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ETHYLENE GLYCOL ACCELERATED WEATHERING TEST – A NEW IMPROVED NON-SUBJECTIVE AGGREGATE DURABILITY TEST METHOD

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ABSTRACT

Ethylene glycol has been used extensively in the past by the concrete and road construction industries to identify rock durability issues associated with smectite clay minerals. The presence of these clay minerals is synonymous with rock degradation under normal environmental wetting and drying cycles. However, such historical test methods are predominately based on a subjective visual interpretation, describing the observed degradation of individual rock pieces at fixed time intervals during the soaking process. In addition, some test methods include complex equations with multiple weighting factors applied to nominated degradation descriptors (e.g. spalling, fracture and disintegration) used to calculate a single durability indicator.

The paper describes the development and implementation of an alternative non-subjective accelerated weathering test also using ethylene glycol. The research included metamorphic and volcanic rock types used extensively in New Zealand for road construction. The greatest benefit of the proposed new test method is the ability to eliminate the subjective visual assessment described in historical test methods and adequately quantify results to specify a contractual acceptance and rejection criteria. The test method also shows that good repeatability is possible from duplicate test samples. However, rock quality and quarry production consistency will influence the ability of the test method to report the same “percentage change in fines” over a prolonged test period. This was particularly evident within problematic and lower quality rock. The test findings are well supported by observed field performance, thus giving confidence in the new method’s usefulness.

Keywords: Ethylene glycol, aggregate durability, smectite clays.

INTRODUCTION

The last decade has seen a significant increase in the delivery of large road construction projects in New Zealand. As a result, the demand for, and subsequent supply of, road aggregate has increased substantially. Due to New Zealand's geological formation, metamorphic (Greywacke) and volcanic rock (Andesite, Basalt and Dacite) is a common source of aggregate used for road construction. However, it is not uncommon for these rock sources to undergo mineral alterations due to weathering. The presence of smectite clay minerals has been linked to aggregate durability issues. As a consequence, the industry has experienced a number of high profile pavement failures. Further investigations into the observed failures exposed possible shortcomings within current aggregate specifications. In particular, these specifications did not include any accelerated weathering test that can successfully quantify clay minerals within road aggregates, notwithstanding the fact that ethylene glycol has been used extensively in various parts of the world to identify durability issues with basic crystalline rock.

When the structure of smectite consists of greater octahedral than tetrahedral substitutions it is called Montmorillonite. Montmorillonite minerals are a product of volcanism and hydrothermal activity, and consist of hydrous aluminum silicates in the form of extremely small particles. These clay particle layers absorb water, which causes swelling. In addition, the clay minerals react with, and absorb, organic liquids, such as amines, glycols (ethylene glycol), glycerols and other polyhydric alcohols, which also cause swelling. Because the clay minerals react with glycols, the use of ethylene glycol has historically proven successful as an indicator test for smectite clays. The exchangeable cations within the layers of the smectite clay will depend on the mineral composition, most commonly made up of sodium, magnesium and calcium, with sodium smectite known to have higher swelling properties. It is this swelling property of the clays, as a result of soaking in ethylene glycol, which forms the basis of historical test methods.

However, such historical test methods appear to be very subjective. Individual rock pieces are visually assessed during the soaking process and degradation reported at specified time intervals. This process can be problematic, as complex multiple degradation criteria (e.g. spalled, fractured and disintegrated) are visually assessed at fixed time intervals and may also include additional weighting factors applied to each degradation criteria. Finally, these weighted values are added to calculate a single performance indicator or durability value.

The purpose of this research, while building on existing international test methods, was to develop and validate a simplified test specification to eliminate any visual subjectivity associated with these historical methods. The research also reports on the Atterberg Limits, plasticity index (PI), clay index (CI) and sand equivalence (SE), as well as thin section petrography/mineralogy and x-ray diffraction (XRD) analysis to identify any possible correlations that may exist, in support of the proposed new test method.

LITERATURE REVIEW

It is evident from literature that various ethylene glycol based test methods are widely used internationally to assess durability of construction aggregate. The most widely used method appears to be a test developed by the U.S. Army Corps of Engineers in 1949 for concrete and cement aggregates (*1*). A sample of approximately 5kg of aggregate between the 76.1mm and 19mm stone particle sizes are soaked in ethylene glycol for 15 days. The sample is inspected every 3 days for visual breakdown. After soaking, the sample is drained and screened through the 19mm sieve size. The percentage particles by weight passing the 19mm sieve are reported.

A modified version of the Corps of Engineers method is described by Davidson (*2*) for road aggregate. In this method, the test sample comprises of smaller stone particle sizes between the 13.2mm and 9.5mm fractions. Similar to the Corps of Engineers method, the percentage particles by weight passing the smaller sieve size, in this case the 9.5mm, is reported. However, a subsequent report by Fielding and Maccarone (*3*) deemed this test inadequate for specifying an acceptance and rejection criteria.

