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Weatherability of Road Aggregates within Engineering Time

Ebrahim Sangsefidi[1], Dr. Douglas J Wilson[2], Dr. Thomas J Larkin[3], Dr. Philippa M Black[4]

[1-3]Department of Civil and Environmental Engineering, The University of Auckland, New Zealand.
[4]School of Environment, The University of Auckland, New Zealand

Email for correspondence: esan256@aucklanduni.ac.nz

Abstract

The Unbound Granular Layer (UGL) is a critical element of pavement structures and its properties play a key role on the performance and serviceability of roadways. However, aggregates are affected by weathering processes within the pavement structure. We examine the natural weathering process of basecourse aggregate materials from an andesite quarry to determine the rate and process of weathering of unbound aggregates within the pavement structure within the time period of a typical unbound pavement's life of approximately 25 years. We have undertaken a series of standard laboratory tests that include Clay Index (CI), Sand Equivalent (SE), and Plastic Index (PI) tests on andesitic aggregates sourced from different levels of the quarry. Since the aggregates were excavated at different times, materials in the quarry have been exposed to the natural environment for time durations varying from four months to 15 years. We demonstrate that fresh aggregates and their physical properties are in some cases significantly weathered after a very short period of time and that current tests fail to adequately simulate real field conditions thereby not adequately addressing in-service aggregate weathering potential. These factors need to be considered when making decisions on aggregate selection within UGLs.

1. Introduction

1.1. Background

Aggregates are a significant structural component of pavements and their characteristics govern the performance and serviceability of the pavement's in-service life. Accordingly, many researchers have stressed the considerable influence of Unbound Granular Materials (UGM's) on the engineering performance of pavements (Gandara et al., 2005, Fookes et al., 1988, Hussain et al., 2014, Chen et al., 2013, Chen, 2009, Sharp, 2009, Tao et al., 2008) and have highlighted the undeniable role of the quality of unbound aggregates on the functional pavement asset life of thin surfaced and unsealed pavements (Chen, 2009, Chen et al., 2013, Hussain, 2012, Sharp, 2009).

Accordingly, using durable, tough and fatigue resistance aggregates is a primary objective in providing long-life pavement construction (Collis and Smith, 2001, Gondal et al., 2008, Woodside and Woodward, 1989, Kleyn et al., 2009) since inappropriate material selection at the time of construction can lead to extremely costly rehabilitation works in the future (Fookes, 1991). In general, both resistance to wear (degradation of particles as crushing loads are applied) and resistance to decay (i.e. resistance to weathering under the complex environmental field conditions experienced by UGMs) affect the durability characteristics of materials (Hussain, 2012, Collis and Smith, 2001). The durability of materials, to greater or lesser degree, affects the other engineering properties of aggregates (Kleyn et al., 2009). Therefore, it is crucial that laboratory based durability tests of aggregates must as closely as possible reproduce the real field conditions (Williamson, 2005). To this end, researchers have developed various tests to determine the durability of aggregates under moist conditions and various standardized index tests have been established in material testing specifications (Table 1 lists the tests). These tests are empirically based (Bartley et al., 2007, Bartley, 2001) and instead of determining the serviceability and aging characteristics of aggregates they are mainly used as an indication of aggregate's performance at the initial stage of construction (Bartley, 2001). Furthermore, although the performance of aggregate materials is strongly related to the in-situ environmental conditions and especially the moisture properties (Chen et al., 2013, Fookes, 1991, Carroll, 2012, Price, 1995, Essington, 2004, Yeo et al., 2012, Li et al., 2016, Salour, 2015), some of the tests are employed only in dry conditions (e.g. Los Angeles Abrasion test method). However, other laboratory tests (as listed in Table 1 – eg. the Micro Deval Test method) use a solution (water or a chemical substance) to simulate an aggregates susceptibility to degrade with moisture. Almost all methods do not consider the possible in-field wet and dry cyclic pavement conditions nor do they effectively characterise the water/environment conditions in UGLs, namely temperature and chemical composition. On the other hand, accelerating the reaction of aggregates with chemical substances is also questionable (Bartley et al., 2007, Fookes et al., 1971, Hudec, 1997) as the simulated conditions may become too aggresive. In support of this opinion (Collis and Smith, 2001, Moors, 1972) referred to the major differences between fine materials characteristics produced in the laboratory and the field. It is notable that a combination of field conditions and certain component of aggregates can produce deleterious minerals (e.g. swelling clays such as smectites) that can cause distress and failure in UGLs in the presence of moisture (Gandara et al., 2005, Chen, 2009, Chen et al., 2013, Lowe et al., 2010). Further, as inferred from (Fookes, 1991), approximately 65% of recorded in-service deterioration of pavements within an engineering time scale is due to the presence of secondary minerals in the UGLs.

