, 2007; Black, 2010; Black, 2014; Sangsefidi et al, 2020). Figure 1 provides an overview of aggregates types across New Zealand.

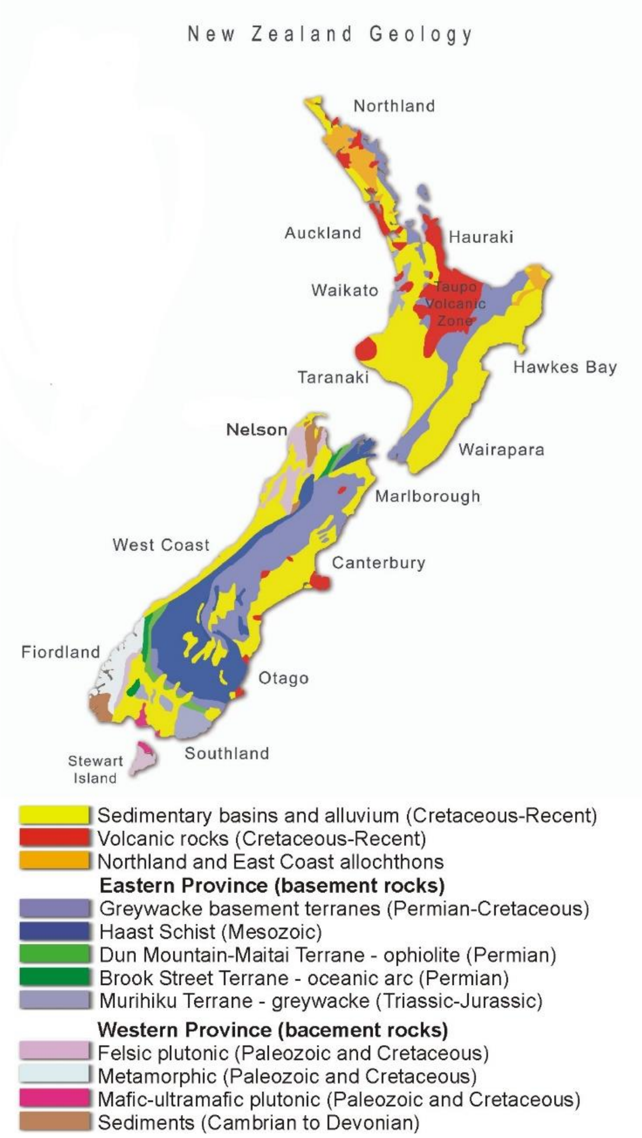

Figure 1: Distributions of primary types of aggregates across New Zealand (image credit: Ulrich Lange; edited by: Dushan Jugum, 2018).

3.2.1 Overview of the Geological Types

New Zealand aggregates can be divided into three broad types depending on their origins:

- Sedimentary: These are fragments of weathered or broken older rocks that have been transported by water and deposited far from their source. The sediments turn into sedimentary rocks by precipitation of mineral cements and recrystallisation of matrix clay materials under pressure and heat. Sedimentary rocks are classed as clastic and the weakest part of a clastic sediment is the matrix that encloses the stone/sand/silt grains. The mineralogy of sedimentary rocks can be very complex, and they are often quite heterogeneous. Greywackes are examples of sedimentary rocks.
- Igneous: These are formed from molten rocks or lava. They have simple mineralogy which is related to the chemistry of the source lava. Some of the minerals begin crystallising at depth and increase in size during the ascent to the surface. The grain size of the igneous rock matrix is a function of the cooling rate where very rapid cooling results in a glassy rock e.g. obsidian. The weakest components of igneous rock are the feldspathoid components, while the glass is the strongest. However, the glass is the most readily chemically altered/weathered component. Examples are: basalt, dacite, andesite and rhyolite.

- Metamorphic: These are rocks that have been reheated at depth and moved back to the surface via folding or faulting. Metamorphic rocks may have sedimentary or igneous roots. They often show foliation/schistosity (the parallel, planar arrangement of mineral grains of the platy, prismatic, or ellipsoidal types, usually mica).

Each rock or aggregate type has material source properties that are intimately related to its geological, mineralogical and geo-chemical characteristics, for example, the crystal structure, the mineral character, the chemical character and the density. A particular quarry may exploit a single rock type, but the geological and engineering properties of the rock in the quarry may change across the quarry and over time.

3.2.2 Greywacke

The geological backbone of New Zealand is made up of Greywacke rock and this is the most important aggregate resource for both hard rock and gravel[2] quarries (Black, 2010). Geologists use greywacke as a term to include sandstones, siltstones, argillites, cherts and volcanics. Quarry engineers on the other hand, reserve the term for sandstones and siltstones. The sands and silts that are contained within the greywackes are highly variable, containing a very wide range of crystal and rock fragments, which indicates that they originated from a range of sources.

In New Zealand, 75% of the aggregate used is greywacke of one type or another, while the other 25% is igneous in origin, with smaller amounts of metamorphic rock.

There are five main types of greywacke mineral across New Zealand, defined here by the material properties that are important to their use as aggregates, for example, crushing resistance, plasticity, and clay index (described in section 4.3). With reference to Figure 2, some further breakdown of material characteristics may offer some insight into their behaviour, and perhaps be relevant to tyre/road noise generation:

- Eastern North Island and Murihiku: The sedimentary texture remains obvious as the nature of the debris is variable; the clay-rich matrix includes smectite[3] and zeolite which produce high plasticity and clay indices. The Murihiku type is 'weaker' than the Eastern North Island type.
- Caples: The Caples type is a metamorphosed type that exhibits strong deformation foliation, and due to the metamorphosis, it has negligible plasticity and clay indices.
- Torlesse and Waipapa: The most widely dispersed of the NZ greywackes and hence the most important source. Waipapa is volcanoclastic, dominated by chlorite with minor smectite matrix and hence low or variable clay index. Torlesse is quartz-feldspar rich and has clay matrix dominated by illite. These greywacke rocks have low porosity, high crushing resistance and form chunky angular-subangular fragments when crushed.

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[2] Gravel being defined as rock sourced from rivers and flood plains that has been washed down rivers and streams and broken down and weathered in the process.

