INVESTIGATING AGGREGATE MARGINALITY THROUGH THEIR WATER ABSORPTION CAPABILITIES

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ABSTRACT

The road basecourse vibrating compaction test has been undertaken to determine the relationship between dry density and moisture content for samples of marginal and premium greywacke aggregates from the Auckland / Waikato region. The results show that the marginal aggregates have higher optimum moisture content (OMC) with a range of 6.5 to 8% compared to premium aggregates, of which the OMC is 5%.

X-Ray diffraction (XRD) analysis of the clay sized component of the aggregates was carried out to investigate the reasons for the higher optimum moisture content of the marginal aggregates. The PSD results do not show a significant difference in the content of fine particles between marginal and premium aggregates. However, the marginal aggregates have a higher water absorption capability when compared with the premium aggregates. XRD diffraction analysis of the clay size fraction of the aggregates studied also indicate that the marginal aggregates contain more swelling clay minerals, particularly smectite, which has high water absorption capability than premium M4-compliant aggregates and thus marginal aggregates provide considerable potential for swelling related pavement failures to occur in field.

Our study indicates that the mineralogical characteristics of aggregates influence their water absorption capabilities which further impacts on their OMCs and their in service performance.

INTRODUCTION

The primary objective of this MBIE – funded research project is to provide a better understanding of the nature and causes of aggregate marginality so that more marginal material might be able to be used in roading and thus achieve a more economic utilisation of mineral aggregate resources in New Zealand.

One of the impediments to using a greater range of materials in pavement construction is the widely held concern about the effect of water ingress on such aggregates, and its role in premature pavement failure (Arampamoorthy and Patrick, 2010). Using non-stabilised marginal materials with higher OMC in road basecourse is likely to cause significant problems, such as rutting and early onset of wheel load based damage (e.g. shoving) as unbound basecourse aggregates are very sensitive to water. All pavement design textbooks stress that the main factor influencing performance is water. Water has multiple roles in the performance of aggregates within a pavement structure. Water penetrates into some minerals, such as clays and zeolites, in the aggregate particles, i.e. are absorbed into the aggregates. Water may also be adsorbed onto the surface of the minerals and particles in the aggregate. Water can also fill the voids between particles, in this role acting as a lubricant decreasing the friction between particles. Water, retained in the aggregates and/or on the surface of the aggregates during or after the compaction process, will affect the performance of aggregates and therefore the whole pavement structure.

Factors significantly influencing the optimum moisture content (OMC) for compaction during construction include aggregate type and compaction effort (Braja, 2014). Due to the utilisation of the same compaction effort (i.e. the same compaction time and the same vibrating compaction hammer), only the factor of the aggregate type was considered in this study. The aggregate type in terms of the grain-size distribution, shape of the aggregate grains, specific gravity of aggregate solids, and the percentage and type of clay minerals present, provides a great impact on the OMC of aggregates (Guerrero, 2004, Braja, 2014).

The objective of this study was to determine the reasons for the observed difference in OMC between greywacke aggregates of similar sedimentary petrographic type and in doing so to better understand the causes of marginality in greywacke aggregates so that better treatment methods could be developed to extend the use of marginal materials.

MATERIALS STUDIED AND TEST METHODOLOGIES

Materials

Five aggregates sourced from two hard rock greywacke quarries, in the Auckland / Waikato Region of New Zealand’s North Island have been examined. In geological terms, the greywacke source rocks are volcaniclastic but the greywackes in one of the quarries have been metamorphosed to prehnite pumpellyite facies (Quarry 1); in the other quarry (Quarry 2), the greywackes have only been diagenetically altered to laumontite-bearing zeolite facies (Black et al., 1993).

The materials studied are aggregates with a maximum particle size of 40 mm which can be categorised as either premium or marginal quality. One aggregate from each or the quarries is a premium M4-compliant aggregate. Two marginal aggregates have been sourced from quarry 1 (marginal aggregates 1A and 1B) and one marginal aggregate (marginal aggregate 2) from quarry 2.