Table 1: Solution characteristics of some standardized durability tests

Test	Reference	Moisture testing conditions and comments
Micro-Deval abrasion test	ASTM D6928 and ASTM D7428	Samples are: - immersed in tap water - at a temperature 20 ± 5 °C - for a minimum of 1 h
Washington Degradation Test	WSDOT Test Method T 113 (Washington State, 2009)	- Test samples must be covered completely by water. - 20 minutes of agitation is required.
Tube Suction Test (TST)	(Scullion and Saarenketo, 1997)	- Water is deionized
Ten percent fines value (TFV)	BS 812-111: 1990 (Standard, 1990a)	- Test specimen is covered at least 50 mm by water for 24 ± 2 hrs. - Entrapped air remove immediately after immersion. - Water temperature maintain at 20 ± 5 °C.
Absorption Test (coarse and fine Aggregate)	ASTM C127 and 128	- Water at room temperature (23.0 ± 2.0 °C for fine aggregate) - Immersion duration of 24 ± 4 hrs (for coarse aggregate).
Soundness Test	ASTM C88- 13	- Crystallization by repeated immersion in salts simulate formation of ice crystals.
Aggregate Durability Index	ASTM D3744/D3744M − 11a	- Generation of fines in presence of water is evaluated. - water is distilled or demineralized - Water temperature is 22 ± 3 °C.
Aggregate Impact Value (AIV) Test	BS 812-112:1990 (Standard, 1990b)	- Measure aggregate resistance to sudden shock or impact in both dry and soaked conditions. In the soaked condition

Test	Reference	Moisture testing conditions and comments
		- Test specimen is covered at least 50 mm by water for 24 ± 2 hrs. - Entrapped air removed immediately after immersion. - Water temperature maintained at 20 ± 5 °C.
Gyratory Testing Machine	(Ruth and Tia, 1998)	- Evaluate dry and wet degradation of aggregates. - In the wet test samples are soaked in tap water for 1.5 hrs to 4 hrs.
Ethylene Glycol Soak Tests	SANS 3001-AG 14 & 15 (The South African National Road Agency, 2014), and (van Blerk et al., 2017)	- Evaluate the durability of the Basic Crystalline group of rocks - Rock fragments are soaked in ethylene glycol.

Durability is also related to various variables of internal and/or external nature, and thus it cannot be measured by a single laboratory test (Collis and Smith, 2001, Bartley et al., 2007, Fookes, 1991, Fookes et al., 1971, Bartley, 2001, Hudec, 1997, Přikryl, 2013). Furthermore, it seems that the change in the inherent characteristics of aggregates due to the action of weathering over time, that is aging, is not well addressed by the current standard test methods. Moreover, each kind of geologically formed rock weathers variably (Bartley et al., 2007, Fookes et al., 1971, Hudec, 1997), depending on the mineralogical properties and the texture characteristics (Ciantia and Castellanza, 2015, Bartley et al., 2007, Fookes, 1991, Carroll, 2012). Thus it seems logical that using the same test procedure for all kind of rocks would be an unrealistic expectation (Bartley et al., 2007, Fookes et al., 1971, Hudec, 1997). The premature failure of UGLs in various parts of the word, such as New Zealand (Stevens and Salt, 2011), whilst they may met the essential initial laboratory test requirements is circumstantial evidence that reveals the existing test methods do not necessarily fully characterise an agrgegate's performance in real field conditions. As some studies (Ciantia and Castellanza, 2015, Collis and Smith, 2001, Bartley et al., 2007, Fookes, 1991, Williamson, 2005, Bartley, 2001, Lowe et al., 2010) have stated these tests are hardly able to determine premium aggregates for superior pavement performance applications.

