CASE STUDY OF HOW AN ENVIRONMENTAL PROTECTION ACTIVITY ADVERSELY AFFECTED THE PERFORMANCE OF A HIGH QUALITY PAVEMENT AGGREGATE

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ABSTRACT

A quarry's aggregate has been successfully used in pavements since processing facilities were significantly upgraded in 1999. However, despite laboratory test results of aggregate properties exceeding specification requirements, performance in service was below expectations in some applications. This was originally attributed to weathering that was thought to produce expansive clays. A series of investigations, trials of modified production processes and other remedial actions did not resolve the problem.

Aggregate in all stages of production process is washed, chemical added to the wash water to settle the suspensions, and the water reused, to minimise discharge into local streams and impact on the environment of the quarry's operations. Although processed water was guaranteed to be chemical-free by suppliers, it was found to contain large amounts of coagulant, which have a high surface charge, and attract any material in suspension. After primary crushing, fine material produced was mostly rock dust that was attracted and strongly held to chip surface, creating a coating. Residual positive surface charge of coating repelled bitumen, resulting in a weak bond and eventually unravelling. Reducing and controlling coagulants corrected problem, producing a clean, durable chip. The paper describes the investigation and solution, in detail.

INTRODUCTION

Poplar Lane Quarry is located in the Bay of Plenty area of the North Island of New Zealand, and produces stone from a porphyritic andesite. Quarrying began at the Maketu site in the 1950's and was operated by a succession of small contracting companies. As nearby competing sources closed down due to exhaustion of resource or encroachment by the expanding urban development, the Maketu quarry became the main supplier of premium aggregates to Tauranga and Western Bay of Plenty, an area of significant population growth due to its climate and lifestyle opportunities.

Fulton Hogan purchased Maketu quarry in 1998 and renamed it Poplar Lane Quarry (PLQ). Significant capital was invested in plant and the market was expanded, so that the quarry grew from producing 200,000 tonne per annum to 500,000 tonne per annum in a period of 18 months. Production has averaged approximately 600,000 tones per annum during the past five years. Growth in demand required significant investment in a new crushing plant during the 2000 financial year with a production capability of 500 tonnes per hour. Mobile plant was replaced with modern plant that allowed for the number of items to be halved.

As all source rock required washing, a significant part of this development was the installation of a water recycling plant. Previously, settling ponds had been used for the treatment and recycling of water but due to the constraints of available space and effectiveness of the ponds a fully contained clarifier, recycling up to 300 m^3 per hour, was installed.

As the site was operated under an existing rights permit and as we intended to expand the operation significantly, resource consents (permits) were applied for under the Resource Management Act; key issues in this process were the significance of the area to the indigenous Maori population and discharges to the environment, especially to local watercourses.

Since 1998, the aggregate from this quarry has been successfully used in road, airport and port pavements, after significantly upgraded the processing facilities. However, despite test results of the aggregate properties exceeding specification requirements, as the aggregates produced from PLQ became used more within the area it became apparent that performance of the aggregate in service was below expectation in some applications..

INITIAL ISSUES IDENTIFIED AND ADDRESSED

Three areas of concern were identified initially; these issues developed over a medium to long time period. Investigations were carried out to identify the causes and then implement process improvements to rectify the problems.

Basecourse

Basecourse specified to Transit NZ M4 (2005) and laid on sites showed rutting very rapidly, especially on greenfields sites, in some instances with minimal traffic volumes. Material recovered from investigation pits showed a rapid deterioration of sand equivalent (NZS 4407.3.6:1991) from 60 when laid to 30 after a relatively short period.

After a few projects where the basecourse aggregate did not perform as expected, the following steps were taken to ensure the required qualities of the aggregates material were consistently achieved:

- A compaction trial was carried out to investigate whether the aggregate was breaking down under compaction; no change in particle size distribution occurred after 10 repeated heavy compaction cycles.
- Mining of source rock was improved to ensure that weathered material was not included in the aggregates.
- Blended fine aggregates were rigorously controlled for quality of stone and proportion added.
- Stockpiling and load out procedures were upgraded to best practice.
- Tracking of aggregates from source location within the quarry through to stockpile to site were implemented.
- Site specific specifications were implemented on the crushing resistance of the aggregate and % passing the 75 micron sieve.