Gomes & Rodrigues (*4*) described an alternative ethylene glycol test protocol for basaltic rock in Brazil. Stone samples are soaked for 21 days, the amount of affected stone particles are visually assessed at 3 day intervals and reported as a percentage value of the total rock samples affected after 21 days. The method appears to be crude and merely a general indicator of degradation associated with smectite clays.

Leyland, Paige-Green and Momayez (*5*) highlighted the work done by Sampson (*6*) in South Africa, which used the British soaked Aggregate Impact Value (AIV) test (*7*). The AIV test is performed on stone particles between the 14mm and 10mm sieve sizes, in a dry and water soaked (24 hours) condition. The crushed fines fraction passing the 2.36mm sieve size, measured by weight, is reported as the AIV. If the AIV for the water soaked sample is greater than 30%, compared to the dry sample, the specification states the source aggregate should be treated with caution. Sampson adapted this test method by substituting the water with ethylene glycol and found the difference between the dry and ethylene glycol soaked aggregate impact values were useful in identifying potential poor performance (*6*).

Paige-Green (*8*) states that the use of ethylene glycol to accelerate the effects of smectite clays within rock has become almost routine practice in South Africa, citing work done by Van Rooy & Nixon, Van Rooy & Van Schalkwyk, and Bell & Jermy (*9, 10, 11*).

Leyland, Paige-Green and Momayez (*5*) proposed a modified Ethylene Glycol Durability Index (mEGDI) test. The test uses forty stone pieces of approximately equal dimension, between 19mm and 13mm in size, covered by ethylene glycol complying with ASTM D2693-07 (*12*). The stone particles are placed in a grid of 5 x 8 covered with ethylene glycol in a tray and inspected at 1, 5, 10 and 20 days. The integrity of each rock sample is inspected and assessed on a definition of: i) *spalling* - shedding of small fragments from the aggregate edges and surface; ii) *fracture* - splitting into two or more pieces; and iii) *disintegration* - splitting into more than three pieces. The mEGDI value is calculated for each observation period and a weighting factor (0.5 x *spalling*, 1 x *fracture* and 5 x *disintegration*) is applied to the number of pieces affected by the three descriptions of degradation. The sum of these weighted values is then used to calculate a single mEGDI value. The proposed test method appears to be complex and subjective, based solely on visual interpretations of the observed three degradation criteria reported at fixed time intervals. In addition, the research shows the 20/5 day mEGDI ratio, which emphasizes the importance of prolonged soaking for at least 20 days. Finally, they noted that other test methods, that do not test durability after soaking and expansion of clays, did not correlate well with the mEGDI test.

The South African National Standards (SANS) 3001 - AG 14 & 15 describe two draft ethylene glycol soaking test methods to assess the durability of basic crystalline rocks used within pavement subbase and base layers (*13, 14*). These draft test methods are referred to in the South African Pavement Engineering Manual and attempt to identify aggregate rock prone to weathering when exposed to the atmosphere, as may occur in the presence of smectite clays (*15*). The ethylene glycol durability index test (AG14) appears to originate from the work done by Leyland, Paige-Green and Momayez (*5*) as it follows the same test protocol. In the second test (AG15), stone particles of a fixed size fraction are soaked for 24 hours in ethylene glycol before being subjected to a 10% fines aggregate crushing test (FACT). The load applied to create 10% fines for the ethylene glycol soaked sample and the load applied to create 10% fines for the dry control sample is reported as a wet to dry ratio.

Paige-Green (*16*) recommends the use of multiple test methods rather than a single test to predict durability problems of basic crystalline materials. More importantly, he makes the statement that many test methods use ethylene glycol, but ethylene glycol combined within a strength test appears to have the greatest merit for inclusion in specifications. He also recommends a percentage aggregate crushing value (ACV) ratio of dry to ethylene glycol soaked (4 days) of less than 20% as a compliance acceptance limit.

From the above, it appears that most of the durability tests consist of observed visual degradation of a small representative rock sample. The subjective nature and complex calculations used to report a single durability value is deemed by the New Zealand quarry industry as inadequate to include in contractual specifications as an acceptance and rejection criteria. Thus, the purpose of the proposed new ethylene glycol test method is to address these shortcomings and industry concerns.

THE PURPOSE AND SCOPE OF THE NEW ACCELERATED WEATHERING TEST (nAWT) METHOD

The purpose of developing the proposed new Accelerated Weathering Test (nAWT) method is to simplify and remove the subjectivity present with a number of the current test methods. Ultimately, the test method should be robust enough to include in contractual specifications as an acceptance and rejection criteria. This new test method builds on existing ethylene glycol durability tests, in particular the SANS 3001 - AG 15 test method (13), while seeking to limit the aforementioned shortcomings. The concept is simple and incorporates a standard crushing resistance test. A control sample of approximately 2.7 kilograms of aggregate within a specified stone size fraction is placed in a steel mould; a constant loading rate over a period of 10±1 min is applied to achieve a specified target load. The amount of crushed fines generated is recorded as a percentage of the initial sample weight. This process is repeated for a duplicate sample soaked in ethylene glycol. Again, as per the control sample, the percentage crushed fines is calculated for the soaked sample crushed in a saturated surface dry condition. The proportional increase in percentage fines for the soaked compared to the un-soaked control sample is calculated and proposed as a durability compliance limit.

