RECYCLED MATERIALS IN ROADING AGGREGATES: AGGREGATE ABRASION

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ABSTRACT

New Zealand relies on road infrastructure to provide access to and from ports for importing and exporting goods. With a decline in the availability of high quality virgin aggregates, it has been recognised that a sustainable alternative needs to be introduced. Recycled crushed concrete (RCC), sourced primarily from the demolition of old structures and from overproduced fresh concrete, is currently being offered as a pavement base and subbase in New Zealand. This research investigated the abrasion characteristics of three constituents of RCC to determine their durability. The Micro Deval machine was used to test the abrasion loss of aggregates in wet conditions and the Los Angeles machine was used to test the abrasion loss in dry conditions. Demolition concrete and fresh concrete were tested separately to assess whether the age of concrete affected the percentage of abrasion loss. Masonry brick was also tested as it is a constituent of RCC which has not been investigated for its abrasion characteristics. Laboratory testing revealed that masonry brick exhibited a greater abrasion loss than either of the recycled concrete aggregates. The age of concrete was found to affect the abrasion loss in wet conditions but not in dry conditions.

INTRODUCTION

Background

Road infrastructure in New Zealand has been referred to as the 'backbone' of its transport system. Roads are the conduit for 84% of New Zealand's daily trips, with state highways and local roads providing the vital function of access to and from ports for importing and exporting goods (Ministry of Transport 2011). New Zealand is heavily reliant on virgin aggregates in the construction and maintenance of its road infrastructure (Chappell 2000). The negative impact that quarrying has on the environment has led to legislative constraints and public resistance around the opening of new quarries. Therefore, many areas in New Zealand do not have a sufficient source of high quality virgin aggregates close by and need to spend large amounts of money on transportation.

Recycling of materials sourced from construction demolition has been cited as an economical and environmentally friendly alternative; one such product is recycled crushed concrete (RCC). Recycled crushed concrete is currently being offered as a pavement base and sub-base aggregate for pavements in New Zealand and overseas. The New Zealand Transport Agency has promoted the use of RCC by adding specifications for its use into the TNZ M/4 specification for base-course aggregates (Peploe, Dawson 2006).

Literature Review

The topics researched in this literature review included the composition of recycled crushed concrete, its abrasion characteristics and the effect of concrete age on the percentage of abrasion loss.

Recycled crushed concrete is the name given to aggregates that contain recycled concrete aggregates and other constituents. Recycled concrete aggregates (RCA) originate from the demolition of concrete structures and the overproduction of concrete at concrete plants. This waste concrete is mixed with other constituents and broken down into aggregates of a specific grade. The other constituents typically include clay brick, masonry brick, glass, ceramics, asphalt and organics.

Recycled concrete aggregates must be tested for a range of different properties to determine whether they will perform adequately as a component in a pavement. Resistance to abrasion is an important characteristic of aggregates used in road construction as it affects the durability of the pavement. Poor abrasion resistance can lead to a change in particle size distribution under traffic loading and during compaction. This issue will be exaggerated if the fines are plastic because they will attract and hold water within the matrix (Stevens, Salt 2011). A report released by NZTA stated that the Los Angeles machine provided a good indication of the estimated breakdown of aggregates during mixing, laying and compaction (Bartley, Peploe & Black 2010). The Los Angeles (LA) test is the traditional method for measuring aggregate abrasion and is conducted on dry aggregates. The Micro Deval (MD) machine was found to provide a good indication of aggregate abrasion loss under traffic loading. This test is a recently developed method for testing abrasion. It tests the abrasion of aggregates in wet conditions and has been gaining popularity among academics due to its strong correlation to field performance (Richard, Scarlett 1997). It is important to test both compaction resistance and resistance to traffic loading when concluding whether an aggregate exhibits sound abrasion characteristics. The combination of the Micro Deval and Los Angeles tests are also beneficial in countries such as New Zealand which have a varied climate, requiring the abrasion of aggregates in wet and dry environments to be determined.

Arulrajah et al. (2014) tested the abrasion loss of clay brick and recycled concrete. The aggregates were tested using only the Los Angeles machine. The average abrasion loss of the concrete aggregates was 28% and the average abrasion loss of clay brick was 36%. These results were similar to the 100% RCA and 100% RCB average abrasion loss values of 18.3% and 36.8% respectively, determined by Diagne, Tinjum and Nokkaew (2015).