[3] Smectite minerals are often referred to as "swelling" or "expandable" clay minerals. NZTA M/6 Specification for Sealing Chip governs the maximum allowable percentage of unsound materials such as clay lumps.

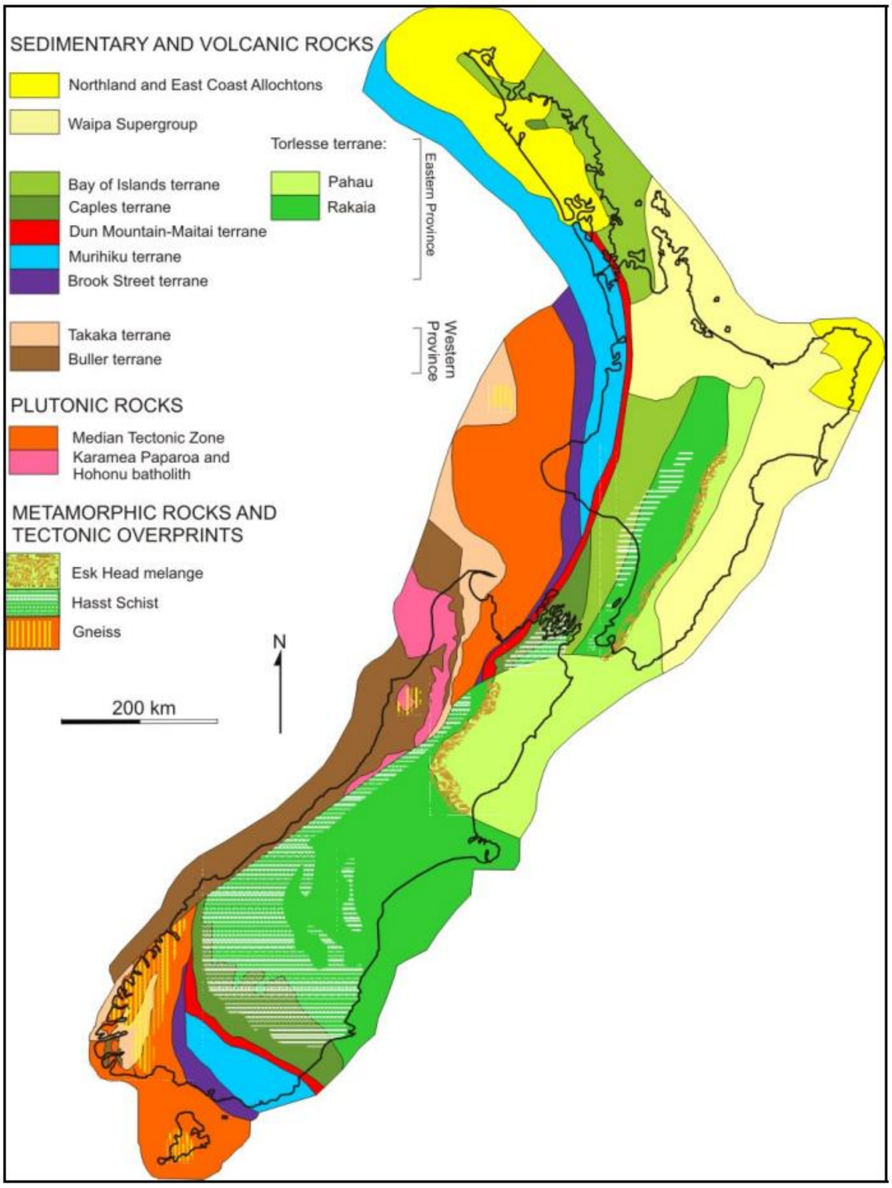

Figure 2: Variation in greywacke across New Zealand (credit: Adamson 2008, modified from Mortimer 2004)

3.2.3 Igneous/Volcanics

Various igneous or volcanic rocks are also used as aggregate resources. These rocks have simple mineralogy, much more straightforward than greywackes, but have variable textures and glass contents. The silica content determines the lava flow, mineral composition and the physical properties. Volcanics that erupted in marine environments include significant sodium and calcium from the seawater, thereby producing significant smectite. Most quarries of volcanics are in a single lava flow. Various lahars are also quarried.

The type of igneous rock follows the silica content, from basalts up to 50% silica, andesites from 50 – 63%, dacites from 63 – 70% and rhyolites from 70+% silica. Volcanics are much more localised in their source and while there are many different sources, they are much smaller in area and volume than greywackes. Young terrestrial basalts are very important in Auckland and Northland and contain feldspar, augite, olivine, magnetite and glass.

- Basalts are non-plastic, clean[4] aggregates with negligible clay index unless they have been weathered or are marine basalts. Feldspar is the weakest part of the basalt and the strength of the rock is determined by the interaction of the feldspar and the glass. Older basalts in Northland and East Cape exhibit significant Ca2+ and Na+ alteration.
- Andesites and Dacites formed by arc volcanism are found across Coromandel and Bay of Plenty. The quarries are in individual flows, the rocks are mineralogically uniform but the textures may vary. Andesites are rich in fine grained glass and poor in feldspars, so are typically strong (high crush resistance).
- Dacites are found in small localised deposits, while rhyolites are wide-spread.
- Taranaki andesites are found in lahars and river gravels so are mixed types. They are more alkali-rich than east coast andesites and have lower crush resistance.
- Significant, typically basaltic, volcanic resources are found in the South Island around Banks Peninsula, Otago Peninsula and Invercargill/Bluff.

3.2.4 Metamorphics

Very few commercial aggregates used in New Zealand are from metamorphic sources. Rocks with geologies that are considered to be schists are located in central Otago, stretch up the Southern Alps and into Marlborough. However, it seems that only the sources in central Otago are exploited commercially for significant aggregate manufacture.

3.2.5 Implications for Tyre/Road Noise

Greywacke makes up the majority of road surface aggregates, but it is highly variable in mineral makeup, which in turn means its material properties are also variable – certainly across the country, but even within a given quarry there may be significant variation by location (and therefore over time). It may be possible that one or more of these material properties could influence noise emission (toughness, for example, see section 3.1.1), which would lead to some variation in acoustic properties between different surfaces and regions. It is not known whether the differences would be substantial enough to be practically significant, or even measurable.