The development of the new test method, along with the main points of difference, is described in the following sections. The new draft specification is referred to as NZTA T20 – Ethylene Glycol Accelerated Weathering Test Method (*17*).

Specified Load

The nAWT method specifies a fixed target load, applied at a constant loading rate over a period of 10±1 min. This approach varies from the South African ethylene glycol test method AG15, which targets a varying load to produce 10% FACT. Predicting the load to produce 10% crushed fines is a moving target and requires multiple tests at various loads to produce a plot of the load versus percentage fines. A straight line and/or extrapolation plot is used to estimate the load value to produce 10% fines. The new test method attempts to simplify and limit the need for multiple crushing tests at various loads. Thus, the approach taken with the new method is to limit testing at various loads and specify a fixed target load and report the percentage crushed fines at this fixed load.

During the initial development, testing was performed at a load of 130kN, as this follows the standard New Zealand aggregate crushing resistance test for base course aggregate (*18*). However, as expected for good quality crushed rock mainly used within pavement base layers, the percentage fines by weight generated from a 130kN load could be very small, sometimes as low as 3%. Thus, under the proposed new test method, any small incremental change in percentage fines between the soaked and un-soaked samples could report an unduly high percentage change. Therefore, the proposed new test method may incorrectly report aggregate durability issues. To ensure sufficient fines are produced during testing of the harder rock types, and to control incorrect reporting of possible durability issues, as a result of small incremental changes in reported percentage fines, the test load was increased and standardized at 230kN. As a result, the 230kN load will produce more crushed fines - in the order of 10% - for the harder rock types. It is also the specified load to produce < 10% fines for surfacing sealing stone chip within New Zealand.

Stone size fraction

Initial testing included multiple stone size fractions to determine any significant change in the reported percentage of crushed fines from each fraction range, and possible correlation between the larger and smaller stone fraction ranges. The crushing tests included the stone fraction ranges between 13.2mm and

9.5mm (reporting % fines passing 2.36mm sieve size) and between 19mm and 13.2mm (reporting % fines passing 3.35mm sieve size). Soaked and un-soaked samples were tested for both these stone particle ranges. Because the two test fraction ranges specify different sieve sizes to calculate the percentage crushed fines, it was difficult to find any correlation or reason why one fraction should be favoured above the other. Thus, it was decided to specify testing of the stone fraction between 13.2mm and 9.5mm, as this is the preferred particle fraction used for the aggregate crushing test for base course material in New Zealand and typically represents approximately 20% of the total gradation.

Ethylene glycol soaking time

Initial testing looked at reducing the soaking time, as this had inherent benefits by reducing the reporting times. Test samples were soaked for three different lengths of time: 24 hours, 7 days and 21 days. After 24 hour soaking some samples showed no change. However, more substantial changes were reported after 7 and 21 days of soaking. This seems to indicate a soaking period greater than 24 hours is required to identify possible durability issues, as tested at a specified load of 130kN. While the majority of the test samples showed very little change between 7 and 21 day soaking, which may indicate 7 days as a sufficient soaking period, it was noted that one sample did show a notable increase in fines after 21 days soaking. This may indicate that rock types with greater solid densities require longer soaking times. So as not to overlook these rock sources, it was decided to specify 21 days soaking in ethylene glycol for the new test method.

This is a key point of difference with similar test methods such as the SANS 3001-AG15 method (*13*), which specify a 24 hour soaking period specified, and the 4 days soaking period proposed by Page-Green (*16*).

Ethylene glycol properties

Various grades of ethylene glycol are available on the market. It was, therefore, specified that the ethylene glycol to be used comply with the ASTM D2693–07 standard.

Reported percentage crushed fines

The nAWT method specifies testing of the stone fraction range between 13.2mm and 9.5mm, and the percentage crushed fines passing the 2.36mm sieve size is reported. The use of a smaller sieve size to report the crushed fines is considered to be more indicative of significant degradation. This approach differs from most other test methods, where the screening of the aggregate breakdown is based on the smaller of the test sample stone fraction range. For example, the Corps of Engineers specify a stone fraction range for the test sample between 76.1mm and 19mm, and report the fines passing the 19mm sieve size.

Representative test sample size and weight

Approximately 2.7 kilograms of stone particles are needed to fill the steel mould to complete a single crushing test. Thus, the resulting larger sample size gives a greater representation of the rock source properties. Historical test methods most commonly follow an approach based on visual inspections and reporting of individual rock particle degradation at fixed time intervals. These test methods generally specify a limited number of stone particles, with the resulting test sample weighing less than 200 grams. The ability to sufficiently describe the rock source properties based on a limited test sample size will always be a challenge. The nAWT addresses this concern to some extent by incorporating much larger quantities of rock within the test method.