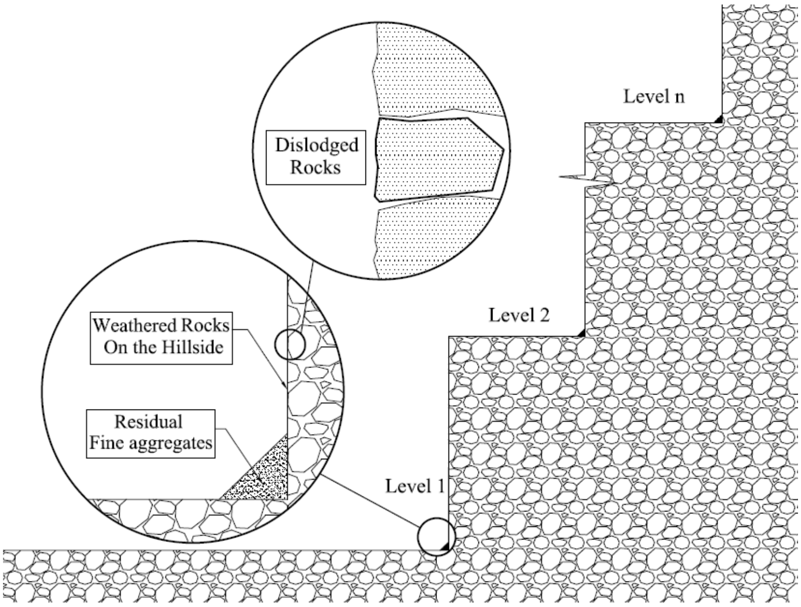
1.2. Objective

Weatherability of aggregates is an environment-dependent process. Thus, in this study, we investigate the weathering processes of road aggregates and possible products that occur at different levels in the quarry (that have been exposed to the atmosphere for different periods of time) to determine if they are the same, and/or whether they vary with time. If the environmental conditions and thus the probable chemical and physical weathering processes are comparable, then the natural weathering of materials within a quarry over time have the potential to be used as an indicator of the weatherability of similar aggregates in the UGLs within a pavement. Eventually, the results of natural weathering process is used to evaluate the efficiency of the current Weathering quality Index (WQI) testing procedure.

2. Materials and methodology

A wide range of aggregates, fresh and weathered, were collected from different levels of a quarry in a late Tertiary andesite flow, which produces materials for road construction purposes. A simple cross-section of this quarry is shown in Figure 1. It is notable that each level of the quarry is located spatially at a different depth in the flow and therefore has been exposed to the atmosphere for durations of time ranging from four months to 15 years. Thus, it is possible to trace the effect of possible weathering processes on materials, including mineralogical changes, in each level and relate them to changes in time.

Figure 1: Schematic cross section of the selected quarry



The visible discoloration, which varies from grey to yellowish and reddish, and the readily discernible changes in physical properties, such as hardness and porosity, provide clear evidence of the weathering process in the fresh materials. Three distinct weathering conditions are investigated at each level of the quarry. Stage 0 is the unweathered condition. The fresh inner parts of a relatively large dislodged rock on the surface of the hillsides in the quarry, where it has been protected from penetration by weathering agents and fresh materials in the stockpile are in this category. With increased time of exposure to the environment, a weathering rind of variable thickness forms around large rocks (Figure 2). The weathering rind is a zone on the surface of a rock which shows a recognizable changes in hardness and colour relative to the inner part. The weathering rind denotes an immediate weathering condition (Stage I). The detached material that was collected at the foot of the hillside has been subjected to a continuous period of intense weathering (Stage II) the intensity of which is related to the duration time of exposure. Figure 3 shows the possible stages of weathering in the quarry.

