A review of New Zealand Specifications and laboratory test methods for fine aggregate and sand

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ABSTRACT

Fine aggregates and sands have the potential to contain levels of deleterious minerals that can have a negative impact on roading aggregate properties. The most frequently employed method in New Zealand to ensure suitability of fine aggregates and sands for concrete is the sand equivalent test. This test has been reviewed, along with the other two readily available test methods in New Zealand, clay index and plasticity index.

The results of testing conducted to compare the three methods are presented and discussed to determine whether these test methods are still the most appropriate approach for roading aggregate compliance testing of New Zealand fine aggregates and sands.

INTRODUCTION

For many years the sand equivalent (SE) test has been the most widely used method of determining the quality of fine aggregate in New Zealand (NZ). The test essentially determines the relative proportion of detrimental fine dust or clay-like particles in sands or fine aggregates [NZS4407 1991].

More recently, the results of the SE test are being supplemented by conducting clay index (CI) tests which is a methylene blue titration test that estimates the percentage of expansive clay minerals in natural fines or rock powders and/or determining the plasticity index (PI) which determines how plastic the material is [NZS4407 1991].

New Zealand's consumption of aggregates is in the region of 45m tonnes per annum, of this nearly 24m tonnes goes in to rock, sand and gravel for roading (53%) and just over 9m tonnes into rock, sand and gravel for building (20%) [Crown Minerals 2008], which is worth an estimated $550 million [Andrews 2008]. Based on these figures and typical testing frequencies for fine aggregates, sand and granular base materials it is estimated that the cost of testing to establish the cleanliness of fine aggregates, sands and granular base materials in New Zealand could exceed $2m per annum. This cost is also growing due to the greater demands being placed on the performance of NZ aggregates, and the increasing focus on aggregate quality compliance.

If the current preferred approach of using more than one test method for demonstration of the materials suitability continues then, given the relative cost of the three tests, the overall cost of fine aggregate testing to establish quality has the potential to increase significantly.

However, an even greater impact on the NZ economy is through not maximising the utilisation of NZ aggregates due to limitations with the current tests. It takes on average over 10 years to consent a new quarry [Boyce 2008], and after so much time, effort and dollars spent it seems almost unforgivable to then not extract the absolute maximum value from this non-renewable resource. Especially, if the reason for doing so, is not related to anything other than the basic rock quality.

Each of the three tests possesses their own distinct limitations and these should always be taken in to account when assessing the cleanliness of a fine aggregate, sand or basecourse.

Some of the issues associated with the current tests are:

- All are laboratory based tests. SE has the ability to be conducted in the field but it is the author's experience that the test is rarely conducted outside of a laboratory;
- The turnaround of results is typically 0.5 – 3 days which could, in some cases, mean the material has left the quarry before the test result is known;
- The accuracy and consistency of tests as all 3 tests rely on the skill and experience of the aggregates technician;
- The inconsistent interpretation and understanding of results by clients, engineers, specifiers and contractors; and
- The increase in recent years of the use of rock fines especially in the production of concrete and potential incompatibility with current tests.

It is proposed to undertake research in conjunction with The University of Auckland to develop an alternative test method that could possibly replace all three current tests and be:

- More accurate, less sensitive to skill and experience of the technician;
- Faster in turnaround and ideally able to give real time results;
- Able to be used in the field as part of the production/stockpiling process;
- More cost effective, both in terms of the overall testing cost but more importantly in the determination and acceptance for use of material that would currently be disregarded due to the limitations of the tests available; and
- Allow the producer to better relate to the materials suitability for use in concrete, asphalt or road base materials, giving greater confidence to the end user.

As a first step to achieving these goals, it has been necessary to undertake a literature review which focuses on the three tests currently employed in NZ and to use available data sets to reveal the relationship between the three tests.

SAND EQUIVALENT

The sand equivalent test (SE) is the most common and frequently employed test for establishing the quality of fine aggregates, sands and granular base materials in New Zealand.