Vibrating compaction test

The New Zealand vibrating hammer compaction test was undertaken on the aggregates passing the 37.5mm sieve with respect to NZS 4402:1986, Test 4.1.3 (1986). The hammer used in this study was a Kango 950K electric vibrating hammer with an input energy of 1050 W and a frequency of approximate 2000 blows per minute. The parameters of the hammer meet the requirements of the standard NZS 4402:1986, Test 4.1.3 (1986).

The compaction test was used to determine the relationship between dry density and moisture content of aggregates, and to determine their Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). Cylindrical moulds of approximately 152 mm diameter and 127 mm height were used; their precise dimensions were measured with a vernier caliper for the density calculation. The weight of mould was measured using a scale. Approximately 5.5kgs of aggregate sample was used for each test.

The aggregate was compacted in two equal layers with a compaction time of (180±10) seconds per layer. After the sample compaction was completed, the height of the specimen and the weight of the mould with specimen were measured using the vernier caliper and the scale, respectively. Finally, each specimen was removed from the mould and placed on a small tray before they were placed in an oven for the determination of the moisture content. Three tests were conducted for each aggregate sample.

Particle size distribution

The collected aggregate samples were mixed and divided using the riffle box into approximate 12.5 kg samples. Subsequently the particle size distribution of the aggregate was determined using the wet sieving approach as per NZS 4407:1991, Test 3.8.1(1991). This test was repeated 3 times and the average values were used to determine the PSD curves.

Water absorption test

During the compaction process, some water penetrates into the aggregate particles, filling in the matrix and voids in and between particles. This water was measured in accordance with the water absorption test in Part 6 of British Standard (BSI, 2013). Sufficient all-in samples of each aggregate were collected from stockpiles. Each sample was then divided into approximately 20kg using the riffle box. The 20kg sample was oven dried at 110°C for over 18 hours. This was followed by dry sieving, using19mm and 2.36mm sieves respectively to divide sample into three fractions (greater than 19mm, 2.36 to 19mm, and 0 to 2.36mm). The masses of the test portions for the three fractions were not less than 4kg, 2kg and 0.8kg, respectively as per the standard method. Before the samples were soaked the portions on the 19 mm sieve and the 2.36 mm sieve were washed to remove finer particles. The washed water passing 2.36 mm sieve was collected and mixed with the dry fraction of 0 to 2.36mm from the previous dry sieving test. Each fraction was then immersed in different containers with sufficient water at a temperature of (22 ± 3) ℃ for a period of (24 ± 0.5) h to ensure that all the pores and voids inside the aggregate were filled with water. The saturated fractions were then surface-dried using the approach specified by the BSI standard. In the case of the coarse fractions of ‘greater than 19mm’ and ‘2.36-19mm’, the surface water was removed by a cloth or towel until the sample surface appeared damp. A fan was used to evaporate surface moisture. The fractions were stirred at frequent intervals to ensure uniform drying until no free surface moisture could be seen and the aggregate particles no longer adhered to one another. The sample was then stirred from time to time and allowed to cool to room temperature. The resulting surface-dried condition was assessed according to (BSI, 2013) by using a cone mould. Three tests were performed on each fraction of each aggregate sample.