Previous research has shown that the percentage of abrasion loss of virgin aggregate varies greatly depending on the parent rock type. In general, constituents in RCC tend to exhibit greater percentages of abrasion loss than virgin rock for the Micro Deval test, but exhibit a similar loss for the Los Angeles test. Cooley, Huner and James (2002) examined the percentage of abrasion loss of 72 aggregate types across Southeast America using both the Micro Deval and Los Angeles tests. The average abrasion loss for the Micro Deval test was 11.9%, with a standard deviation of 8.2%. The average abrasion loss for the Los Angeles test was 31%, with a standard deviation of 13%. Although the Micro Deval tests consistently produced a lower percentage of abrasion loss than the Los Angeles tests, no direct relationship could be established between the abrasion loss values from the two test methods.

The TNZ specifications for a sub-base, base-course and sealing chip do not discuss abrasion loss. In contrast, overseas government and local body agencies place a limit on the maximum amount of abrasion loss allowed for aggregates in different pavement layers. In Winnipeg, Canada and Western Australia, the Los Angeles abrasion loss for an aggregate used in the base-course layer must not exceed 35% (Main Roads Western Australia 2011, Winnipeg City Council 2014). The State of New Jersey specifies that the Los Angeles abrasion loss for a dense graded aggregate in the base-course layer must not exceed 50% (New Jersey Department of Transportation 2014). The maximum abrasion loss specified is dependent on environmental factors, the amount of maintenance work desired and the availability of high quality aggregates in the local area.

The age of concrete used in recycled crushed concrete varies significantly. Concrete plants deliver excess, unwanted concrete to recycle yards within a week of batching. In contrast, demolition concrete from the removal of old pavements and structures is generally 10-50 years old. Concrete is known to cure over time and this affects the strength of the concrete. A study by the Indian Institute of Technology tested the Los Angeles abrasion loss of concrete at 28 days and 90 days to see if the abrasion loss varied with the difference in age (Kumar, Sharma 2014). The test was conducted by preparing ten samples of aggregates with varying concrete strengths and aggregate abrasion loss values. The results found that the abrasion loss decreased as the age of concrete increased. The results were consistent across all ten samples which gave confidence in the findings.

It is important to understand the effect that concrete age has on performance beyond 90 days. This will help to determine whether limits need to be imposed on the percentage of old or new concrete aggregates in RCC.

Gaps in research

After examining international literature it has been concluded that there is an increasing demand for recycled crushed concrete to be used as an aggregate in pavement construction. Clients require more information about RCC to feel confident in its reliability as a pavement aggregate.

One study found that the age of concrete influenced the percentage of abrasion loss in the first 90 days since batching. This study was only performed on fresh concrete. Demolition concrete entering the yard is 10-50 years old and has been exposed to extreme weather conditions. It is currently unknown how this affects the percentage of abrasion loss.

Another area which is lacking in research is masonry brick. Current abrasion research found that an increasing percentage of clay brick increased the percentage of abrasion loss of the overall RCC mix. Masonry brick is a constituent currently used in RCC and so it is beneficial to determine its abrasion loss characteristics to assess whether it is also causing an increase in abrasion loss of the overall RCC mix.

Objectives

The main purpose of this research was to determine the abrasion characteristics of recycled crushed concrete to determine its long term durability. In particular, the abrasion loss of recycled concrete aggregates and recycled masonry brick in wet and dry conditions were investigated. Concrete aggregates were divided into new concrete and old concrete to assess whether the abrasion loss varied with the age of concrete.

METHODOLOGY

Research was separated into the following distinct phases:

I. Calibration of the Micro Deval machine.
II. Micro Deval testing.
III. Los Angeles testing.
IV. Foreign constituent analysis.

To investigate the effect of concrete age on abrasion loss, concrete from demolished structures was used to represent old concrete. Fresh concrete was used to represent new concrete. The concrete from demolished structures was ten to fifty year old horizontal concrete which originated from footpaths, kerb and channels and driveways. The estimated 28 day strength of the recycled concrete was 15-20MPa.

The fresh concrete had been mixed approximately seven days prior to arriving at the recycling yard. This was excess concrete which had been mixed and subsequently not required on site. The 28 day strength of this concrete varied greatly as it was not known whether the concrete was batched for horizontal or vertical structures.