Testing soaked samples in a dry and saturated surface dry condition

After soaking for 21 days in ethylene glycol the samples were drained and tested in a dried-back oven-dry and saturated surface dry (SSD) condition. It was clear that samples with “abundant” smectite clay minerals, as identified later in Table 2 using x-ray diffraction (XRD) analysis, had a dramatic increase in crushed fines when tested in the saturated surface dry condition. The reason may be that the expansion and swelling effect experienced by the clay minerals during the soaking process is diminished during the dry-back in the oven, after soaking. It could be that the clay minerals shrink to some degree during the oven drying to constant mass. This may reduce the extent of the microscopic crack initiation from the swelling clays and ultimately affect the percentage of fines produced during the crushing test. A secondary reason may be hydraulic pressure build up as a result of trapped ethylene glycol within the more porous rock types. To ensure the “true” effect of the ethylene glycol is assessed, the nAWT specifies a saturated surface dry test condition.

Based on the above discussions various historical test method procedures and technical data are summarized in Table 1 and compared to the nAWT.

TABLE 1 Summary of Historical Test Procedures Compared to the nAWT

Origin and Test Reference	**Test Method**			**Test Procedure**					
	Visual Test *(inspection days)*	**Report % Fines** *(passing sieve mm)*	**Strength Test** *(crushing /impact)*	**Stone Fraction Size** *(mm)*	**Sample Size** *(kg)*	**Soaking Agent**	**Time Soaked**	**Test Control Sample**	**Sample Test Condition**
US Army Corps of Engineers *(1)*	**3, 6, 9, 12, 15**	**< 19**	**No**	**76.1 – 19**	**± 5**	**E.G.**	**15 days**	**No**	**N/A**
Mod Corps of Engineers (Davidson) *(2)*	**No**	**< 13.2**	**No**	**13.2 – 9.5**	**± 5**	**E.G.**	**15 days**	**No**	**N/A**
Gomes & Rodrigues *(4)*	**3, 6, 9, 12, 15, 18, 21**	**No**	**No**	**Unknown**	**Unknown**	**E.G.**	**21 days**	**No**	**N/A**
British AIV, *(7)*	**No**	**< 2.36**	**Impact**	**14 - 10**	**± 4**	**Water**	**24 hours**	**2 x Dry**	**2 x SSD**
Mod British AIV, Sampson *(6)*	**No**	**< 2.36**	**Impact**	**13.2 – 9.5**	**± 4**	**E.G.**	**24 hours**	**2 x Dry**	**2 x SSD**
Draft SANS 3001-AG14 *(13)*	**1, 5, 10, 20**	**No**	**No**	**13.2 - 19**	**40 stone pieces**	**E.G.**	**20 days**	**No**	**N/A**
Draft SANS 3001-AG15*(14)*	**No**	**< 2.36**	**Crushing (10% fines)**	**13.2 - 19**	**± 10**	**E.G.**	**24 hours**	**2 x Dry**	**2 x SSD**
Draft NZTA T20 *(17)*	**No**	**< 2.36**	**Crushing (230kN load)**	**13.2 - 19**	**± 10.8**	**E.G.**	**21 days**	**2 x Dry**	**2 x SSD**

E.G. = Ethylene Glycol, SSD = saturated surface dry

OBSERVED PAVEMENT FAILURES AND DISCUSSION OF THE ETHYLENE GLYCOL ACCELERATED WEATHERING TEST RESULTS

Over the last decade, the New Zealand Transport Agency (NZTA) experienced early pavement failures on various high profile projects, of which the most prominent pavement failures were specific to a local aggregate quarry source, referred to as Poplar Lane (Table 2). The continuing nature and extent of the failures is such that investigations are on-going.

In this case, the quarry supplied crushed Andesite rock compliant with the road agency's specification for high quality base course material. However, the NZTA specifications at the time did not include any accelerated weathering (durability) tests specifically aimed at identifying clay minerals. These early pavement failures brought a renewed focus, seeking an appropriate test method to prevent similar failures. The most prominent failure mode was excessive wheel track rutting - noted within the first 12 months of service - with steep rut progression trends as reported from annual high speed data (HSD) surveys. A rut depth (left wheel path) performance plot from a representative 1.2 kilometre section, within the project length is shown in Figure 1. Initial attempts were made to rehabilitation the failed sections by stabilizing the unbound base layer to a depth of 200mm with 3% cement. However, this treatment had limited success, as thermal/hydration and fatigue cracks developed within 3 to 5 years, impacting on ride quality and allowing moisture infiltration. The plot also shows that periodic maintenance intervention (thin asphalt correction layers) failed to stop the rut progression. Finally, the base layer was milled out to a depth of 200mm, disposed of and replaced with structural asphalt. Investigations into the failures improved the understanding of the failure mechanism and eventually became the catalyst for the development and implementation of the new ethylene glycol accelerated weathering test. However, it was important that the new test method could stand up to industry scrutiny, as the intent was to ultimately specify a contractual acceptance and rejection criteria for future construction.