Figure 2: Weathering rinds on the exposed surface of andesite rock samples

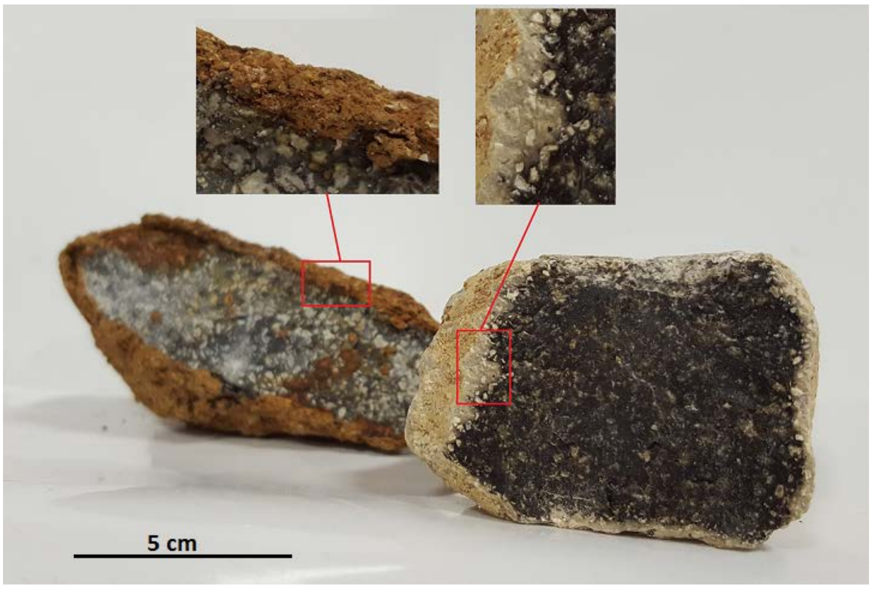
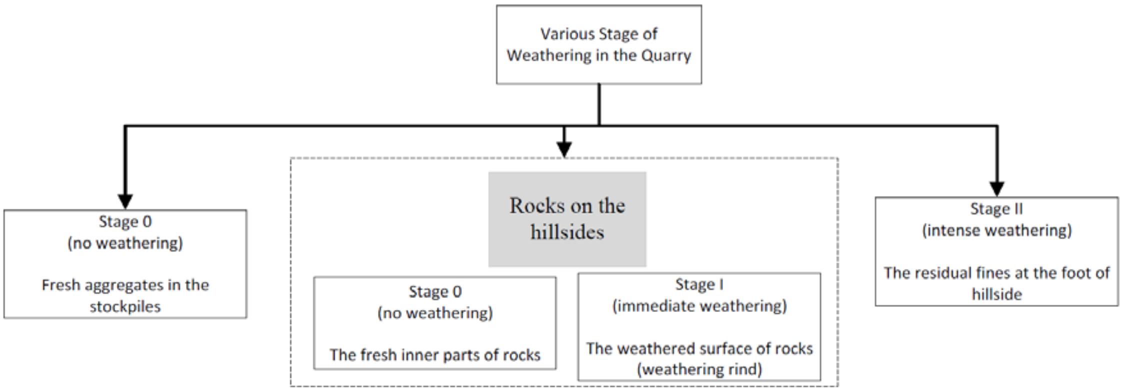
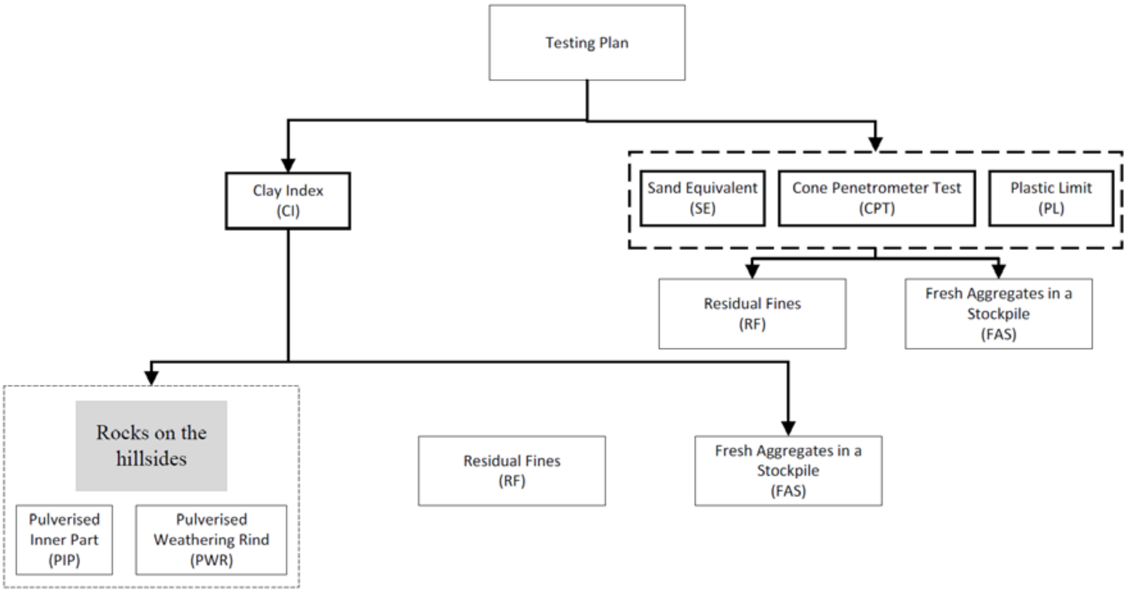