The test was developed over 50 years ago by Hveem as a quick test to determine "the presence of undesirable quantities of adverse clay-like materials… since an excess of clays is usually detrimental to the performance of any aggregate". [Hveem 1953]

Hveem developed the (California) sand equivalent test based on Californian materials and although predominantly for concrete aggregates and natural sands also provided proposed SE values for bases and bituminous mixes (refer to Table 1). The work was quickly followed by research conducted by suggesting SE limits for granular base materials and aggregates intended for use in bituminous mixtures related to a wider geographic spread of aggregate and sand. [O'Harra 1955; Clough & Martinez 1961]

Table 1: Minimum SE for various uses of Fine Aggregate / Sands adapted from Hveem 1953

Types of Fine Aggregate/Sands	Sand Equivalent Minimum
Crusher run or gravel base material	**30**
Aggregates and selected materials for road mix bituminous treatment	**35**
Aggregates for plant mix bituminous surface	**45**
Aggregates for asphaltic concrete or Class A plant mix	**55**
Concrete Sand	**80**

O'Harra's findings suggested that the SE results "reflect the quality of the material" and that the "test is of definite value as a rapid field test to determine acceptability of materials".

The sand equivalent test went on to gain acceptance in many countries as a quick measure of the quality of fine aggregates, sand and granular bases, and is still employed in several countries as the preferred test method for this purpose.

Most literature, research and discussion on the test are in agreement that the main benefits of the sand equivalent test relates to it being a simple, low cost test producing relatively quick results [Sameshima 1977; Kandal et al 1998; Black 2009].

In New Zealand, there are currently two accepted test methods for determining the sand equivalent, one relating to the testing of concrete aggregates (NZS 3111:1986) and the other for roading aggregates (NZS4407:1991).

Essentially, both test methods are similar and much of the difference is in the language used and the additional guidance and notes that are supplied with the NZS 4407:1991 method, including the repeatability and reproducibility indicators. NZS 4407 also warns that the two methods have the potential to give significantly different results.

Literature indicates that there are downsides to the test, the most obvious being that the test is not a direct measurement of deleterious minerals and clays. Instead the test gives a indication of suitability by measuring a relative percentage of all fine material in the silt and clay range. This has led to several researchers [Sameshima 1977; Van Barneveld et al 1984; Black 2009] commenting on the risk of unsuitable material being classified as acceptable and conversely good material being rejected on the basis of a low SE value.

This situation is highly undesirable and the most commonly employed resolution currently is to reinforce a SE result with one of the other quality test methods, often methylene blue adapted to be clay index in New Zealand, or Atterberg limits (plasticity index).

The failings of the SE test in adequately distinguishing those hard competent fines is likely to magnify and become even more prevalent with the continued thrust to utilise more industrial waste products such as recycled concrete aggregates, glass and artificial aggregates.

Other frequently referred to issues with the test is the accuracy, in terms of the test repeatability when conducted by the same operator and reproducibility of the test between Laboratories.

NZS 4407:1991 states "the repeatability of the sand equivalent result obtained when using this test method is considered to be 4 and the reproducibility of the sand equivalent results is considered to be 10", these percentage difference values are similar to those stated in other sand equivalent specifications [ASTM 2002; TxDOT 1999; AP-T31 2003]
AFNOR 1990 gives estimates of the repeatability and reproducibility standard deviations of:

S_r = 1.5 SE units

S_R = 2.5 SE units

Where:
S_r = repeatability
S_R = reproducibility

BRE 2009 report a minimum repeatability given rounding errors of S_r = 0.5 SE units, and the findings of that study were that repeatability "should rarely exceed 3 SE units"
The reproducibility of the SE stated should be put into context by taking in to account research suggesting that the reproducible standard deviation of a mechanical test, expressed as a coefficient of variation, should be no more than about 8% if the test method is to be used to assess compliance of aggregates with specifications. [Jick et al 1994]

In 1985 the Testing Laboratory Registration Council of New Zealand (TELARC) undertook a preliminary sand equivalent proficiency trial in New Zealand involving 21 laboratories. The findings reported were:

Repeatability (r) = 3.0 Reproducibility (R) = 7.4

These findings resulted in the suggestion that "as might be expected, the coefficient of variation turned out to be somewhat high, viz 10%", suggesting "the major contribution to this are systematic differences between laboratories" [TELARC 1985]

As discussed previously a commonly stated benefit of the test is that it is considered to be a quick test, with a turnaround time of less than 1 hour. However, in reality that turnaround time takes no account of the aggregate sampling and delivery to the point of test. Therefore in a lot of cases total turnaround time will be in excess of 1 hour and could be significantly longer.

This turnaround time is critical when considering that the larger quarries within New Zealand can be processing material at tonnages in excess of 500 tonnes per hour. Taking this in to account, in conjunction with the total test turnaround time from sample to result, it can be seen that there are significant risks with delayed results, and conversely significant benefits to be gained with a faster turnaround of results, in terms of, identifying the quality of the fine aggregate.

CLAY INDEX

The clay index (CI) test method was developed in New Zealand by Sameshima in response to issues related to the suspected failure of granular base materials on part of Auckland's southern motorway. The test is adapted from the methylene blue test widely accepted to have been devised by Jones in 1967 in relation to measuring the bentonite content of drilling mud. [Sameshima 1977]

The test was adopted in New Zealand and is still used in a variety of forms around the world to primarily identify the presence of swelling clays in fine aggregate samples. As described by Black 2009 "the clay index test is actually measuring the surface area of the fine fraction of the aggregate by titration to determine how much methylene blue can be absorbed on the surface of the aggregate fines".

Of the clays regularly found in common NZ rock types, it has been shown that smectite is the one of greatest concern [Scmitz et al 2004; Higgs 1987; Black & Sameshima 1980] when classifying the quality of the fine aggregate and assessing it's suitability as a concrete or roading aggregate. Therefore, most literature [Black & Sameshima 1980; Higgs 1996; Szymoniak et al 1986; Nikolaides et al 2007] points to the clay index as a production test to detect the presence of smectite.

A major issue with the CI test is that it is not just deleterious swelling clays, such as, smectites that can trigger the test. "All substances present which have exchangeable cations or surface imperfections that are accessible to water will absorb the methylene blue". [Stapel & Verhoef 1989]

Therefore other minerals such as zeolites possess the potential to absorb methylene blue [Black 2009]. Sameshima found that "the clay index test method does not measure the cation exchange due to zeolites." However, zeolites are common in a number of NZ source rocks such as certain greywackes, andesites and oceanic basalts [Black 2009].

Essentially CI values do not categorically confirm the presence of deleterious minerals if other minerals or substances present also have exchangeable cations [Stapel & Verhoef 1989]. This means there is potential for a fine aggregate sample to test high for clay index yet be fit for purpose as an aggregate although most current specifications would preclude its use.

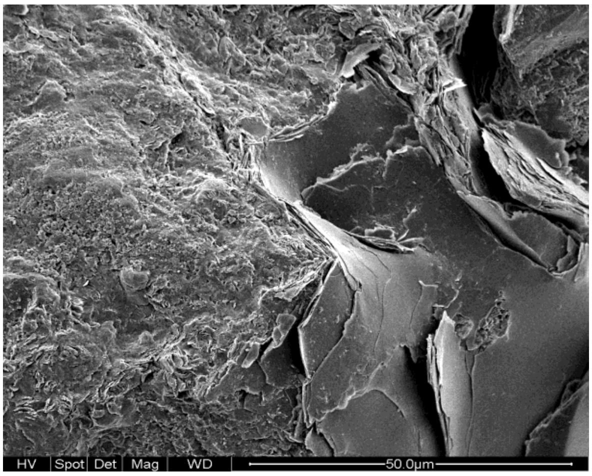

Figure 3: SEM photograph of fracture surface of Lower North Island Greywacke aggregate chip showing presence of detrital muscovite (mica) grain and small flakes of matrix illite.