4 Aggregate production, testing, size and shape.

In this section, the production and abrasion tests for assessment of aggregate properties are discussed.

4.1 Crushing and aggregate production

Roading aggregates are sourced from either hard-rock or alluvial river gravel quarries. Hard rock quarries require large stones to be removed from rock faces and then broken and crushed into the range of sizes required for any particular job type. Alluvial quarries extract stones from riverbeds (old or existing) that are many different sizes. The stones are then crushed to produce aggregate of the sizes required for any particular job. Crushing is done in several stages with different types of equipment as outlined below.

4.1.1 Primary crushing

The primary crusher is used to make it possible to transport the broken rock or stones on a conveyor belt to the next stage of crushing. In most aggregate crushing plants, primary crushing is carried out in a jaw crusher, although a gyratory primary crusher may be used. If material is easily crushed and not excessively abrasive, an impact breaker could also be chosen. The most important

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[4] Cleanness relates to the amount, fineness, and character of clay-like material in the aggregate

characteristics of a primary crusher include the capacity and ability to accept raw material without blockages. A large primary crusher is more expensive to purchase than a smaller machine; for this reason, investment cost calculations for primary crushers are weighted against the costs of blasting raw material to a smaller size. In most cases, the raw material is transported by trucks to a fixed primary crusher. A pit-portable primary crusher can also be used in cases where the producer is crushing at the quarry face. In modern plants, it is cost-effective to use a mobile primary crusher, so it can follow the movement of the face where raw material is extracted.

4.1.2 Intermediate (secondary) crushing

The intermediate crushing is used to produce various coarser fractions – basecourse, rail ballast as examples – or to prepare the material for final crushing. If the intermediate crusher is used to make AP60 sub-base, product quality is important. In other cases there are normally no strict quality requirements, although the product must be suitable for fine crushing. In most cases, the objective is to obtain the greatest possible reduction at the lowest possible cost.

4.1.3 Fine (tertiary) crushing

In this crushing stage, the quality and quantity of fine products are determined. Quality requirements can be stringent for the final products, especially within the quarrying industry. Customer requirements common to both the aggregate and mining industries are capacities and quality (fraction/particle size). The quarrying industry has additional quality demands such as soundness and particle shape (cubicity). In most cases, the fine crushing and cubicising functions are combined in a single crushing stage. The selection of a crusher for tertiary crushing calls for both practical experience and theoretical know-how.

4.1.4 Types of crushers

Most crushers used for aggregate production can be categorised as one of three main types:

- Compression crushers – which squeeze the material until it breaks,
- Impact crushers – which use the principle of rapid impact to shatter material,
- Attrition crushers – which use both impact and grinding to shear material.

4.1.4.1 Compression crushers

Jaw crushers are often used as primary crushers and are perhaps the most popular crusher worldwide. They are suitable for most any type of material. Crushing takes place between a stationary jaw plate and a moving jaw plate, made from hard steel. Jaw crushers are reliable, robust machines, offering a 6:1 reduction ratio in most materials, and will accommodate hard, abrasive materials.

Roll crushers are a compression-type reduction crusher with a long history of success in a broad range of applications. The crushing chamber is formed by massive drums, revolving towards one another. Double roll crushers offer up to a 3:1 reduction ratio in some applications, depending on the characteristics of the material. Triple roll crushers offer up to a 6:1 reduction. As a compression crusher, the roll crusher is suited for extremely hard and abrasive materials. These are rugged, dependable crushers, but not as productive as cone crushers with respect to volume. Roll crushers provide very close product distribution and are excellent for chip stone, particularly when avoiding fines.

Cone and gyratory crushers are gyrating shaft machines. They have a main shaft that gyrates and provides the crushing motion. Crushing takes place between a fixed outer crusher member (the concave ring) and a moving inner crushing member (the mantle), mounted on the gyrating shaft assembly. Cone and gyratory crushers are typically used on abrasive materials of considerable hardness. Due to high investment value, they are used in cases where impact crushers are not appropriate.

4.1.4.2 Impact crushers

Primary impact breakers are noted for large expansion chambers above one or two revolving rotor assemblies. As the rock falls into the rotor circle it is struck by manganese hammers fixed onto the outer surface of the rotor(s). The rock shatters upon impact with the hammer, sprays against the back wall of the impactor, and then tumbles back into the hammer circle. These breakers are ideal for limestone quarries and are known to provide 20:1 reduction or even as high as 40:1 reduction in the case of a double rotor configuration. The expansion chamber allows stone to shatter at its weakest fissures, minimising fines while generating a high percentage of minus 38 mm (1" to 1/2") product with superior soundness. They are also noted for their ability to accept a maximum feed size much larger than other primary crushers.

Primary horizontal shaft impactors (HSI) are noted for their accessibility, with a housing that opens like a clamshell. Quarry shot material enters the crusher, and upon impact with the hammers (blowbars), it strikes the curtain(s), and then immediately rebounds back into the hammer circle. Reduction ratios associated with primary HSI crushers range from 4:1 to 6:1 depending on the material characteristics. The maximum feed size varies with each model but is generally limited to 609 mm to 914 mm. The output gradation of the primary HSI crusher is generally coarser than the primary breaker due to the lack of expansion above the rotor, which also affects the capacity.

Secondary HSI crushers are characterised by a high 10:1 reduction ratio and by their suitability for generating a cubical product. They can also be used for a variety of applications. Secondary impact crushing is commonly used to improve product soundness and remove deleterious materials. These high production crushers incorporate chromium alloy wear parts that allow for economical use on materials with abrasive characteristics. Some secondary HSI crushers offer curtains that can be added in the field for increased production of chip stone. Secondary HSI crushers have become very versatile, with multiple rotor configurations, special alloy wear parts, and maintenance features designed to reduce downtime and lower the cost of ownership.

Vertical shaft impact crushers are generally recognised as tertiary crushers. Vertical shaft impact crushers (VSIs) have material fed into the centre of the crusher through a feed tube and onto the centre of a rotating table or rotor. The material is then accelerated to high velocity and is thrown into the anvil ring or outer shell. Crushing takes place upon impact with the anvil ring or against other material that is in the rock shelf (rock on rock). Product gradation in VSIs is controlled primarily by the speed of the table or rotor.