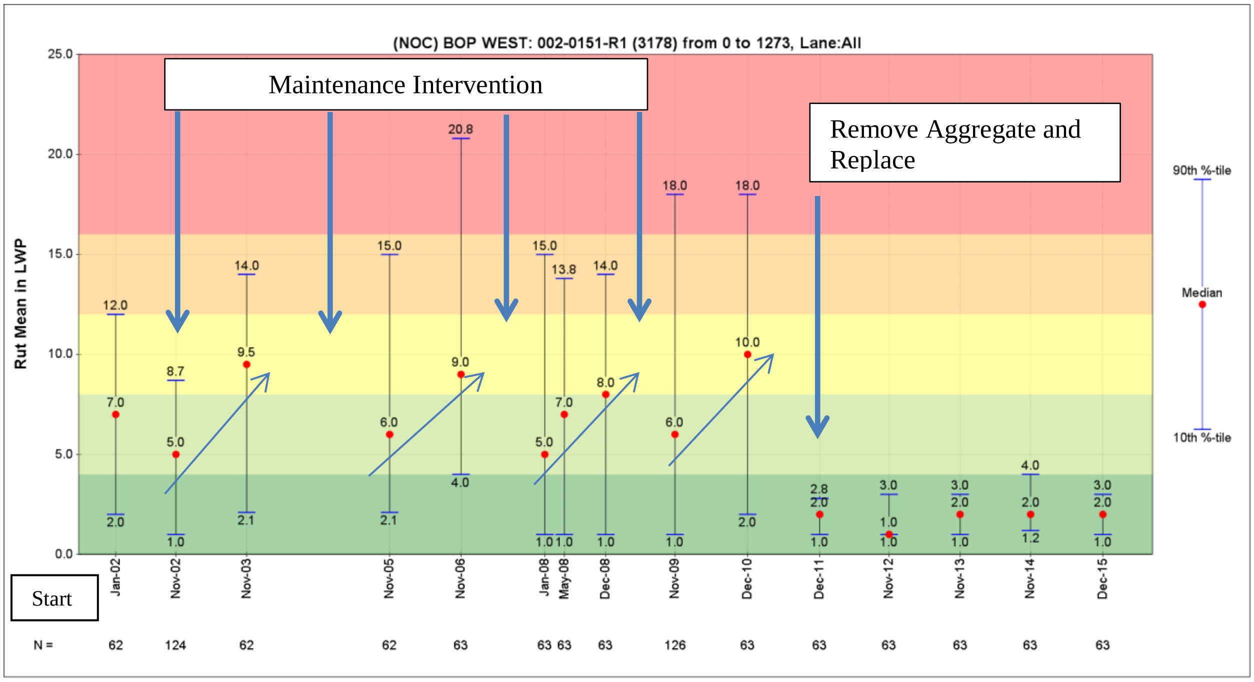

Figure 1 Typical rut depth and progression trends reported from annual high speed data surveys

As with most pavement failures, proving the failure mechanism and liability within a contractual environment can be very complex and challenging after the event. Extensive pavement and material testing were undertaken, which showed the original construction material properties underwent significant changes. The most prominent changes were a significant increase in clay fines (< 0.075mm) from 5% to 11%, followed by an increase in plasticity index (PI) from 5 to 14 and a steep reduction in the sand equivalence (SE) from initial values greater than 40 to less than 25.

These material changes, observed over a very short period of time, clearly indicated excessive aggregate degradation and the "introduction" of additional clay minerals, which could explain the observed rut failures. The introduction of excessive plastic clay fines combined with moisture act as a lubricant, resulting in increased "slippage" between the finer particles and shear failure within the unbound aggregate layers. As a result, the matrix of finer particles will most likely be displaced and deform under traffic induced loading; resulting in the observed wheel rut failures.

Unfortunately, the material changes were identified post failure following the investigations. This exposed a major shortcoming at the time, as no advance durability tests were performed on the aggregate prior to construction. The information obtained from the investigations gave a better understanding to the failure mechanism. However, at the time of the investigations it was unclear why the aggregate degraded within such a short period of time and, more importantly what the "trigger" was that initiating these early failures. The significant increase in plastic clay fines led the investigation to test the rock for accelerated weathering making use of ethylene glycol. The initial testing focused on various quarry sources within close proximity of the failed project, in addition to the Poplar Lane aggregate under investigation (Table 2).