The scanning electron microscope (SEM) photograph in Fig 3 shows a fracture surface of a lower North Island greywacke Grade 3 sealing chip. The large crystal forming the right side of the photograph is detrital muscovite (mica) which is characteristic of the Torlesse type greywackes found in the lower North Island but detrital mica can also occur in some northern North Island greywackes. Mica crystals are flexible and as it has been bent the outer sheets of the mica have popped off. The flaky clay material (bottom left) is almost certainly illite since X-ray diffraction analysis revealed abundant illite associated with minor chlorite; no swelling clays (eg smectite) were detected.

Greywacke aggregates containing detrital mica often have abnormally high PI values as crushed muscovite crystals have high plasticity but the flakes formed are non swelling. Thus the aggregate will give a low CI value but a high PI value [Black 2009]. This is not ideal as the aggregate could be deemed unsuitable for use due to a high PI result which in reality may have minimal influence on whether the aggregate is fit for purpose.

The only significant recent development in trying to improve on the existing tests is work conducted by Yool et al 1998 in the UK to try and determine the individual clays present by attempting to use different combinations of dye to distinguish between them. The work was largely inconclusive and the paper stated that "further work is required to include a broader range of clay types and to develop the test for use on aggregates". If the test was successful, the ability to identify the non swelling clays or less harmful clays would be beneficial, however it would likely add further time to the test and still not tackle the issue of turnaround time. It is the author's opinion therefore that if there is perceived benefit in attempting to adapt the current CI test any work would need to address the turnaround times.
The CI test is also considered to be a quick and cost effective production test compared to the time and cost involved in conducting an x-ray diffraction (XRD) or differential thermal analysis (DTA) [Stapel & Verhoef 1989; Cole & Sandy 1980].

Again this is dependant on what tests are being compared. There is little doubt that the clay index is quicker and more cost effective than XRD. However, if compared with say, the SE test it is slower and more expensive.

As already discussed, the turnaround time from sample to result is critical in determining acceptable quality during quarry production and hence maximising the potential yield of high quality aggregates from the resource while at the same time minimising the risk associated with sub quality material entering finished product stockpiles.

Therefore, although the clay index is an effective "quick" test in determining the quality of fine aggregate, there is definite room for improvement both in terms of accuracy, cost and turnaround time.

PLASTICITY INDEX

The third test that is commonly performed in New Zealand is the plasticity index (PI). This index is derived from a group of tests collectively known as Atterberg limits. Atterberg limits were developed by a Swedish chemist, Albert Atterberg.

They were originally intended as a basic measure of a fine grained soil. The limits are based on water content and states that "depending on the water content of the soil, the soil may appear in four distinct states: solid, semi-solid, plastic and liquid".
In each of these states the consistency and behaviour of a soil is different and therefore so are its engineering properties. Atterberg limits distinguish these changes and can be used to differentiate between silts and clays.

When considering NZS 4407:1991 only three of the index's are used, namely, plastic limit (PL); liquid limit (LL); and plasticity index (PI).

Plastic Limit (PL)

The plastic limit (PL) is conducted on the material passing a 425um test sieve. It is a test that is very much dependant on the skill and experience of the laboratory technician, as it involves rolling threads of the material until it reaches the plastic limit.

If the specimen cannot be rolled to a 3mm thread then the sample is reported as non plastic (NP). A second sample is tested, repeating exactly the same procedure, and the PL is reported as the average of the water contents measured over the two tests, given that they do not differ by more than 5%.

When considering the test method there are several areas of concern with respect to test accuracy. Firstly, as previously stated the test is largely reliant on the technician and therefore has the potential for a high degree of variability [Kandal et al 1998]. Common areas of error for the plastic limit are reported as poor technique rolling threads; not achieving the 3mm thread; incorrect air drying of sample prior to moisture contents.

Liquid Limit (LL)

The liquid limit (LL) is the point at which the water content of the test sample changes and starts to exhibit liquid behaviour.