Figure 3: Three stages of weathering and their occurrence in the quarry



To better specify the impact of weathering on the physical properties of aggregates a testing plan (Figure 4) has been devised, which includes testing for the presence of clay minerals, common indicators of weathering in geomaterials. The proposed tests will detect and also determine the nature of any clay minerals present in order to estimate the intensity of the weathering process. Finally, the reliability of the artificial weathering test commonly used in New Zealand, to simulate natural weathering condition, the Weathering Quality Index (WQI), will be evaluated.

Figure 4: Testing plan



3. Results and discussion

3.1. Clay Index (CI) test

The CI test, or methylene blue titration test, is mainly employed to determine the presence of expansive clay minerals (Hussain et al., 2014, Lowe et al., 2009, NZS4407- Test Method 3.5, 2015) in either the fines component of aggregates or in rock powders. The CI test also indirectly provides information about the surface areas and exchange capacities (Lowe et al., 2009, Hang and Brindley, 1970), and the ability of clay minerals to attract and hold water (Stevens and Salt, 2011). TNZ M/4 code (Transit New Zealand (M/4), 2006) recommends a maximum CI of three for the portion of basecourse passing the sieve 200#, when the test is carried out according to the (NZS4407- Test Method 3.5, 2015).

We have conducted CI tests on weathered rocks (i.e. the interior of the rock and also the weathering rind), residual fines and fresh aggregates. A ring mill pulveriser was used to powder the rocks and coarse aggregates. The New Zealand standard (NZS4407- Test Method 3.5, 2015) recommends that if more than 50% of the powder passes the 0.075 mm sieve, the pass fraction can be used for the CI test.

Figure 5: CI test results for weathered materials

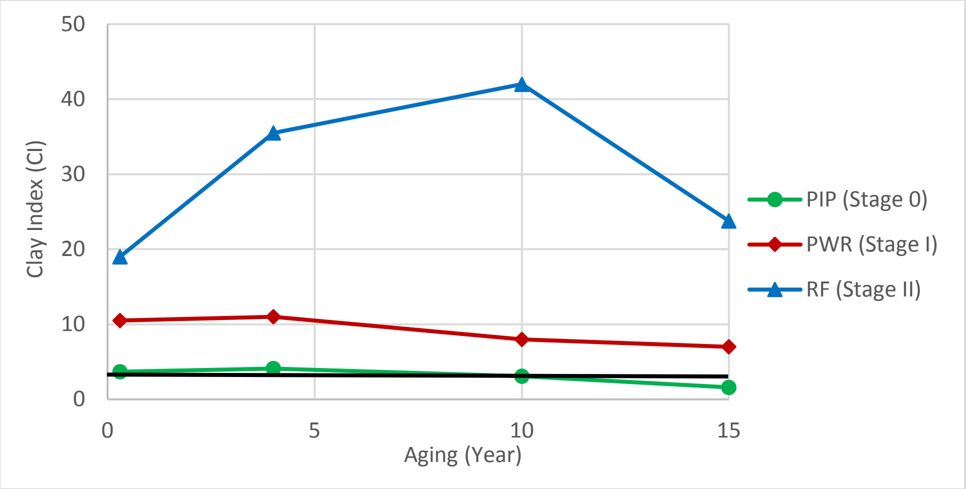


Figure 5 shows that materials at stage 0 (i.e. the fresh inner part of rocks), have CI values (mean= 3.1 and SD= 1.1) which are very close to being acceptable for the material to be used in basecourses. Since there is a small variation in CI results, it seems that the depth of the extraction of the aggregate may affect the quality of final product. The zone of intermediate weathering (Stage 1, as exemplified by the weathering rind) has significantly increased CI values compared with unweathered material and the results are more variable (mean= 9.1 and SD= 1.9). A CI value in excess of 5, indicates that a moderate to high content of expanding clay content can be produced within a very short weathering time. Interestingly, samples from weathering Stages 0 and 1 show the same trend with increasing time of weathering. On one hand, it can be associated to the influence of initial resistance of materials to the weathering process (higher initial CI; increase the propensity of materials to weathering). On the other hand, as the CI results of materials at the Stage 1 is not affected by the duration of weathering, it can be concluded that the weathered products were detached from the outer surface of weathering rind when they reach specific intensity of weathering.