Asphalt Aggregates

Asphalt surfaces in some instances showed a fretting of stone and a rapid discolouration from black to grey, with the surfaces becoming unravelled and rough over a 3 to 5 year period. It was thought that a combination of chip breakdown, high absorption and excessive fines within the AP 7mm was creating these problems.

For aggregates used in asphalt mix production, steps taken to ensure quality improved included:

- Implementation of strict source rock characterisation tests at increased frequency.
- Blending of fine aggregates to reduce the % passing 75 micron sieve.
- Investigation of Australian and European specifications and testing of PLQ aggregates against these, with the wet / dry strength variation test being the only one that the aggregates were near to failing.

Sealing Chips

After 3 to 5 years in service, some sealed sites showed breakdown of chip especially on the fine chips exposed to the weather; mode of distress was predominantly stripping of the entire seal in high stress areas as the fine chips broke down and the seals lost their structural integrity. Actions implemented to enhance quality of sealing chips included:

- Frequency of source property testing for aggregates was increased.
- Frequency of washing on screens of aggregate increased.
- Strict controls applied to wash water to ensure that the process water was as clean as possible, as advised by the supplier of water clarifier and chemicals.

Quality Improvement

Once these actions had been put in place, the Quality Improvement team was concerned that though there appeared to be improvements, these were not to an acceptable level that satisfied our quality requirements. As local expertise had been exhaustively consulted, we searched for an international expert to advise us. As the team believed that the issue was related to rock durability, Professor Peter Hudec, a Canadian expert with extensive experience in the field of aggregate durability, was asked to investigate, and his investigation and findings are described in the next sections of this paper.

QUARRY GEOLOGY

Rock type and description

The quarry is currently operating exclusively in porphyritic andesite; the rock in the face varies from massive to strongly jointed and fractured. At least two lava flows comprise the rock currently quarried. One is medium gray in colour, and the other brownish gray in colour (Figure 1). The latter is more coarser grained. Both are porphyritic andesite of essentially same composition and quality. No volcanic ash or ignimbrite (welded tuff) were found in active faces. Figure 1 shows the fresh rock, and the contact between the two lava flows. The picture also shows the orientation and the frequency of fractures that are pervasive in the rock. The fracturing cuts across flow lines and flow contacts; the devitrified glass filling of fractures suggests that fracturing and healing (filling) of fractures took place while the rock was rigid, but still hot, i.e., shortly after emplacement. The regular orientation of fractures throughout the quarry suggests that fracturing was in response to a regional stress.

Figure 2 shows a typical thin section photomicrograph. Thin section examination shows angular single crystal phenocrysts that are composed of plagioclase laths and minor hypersthene crystals; plagioclase laths exhibit simple twining, suggesting albite-oligoclase composition, and are sometimes zoned, suggesting slow cooling before eruption. Lithic clasts about two to six times larger than the individual phenocrysts are generally rounded, and filled with a mixture of plagioclase and hypersthene/augite crystals. The phenocrysts and clasts occasionally show ragged edges, suggesting rotational abrasion during flow and emplacement. The groundmass consists mostly of elongate prisms of simply twinned plagioclase, with minor crystals or nests of augite. Minor devitrified volcanic glass is present in the ground mass and as filling of fractures. Although generally randomly oriented, the groundmass prismatic crystals show local alignments of crystals into swirls, indicating lava mass flow; some are aligned in zones, indicating fluid flow. The rock is peppered with abundant, small magnetite grains. All thin section specimens studied showed sub-parallel fractures that were variously filled with devitrified glass (tridymite), clay (montmorillonite), some calcite (usually associated with clay), magnetite and iron oxide (limonite).