TABLE 2 Initial Test Results with Ethylene Glycol

Quarry Source	Rock Type	Specified Load of 130kN (Stone Fraction 9.5mm – 13.2mm)		
		% Fines Passing < 2.36mm		Percentage Change in Fines (X - Y) / (Y)
		Control	21 Day Soaked	
		Crushing dry condition (Y)	Crushing oven dry condition (X)*	
Matamata	Andesite	6.3	5.9	-6%
Tauhei	Greywacke	6.1, 7.3	5.6, 7.1	-8%, -3%
Poplar Lane	Andesite	7.3, 5.4, 4.1, 4.2	13.7, 9.3, 7.3, 6.8	88%, 76%, 78%, 62%
Whitehall	Greywacke	5.5, 4.2	5.7, 4.3	4%, 2%
Toatoaroa	Greywacke	1.6, 4.2, 4.3	1.6, 4.3, 4.7	0%, 2%, -
Smythes	Greywacke	4.3	3.6	-16%
Baldwins	Greywacke	6.7, 8.4	8.7, 9.9	30%, 18%
Otaki	Greywacke	3.9, 3.5, 3.7	4.5, 4.2, 4.4	15%, 20%, 19%

*soaked then dried-back in an oven to constant mass

The initial test protocol was exploratory and based on a standard aggregate crushing resistance test method, extended to include a duplicate secondary sample soaked for 21 days in ethylene glycol. The soaked sample was dried-back in an oven to a constant mass prior to crushing, to mimic the standard crushing resistance test procedure. However, this approach is different to other wet and dry test methods, which test the soaked sample in a SSD condition. Table 2 shows the percentage crushed fines (< 2.36mm) produced from the un-soaked control samples and soaked samples crushed at a specified load of 130kN.

The test results clearly show the Popular Lane quarry source as an outlier, reporting an approximate 75% increase in crushed fines after soaking. Note, the soaked samples were dried-back in an oven and tested in a dry condition.

The test results were seen as a major breakthrough, as it validated and confirmed typical observed field performance from this aggregate source (Figure 1). As a result, the pavement failures could now be linked with greater confidence to poor durability of the rock source.

Following the success of the initial test results, the new Accelerated Weathering Test (nAWT) was further refined and accepted as a draft specification NZTA T20 – Ethylene Glycol Accelerated Weathering Test (Draft) (*17*). The final draft specification included various improvements from the initial exploratory test protocol.

The scope of the research was extended to include 27 additional quarry sources within a greater geographical area and the inclusion of extra material tests (Atterberg Limits, PI, CI and SE, as well as thin section petrography/mineralogy and x-ray diffraction analysis). All rock test samples, except one, met the current NZTA specifications for high quality crushed base course aggregate.

TABLE 3 Test Results from nAWT

Quarry Source	Rock Type	Specified Load of 230kN (Stone Fraction 9.5mm – 13.2mm)								Presence of smectite clays through XRD analysis
		% Fines Passing < 2.36mm						Percentage change in averaged % fines for duplicate test samples		
		Control		21 Day Soaked						
		Crushing dry condition (Y)		Crushing oven dry condition (X)		Crushing *SSD condition (Z)				
		# 1	# 2	# 1	# 2	# 1	# 2	(X-Y)/Y	(Z-Y)/Y	
Smythes	Greywacke	8.6	-	9.6	-	-	-	12%	-	Minor
Tirohia	Andesite	11.9	11.9	11.9	11.7	11.1	-	-1%	-7%	None
Waitawheta	Andesite	15.2	15	15.2	15.1	16.4	-	0%	9%	Trace
Tauhara	Dacite	16.8	16.5	19.1	19.2	16.1	-	15%	-3%	None
Matatoki	Andesite	14.4	14.1	15.2	14.7	14.7	-	5%	3%	Trace
Ngaruroro	Greywacke	7.1	6.9	7.0	7.2	7.4	-	1%	6%	Trace
309	Andesite	12.6	-	19.7	20.3	23.8	-	59%	89%	Abundant
McBeths	Andesite	9.7	9.6	9.8	10.1	9.7	-	3%	1%	Trace
Hendersons	Andesite	27	26.6	27.3	28.3	27.1	-	4%	1%	None
Tuckers	Greywacke	5.9	-	7.7	-	7.7	-	31%	31%	Abundant
Osterns	Greywacke	8.9	9.3	9.8	10.5	10.2	-	12%	12%	Minor
Pukekawa	Basalt	11.9	12.1	11.3	12.3	11.3	-	-2%	-6%	None
Flat Top	Basalt/ Andesite	13.8	13.8	18.2	-	21.4	-	32%	55%	Abundant
Bombay	Basalt	10.2	10.6	9.0	9.3	9.1	-	-12%	-13%	None
Drury	Greywacke	3.5	-	2.6	3.3	2.9	-	-16%	-17%	None
Otaika	Greywacke	7.8	6.7	7.8	7.6	8.7	-	6%	20%	Minor
Matawai	Greywacke /Mudstone	11.3	11.2	25.7	26.3	34.5	-	131%	207%	Abundant
Waerengakuri	Limestone	20.0	20.4	23.7	22.1	24.7	-	13%	22%	None
Jones	Basalt	20.6	20.4	22.2	22.4	22.4	-	9%	9%	None
Vickers	Andesite	22.1	22.2	24.5	24.8	24.6	-	11%	11%	None
Poplar Lane	Andesite	9.5	9.8	-	-	14.2	14.7	-	50%	Abundant
Kakariki	Greywacke	4.7	4.2	-	-	5.4	5.8	-	25%	Not Tested
Matamata	Andesite	11.1	10.2	-	-	11.1	10.9	-	3%	None
Wiremu	Andesite	22.4	21.3	-	-	21.5	22.5	-	1%	Not Tested
Ferndene	Andesite	22.4	22.2	-	-	23.9	23.8	-	7%	Not Tested
Brynderwyn	Greywacke	8.7	8.7	-	-	9.7	10.1	-	14%	Not Tested
Tauhara	Dacite	19.1	19.2	-	-	18.5	19.1	-	-2%	None
Millbrook	Greywacke	8.0	8.2	-	-	8.9	8.8	-	9%	Not Tested