4.1.4.3 Attrition crushers

Hammermill crushers are similar to impact crushers in the upper chamber where the hammer impacts the in-feed of material. Hammermills also incorporate a grate circle in the lower chamber of the crusher that the product must pass through as it exits the machine, ensuring controlled product sizing. Hammermills crush or pulverise materials that have low abrasion. The rotor speed, hammer type and grate configuration can be converted for different applications. Hammermills can be used in a variety of applications, including primary and secondary reduction of aggregates, as well as numerous industrial applications.

4.1.5 Implications for Tyre/Road Noise

The crushing process has a large effect on the size and shape of the resulting aggregate, though these are modified to a large extent by the grading process (section 4.2), and on the surface microtexture. Combined with different geologies, the crushing process may influence the shape and face properties of the aggregate. The type of crushing used may therefore be relevant to the acoustic properties of resulting road surfaces.

Unfortunately, there is no centralised database available on what crushing regime operates at any given site, at a given time, for a given product. The only way we know of to obtain this information would be to contact the individual (active) quarries, and rely on their own record-keeping and willingness to share that data.

However, even if the information was available, there is a large dependence on the site geology, the individual machine characteristics, and the operating parameters, which would be challenging to unpick.

4.2 Grading

Grading, or the size range of the particles that are used in a road surfacing (chipseal or asphalt), is a vitally important component of any given surfacing. Between chipseals and asphalts, it is mostly the size range of the aggregate particles and their cleanness that differ. Grading of sealing chips uses narrow size ranges to achieve chips of consistent size within each grade (Table 1). Chips for use in dense graded asphalt use a range of sizes to achieve a mix that packs together well. Chips for open graded asphalt are predominantly larger-sized with few smaller-sized chips, to achieve a mix where chips have voids between them when packed (Table 2).

Table 1: NZTA M/6 sealing chip grading sizes

Chip grade	Minimum ALD[1] (mm)	Maximum ALD (mm)
1[2]	11.5	14.0
2	9.5	12.0
3	7.5	10.0
4	5.5	8.0
5[3]	2.36 (2% max)	9.5 (95-100% passing)
6[3]	0.3 (8% max)	6.7 (95-100% passing)

[1] ALD = Average least dimension.
[2] Grade 1 chip is not specified in NZTA M/6, but can be used for unsealed roads such as in forestry.
[3] ALD not appropriate for small chips, so % passing sieve (mm) is used.

Table 2: NZTA P/11 porous asphalt specified mix envelopes (% passing)

Sieve Size (mm)	PA 10	PA 14	PA 7 HV	PA 10 HV
19		100		
13.2	100	85-100		100
9.5	85-100	25-50	100	85-100
6.7			85-100	
4.75	30-40	12-22	10-30	10-30
2.36	19-25	5-15	5-15	5-15
0.075	2-5	2-5	1-5	1-5
Minimum Asphalt Thickness (mm)	25	30	20	30

4.3 Aggregate Tests

Source property tests are performed on the source rock to assess its strength and durability. Production Property tests are performed on the processed material to determine its size, shape, and cleanness.

4.3.1 Source Property Tests

The physical properties of aggregates used in chipseal surfacings in New Zealand are currently controlled by the NZTA M/6 specification (Specification for Sealing Chip). Most of the same properties also apply to OGPA aggregates.

These test methods were developed for characterising aggregates for good quality, strong, durable road pavement and surface construction. The test methods may not fully represent the conditions aggregate experience before or during service, such as the abrasion and fracturing that occurs during handling (chip to chip abrasion, Figure 3), construction (machine induced chip breakage/abrasion) or trafficking (chip rollover, chip abrasion, chip fracturing).

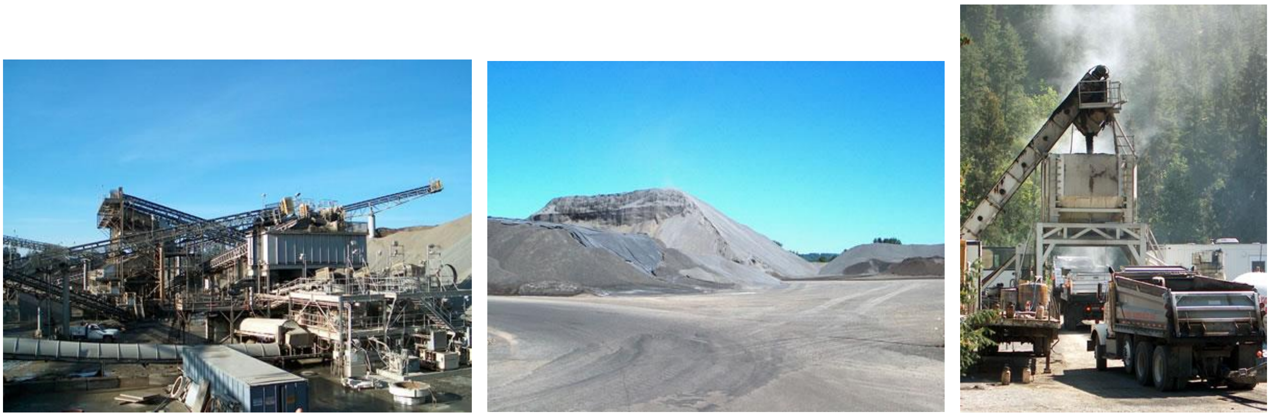

Figure 3: Aggregate production, stockpiling, and mixing

The measurement of aggregate source properties is used to control for the differences in the mechanical and chemical characteristics of the aggregates, and then to understand how they will behave in-service.

- Crushing resistance has a dominating effect on four of the subsequent tests and is strongly related to the geological/mineralogical properties and is one of the more important of the source property tests (NZS 4407 Test 3.10).

- Weathering quality index appears to be very dependent on processing methods, but will also be strongly determined by the amount of plastic or expansive material in the aggregate (NZS 4407 Test 3.11).

- Clay and plasticity indices are largely related to the mineral content, primarily the clay matrix and the nature of the clay itself, i.e. smectite, illite or zeolite. These indices are measured on the fine materials produced from a given aggregate during production.