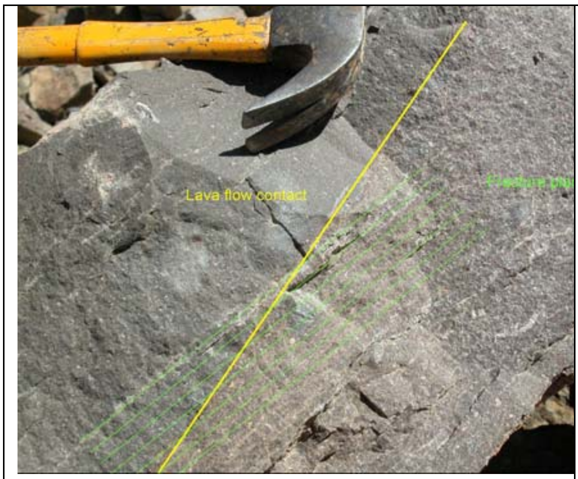

Figure 1. Contact of two andesite flows. Frequency of and orientation of fractures

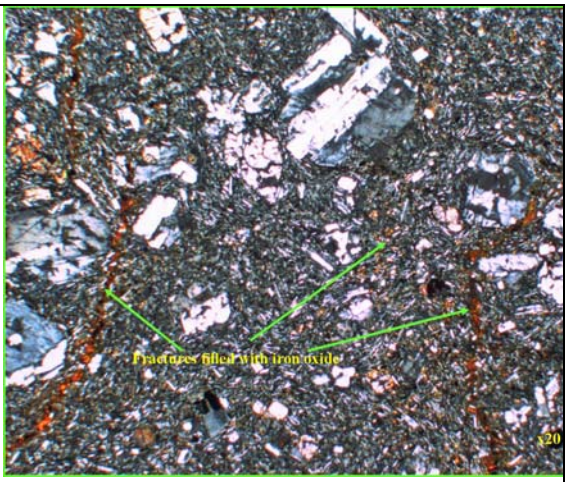

Figure 2. Thin-section photomicrograph of a typical porphyritic andesite.

The fracture system, along with a joint system, controls the size and shape of rock particles upon crushing. The fractures also affect the stability of rock chips in service. Weathering along the fracture was seen to cause the chip to split in closer examination, presenting a depression with a flat, rusty-covered surface.

Weathering, alteration, and smectite development

Bartley *et al* (2007) state that there is evidence that the Poplar Lane aggregate has been modified by hydrothermal alteration. No such evidence was found in the thin sections studied, or in the fresh faces of the quarry. Crushed rock exhibits some inclusions and veinlets containing zeolites and clays; however, the body of the rock is unaltered. Elsewhere in the quarry, especially in the older, upper levels, some alteration is evident, as well as an abundance of zeolite coatings on joint surfaces. This may be due as much to surface weathering as to hydrothermal surface alteration. Other areas of the quarry, especially those in the vicinity of the fault zones, are deeply weathered. The deeper portions of the present quarry have a relatively unaltered, unweathered rock.

The devitrified volcanic glass present in the rock has the potential to weather rapidly, and develop into expansive clay montmorillonite (smectite). Even in the fresh rock studied, clays were found in the fractures and as small grains in the groundmass (as stated above). Clay Index test results from Poplar Lane quarry is given as 1.2 on ground fresh rock, and 3.26 on partly weathered rock; interestingly, lime treatment lowers the clay index in the latter to 0.8 (Bartley etal, 2007). The type of smectite reported in the fresh rock is Na-rich, and susceptible to cationic replacement (treatment with Ca) to stabilize it.

Smectite present in the fresh rock now quarried may be partly liberated by crushing; the rock will split along the weaker fracture planes containing smectite, and part of the smectite will be removed by abrasion; however, the past use of chemical-laden water probably caused the abraded smectite to become part of the outer dust coating, thus potentially increasing its content in stockpiled material. However, the analysis of the rock dust obtained by washing the aggregate shows that the dust is composed of principally of rock flour, with very minor amounts of clay (smectite) or chlorite.

PERFORMANCE OF POPLAR LANE AGGREGATE IN SERVICE

Srayed seal surfaces and concrete using the Poplar Lane aggregate were examined. The examination consisted of hand-lens viewing of the aggregate in place, and zones where the aggregate was missing – weathered out, or popped out.