Collecting aggregates

Three stockpiles were prepared at Green Vision Recycling; new concrete, old concrete and masonry brick. Each stockpile was visually divided into quarters. Four bags of aggregate were collected from each stockpile for the Los Angeles tests, with one bag filled from each quarter. Only one bag of aggregate was required from each stockpile for the Micro Deval tests and so one quarter of the bag was filled from each quarter of the stockpile. Samples were collected using a shovel to place aggregates in a 9.5mm sieve overlaid by a 26.5mm sieve. The sieves were shaken and any material retained on the 9.5mm sieve was placed in a bag to take back to the lab for testing.

Towards the end of the study, a stockpile of recycled crushed concrete, sold as 'ECO 40' aggregate, was prepared to collect samples for the foreign constituent analysis study. One bag was filled from each sixth of the stockpile. No sieving on site was performed for these samples.

Calibration

The Micro Deval machine at the University of Auckland (UoA) was a new machine and so it was important that it was calibrated. The ASTM standard suggested using the Brechin Quarry No. 2 aggregate as it is an aggregate of known abrasion loss. New Zealand does not produce this aggregate type and so a new calibration method was required.

Another Micro Deval machine was available for use in the Fulton Hogan labs. Four Micro Deval tests were performed in the Fulton Hogan labs and another four in the University of Auckland labs. M4 AP40 aggregate was collected from Stevenson's Quarry and used for the tests as it was considered a reliable aggregate due to its extensive use and regular testing in roading projects. The tests followed the Fulton Hogan specification which is markedly similar to ASTM D6928-10. The Fulton Hogan specification was chosen as the standard to be followed because the lab technician, who helped us perform the first test, was trained in the use of this method. It was therefore decided that this method would have the greatest accuracy for calibration tests; in which precision is the critical factor.

The abrasion loss from each machine was compared to draw conclusions about the precision and accuracy of the University of Auckland's Micro Deval machine. The University of Auckland machine was considered calibrated if the results were similar.

Micro Deval tests

The Micro Deval tests were carried out in accordance with the ASTM D6928 – 10 "Standard test method for resistance of coarse aggregate to degradation by abrasion in the Micro Deval apparatus" (ASTM International 2010). This method was used to determine the resistance to abrasion in wet environments.

An oven dried sample of 1500g was prepared to conform to grading 8.2. Test sample 8.2 was chosen as it was the grading which most closely aligned with one of the gradings from the LA standard. The initial weight was weighed to the nearest 1.0g and recorded (A). The sample was subsequently soaked in 2.0L of water for a minimum period of two hours. The sample and 2.0L of water were then carefully transferred to a Micro Deval abrasion jar along with 5000g of steel abrasive charge. The jar was rotated in the Micro Deval apparatus for 12000 revolutions. The sample was then washed over a 1.18mm sieve, discarding the particles passing, and oven dried. The removal of the abrasive charge was undertaken following the wet method. Care was taken to remove any particles adhering to the abrasive charge which would have affected the results. The final weight of the material was weighed to the nearest 1.0g and recorded (B).

The Micro Deval abrasion loss is expressed as a percent by mass of the original sample by the following equation:

$$Percent\ Loss = \frac{A-B}{A} \times 100 \qquad (1)$$

Four repeats of the Micro Deval test were carried out on the samples of old concrete, new concrete and masonry brick.

Los Angeles tests

The Los Angeles tests were carried out in accordance with the Standards New Zealand NZS 4407:1991 Test 3.12 "The abrasion resistance of aggregate by use of the Los Angeles machine" (Standards New Zealand 1991). This method was used to assess the resistance to abrasion in dry conditions.

An oven dried sample of 5000g was prepared to conform to grading B. The initial mass was weighed to the nearest 1.0g and recorded (M_1). The sample was placed in the Los Angeles apparatus with 11 spheres of abrasive charge weighing 4580g. The New Zealand Standard test method requires the sample and abrasive charge to be rotated at a speed of 30 to 33 revolutions per minute for a total of 500 revolutions. Due to the revolution counter not working, the number of revolutions per minute was counted and the time required to reach 500 revolutions was calculated. The sample was discharged from the machine and sieved over a 1.70mm sieve, discarding the material passing. The material coarser than 1.70mm was then washed over the same sieve and oven dried. The final weight was recorded (M_2).