- Polished Stone Value tests (BS EN 1097-8:2009) indicate the susceptibility of the aggregate to lose surface microtexture with trafficking (for the primary purpose of providing skid resistance). The test is carried out on grade 4 sized chip, and generally only once per source, and the results are used to characterise all grades from that source unless it is deemed to be 'variable'.

- Other test methods in post-production, where the results are determined by interactions of the processing method and the mineralogy, include: California Bearing Ratio (CBR), particle size distribution (PSD), and various other less common tests.

Experience has made it clear that aggregate materials from similar sources behave similarly, but not necessarily identically. Conversely, aggregates that have diverse geology and mineralogy can behave very differently in these source and property tests.

In terms of application of any given aggregate, in the main, aggregates tend to be used locally, i.e. near to their source quarries, due to the high costs of transporting aggregates long distances. This, therefore, does suggest that road surfaces may have local performance idiosyncrasies. However, the local use is not completely universal as there are one or two aggregates (e.g. melter aggregate) that are transported long distances. The susceptibility of aggregate to breakdown and abrasion will be the key determinants to their change of shape as they age in-service. If macro- and micro-textures are factors in tyre/road noise emissions, then understanding the breakdown and/or abrasion of given aggregates may well be relevant to understanding the evolution of noise emission over time.

4.3.2 Production Property Tests

The production property tests considered here are specific to the requirements for NZ road aggregates that will be used in chipseals (NZTA M/6, 2011) and OGPA (NZTA P/11, 2007). The testing methods for both are generally as described in NZS 4407:2015, though some additional methods are used.

The requirements for sealing chip are well-specified:

- Cleanness Value is a measure of the amount, fineness, and character of the clay-like material coating the chip, which detrimentally inhibits the bond between binder and chip. The test involves mechanically washing out and measuring the quantity of fines.

- Average Least Dimension (ALD) of sealing chip is the average thickness of the chip when they are lying on a flat surface in their most stable position (c.f. having been rolled). A sample of at least 100 chips of a single grade is collected and the thickness of each is measured using a dial gauge, and the results averaged to produce the ALD in millimetres. This test is impractical for finer grades, so is only performed for grades 2, 3, and 4.

- Chip Size Uniformity Testing determines what percentage of chips fall within a range of ± 2.5 mm of the ALD for grades 2, 3, and 4.

- Percent Passing is a measure of the size of chips of grade 5 and 6. This is a sieve test, performed using a range of sieve sizes, and as such it quantifies the distribution of sizes in the sample rather than by providing an ‘average’ size. The specification is also for an envelope rather than a separate target size and uniformity tolerance requirement.

- Average Greatest Dimension (AGD) is (only) used in ratio with ALD to provide an indication of the typical shape of sealing chip. AGD is measured on the same sample of 100 chips used for the ALD measurement, by placing the chips end-to-end longways in a trough, and dividing their total length by the number of chips.

- Chip Shape (AGD/ALD) is the ratio of AGD to ALD, and is compared against a maximum ratio of 1:2.25 for chipseals of grade 2, 3 and 4. This helps to prevent flaky or misshapen chips from being used.

- Angularity of sealing chips is a desirable characteristic to increase the stability of the chipseal, and is determined by visual inspection of a sample of chips, with a requirement that at least 98% have two or more broken faces.

The production test requirements for OGPA are Cleanness Value, Chip Shape, and Angularity, as above.

4.3.3 Implications for Tyre/Road Noise

If there are any aggregate attributes that we wish to examine for their possible acoustic impact, these will either need to be derived from quantities that are currently measured and recorded (as listed above), or they will need to be measured specifically for the purposes of noise research, for example, in a future surface trial or scheduled resurfacing.

4.3.3.1 Size

It is already well known that chip size has a strong influence on chipseal tyre/road noise, and that the maximum particle size within asphalt mixes influences the tyre/road noise emission of OGPA, and the mechanism – via macrotexture – is reasonably well understood. Much of this influence is controlled by the grading process (section 4.2), but not all. There is still variation in the product size within a grade or envelope, due to the tolerances allowed by the specification. It is unknown whether these might extend to local or regional differences due to variations in geology, equipment, or operations between quarries.

Given that we have previously measured $L_{CPX:P1,80}$ differences of 1 dB between adjacent chipseal grades (Jackett, 2019), and 4 dB between adjacent EMOGPA specifications (Jackett, 2018), the variation in size within a single specification would be a prime candidate for further study. There is data in RAMM that would facilitate a desktop analysis of this.

4.3.3.2 Shape

One method to quantify chip shape is to use the ratio of the length to the height of the chip (AGD/ALD), as described in section 4.3.2. The NZTA M/6 Specification requires a maximum of ratio of 2.25 for both sealing chip and OGPA coarse, and the lack of a minimum constraint implies that it is 1.0.

Unfortunately, while the RAMM database does hold ALD measurements for chipseal surfaces, it does not contain either AGD or the ratio. This is despite the same sample of chips being used for both AGD and ALD measurements and one measurement never being performed without the other, according to a WSP technician who performs this testing. WSP's leading RAMM expert noted that ALD is crucial to determining the application rate for the binder (because it dictates the depth of chip that needs to be bound), whereas AGD has no practical use in the construction phase of chipsealing, and that is likely why one is recorded and not the other. The result is that it is not possible to get a determination of shape for either sealing chip or OGPA coarse for an existing road from RAMM.

Given that the measurements of AGD are already being made in the course of showing compliance with NZTA requirements, it may be reasonable to request that they are also included in the *cway_surface* table in future, alongside the ALD measurements. For the moment, the options for investigation of shape appear to be limited to contacting individual quarries to request that they release their historical testing data (i.e. an observational study), or conducting new trials (i.e. an experiment).

4.3.3.3 Physical Breakdown Under Load

It is known that laboratory tests of aggregate toughness and strength relate well to the in-situ behaviour of those aggregates, but no link has yet been established between in-situ broken-down or worn surfaces and noise emission. If such a relationship was found, it is likely that the laboratory Source Property test data would be of direct relevance to predicting noise emission trends over the long-term (or high-traffic-volume).

It is noted that breakdown could influence noise emission in either direction, for example through the mechanism of surface flushing, or through stripping or rutting.