The raveled chips found alongside roadsides and in gutters of most other locations consisted of unweathered, or slightly weathered andesite; the cause of raveling was probably two-fold: Breaking of the chip along the fracture planes (identified in the geology section above), and loss of bitumen aggregate bond. The chips were generally clean of bitumen coatings, or partially coated, suggesting the loss of bond as the principal cause of ravelling. Bitumen surface also showed pits whose bottoms were flat, rusty aggregate surface. These were definitely aggregates cleaved off at the fracture surfaces, and the surface coating evident in the pit was the clay-iron oxide surface of the fracture.

Samples of the shoulder material along one road were collected, washed, and dried. Examination of the material showed that the aggregate particles were generally unweathered, and intact.

The above examination suggests that the aggregate material is essentially good, and resists weathering (at least during the period of placement, which in most cases was less than 5 years) reasonably well.

ROCK PROCESSING (prior to this study)

The processed rock chips stored in stock piles were observed to be coated with a layer of white dust. The dust layer was difficult to remove with normal washing; only prolonged soaking of the chip in water was able to loosen the coating.

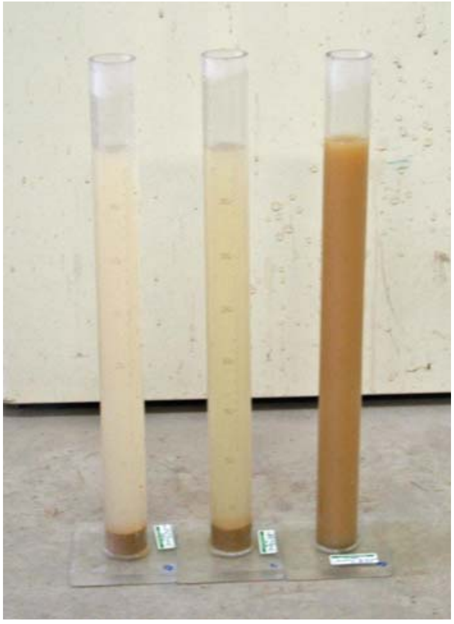

Figure 3. Settlement columns containing treatment water (left and centre), and distilled water

After initial crushing, the stone is washed, and relatively clean, large pieces of stone progress to secondary crushing and tertiary rounding treatment. Therefore, the dust that coated the particles can only be liberated by the secondary and tertiary treatment. Yet, the secondary and tertiary treatment wash water exiting the system was relatively clean. All the dust so produced therefore stuck to the rock chips.

The reason for this becomes clear when the quarry wash water treatment plant was examined. For environmental purposes, and to reduce the water use, the quarry used coagulant and flocculant to treat the water to settle the fines, and re-used the treated water. The coagulant and flocculant (hereafter referred to as CF) used is an organic chemical, a synthetic polymer, and is essentially a large cation designed to attract clay particles, form them into clumps, and settle them out of the water. The treated water re-entering the plant is clear; however, it is also fully laden with the CF, as a simple experiment in the lab proved.

Two samples of clear processed water were collected, one representing a light, and the other a heavy load of clay suspension that was treated. A 'virgin' untreated clay from the scalping pile was obtained, and wet-sieved to obtain the minus 0.075 mm fraction common in clay suspensions. A 100 ml suspension of this fraction was mixed with 900ml of the two treated water samples, and one distilled water sample. The two treated water sample immediately flocculated the suspension; the distilled water sample retained the suspension for several hours. This proved that the treated water contained a large amount of CF. The three columns of water shortly after the experiments are shown in Figure 3. The processed water contained sufficient CF to quickly settle the clay suspension.

Aggregate and clay particle surfaces are negatively charged, as are all surfaces. The negative charge is due to broken bonds at the surface, and imperfections in the internal lattice of the minerals. Water is a polar fluid with net negative and positive charge; water molecules are attracted to the negative surfaces, as are any positively charged molecules. The flocculating and coagulating agents used in the water treatment are large, positively charged polymer molecules. The chemical-laden water used in secondary and tertiary processing was attracted to the chip surface and coated the particle with CF. Dust produced during the processing was negatively charged, and is attracted to the coating. The dust particles adhered to the aggregate due to *van der Walls* force. There were several layers of dust coatings produced by this process. The process is illustrated in Fig. 4. Aggregate showing the dust coatings is shown in Fig. 5. The dust is essentially ground silica-rich rock powder containing mostly feldspar.