Samples from weathering Stage II show a very different pattern. The CI values are significantly higher than those determined for samples from Stages 0 and 1, and they increase rapidly and are more variable with the time period of weathering (mean= 30.1 and SD= 10.6). This data suggests that the increase in the rate of weathering can be related to the increasing surface area of the residual fines. The CI results increase as the duration of weathering increases. However, the results show a significant decrease with an increase in the intensity of weathering from 10 to 15 years. This trend can be explained by the sequence of forming clay minerals. By increasing the intensity and duration of weathering kaolinite and iron and aluminium oxides can be produced in last stages of weathering (Bartley et al., 2007) that dramatically reduce the exchange capacity and thus the CI results of the product.

Furthermore, as Table 2 shows, the one-way analysis of variance (ANOVA) (p-value< 0.05) statistically reconfirms significant differences in CI results of materials. In order to detect significant differences between the pairs of materials, the ANOVA test was followed by a pairwise post hoc test. The results confirmed that there are statistically significant differences in CI values among each pair of tested materials.

Table 2: ANOVA test results

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1600.010	2	800.005	20.625	.000
Within Groups	349.092	9	38.788		
Total	1949.102	11			

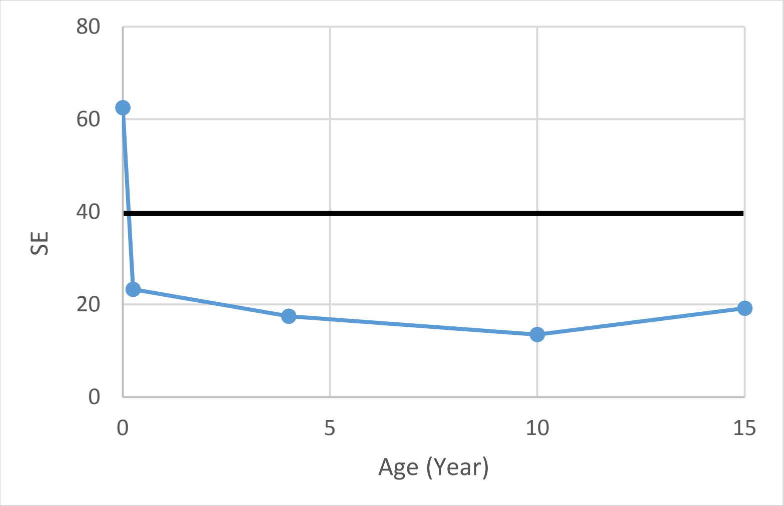
4.2. Sand Equivalent (SE) test

The SE test (NZS4407- Test Method 3.6, 2015) is commonly used in New Zealand for evaluating the characteristics of sand portion of basecourse materials (Lowe et al., 2009). Low values of this test indicate the presence of detrimental and plastic clays as far as use for construction purposes are concerned (Lowe et al., 2009, Stevens and Salt, 2011, Hussain et al., 2014).

Figure 6 shows the results of SE tests for fresh and residual fine materials. The rapid reduction in SE values following only a short period of weathering to values below the acceptable minimum SE value of 40, required by (Transit New Zealand (M/4), 2006), reveals how significant short-term weathering is and how rapidly the primary mineralogy will alter into deleterious clay minerals.

The SE values increase slightly following a prolonged period of weathering. There are two possible explanations for this phenomena. It could indicate that an equilibrium has been reached between the alteration reactions and the environment. However, it may also indicate a change in the nature of the clay minerals in the alteration assemblage. The small increase in SE value determined for the 15 years old materials following a gradual decrease favours the second hypothesis.