4.3.3.4 Microtexture

Although arguably least important in terms of noise generation mechanisms, the surface microtexture is highly relevant to skid resistance, so the data is readily available. Because microtexture is dependent on the geology and crushing process, the PSV measurement is considered to be representative of a given quarry site (as long as that site or production process is not considered 'variable') and is not frequently re-measured.

It would be possible to use data already in RAMM to study whether microtexture varies significantly on a region-to-region basis. However, quantifying how that variability contributes to tyre/road noise would be difficult, due to the weak underlying effect.

5 Analysis of In-situ Macrotexture Variation

The NZTA's road surface noise research programme has established that there exists a strong correlation between surface macrotexture (measured as mean profile depth (MPD) in millimetres) and measured noise emission level (as $L_{CPX:P1:80}$) when both are aggregated over a sufficient distance (Jackett, 2019). If the macrotexture of chipseal or asphalt surfaces is found to differ by the source of their aggregates or sealing chips, then it should be expected that the noise emission level would also differ.

The RAMM database contains both MPD and aggregate source information, which have been aggregated and analysed to provide an initial estimate of noise differences between products from different quarries. Two surface specifications, OGPA PA-10 and Two-coat 3/5, have been analysed as pilots for asphalt and chipseals, respectively.

5.1 Methodology

5.1.1 Data Sources

Data have been drawn from the RAMM database, including: surface material and grade, "pavement" source (the quarry from which the surface aggregate originated), and the HSD texture survey (as MPD).

All SH sections with the target surface specification laid in NZ within the last 8 years have been identified, and the origin of the aggregate used for each running surface determined. The MPD from the highspeed survey, as measured in the financial year (July to June) following the surfacing year (i.e. 1 year-old surfaces), has been averaged across each road section. Other parameters such as the total lane length and number of surfaces deriving from each quarry were also calculated.

5.1.2 Relationship between MPD and $L_{CPX:P1:80}$

Jackett (2019) found a strong correlation ($r^2 = 0.87$) between surface macrotexture (as MPD) and noise emission level (as $L_{CPX:P1:80}$) when those data are aggregated by surface type, provisionally quantified as:

$$L_{CPX:P1,80} \approx 3.42{*}\mathrm{MPD} + 94.5 \text{ in dB} \qquad \text{(Eq. 1)}$$

That survey of 250 lane-km of state highway had sample sizes for each surface type of between 2 km and 50 km, aggregating over 20-metre-long samples. The current analysis aggregates 10-metre samples over generally much larger lane-distances, so the sample size is not expected to influence the applicability of the equation. However, note that the coefficients for slope and offset are only estimates and have not been precisely defined.

5.2 OPGA PA-10

PA-10 is the only OGPA specification that appears in the top 15 surface specifications (including grade) ranked by lane-length, and is the highest ranked asphalt.

Of the 250 active quarries recorded in RAMM, there are 10 that have contributed aggregate to OGPA surfaces within the last 8 years. Unsurprisingly these are located near to the main urban centres (Figure 4).

Figure 4: Locations of quarries that recently produced PA-10 aggregates

The average MPD in mm and corresponding derived CPX:P1:80 level in dB for each quarry are presented in decreasing order in Table 3, and Figure 5 displays the noise level only, with error bars representing confidence in the mean at the 95% level (not the overall uncertainty in derived level).

Table 3: Texture measurements from 1-year-old PA-10 surfaces deriving from different quarries

Quarry	NOC	MPD Average (mm)	MPD SD (mm)	Derived LCPX:P1,80 (dB)	Unique Road Sections	Lane Length Surfaced (km)
Hunua Quarry	AUCK ALLIANCE	1.39	0.23	99.2	15	108.4
Glenbrook Mill	AUCK ALLIANCE	1.38	0.16	99.2	15	206.2
Miners Road	NORTH CANTERBURY	1.32	0.44	99.0	2	14.3
Kiwi Point Quarry	WELLINGTON	1.31	0.13	99.0	2	51.4
Hilderthorpe	COASTAL OTAGO	1.30	0.35	98.9	4	37.7
Brookby Quarry	AUCK ALLIANCE	1.29	0.15	98.9	10	98.6
Belmont Quarry	WELLINGTON	1.29	0.24	98.9	27	84.7
Ngaruawahia	WEST WAIKATO NORTH	1.28	0.11	98.9	8	42.1
Waitawheta Quarry	BOP WEST	1.26	0.08	98.8	7	31.0
Otaki Quarry	WELLINGTON	1.22	0.24	98.7	2	22.9