The Los Angeles abrasion loss is expressed as a percent by mass of the original sample by the following equation:

$$Percent\ Loss = \frac{M_1 - M_2}{M_1} \times 100 \qquad (2)$$

Six repeats of the Los Angeles test were carried out on the samples of old concrete, new concrete and masonry brick due to the results being less consistent than the Micro Deval method.

Figure 1: Performing the Los Angeles tests

Constituent analysis

The constituent analysis followed the New South Wales Roads and Traffic Authority (RTA) T276 "Foreign materials content of recycled crushed concrete" (Dash 2001). This specification was chosen because it was recommended by the TNZ M/4 standard.

The sample was obtained from the main ECO 40 RCC stockpile at Green Vision Recycling Ltd. Each sample was riffled to obtain a weight of at least 6kg. This was then oven dried and the total mass recorded. The sample was sieved for 2 minutes over a 4.75mm sieve in the mechanical agitator, discarding the material passing. The total sample weight was recorded (A). The constituents were sorted visually in accordance with the following types.

Type I	Glass, brick, asphalt, stone and ceramic.
Type II	Plaster, clay lumps and other friable material.
Type III	Rubber, plastic, bitumen, paper, wood and other vegetable or decomposable matter.

Table 1: Constituent classifications according to the TNZ M/4 standard

Each group of constituent was then weighed (B). The percentage of each foreign constituent type was calculated as a percentage of the mass of the original dried sample weight as shown in the following equation.

$$Percent\ of\ constituent = \frac{A-B}{A} \times 100 \qquad (3)$$

RESULTS

A summary of the average abrasion loss values from the Micro Deval and Los Angeles tests are shown in table 2.

Type of constituent	Los Angeles abrasion loss (%)	Micro Deval abrasion loss (%)
Old concrete	30.0	19.6
New concrete	30.4	21.0
Masonry brick	36.4	26.1

Table 2: Average abrasion loss values for the Los Angeles and Micro Deval tests.

Average abrasion loss

It was seen from the average abrasion loss values in figure 2, that the Los Angeles tests resulted in a higher percentage loss than the Micro Deval tests.

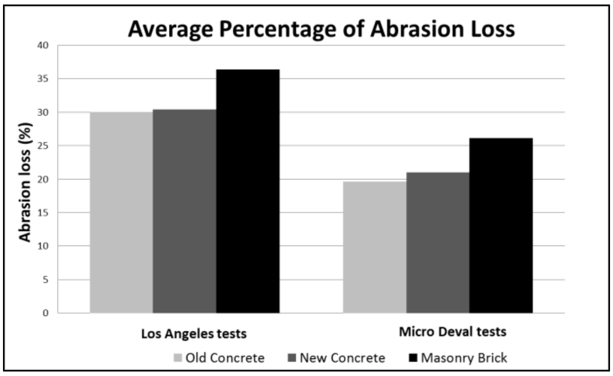

Figure 2: Average abrasion loss percentages for the Micro Deval and Los Angeles tests.

The interaction plot shown in figure 3 revealed an interesting relationship between the two sets of results. The Los Angeles tests yielded average abrasion loss percentages equal to the Micro Deval abrasion loss plus 10±0.6%. This is shown by the consistent gap width in figure 3.

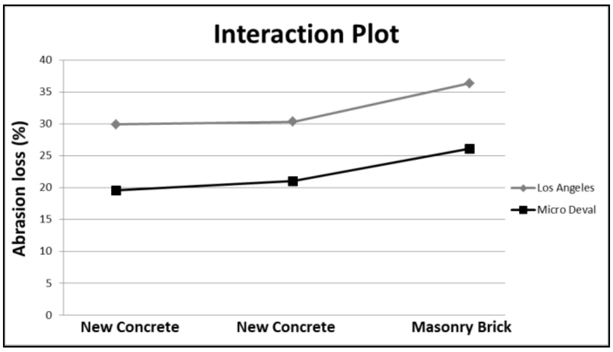

Figure 3: Interaction plot between the Micro Deval and Los Angeles tests.

The average abrasion loss for masonry brick was higher than old and new concrete for both the Los Angeles abrasion and Micro Deval tests. For the Los Angeles machine, masonry brick yielded a percentage loss of 36.4% in comparison to 30.4% and 30.0% for new and old concrete respectively. For the Micro Deval machine, masonry brick yielded an average percentage loss of 26.1% in comparison to 19.6% for old concrete and 21.0% for new concrete.