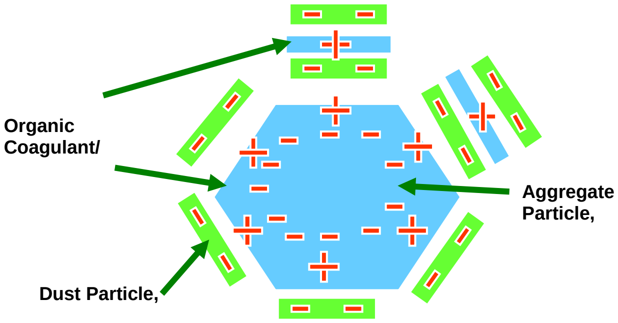

Figure 4 Dust coating process of aggregate

Figure 5. PAP aggregate coated with dust and fine particles.

Because of the *van der Walls* forces, the dust cannot be readily separated from the aggregate by simple washing. Soaking the aggregate in water allows the polar water molecules, over time, to replace the CF polymer molecules holding the particles together, dispersing them.

Bitumen – Aggregate Bonding

There are two aspects of aggregate bonding with the bitumen that should be considered.

1. Dust coatings: Coatings, or dirty aggregate is well known to cause poor bonding with bitumen. The bitumen bonds with the coating rather than the aggregate. Since Poplar Lane aggregate was well coated with clay-sized particles, which initially adhere strongly to the aggregate, it is to be expected that the bitumen will bond with the coating. With

time, the coating dissociates from the chip surface (being formed by soluble CF and clay-sized particles), and the bond is lost.

2. CF coating: CF present in the wash water adheres to, and eventually dries on the aggregate surfaces. Even without the dust layer present, therefore, bitumen is not bonding directly to the mineral surface of the aggregate, but to the CF coating.

Initially, the surface of a volcanic aggregate particle is negatively charged, and cationic bitumen emulsion is used to ensure a good bond. However, the CF coating negates, neutralizes, or even reverses the aggregate surface charge to positive; using cationic emulsion would result in repelling action between the two, preventing the volatiles from entering and bonding with the aggregate. The evidence of emulsion incompatibility is exhibited by chips being easily pried from the seal.

The CF-laden wash water used in processing is therefore a main cause of the problems encountered with the Poplar Lane aggregate. The changes made in the processing, which included reducing the amount of CF in the water and separating the two Jadair streams, eliminated the problem and produced an acceptable, high quality aggregate.

LABORATORY TESTS

Accelerated weathering tests

The porphyritic andesite being quarried contains high temperature minerals and some volcanic glass, both of which are subject to rapid weathering under semi-tropical climates of the region. To determine how these rocks could be affected, a simulated rapid weathering test was designed, based on similar tests for basalt from Europe. Essentially, the test consists of exposing the rock for several hours and days in a common household pressure cooker. The pressure cooker under normal operation will produce steam pressure of 103 kPa and a temperature 135°C, which accelerate mineral decomposition. The test conditions are severe, and simulate years of weathering under temperate to tropical conditions. The intent of the test was to determine if the accelerated weathering would significantly alter the mineral composition of the aggregate, and cause physical deterioration.

Two sizes of samples were subjected to five 4-hour “cooking” cycles. At the end of each 4 hour cycle, the sample was dried, and back-sieved on the original sieve. The percent passing the sieve was calculated. The retained and passing samples were then exposed for 72 hours at 95% relative humidity. The sample was re-weighed, and the amount of water adsorbed and absorbed after 24hr saturation determined. The retained and passing material was then recombined and subjected to the next cycle.