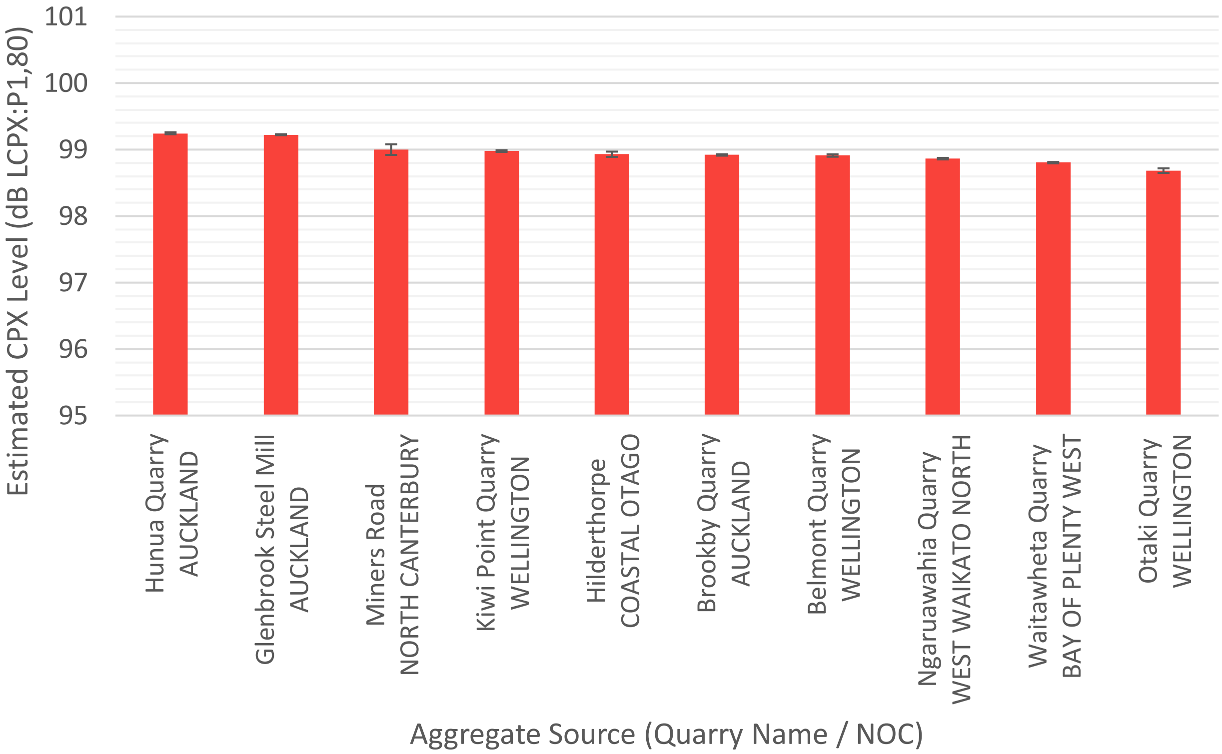

Figure 5: Variation in (derived) noise emission of OGPA across aggregate sources

5.2.1 Tests for Statistical Significance

There is a statistically significant difference in macrotexture between quarries as determined by one-way ANOVA (*$F(9,69752) = 486.7$, $p < 0.001$*). Note that whilst the variances within each group are not equal, Welch's F-test has been used to demonstrate that the outcome of this significance test is not influenced.

The Tukey-Kramer HSD post-hoc test has been employed to investigate which pairs of sites give rise to the finding of statistical significance. At the $p < 0.01$ level of confidence, almost all pairs of sites are significantly different (37 of 45 possible pairs). The key observations are that Waitawheta and Otaki each achieved significance in every pairing they featured in, whilst Hilderthorpe's large standard deviation meant it could not be shown to be different from its four neighbouring quarries in the ranking list (Table 3).

It must also be stressed that there are other possible reasons for regional variations in MPD besides the aggregate source. For example, influences from climate, different road crews, or even factors affecting the measurement of surface macrotexture.

5.2.2 Implications for OGPA Tyre/Road Noise

These significance tests have extraordinary statistical power due to the very large overall sample size (~70,000 measurements), which allows the confirmation of even very small differences in macrotexture between quarries. However, statistical significance does not imply that the differences are significant in a practical sense.

Average macrotexture attributed to the different quarries ranges from 1.22 mm to 1.39 mm. If the general relationship (Eq. 1) between macrotexture and CPX noise level holds then this corresponds to a range of approximately 0.6 dB $L_{CPX:P1:80}$ between the quarries supplying the noisiest and quietest surfaces.

A key question would be "what effect does the source of aggregate have on PA-10 tyre/road noise?". From the data we derive that the contribution to uncertainty arising from random selection of the aggregate source, with respect to macrotexture, is ± 0.3 dB at the 95% level. This is negligible in terms of both the possible noise effects and the variation we have measured acoustically between OGPA road sections of nominally the same specification, and it implies that the aggregate source is not a driving factor in variation between PA-10 surfaces.

5.3 Grade 3/5 Two-coat Chipseal

Two-coat 3/5 is the most common specification of chipseal on NZ state highways, ranked by lane-length, and the most common top surface overall. 35 quarries have contributed grade 3 and grade 5 chip to two-coat surfaces in the last 8 years, across 20 NOCs.

The average MPD across all 1-year-old road surfaces deriving from each quarry has again been calculated, and used to derive an indicative LCPX:P1,80 level for each quarry (Figure 6). Each combination of NOC and quarry is shown (n=46), though only the NOCs are labelled. If a NOC appears more than once, it is because more than one quarry contributed. Conversely a single quarry may contribute to several NOCs (e.g. the five dark columns in the figure all correspond to the Glenbrook Steel Mill). Error bars represent confidence in the mean at the 95% level (not the overall uncertainty in the derived CPX level).