The box and whisker charts shown in figure 4 show the variation between repeats for each type of test.

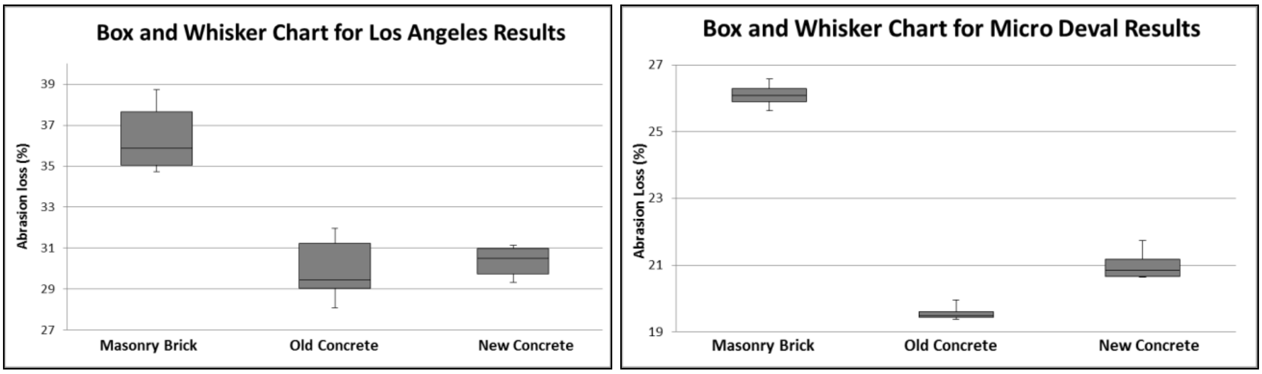

Figure 4: Box and whisker chart for the Los Angeles and Micro Deval test results.

The variation for the Micro Deval tests was less than the Los Angeles. These variations were monitored as the tests were performed. The low variation between results for the Micro Deval tests was the reasoning for only performing four repeats.

Age of concrete

It was seen in figure 2 that the average abrasion loss is higher for new concrete than old concrete. A Welch two sample t-test was used to determine whether this difference was statistically significant. The test compared the means of the old and new concrete results from the Los Angeles and Micro Deval tests separately.

Test	P-value
Los Angeles	0.6251
Micro Deval	0.005724

Table 3: P-values from t-tests performed on the new and old concrete.

The results indicated that there was no evidence against the null hypothesis that the means were the same for the Los Angeles test. There was strong evidence against the null hypothesis for the Micro Deval test. This concluded that the age of concrete affected the abrasion loss in wet conditions, but was insignificant in dry conditions.

The box and whisker chart in figure 4 illustrated that, while the new concrete tests had a higher average abrasion loss, there was some overlap between the individual test results for old and new concrete. This contributed to the high p-value seen in table 3. Conversely, there was no overlap between the box plots for the Micro Deval tests indicating a statistical difference.

Constituent Analysis

The percentage of each constituent is shown in table 4. It should be noted that bitumen and plastic were present in the recycled crushed concrete stockpile, however the weights were so minimal that, expressed as a percentage, they equated to 0.00%.

Constituent	Percentage (%)
Concrete	94.10
Masonry brick	5.24
Friable	0.35
Clay brick	0.16
Asphalt	0.13
Ceramics	0.01
Organics	0.01
Bitumen	0.00
Plastic	0.00

Table 4: The percentage of each type of constituent in RCC.

The constituents of particular significance in this research were recycled concrete aggregates and recycled masonry brick. These are shown in figure 5.

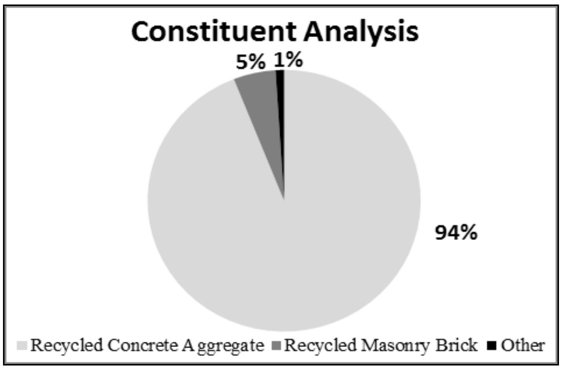

Figure 5: Percentage of concrete, masonry brick and 'other' in recycled crushed concrete.