The sieve loss is shown in Figure 6. The coarser 13 mm to 19 mm chip shows a larger loss than the fine chip, due to greater incidence of shear planes in larger particles and cleaving along them. The “cooking” transformed the volcanic glass filling the fracture planes into clay, iron oxide and calcite, weakening the bond. The weathering effects are described below. The transformation of volcanic glass was confirmed in the petrographic analyses of thin sections.

Some of the loss can also be attributed to the thermal stress and abrasion encountered during the test.

Petrographic Analysis of rock subjected to accelerated weathering test.

The blocks from which the original thin sections were made were subsequently subjected to the same accelerated simulated weathering in the pressure cooker, and a second set of thin sections were made of the ‘cooked’ rocks. The thin sections were examined under a petrographic microscope to determine the effect of high temperature and steam pressure on the minerals.

Most of the glass/tridymite in the fractures was converted to clay, calcite and iron oxide. In some sections there was also a significantly larger proportion of clay minerals in the

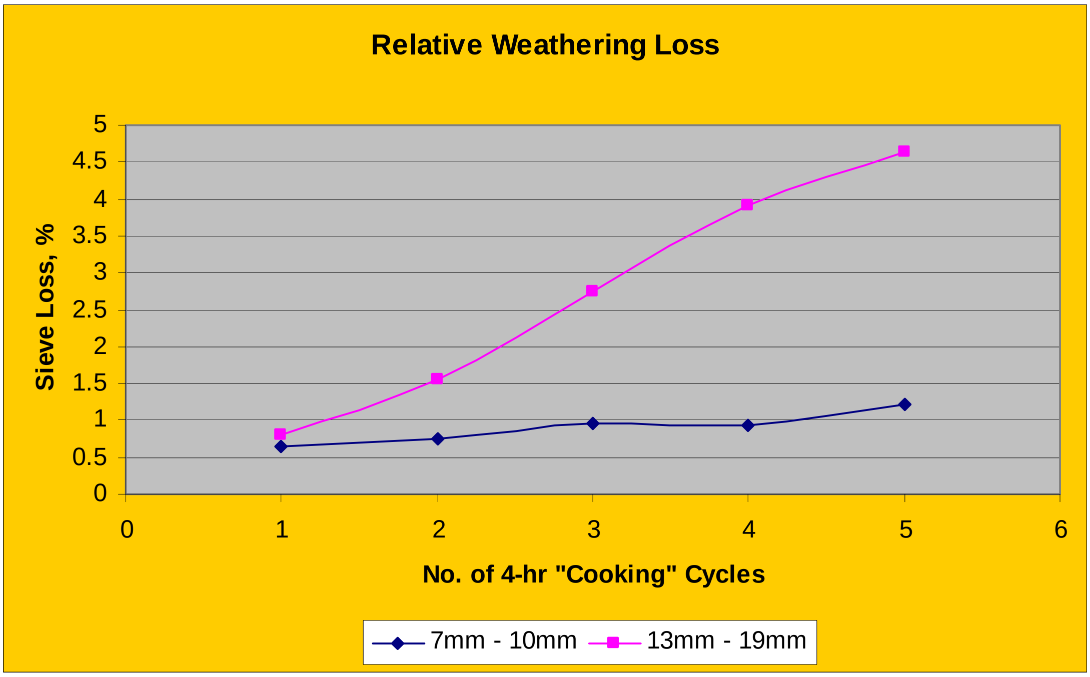

Figure 6. Results of simulated rapid chemical weathering test

groundmass, and a slight alteration of the feldspar phenocrysts. Smectite in the altered groundmass probably derived from the very small globules of volcanic glass. Other sections showed very minor alteration. Some of the augite phenocrysts showed a weathering ring or border, and rarely a development of secondary zeolite.

One new thin section was made from a weathered piece of andesite selected from the aggregate rock frames next to the quarry office. The rock sample was not ‘cooked’, but had been exposed to the elements for at least one year in the frame. The petrographic examination showed no fracturing; the groundmass had an elevated number of clay particles, but the feldspar grains within the groundmass were relatively unaltered, similar to the ‘cooked’ groundmass. The phenocrysts, especially those containing augite/plagioclase clasts showed prominent alteration rims around augite, but were relatively unaltered internally. The larger voids, associated with pyroxenes, were filled with what appears to be a zeolite mineral – the latter mineral readily observed in the quarry along weathered fracture planes. Zeolite is a common alteration byproduct of igneous rocks. Zeolites are known for their ready absorption and exchange of ions, but are generally non-expansive and relatively stable.