X-Ray diffraction analysis of the aggregates

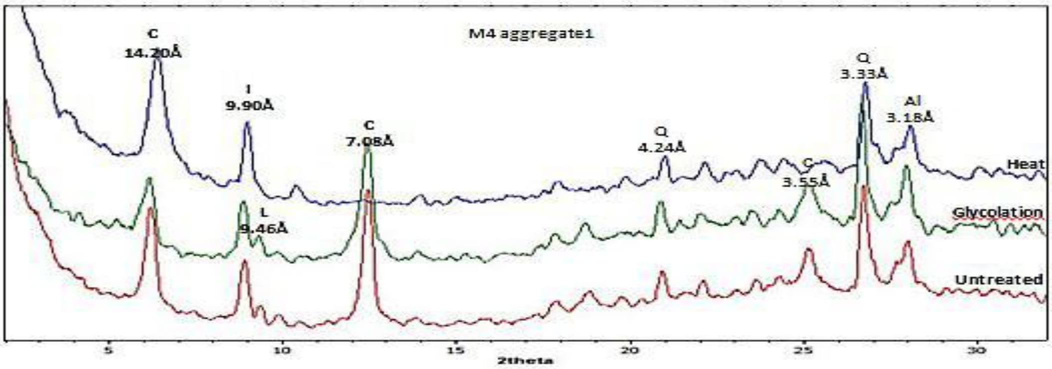
The mineralogical composition of aggregates has a significant impact on its water absorption capabilities through their specific surface area and swelling properties. Many studies of soils have demonstrated the relationship between water absorption and surface area (Black, 2009). Compared with sand, clay minerals (such as smectite, chlorite, illite, and kaolinite) have higher specific surface areas and water absorption capabilities (Black, 2009, White, 2013). Smectite in particular has a much higher specific surface area than the other clay minerals (Black, 2009, White, 2013, Dixon and Weed, 1989). However since it is a swelling mineral, smectite will show a volume expansion which is related to the hydration process (Baeshad, 1955). The swelling deformation is proportional to the volume of water absorbed (Xu, 2003). The hydration of laumontite, a zeolite, is accompanied by a small (about 2.4%) volume change which is sufficient to cause expansion effects in structures (Black, 2009). Since the greywacke aggregates commonly contain swelling minerals it was necessary to consider the mineralogical composition of the aggregates when analysing their water absorption capabilities.Research has demonstrated that OMC increases with the increasing clay percentage in soils. (Jesmani et al, 2008)

A portion of the crushed (but not yet powdered) samples was placed in a 10 ml graduated test tube to fill it to the 2mm mark. Distilled water was then added to fill the tube to the 10mm mark. The sample was then shaken to disperse the sample in the distilled water and the tube was then set aside and allowed to settle. The clay size fraction still in suspension after 10 minutes was then drawn off and pipetted on to a glass slide and allowed to air dry to provide an oriented sample of the clay fraction. Each oriented sample was run three times – first as an untreated air dried oriented sample; the sample was then placed in a desiccator and held overnight at 30°C in ethylene glycol vapour before being taken out, and immediately thereafter, a second X-ray diffractogram was run. Finally, the samples were placed in a furnace and held at 550°C for several hours before being cooled and the third X-ray diffractogram run. Note that the clay size is the size of minus 2µm.

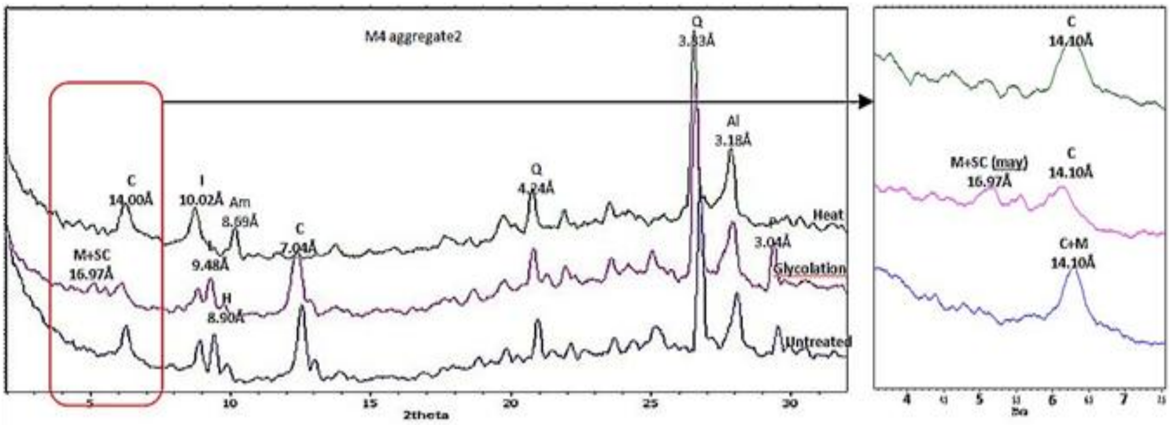
The powder X-ray diffraction data were obtained using a Siemens D5000 Kristalloflex, using Cu Kα radiation (run at 30mA and 40 kV) and fitted with a flat-surface sample holder with 360 degrees rotation.The XRD diffractograms were analysed to identify the presence of clay minerals using Moore and Reynolds' methodology (Moore and Reynolds, 1989). In the case of the random bulk rock sample diffractograms, mineral identifications were made by matching *d*-spacings and their intensities with mineral data in the JCPDS (Joint Committee on Powder Diffraction Standards) database (Wong-Ng et al., 2001, Smith and Jenkins, 1996) using a software database, Bruker EVA.