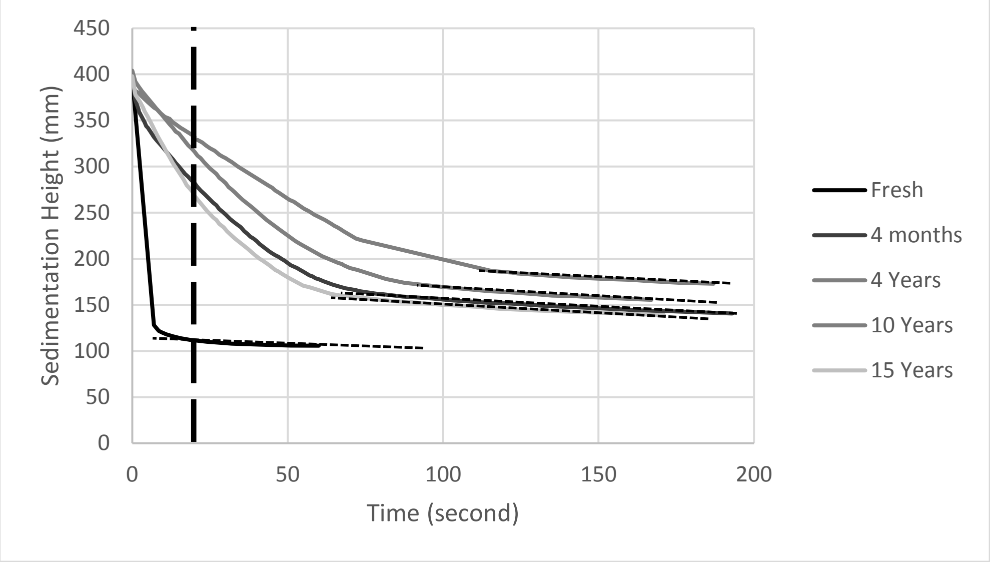
Figure 6: Sand Equivalent results



To improve understanding of the characteristics of the fine materials in the UGLs, the behaviour of the uppermost distinct surface of the clay size fraction of materials in the Sand Equivalent cylinder (see Figure 7) was traced until a steady state was reached (Figure 8). The rate of sedimentation decreases with time until finally, regardless of duration of weathering of the sample being tested, all materials reached a similar steady sedimentation rate. However, there is a notable difference in the sedimentation behaviour of fresh compared with weathered materials. While fresh materials reach the steady state in approximately 20 minutes (the standard settlement period required for the SE test), the weathered materials are still in the initial stage of sedimentation. It is also noteworthy that the height of the upper distinct surface of the sedimenting materials at the steady state stage is a function of the duration of weathering of the sample being tested, and it rises with the increasing intensity of weathering. However, the most intensely weathered material (15 years) has the lowest height of the weathered materials. This can be attributed to the presence of increased amounts of kaolinite in the clay component of these materials. Kaolinite is the common product of intense weathering in the free drainage condition (Bartley et al., 2007), as this mineral has a higher hydrated density than montmorillonite and/or vermiculite (Osipov, 2012) which are the clay minerals that form during the earlier stages of weathering (Bartley et al., 2007).

Figure 7: The reference surface used to trace the sedimentation behaviour of the clay size fraction of the unbound granular materials during Sand Equivalent Test.

Figure 8: Change in level of sedimentating materials in the SE cylinder



4.3. Plasticity Index (PI)

The PI of the fine fraction of aggregates can be calculated as the numerical difference between the Cone Penetration Limit (CPL) and the Plastic Limit (PL) (NZS4407- Test Method 3.4, 2015). The PL can be used to differentiate between silts and clays; the CPL is more commonly used in New Zealand to determine the Liquid Limit of fine materials (Lowe et al., 2009). In general, PI evaluates the sensitivity of the aggregates in the presence of water (Stevens and Salt, 2011) and it is affected by the clay mineral fraction (Lowe et al., 2009, Dolinar and Škrabl, 2013, Andrade et al., 2011), the type of clays present (Dolinar and Škrabl, 2013, Andrade et al., 2011), and the degree of weathering (Bell et al., 2009). The local code (Transit New Zealand (M/4), 2006) recommends the maximum PI of five for premium basecourse aggregates.

Table 3 shows the PL, CPL, and PI values for samples which have been weathered for periods up to 15 years. Although the fresh materials were non-plastic, within a very short period of weathering (four months) they had become highly plastic. It is particularly notable that with increasing duration of weathering the PI results decrease to the extent that the most intensely weathered materials have a PI values within the recommended acceptable range for basecourse aggregates. Further, as the materials are subjected to longer periods of weathering (up to 10 years) their PL and CPL values tend to increase, although there is a significant drop in these values following 15 years of weathering. The initial increase in PL and CPL values are probably related to the production of smectites while the reduction in PL and CPL values following a more intense weathering/leaching process, can possibly be associated with the production of kaolinite and iron oxides, minerals that possess nonplastic properties (White, 1949, de Oliveira Modesto and Bernardin, 2008).