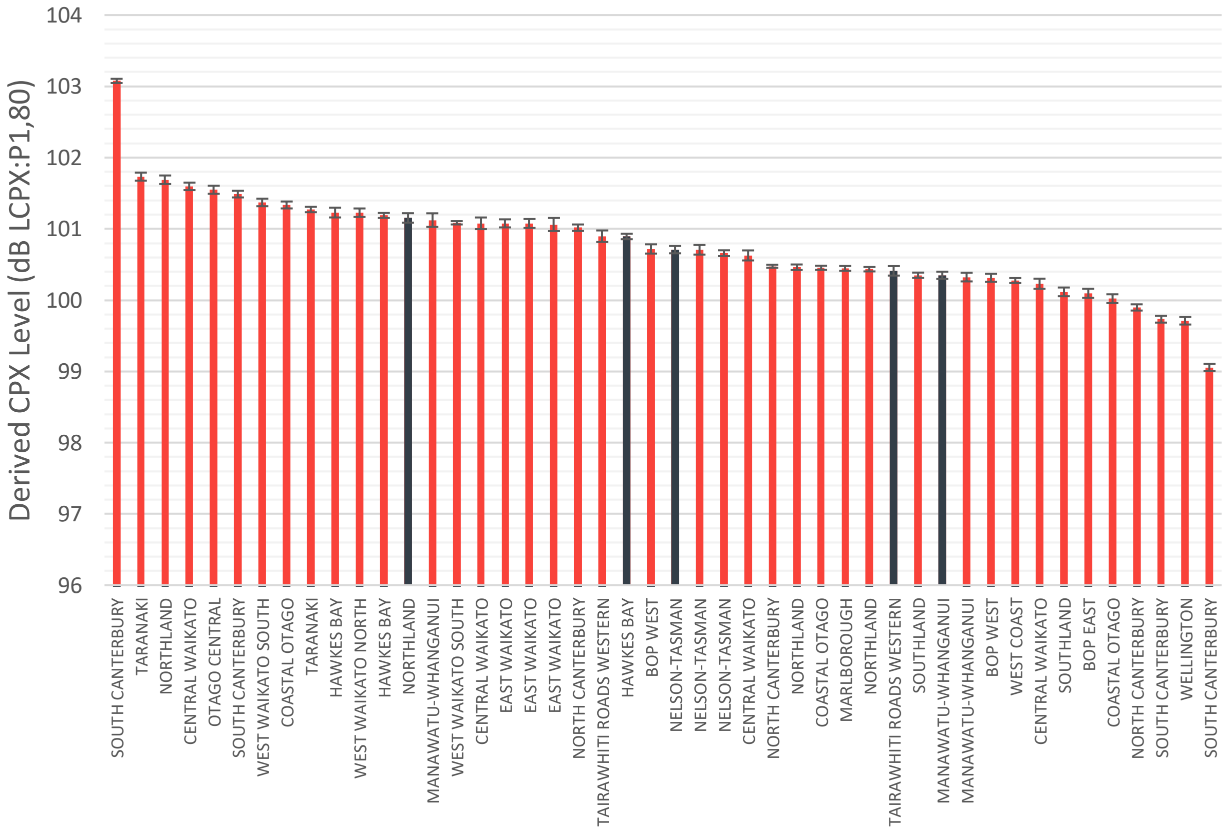

Figure 6: Variation in (derived) noise emission of two-coat 3/5 chipseal across aggregate sources

5.3.1 Tests for Statistical Significance

There is a statistically significant difference in macrotexture between observations as determined by one-way ANOVA (*$F(45,251395) = 589.8$, $p < 0.001$*). Note that whilst the variances within each group are not equal, Welch's F-test has been used to demonstrate that the outcome of this significance test is not influenced.

The Tukey-Kramer HSD post-hoc test has been employed to investigate which pairs of observations give rise to the finding of statistical significance. At the $p < 0.01$ level of confidence, most pairs of sites are significantly different (871 of 1035 possible pairs).

As before, there are many other possible reasons why MPD might vary, besides the aggregate source, and the following example illustrates this. The Glenbrook Steel Mill (dark bars in Figure 6) produces melter aggregate that has been used in two-coat 3/5 surfaces across five different NOCs. However, across all those NOCs (10 potential pairs), only the macrotexture difference of the Manawatu and Tairawhiti Roads pairing was *not* statistically significant at $p=0.01$. All other pairs were sufficiently different in macrotexture to achieve significance from each other, despite the sealing chip originating from the same quarry. Across these five NOCs the range in derived LCPX:P1,80 level on Glenbrook aggregate was approximately 1 dB.

The implication is that other factors are playing an important role in the variation of chipseal macrotexture. Identifying those factors and quantifying their relative influence on the eventual tyre/noise emission of chipseal surfaces would require further study.

5.3.2 Implications for Chipseal Tyre/Road Noise

Average macrotexture attributed to the different quarries in the first year after sealing ranges from 1.33 mm to 2.51 mm, with an average of 1.84 mm and a standard deviation of 0.20 mm. If the general relationship (Eq. 1) between macrotexture and CPX noise level holds then this corresponds to a range of approximately 4 dB $L_{CPX:P1:80}$ between the quarries supplying the noisiest and quietest surfaces[5], which is considerable and warrants further investigation.

It follows that the contribution to uncertainty in noise level (with respect to macrotexture variations only) arising from a random selection of the sealing chip source is ± 1.3 dB at the 95% level ($n=46$). This level of uncertainty could have implications for the compliance of roading projects with respect to noise. The difference in noise level between the upper and lower ends of the 95% confidence interval for two-coat 3/5 surfaces is similar to the threshold of audibility, so it is conceivable that it could contribute to noise effects in some circumstances.

6 Recommendations

When considering the effects of aggregate properties on the noise emission of the finished surface, the size, shape, surface properties, and mechanical properties of aggregate all appear to be of relevance, to various degrees. There is data in RAMM on all of these properties, again, to various degrees:

- The size of road surface aggregates is known to have a significant effect on noise. While size is controlled for by the grading system, it is within a tolerance, so real-life variation in chip size or distribution within nominally the same specification would be a useful area for further study, and there is data available in RAMM that would facilitate this.
- The shape of the aggregate particles is likely to have an influence on noise. Shape is already measured for compliance reasons, but not all the necessary data is stored in RAMM. The options for further investigation appear to be limited to contacting individual quarries to request that they release their historical testing data (i.e. an observational study) or conducting new trials (i.e. an experiment).
- The microtexture of the road surface is thought to have a very small effect on noise. It would be possible to use data already in RAMM to study whether microtexture varies significantly on a region-to-region basis. However, quantifying how that variability contributes to tyre/road noise would be difficult, due to the weak underlying effect.

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[5] Incidentally, both these surfaces are on South Canterbury roads, which highlights the level of diversity possible even within a single region, though the quarries themselves are over 200 km apart.

Microtexture is required for road safety and would be prioritised over any tyre/road noise emission consideration.

- The mechanical properties of aggregate are not generally considered to be significant in terms of their direct effect on noise generation, but WSP's road surface durability research indicates they may have an indirect effect over time (and trafficking) via breakdown and weathering. If such a relationship was found, it is likely that the laboratory Source Property test data would be of direct relevance to predicting noise emission trends of surfaces with age.

Whilst noting that the noise levels discussed in section 5 have been derived from macrotexture rather than from acoustic measurements, and acknowledging that additional and confounding factors are certainly also at play:

- PA-10 was found to exhibit low sensitivity to the aggregate source (± 0.3 dB at the 95% level), which suggests that the variation in aggregate properties across NZ is not a primary driver behind variation in acoustic performance of OGPA, and that there may be limited scope for further improvement in this regard.
- Two-coat 3/5 appeared to exhibit a much greater sensitivity to the aggregate source (± 1.3 dB at the 95% level), and therefore variation in aggregate properties across NZ may be one of the factors that have practical significance on chipseal noise emission levels. Further study would be required to separate out specific aggregate properties from the multitude of confounding variables (e.g. different crews in different regions). There are a number of possibilities within the existing CPX and RAMM data, including exploring the variation in macrotexture from each individual quarry, investigating the range of chip sizes that actually occur within a grade, and attempting to isolate some of the confounding variables.

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