The basal spacings for the clay mineral component of the clay-size fraction (oriented clay sample) of the five aggregates over the 2 theta range 0 to 10 degrees are shown in Figure 1a, b and c. The M4-compliant aggregate from Quarry 1 is seen to contain only the sharp basal peaks for chlorite and illite (with a small peak belonging to laumontite). The diffractograms for the oriented clay size fractions of the other four samples (Figure 1 (b), (c), (d) and (e)), show a 14Å peak, which expands to 17Å after glycolation treatment, thus indicating the presence of an expanding clay mineral. That part of the glycolated peak which collapses to 10Å after heat treatment at 550°C indicates the presence of smectite; Should the peak only collapse to 14Å then the presence of a "swelling chlorite" that is an interstratified chlorite – smectite or chlorite – vermiculite mineral is indicated. Such interstratified mineral often form as the result of weathering of chlorite (Moore and Reynolds, 1989, Velde and Meunier, 2008). The swelling clay minerals occur in the three marginal aggregates and in the M4 –compliant aggregate from quarry 2.

Laumontite, a zeolite, also show a certain water-absorption capability. The XRD results show that laumontite, which is at approximate 9.46Å peak, exist in the five aggregates. However, the peak at 9.46Å is not significant for M4 aggregate 1 but significant for M4 aggregate 2 and the three marginal materials. This indicates that M4 aggregate 2 and the three marginal aggregates have higher laumontite content compared to M4 aggregate 1.



(a)



(b)

Figure 1 (a) and (b): XRD patterns for the M4- compliant aggregates from quarry 1 (a) and quarry 2 (b) in which the area of the diffractogram covering clay mineral basal spacings is enlarged.

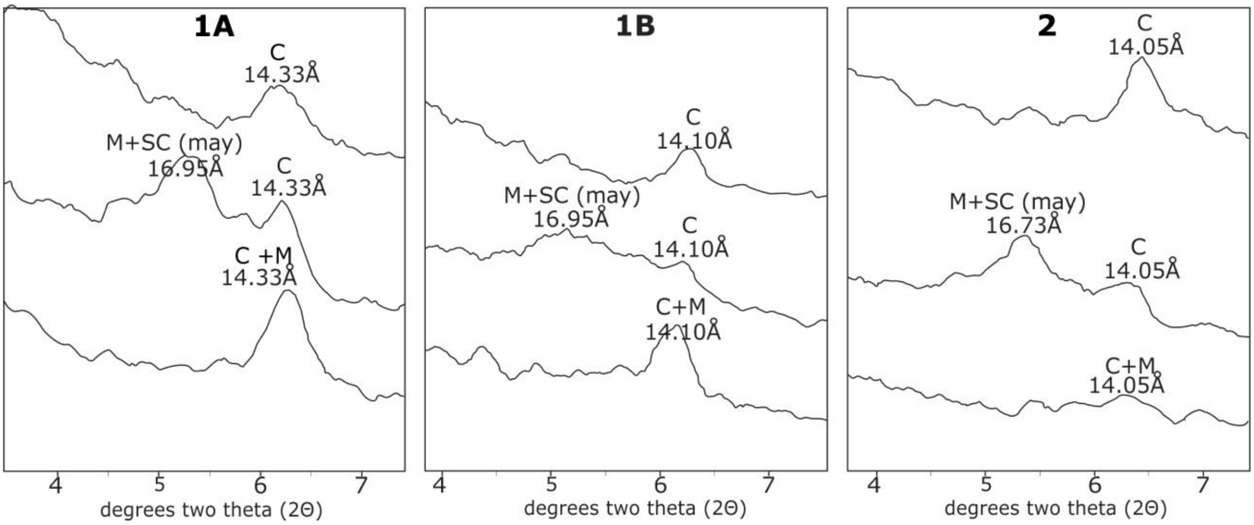


Figure 1(c): A collage of the enlarged clay basal spacings of the three marginal aggregates, 1A and 1B from quarry 1 and 2 from quarry 2.