Calibration data

The percentage of abrasion loss of the Stevenson's M4 aggregate, resulting from the Fulton Hogan (FH) and University of Auckland Micro Deval tests, is shown below.

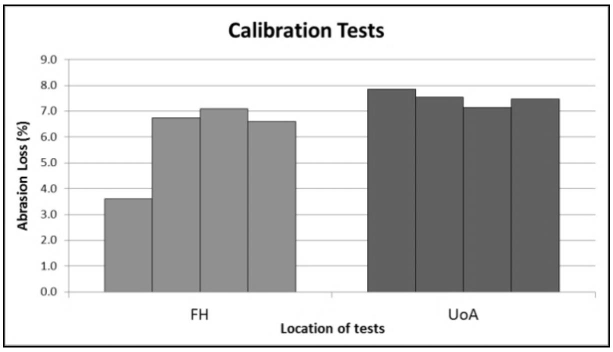

Figure 6: Abrasion loss from the calibration tests at FH and UoA.

An extreme value (3.6%) was present in the test results from the Fulton Hogan labs. The standard deviation of the FH results, excluding the extreme value, was 0.257. This meant that the extreme value equalled:

$$\mu - 12.4\sigma \quad (4)$$

This was classified as an outlier and was therefore excluded in the following calibration analysis.

There were only three results from FH and four results from UoA and so a definitive answer could not be drawn from the small sample size. There did appear to be a tendency for the University of Auckland machine to yield a larger percentage of abrasion loss than the Fulton Hogan machine. This was considered when analysing the recycled aggregate Micro Deval results.

DISCUSSION

Abrasion loss in wet and dry conditions

The abrasion loss of the recycled concrete aggregates observed in this research was similar to the abrasion loss seen by Diagne, Tinjum and Nokkaew (2015), and also Arulrajah et al. (2014). The average results for concrete aggregates subjected to the Micro Deval machine in our research, 19.6% and 21.0%, were larger than the 16.4% abrasion loss found by Diagne, Tinjum and Nokkaew (2015). This slight increase could be due to the different parent rock types in the concrete aggregates. Studies have found that parent rocks such as basalt are more resistant to abrasion than those such as limestone. The type of rock in recycled crushed concrete would therefore influence the overall abrasion of RCC (Kahraman, Fener & Gunaydin 2010). The calibration tests also indicated that the University of Auckland Micro Deval machine may yield a larger percentage of abrasion loss. This could also have been a contributing factor to the increased percentage of abrasion loss presented in this research.

The interaction plot between the Micro Deval and Los Angeles test results showed a distinct relationship between the test types. The Los Angeles tests were equivalent to the Micro Deval abrasion loss percentage plus 10±0.6%. Other research conducted by (Cooley, Huner & James 2002) had also noticed that the Los Angeles test yielded a larger abrasion loss than the Micro Deval test, however a direct relationship had not been observed. The Los Angeles test is said to simulate the degradation of aggregates during mixing, laying and compaction. The Micro Deval test is said to simulate the breakdown of aggregates under traffic loading. This relationship would suggest that a direct correlation exists between the ability of recycled aggregates to withstand compaction and traffic loading.

The two tests also portray the behaviour of aggregates in wet and dry environments, from the Micro Deval and Los Angeles tests respectively. The direct relationship suggested that there is a correlation between the performance of concrete aggregates in wet and dry conditions. With New Zealand’s varied weather conditions, a correlation between the aggregates performance in wet and dry conditions is vital. Over the lifespan of a roading aggregate, the aggregate will be repeatedly subjected to periods of intense rainfall and periods of dry conditions. The aggregates’ ability to withstand both of these environments will lead to a pavement which is not easily degraded.

Overseas specifications provide limits on the maximum acceptable amount of abrasion. The specifications follow the Los Angeles test methods and therefore only assess the abrasion performance in dry conditions. The Los Angeles abrasion loss values from the masonry brick, old concrete and new concrete have been compared to the specifications in New Jersey, Western Australia and Winnipeg, Canada.