There are two recognised and widely used methods for determining the LL, the original method developed by Atterberg and later standardised by Casagrande and the use of a cone penetrometer which is the preferred method stated in the NZ Standards.

The original method involves placing the sample in a round bottomed porcelain bowl and cutting a groove down the centre of the sample. The bowl is then repeatedly dropped 10mm on to a hard rubber mat. When the groove closes by 13mm the number of drops to achieve this is recorded and the moisture content determined.
The moisture content at which it takes 25 drops to close the 13mm groove is defined as the liquid limit (LL).

The second method and more common in NZ, is the cone penetration limit. The test is again conducted on a 425um sample and essentially based on the measurement of penetration into the sample by a cone of specific mass. The cone penetrometer is often seen as a more consistent test than the original because it cuts down on variation due to human error.

Plasticity Index (PI)

Finally, the plasticity index (PI) is calculated and this is derived from the previous two tests and can be described by the formula:

$$\mathbf{PI = LL - PL}$$

If the plastic limit cannot be determined or is equal to or greater than the liquid limit then the material is reported as non plastic (NP). Soils or aggregates with a high PI tend to be clay, a mid range PI would suggest silt and low PI or a NP rating usually interpreted as an indicator of little or no silt and/or clay present. The Atterberg limits are soil classification tests that have been adopted for aggregate specification testing.

RESULTS OF COMPARATIVE TESTING BETWEEN THE THREE MAIN TEST METHODS

Data relating to sand equivalent, clay index and plasticity index was analysed to firstly determine if there was any correlation between the different test methods and secondly to understand the risk of materials being wrongly accepted or rejected based on the current test methods.

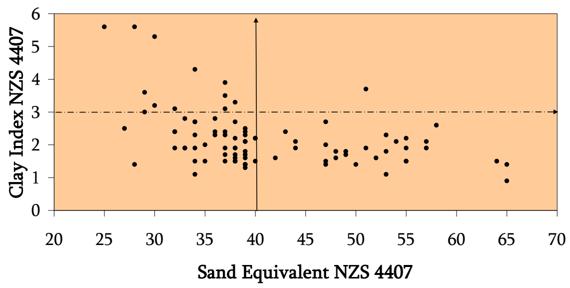

Figure 4: SE vs CI from the same Upper North Island Greywacke

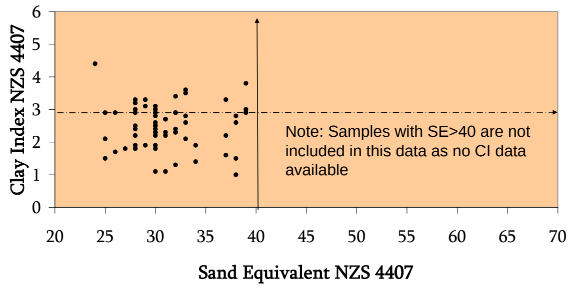

Figure 5: SE vs CI from the same Lower North Island Greywacke

Previous work [Sameshima 1977; Black & Sameshima 1980; Nikolaides et al 2007] has reported no correlation between sand equivalent and clay index test results. Comparative testing of 79 NZ Upper North Island Greywacke samples from the same source and tested in the same laboratory confirms no significant correlation between the two test methods. Fig 4 is split into 4 quadrants using commonly applied NZ limits to distinguish good quality fine aggregates of SE =/> 40 and CI =<3[TNZ M/04 2006; TNZ M/10 2005]. The plot shows a significant spread of CI results for the same SE. However, interestingly the data does indicate a trend of decreasing CI with increasing SE, as the results appear to track from the upper left quadrant through to the lower right quadrant suggesting that although no strong correlation exists, it appears that the two methods may identify similar differences in the quality of the material. The plot also shows 66 of 79 results fit a CI of 1-3. This would tend to suggest that some of the samples showing relatively low SE results in the bottom right quadrant, actually consist of hard rock fines that are influencing the SE test rather than clay fines.