RESULTS AND DISCUSSION

Vibrating compaction test

The results of the optimum moisture content and maximum dry density of the five aggregates are listed in Table 1. In each quarry, the marginal aggregates have a much higher OMC than the M4 aggregate, i.e. 28% and 34% increment in OMC for the two marginal aggregates 1A and 1B compared to the M4 aggregate in quarry 1 and a 23% increment for the marginal aggregate in quarry 2 compared with the M4 aggregate from quarry 2. However, not much variation occurs in the maximum dry density (MDD) between the marginal aggregates and the M4-compliant aggregates:-1.71% for Marginal aggregate 1A; -3.42% for Marginal aggregates 1B and 2. Other researchers (Karan et al., 2014, Zlender, 2008, Lowe, 2007) have shown that the OMCs of M4 aggregates are usually between 4-5%. However, it is interesting to note that the OMC of M4 aggregate 2 significantly exceeds 5%.

Table 1: Dry density and moisture content of the aggregates

Aggregate	Optimum moisture content, %		Maximum dry density, t/m^3	
	Test value	Variation, %	Test value	Variation, %
M4 aggregate 1	5.0	0	2.34	0
Marginal aggregate 1A	6.4	28	2.30	-1.71
Marginal aggregate 1B	6.7	34	2.26	-3.42
M4 aggregate 2	6.5	0	2.28	0
Marginal aggregate 2	8.0	23	2.20	-3.51

Particle size distribution (PSD)

Figure 2 shows the PSD results for the five aggregates, including the lower and upper limit envelopes, which are specified by NZTA M/4 specification.

The PSD can be expressed by Talbot's grading curve (Talbot and Richart, 1923) represented by the value of the exponent *n* in equation 1.

$$p = 100\left(\frac{d}{D}\right)^{n} \qquad (1)$$

Where *p*= the percentage passing sieve size d
D= maximum particle size and
N= grading type factor.