*SSD Saturated Surface Dry

The test results show that rock sources identified with “abundant” smectite clay minerals also reported greater than 30% fines increase (Table 3). The Flat Top, 309 and Matawai quarries showed a significant increase in reported fines for samples tested in a saturated surface dry (SSD) condition compared to a dry (oven dried-back) condition. However, in this respect the Tuckers quarry showed no change. A possible explanation could be the high crushing resistance achieved from the Tuckers quarry, as it produced approximately half the percentage fines compared to the other three sources. Being a harder rock with greater solid density, the penetration of the ethylene glycol is restricted through the denser rock - limiting the effect of the ethylene glycol - as noted from the SSD and dry condition test results. However, the swelling effect as a result of “abundant” smectite clay minerals within these rock sources is clearly demonstrated, as all these problematic rock sources produced > 30% fines after soaking.

The research acknowledges the limited number of quarry sources tested. However, the data seems to indicate that an appropriate upper limit for contractual acceptance and rejection could be set at a value of > 30% fines increase after soaking and tested in a SSD condition. In support of this, the proposed upper limit of 30% increase in fines closely follows international experience with similar wet and dry aggregate durability test methods. The British AIV (wet/dry test) states that if an AIV greater than 30% fines is reported then the aggregate should be treated with caution. Paige-Green (*16*) recommends an upper limit of 20% increase in fines after 4 days soaking in ethylene glycol for an aggregate crushing test at a specified load of 400kN. However, the Australian wet/dry strength test (*19*) targets a load to produce 10% fines, similar to the South African test method SANS 3001 - AG 15. South African research refer to a wet/dry load (kN) ratio > 75% to produce 10% fines, as a compliance acceptance limit (*16*). Similarly, Australian research specify wet/dry load (kN) ratio > 65% for coarse asphalt aggregate *(20)*. Note, both these methods specify a wet/dry load (kN) ratio. In contrast the nAWT method specifies a wet/dry percentage change in fines at a fixed load of 230kN, which makes a direct comparison of compliance acceptance limits difficult for the two differing approaches.

The credibility and usefulness of the test method will be determined by the ability to verify the test findings through actual field performance. In support of the research, all five quarry sources - producing > 30% increase fines - have a known history of poor field performance. This gave confidence in the test method's ability to predict poor aggregate durability. In addition, the test method shows good repeatability is possible for duplicate test samples as shown in Table 3. The test method is also sensitive enough to indicate changes in the aggregate production quality over a prolonged period of time. Therefore, the rock quality and quarry production consistency will influence the ability of the test method to report the same "percentage change in fines" over an extended test period. This was particularly evident within problematic and lower quality rock sources. As an example, referring to Table 2, aggregate from the Poplar Lane quarry were tested over an extended quarry production period of 2 years and four discrete test samples tested during this time reported a variation in percentage fines increase ranging from 62% to 88%.

Additional material properties were tested in parallel to assess possible correlations that may exist in support of the nAWT test findings.

TABLE 4 Additional Material Properties Tests

Quarry Source	Rock Type	CPL	PL	PI	CI	SE	Presence of smectite clays through XRD analysis
Smythes	Greywacke	-	-	-	-	-	Minor
Tirohia	Andesite	25	N/P	N/P	3.7	60	No Evidence
Waitawheta	Andesite	28	N/P	N/P	6	60	Trace
Tauhara	Dacite	N/A	N/P	N/P	0.4	78	No Evidence
Matatoki	Andesite	24	N/P	N/P	3.5	74	Trace
Ngaruroro	Greywacke	22	N/P	N/P	1.4	36	Trace
309	Andesite	26	N/P	N/P	8.2	50	Abundant
McBeths	Andesite	31	22	9	2.9	53	Trace
Hendersons	Andesite	N/A	N/P	N/P	1.7	65	No Evidence
Tuckers	Greywacke	31	19	12	8.4	41	Abundant
Osterns	Greywacke	21	N/P	N/P	2.7	50	Minor
Pukekawa	Basalt	24	N/P	N/P	3.0	25	No Evidence
Flat Top	Basaltic/ Andesite	30	23	7	7.4	28	Abundant
Bombay	Basalt	N/A	N/P	N/P	1.1	61	No evidence
Drury	Greywacke	20	N/P	N/P	1.2	38	No evidence
Otaika	Greywacke	25	N/P	N/P	5.5	48	Minor
Matawai	Greywacke/ Mudstone	26	20	6	3.4	66	Abundant