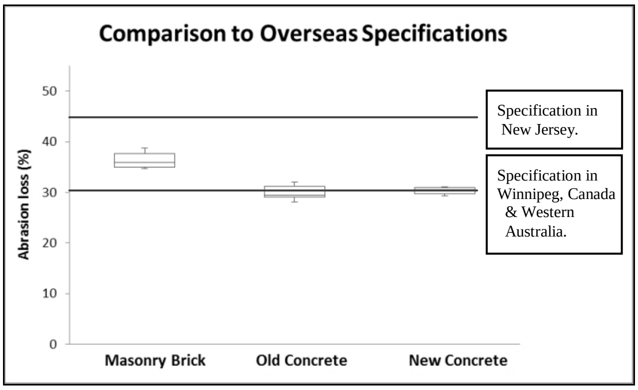

Figure 7: Comparison of Los Angeles results to overseas specifications.

The specifications shown are for the maximum acceptable abrasion loss of an aggregate in the base-course layer. The old concrete and new concrete conformed to all three specifications. This implied that the recycled concrete aggregates could be used as the sole aggregate in the base-course layer. Masonry brick exceeded the standard set by Winnipeg and Western Australia. As a result, masonry brick could not be used exclusively in the base-course layer. The percentage of masonry brick that can be included before exceeding 35% should be tested to determine the maximum acceptable percentage in a RCA and recycled masonry brick mix.

From the constituent analysis, 5.2% of the total recycled crushed concrete stockpile was masonry brick. This visual analysis introduced a strong chance of user error and this percentage is thought to be conservative. It is predicted that the abrasion loss of the overall RCC stockpile, with 5.2% masonry brick, will be less than 35%.

Comparison of results to virgin aggregates

The calibration tests provided abrasion loss values of virgin M/4 aggregate that could be used to compare to the recycled aggregates. The virgin aggregates were only tested using the Micro Deval machine. A comparison of the virgin aggregate to the recycled aggregates abrasion loss is displayed in figure 8. The average virgin aggregate abrasion loss is calculated using only the results from the University of Auckland machine to avoid any issues with calibration.

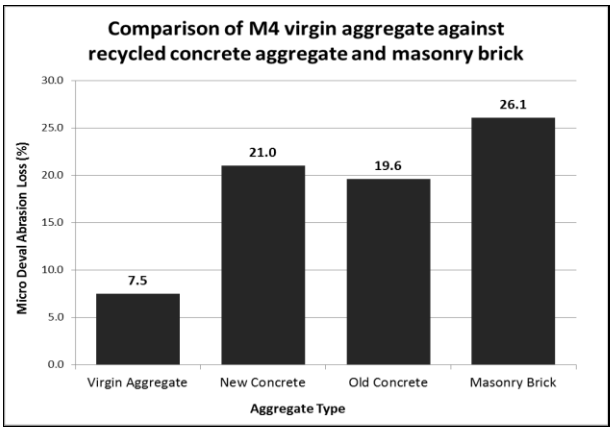

Figure 8: Comparison of average Micro Deval RCC results to virgin aggregates.

The Stevenson's M/4 aggregate produced a significantly lower abrasion loss than any of the recycled aggregates. It is important to recognise that the average abrasion loss of 7.5% is lower than the abrasion loss of virgin aggregates found through literature reviews. (Cooley, Huner & James 2002) performed Micro Deval tests on 72 aggregates and found the average abrasion loss to be 11.9% with a standard deviation of 8.2%. A consequence of increased abrasion loss is the increase in the number of fines in the pavement. A large quantity of plastic fines in the base course layer will cause the aggregates to swell. As recycled crushed concrete was found to have a greater percentage of abrasion loss than virgin aggregates, it is essential to determine the quality of fines produced from the recycled aggregates.

The sand equivalence test determines the relative proportion of detrimental fine dust or clay-like particles in fine aggregates. The percentage of expansive clay materials is assessed through a clay index test, which is accompanied by a plasticity index test and sand equivalence test to conclude its degree of plasticity. A study by Soliman and Shalaby (2015) found that the effect of plastic fines was drastic if the fines had a plasticity index of 10 or higher. These plastic fines are more sensitive to changes in moisture content and produce a less elastic pavement.

When testing the fines, the researcher should be aware of the limitations of these testing procedures when used with concrete aggregates (Lowe, Wilson & Black 2010). The sand equivalence test is not a direct test of deleterious materials and clays. The inaccuracy of the test is said to be amplified in recycled aggregates due to the inability of the test to distinguish between deleterious and hard competent fines. As a result, suitable concrete aggregates can receive low sand equivalence values.