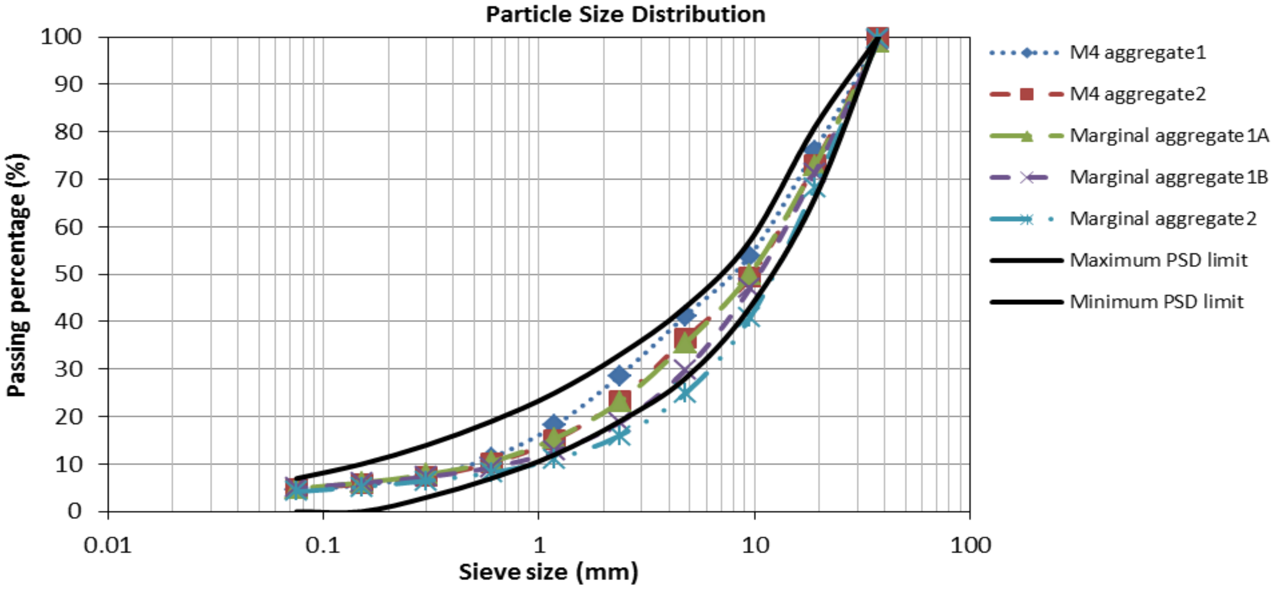


Figure 2: PSD results of the five aggregate materials

The exponent *n* is used as an indicator for the grading of aggregates. A lower value of exponent *n*, such as 0.35, is described as sandy while a higher *n* of 0.55 is described as rocky (Panchalan and Ramakrishnan, 2007). Lay (2009) reported that in most specifications the exponent *n* was found to be between 0.3 (fine grading) and 0.5 (coarse grading). The *n* values lower than 0.3 or higher than 0.5 would represent fine or coarse grading out of the limit of the specifications.

The exponent *n* for the five aggregates and the limits of NZTA specification were calculated and listed in the Table 2. It is clear that marginal aggregates 1B and 2 have coarse gradings, for which the exponent n values are 0.61 and 0.65, respectively. These gradings for marginal aggregate 2 lie in part outside the limits specified by NZTA. However, the PSDs of the other three aggregates with *n* values of 0.54 to 0.55 fit within the limits of NZTA specification.

Research conducted by Arnold (2007) to find the relationships between MDD/OMC and the PSDs of aggregates (shown in Figure 3), indicated that the OMC of aggregates decreases with the increasing exponent *n* i.e. the gradings change from fine to coarse. A similar conclusion was reached by Karan (2014) for permeable aggregates, which had a much lower OMC values compared to that of the OMC values of aggregates fitting within the limits specified.

However, the data from this research are in conflict with the conclusions of both Arnold and Karan in that our marginal aggregates 1B and 2 with higher exponent n (coarse gradings) have higher OMC values than the two M4 aggregates with lower n (i.e. relatively fine gradings). Thus, it is concluded that factors other than grading are responsible for the higher OMCs of marginal aggregates 1B and 2.

Similarly, grading cannot be the cause of the higher OMC of marginal aggregate 1A relative to the M4-compliant aggregate from the same quarry, since marginal aggregate 1A has a similar exponent *n* (i.e. a similar grading) which should result in a similar OMC to that of the two M4 compliant aggregates.

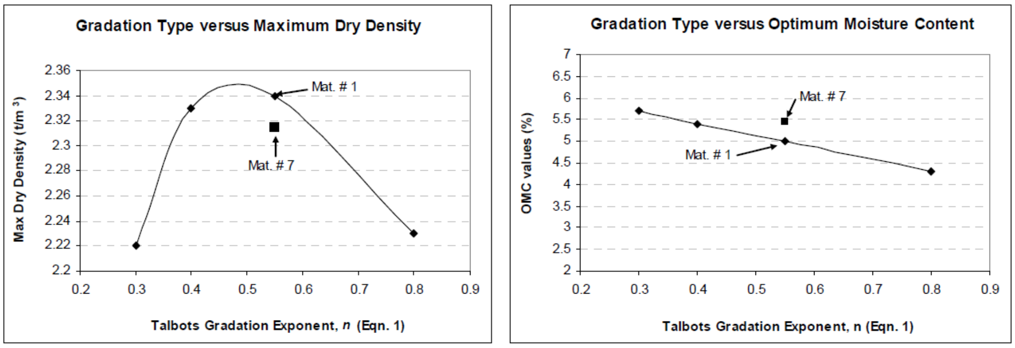


Figure 3: Effect of Talbot's grading exponent, n (Equation 1) on MDD and OMC (Arnold et al., 2007)