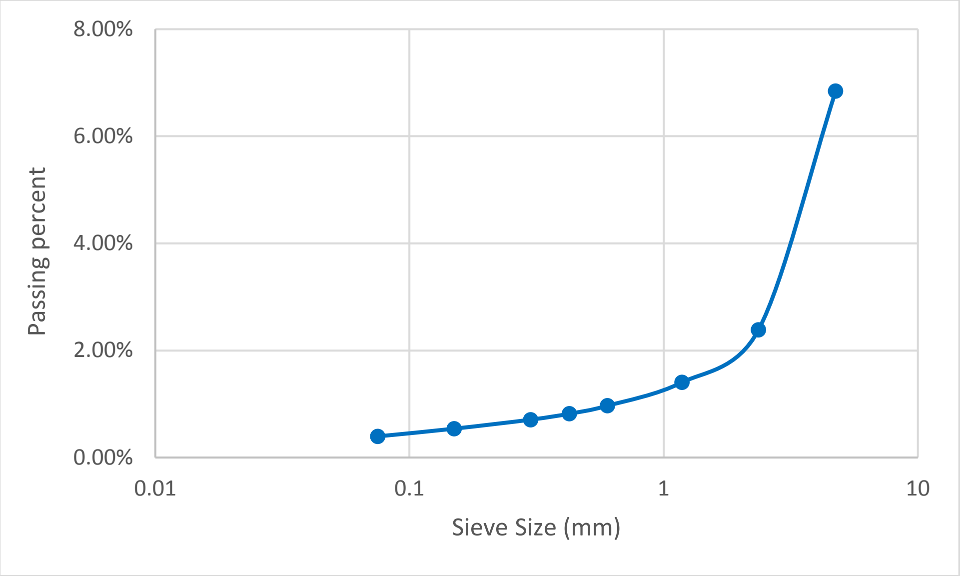
Table 3: Atterberg limit test results

Duration of weathering	PL	CPL	PI
Fresh material	NP	22.2%	NP
4 months	21.4%	35.1%	13.7%
4 years	26.0%	34.1%	8.1%
10 years	30.5%	39.9%	9.4%
15 years	26.9%	29.1%	2.2%

4.4. Weathering Quality Index (WQI)

Stevens and Salt (Stevens and Salt, 2011) suggested the WQI (NZS4407- Test Method 3.11, 2015) test as a helpful measure of the resistance of aggregates to the complex effects of Wetting and Drying (W-D), and heating and cooling (H-C). The WQI test is mainly based on values for two variables, the percentage of materials that retain on the 4.75 mm sieve (after 10 cycles of rolling, W-D and H-C in the WQI testing) and the cleanness value (CV) of the dirty wash water. The fresh aggregates in a stockpile were subjected to WQI test and after the test 93.2% of aggregates retained on the 4.75 mm sieve and the CV of the dirty wash water was 23. Accordingly, based on the specification, the fresh materials are labelled (BC) that shows an average to poor resistance to the complex weathering processes as planned in the WQI testing procedure. Figure 9 shows the gradation of the resultant fine aggregates (smaller than 4.75 mm) afetr the WQI test. As it can be seen, a very small fraction of these materials (0.4%) passed the 0.075 mm sieve (clay and silt size materials). Further, the materials passed the 0.075 mm sieve were subjected to CI test. There was a negligible change in CI value compare with the original fresh fine materials (4.2 compare to 2.9). Having determined the characteristics of weathered materials in the quarry at various stages of weathering, it can be concluded that while the WQI test might be able to subject materials to physical degradation it fails to accurately simulate the possible chemical reactions that occur in field conditions.

Figure 9: The size gradation of the fine aggregate produced by the WQI test



5. Conclusion

Contrary to the common belief that the inherent properties of geomaterials in a pavement remain constant throughout the pavement's life, this study has shown that the aggregates "age" as a result of a physical and mineralogical weathering process. Degradation of coarse rocks and the production of detrimental clay minerals considered as indications of weatherability of materials.

The current durability tests evaluate the properties of aggregates at time zero and poorly predict their behaviour in service conditions.

It has been revealed that the current local outlines do not necessarily ensure the characteristics of aggregates in New Zealand over the time and even premium aggregates, conforming to TNZ M/4, may suffer from an intense short-term weathering, which may affect the pavement performance largely.

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