When treated PAP material was examined under a binocular microscope, it was noted that the CF used in the wash water acted as a temporary ‘glue’ to bind finer particles to coarser ones – see figure 7. Washing and agitating the sample ‘unglued’ the particles. In blending the aggregate for placement, the ‘glued’ particles will pass for a larger chips. After exposure to rain or groundwater, the ‘glued’ particles will disaggregate, resulting in a greater proportion of fines than intended. The fines will be become concentrated near the base. The presence of CF on the fines attracts water, causing water content to increase.

REMEDIATION

The primary goal of remedying the problem was to remove or reduce the CF in the wash water. As long as the treated water is slightly turbid, i.e., contains some suspended dust/clay particles, the water is relatively free of CF, or the amount of CF is in small enough quantity not to affect the integrity of the aggregate surface. A simple test, similar to that described by Figure 4, is carried out periodically on site to assure that the water is CF free. To further guarantee that no or little CF is available in the secondary crushing process, the water treatment process was modified by reducing the concentrations of CF to levels that provided an acceptable level of turbidity. The quarry is now producing dust-free, uncoated aggregate for sealing chips, asphaltic concrete mixes and basecourse applications that is performing well in service to date. Ten asphalt and sealing sites have been monitored since 2006 (5 contain aggregate from before the CF changes and 5 contain aggregate produced after the CF changes).