Table 2: Exponent *n of* the aggregates

	M4 aggregate 1	M4 aggregate 2	Marginal aggregate 1A	Marginal aggregate 1B	Marginal aggregate 2	Lower limit of NZTA specification	Upper limit of NZTA specification
n	0.54	0.55	0.55	0.61	0.65	0.61	0.40

Water absorption test

A literature review shows that the fines content (i.e. the component passing the 0.075mm sieve) has an important influence on the OMC of materials but has a negative relationship to the OMC (Soliman and Shalaby, 2015, Guerrero, 2004). The five aggregates that were studied in this research have similar percentages of fines within a range of 4.2% to 5.0% (as shown in Table 3), which is only a small portion of each aggregate. Thus it would not be expected that the fines would have a significant effect on the water absorption capability of the aggregates sufficient to explain the observed difference between the aggregates.

In order to accurately assess the water absorption capacity of the aggregates, it is necessary to take into account all size fractions included in aggregates, instead of only considering fine particle sizes (i.e. those passing a 0.075mm sieve).

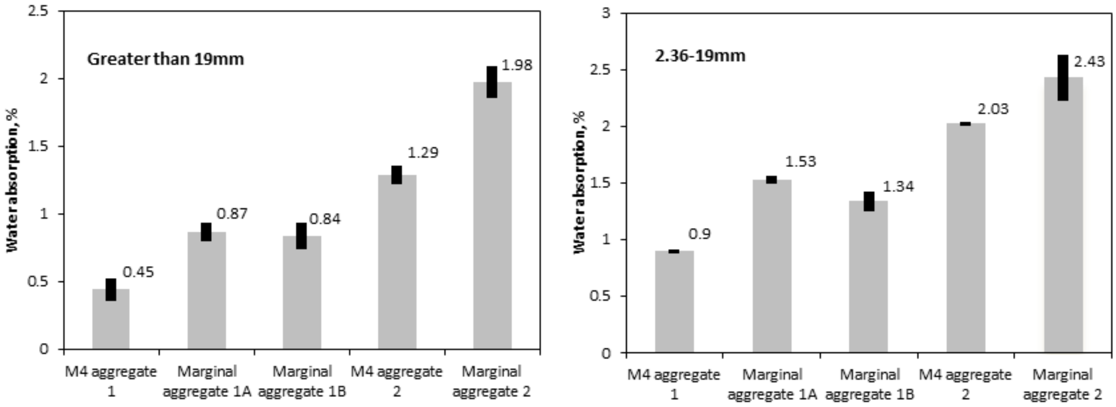
Table 3: Percentage of different fractions for the five aggregates

Fractions	Greater than 19mm, %	2.36-19.0mm, %	0.075-2.36mm, %	0-0.075mm, %
M4 aggregate 1	24.0	47.4	24.1	4.5
M4 aggregate 2	27.0	49.5	18.7	4.8
Marginal aggregate 1A	27.1	49.8	18.2	4.9
Marginal aggregate 1B	28.7	52.6	13.7	5.0
Marginal aggregate 2	31.7	52.3	11.8	4.2