Fig 5 further supports this with 46 of 57 NZ lower North Island greywacke samples also lying in the same band of CI 1-3. However, Fig 5 does not show the same trend of decreasing CI with increasing SE. This may be related to the spread of SE being analysed. It appears that the trend is more pronounced in Fig 4 where there is sample data set relating to SE greater than 40. As opposed to Fig 5 for which all samples were tested as being under an SE of 40 and therefore clustered in the lower left quadrant. It must be noted that samples with SE>40 are not included in Fig 5 as no CI data was available.

A data set shown in Fig6 was analysed to try and understand and establish any correlation between SE and PI.

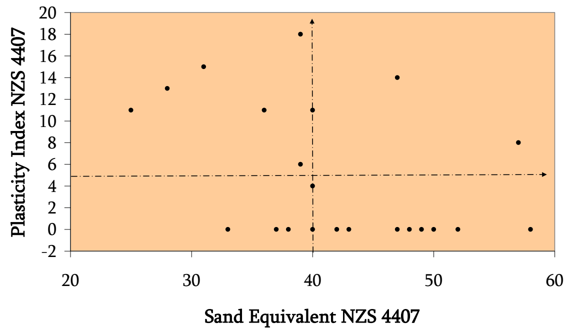

Figure 6: Sand Equivalent vs Plasticity Index from an Upper North Island Greywacke

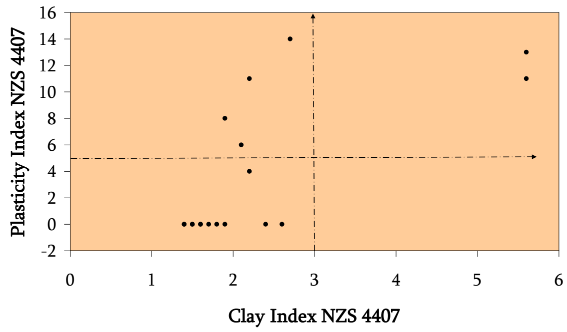

Figure 7: Clay Index vs Plasticity Index from an Upper North Island Greywacke

The study by Sameshima in 1977 failed to find any correlation between SE and PI. The results reported as part of this study also fail to establish any form of strong correlation between the two tests. Of interest is that Fig 6 data has 80% of the samples that are greater than SE 40 being determined as non plastic. When looking at the data it is also quite possible that the two results showing a SE>40 that are identified as plastic could be testing anomalies. Thus, concluding for this source that an SE ≥ 40 would likely result in a non plastic product. Further research would be required to determine if a compliance limit of 40 is conservative and also if an SE <40 could be acceptable and therefore better maximise the use of the resource.

Black and Sameshima 1980 reported a positively sloped linear correlation between clay index and plasticity index. The field testing data analysed in this research project (refer to Figure 7) is inconclusive in confirming this correlation. A possible explanation could be due to testing the same source and also the relatively narrow band of material quality and samples tested as part of this study when compared to the work of Black and Sameshima 1980 who tested a greater spread of aggregates and clays with the specific intention of identifying and determining the relationship.

CONCLUSIONS

The aggregate, concrete and roading industries have a responsibility to NZ to endeavour to maximise the utilisation of the finite supply of sands and aggregates available. Part of that responsibility is to work towards maximising the ability of each industry to produce and use fine aggregates to their greatest possible potential and minimise waste.

It is likely that the cost of testing and compliance will continue to rise as greater demands are placed on the aggregates and their ability to perform under usually increasing loads.
It is not ideal to have three distinct tests, with each measuring something different and all having their own individual limitations.

A key area of focus for the research is determining whether the current test methods and specifications allow best use of aggregate resources in NZ. This paper has highlighted limitations with each of the three tests currently employed in NZ. It has also found that overseas experience is very similar with most parts of the world currently specifying similar test methods to categorise the quality of fine aggregates and sands.

Thus, there is a need to conduct further research to identify opportunities to refine and improve the current methods or alternatively look to develop a new test method that is better able to identify the quality of aggregate and sand fines and that does not have the limitations of the existing test methods.

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