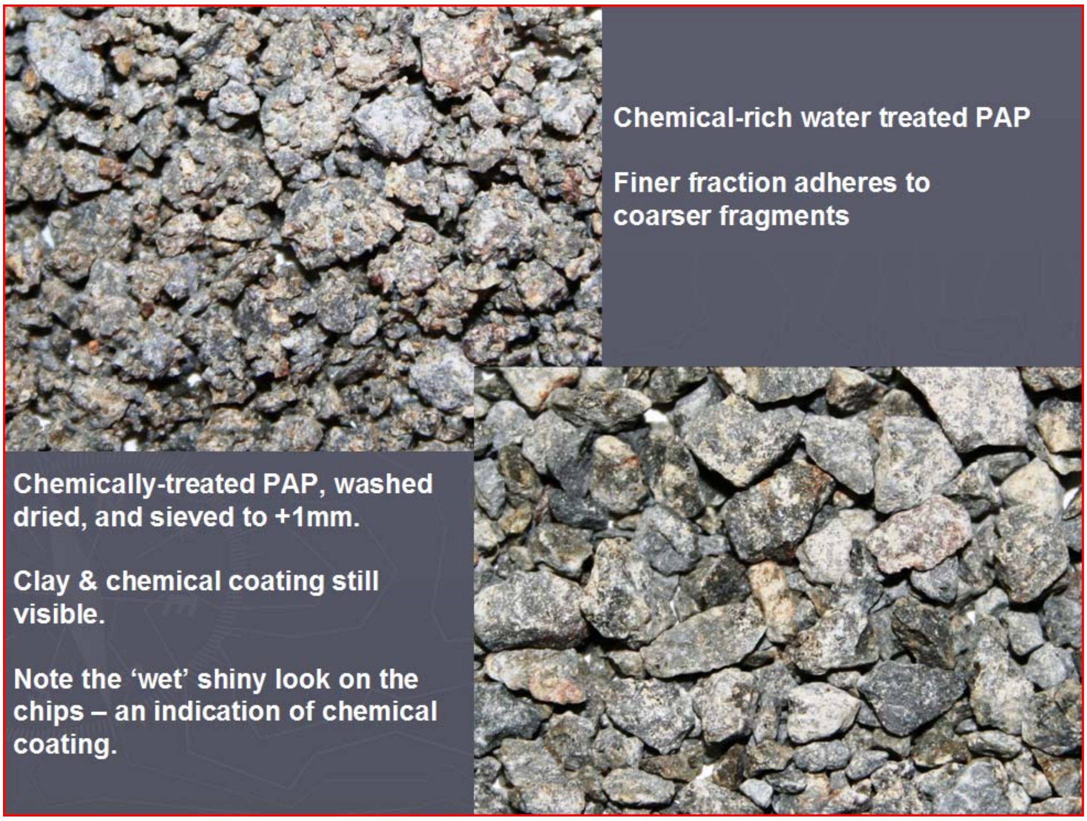

Figure 7. Adherence of dust and fine particles to due to chemical-rich wash water in PAP product from the quarry.

CONCLUSIONS

Problems with the stone were attributed to weathering of minor volcanic glass within the stone: the weathering was thought to produce expansive clays, and cause the stone deterioration and chipping from bitumen surfaces. A series of investigations, trials of modified production processes and other remedial actions taken did not resolve the problem of the additional fines found in the aggregate after construction. Some soft ignibrite (volcanic ash) was found in early products from the quarry, but is not present in current production.

The aggregate currently mined in the quarry appears to be sound and strong, but somewhat susceptible to weathering because of its volcanic glass content. It is also strongly fractured, and prone to break along weathered fracture surfaces.

Severe accelerated weathering tests had relatively minor effect on the minerals within the rock; however, the glass/tridymite fracture fillings were rapidly altered to clay, calcite, and iron oxide. This explains why the rock chips tend to split along these surfaces when in service. However, the integrity of the rock itself remains relatively unaltered. The weathering also produced alteration rims around pyroxene crystals, and conversion of the small amount of volcanic glass in the groundmass into smectite. However, the integrity of the mass of the aggregate was little affected.

To minimise the impact on the environment of the quarry's operations, the aggregate in all stages of the production process is washed, chemical added to settle the suspensions, and the water reused, to minimise discharge into local streams. Although the processed water was clear and guaranteed to be chemically free by the chemical suppliers, it was found to contain large amounts of coagulant and fluocculant, which coated the aggregate and caused a number of problems in practice.

The washing of the aggregate is considered the major cause of the problems encountered with the stone. The case can be ascribed to re-circulated treated wash water which was laden with coagulant and flocculant; the chemical coats the aggregate, and the coating attracts clay-sized particles. In addition, smaller rock chips in sub-millimeter range are "glued" temporarily to larger particles by the CF.

CF chemical coating on the fine chip product (PAP) may result in a material that appears and behaves as more granular than it is in reality; the CF coating, by its polar nature, will attract water, making the clay-sized rock dust wetter than desired after placement and exposure to soil moisture.

Coagulant and flocculant coating alone and/or with dust coating reduce the adhesion of aggregate to bitumen emulsion.

The concrete produced with the aggregate is not affected by the rock dust coating, which is similar in composition to components of cement, and may even have beneficial pozzolanic properties. The stockpiles of coated aggregate may be used in concrete with impunity.

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AUTHOR BIOGRAPHIES

Dr Peter Hudec is Professor Emeritus in the Faculty of Science at the University of Windsor, Canada. His qualifications include a B.Sc. (Western Ontario), M.Sc. and Ph.D. (Rensselaer Polytechnic). He has over 40 years of experience and research in engineering geology, specialising in chemical and physical deterioration of construction materials (such as stone, aggregate, concrete, brick, tile), exploration and valuation of aggregate deposits, and evaluation and development of aggregate testing methods.

After graduating with a BSc (Geology) from the University of Otago in 1993 and a post-graduate diploma in Engineering Geology from the University of Canterbury in 1994, Arthur Fulton has worked for an engineering geology consultancy in Auckland, a mine in Western Australia, and site investigation companies in the UK carrying out Engineering Geological and Environmental Investigations. In 2000, he returned to New Zealand and worked for a Christchurch based engineering geology consultancy before joining Fulton Hogan in 2001, first as quarry engineer at the Poplar Lane Quarry and then manager.

Dr Bryan Pidwerbesky is General Manager-Technical, and is responsible for the company's technical strategy and Technical Services team, and manages the company's Research and

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