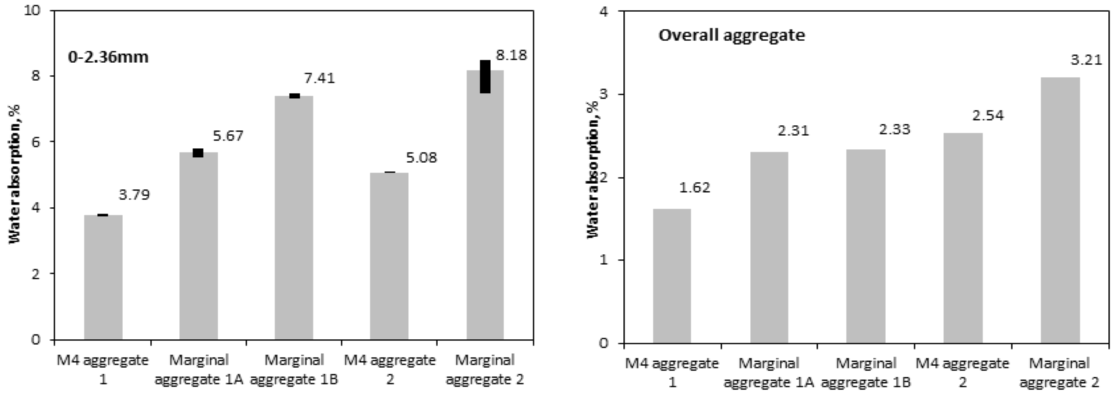
Figure 4 (a), (b), and (c) displays the water absorption capabilities of the different size fractions of each aggregate. It is clear from the data that the aggregates' water absorption capability increases with the decreasing size fractions for each aggregate. At first glance, it seems that the marginal aggregates generally have higher water absorption capabilities than the M4 aggregates. This is consistent with the observation that the marginal aggregates have higher OMCs and the M4 aggregates lower OMCs. However, due to the difference in the percentage of different size fractions in the aggregates, the overall water absorption capability of individual aggregates may differ. Equation 2 has been used to calculate the overall water absorption capability of the aggregates. The percentages of each fraction of each aggregate can be found in Table 3, from which the percentage of the fraction of 0-2.36mm can be obtained by adding up the percentages of 0.075-2.36mm and 0-0.075mm. The calculated results are shown in Figure 4 (d).

$$Overall\ water\ absorption\ capability = \frac{\sum(\%of\ each\ fraction * water\ absorption\ capability\ of\ each\ fraction)}{100} \quad (2)$$

The absorption results show that aggregates with similar qualities produced from different quarries have significantly different water absorption capabilities. For example, the M4 aggregate produced from Quarry 2 has much higher overall water absorption than the M4 aggregate from Quarry 1. The observed difference is most probably the result of the different mineralogical characteristics of the source rocks in the two quarries. However, in each quarry, the marginal aggregates have higher overall water absorption capabilities than the M4-compliant aggregates, which result in the marginal aggregates having higher OMCs.



(a) (b)



(c) (d)

Figure 4: Water absorption test results for different size fractions of the aggregates studied

CONCLUSIONS

The following conclusions can be drawn from this research:

- The swelling clay minerals, smectite and “swelling chlorite”, were found in the three marginal aggregates and M4 aggregate 2. Laumontite, one of the few zeolites which have swelling capabilities, occurs in the five aggregates. However, the M4 aggregate from quarry 1 has lesser amounts of laumontite than has the M4 aggregate from quarry 2 and the three marginal aggregates.
- In each quarry, the marginal aggregates generally have much higher OMCs than the M4 aggregate. The OMC of the M4-compliant aggregate in quarry 2 exceeds 5%, which is the recommended limit for OMC in premium M4 aggregates.
- The results of particle size distribution indicate that grading is not the cause of the relatively high OMC recorded inthef Marginal aggregates 1A, 1B and 2.
- Compared to the M4 aggregate in each quarry, the marginal aggregates have higher overall water absorption capabilities, which lead to their higher OMC. A comparison between the OMC of the two M4 aggregates demonstrates that aggregates with similar qualities produced from different quarries have significantly different water absorption capabilities. The difference most probably results from the different mineralogical characteristics of the source rocks in the two quarries.

FURTHER RESEARCH

The performance of the compacted specimens of marginal aggregates with high OMCs needs to be further investigated. Repeated Load Triaxial tests (RLT) will be undertaken in the future to simulate the field performance of these aggregates. Marginal aggregates treated with stabilisers will also be studied to investigate the stabilisers’ effectiveness in reducing the negative effect of the swelling minerals on the performance of marginal aggregates.

ACKNOWLEDGEMENTS

The research reported in this paper forms part of a doctoral research programme undertaken at the University of Auckland, partly funded by an MBIE contract and partly by a China CSC Scholarship. The authors would like to thank the University of Auckland, Faculty of Engineering laboratory technicians and staff for their assistance during the testing.

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