Waerengakuri	Limestone	25	N/P	N/P	5.7	31	No Evidence
Jones	Basalt	23	N/P	N/P	0.7	74	No Evidence
Vickers	Andesite	25	N/P	N/P	0.7	73	No Evidence
Poplar Lane	Andesite	27	20	7	6	50	Abundant
Kakariki	Greywacke	22	N/P	N/P	3.4	49	Not Tested
Matamata	Andesite	25	N/P	N/P	3.4	57	No Evidence
Wiremu	Andesite	24	N/P	N/P	1.8	49	Not Tested
Ferndene	Andesite	23	N/P	N/P	0.8	39	Not Tested
Brynderwyn	Greywacke	28	19	9	4	48	Not Tested
Millbrook	Greywacke	27	20	7	4.4	59	Not Tested

CPL = Cone Penetrometer Limit, PL = Plastic Limit, PI = Plasticity Index, CI = Clay Index (Methylene Blue Test), SE = Sand Equivalence, XRD = X-Ray Diffraction

Initial indications are that there may be a relationship between the percentage fines increase > 30%, the CI ≥ 6 and reported “abundant” clay minerals (Tables 3 and 4). From the limited quarry sources tested, the CI seems to be a simple and possible useful advance indicator to predict the presence of clay minerals linked to poor aggregate durability. However, the Matawai quarry did report a CI < 6. It should be noted, that the research used the fines from the sample bags taken from quarry supply stockpile to complete the CI tests. This may result in false reporting of the CI because of blending or addition of other sources to produce the specified gradations. Therefore, the research recommends that an additional CI test is performed on the source rock crushed fines produced during the crushing of the two test control samples.

SUMMARY OF FINDINGS

The test method successfully identified five problematic quarry sources (> 30% increase fines), all with a known history of poor field performance. In support of the new test method, a selection of road sections constructed from aggregate sourced from the remaining quarries (< 30% fines) were followed up and no field performance issues were identified specific to aggregate durability.

Investigations into the Poplar Lane aggregate failures show the aggregate underwent significant changes after construction was completed. The percentage plastic fines (< 0.075mm) increased dramatically within a short period of time, clearly indicating excessive aggregate degradation and the “introduction” of additional plastic clay fines. The nAWT test method identified this rock source as problematic and high risk. Ongoing maintenance issues with remaining aggregate still in place, combined with poor field performance, confirms the research findings.

It is a concern that four of the five problematic quarry sources met all NZTA specifications for high quality crushed base course aggregate. Thus, the findings strengthen the case for an alternative aggregate durability test method, specific to the identification of smectite clay minerals within rock sources. In addition, the x-ray diffraction analyses identified the presence of “abundant” clay minerals (smectite) within all five problematic rock sources. This give confidence in the nAWT method’s ability to identify and quantify durability issues associated with smectite clay minerals. The remaining 16 rock sources labeled as having “no evidence”, “trace” or “minor” smectite clay minerals, were not affected to the same extent by the ethylene glycol. In support of the test results, these rock sources did not show the same poor performance in the field.

The research acknowledges that any laboratory testing of materials is not an exact science and that it has limitations. Thus, to further increase confidence in the test method’s ability to adequately quantify the materials properties and remove subjectivity, the test procedure specifies the use of duplicate samples. The averaged values from the duplicate test samples are used to calculate the percentage change in fines used to calculate the durability indicator. In support of this approach, the duplicate samples show good repeatability is possible.

The research was unable to show any strong correlation between the nAWT results and the CPL, PL, PI and SE material properties. However, to improve the usefulness of the PI as a supporting indicator for durability, the research recommends that the PI is tested on the 0.075mm and 0.432mm fractions of the parent rock. The CI (methylene blue test) on the other hand shows more promise as an advance indicator to predict aggregate durability issues.

CONCLUSION

The research conducted on typical metamorphic and volcanic crushed rock proved successful in quantifying the degradation associated with smectite clays within road aggregates. As a result, a new aggregate durability test specification also using ethylene glycol was developed and implemented. The success of the nAWT is based on the ability to eliminate the subjective visual assessment described in most historical ethylene glycol based test methods. It is the view of the NZTA that the test method can adequately quantify results to enable its inclusion in contractual specifications as an acceptance and rejection criteria. To ensure industry acceptance of the new test method, the NZTA completed consultation with the Aggregate Quarry Association, the Civil Contracting Industry and the Civil Engineering Testing Association. Following consultation, the draft test method has been accepted and will be published on the NZTA website in due course. However, at the time the quarry and road construction industries were unable to agree on a pass/fail limit for the specification. Thus, initial thoughts are that this may be best addressed on a regional level based on local resource availability, rock quality and historical field performance.

In conclusion, the results from the research are perceived by the NZTA as adequate to proceed with the specification of the nAWT for multiple large road agency projects, with the hope of preventing similar pavement failures.

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