Influence of concrete age on abrasion loss

The raw data showed that new concrete yielded a marginally greater percentage of abrasion loss than old concrete. This was expected because concrete continues to cure over time, thus increasing the strength of the aggregates. It was predicted that an increase in strength would reduce the tendency to abrade. Arulrajah et al. (2014) also discovered that the age of concrete affected the percentage of abrasion loss. The variation between our tests were not as extreme as those seen by Arulrajah et al. This is thought to have occurred due to the different sources of concrete. The 28 day and 90 day old concrete from the previous study were both sourced from fresh concrete. All variables remained constant except for age. The aggregates used in our research varied in terms of age, but also in terms of source. The old concrete was sourced from demolished structures. Therefore, the aggregates had been exposed to extreme weathering which would be likely to reduce the strength and increase the abrasion tendency of the concrete. Thus when the old concrete, with a reduced abrasion resistance due to weathering, was compared with new concrete, with a reduced abrasion resistance due to age, the difference in abrasion loss values were not as extreme.

Statistical analysis found that the age of concrete only had a significant effect on the results from the Micro Deval machine. This is thought to have ensued as a result of the test being conducted in wet conditions. A dry test purely tests abrasion. A wet test may be testing the abrasion loss of aggregates that have undergone a chemical reaction between the aggregate and water. The time since hydration and quality assurance are thought to cause a difference in abrasion loss following the chemical reaction. When water is added to cement, a hydration reaction occurs which causes the concrete to harden and increase in strength (De Schutter 2002). There may have been a substantial amount of time since the old concrete had been subjected to large volumes of water. When water was added to the old concrete during the Micro Deval test, the concrete absorbed the water and lead to further hydration.

The percentage of water added during batching is critical to the performance of the concrete. Concrete with too little water will not fully bind to the aggregates. There were less stringent quality controls in place at the batching plants at the time that the old concrete was produced. As a result, the volume of water added may not have been sufficient to allow the cement to fully bind to the aggregate. When the water was added to the old concrete aggregates during the Micro Deval test, this extra water may have caused further binding to occur. The binding reaction would have increased the strength of the concrete and reduced the tendency to abrade.

Significance to the industry

While the age of concrete has been proven to have a statistically significant effect on the abrasion resistance of recycled aggregates in wet conditions, the increase in abrasion loss is not substantial enough to affect the future make-up of recycled crushed concrete. Both old and new concrete have similar abrasion resistance properties and can therefore be used interchangeably and in combination with each other.

The abrasion loss of masonry brick is higher than concrete aggregates. The percentage of masonry brick in RCC needs to be monitored to ensure that the overall abrasion loss of the stockpile conforms to the standards that are being measured against.

CONCLUSIONS

Based on the results and discussion of the results from the Micro Deval and Los Angeles tests performed on new recycled concrete aggregates, old recycled concrete aggregates and masonry brick, the following conclusions have been drawn:

1. The average abrasion loss of the new and old concrete was 30.0% and 30.4% respectively for the Los Angeles machine, and 19.6% and 21.0% for the Micro Deval machine. These results conformed to the specifications set by Winnipeg, Western Australia and New Jersey for aggregates in the base-course layer.
2. The average abrasion loss for Masonry brick was 36.4% for the Los Angeles test and 21.0% for the Micro Deval test. The result exceeded the specification set by Canada and Western Australia. This concludes that masonry brick cannot be used as the sole aggregate in the sub-base layer, however it can be used in combination with recycled concrete aggregates.
3. All three of the recycled aggregates tested yielded a substantially higher abrasion loss than the virgin M4 aggregate used in the calibration tests. It is therefore essential to test the quality of fines of the recycled aggregates to determine whether this increase in abrasion will cause swelling of the pavement.
4. The new concrete aggregates produced a marginally higher percentage of abrasion loss than the old concrete aggregates. A statistical analysis was performed to determine whether the difference was significant or not. The t-test concluded that the age of concrete only had a significant effect on the Micro Deval test, which is attributed to the test being conducted in wet conditions. Two suggestions have been put forward to answer why the difference was only significant in wet conditions. Firstly, there may have been a substantial amount of time since the old concrete aggregates had been exposed to large volumes of water. This would result in a hydration reaction occurring during the Micro Deval test. Secondly, there were less stringent quality controls at the batching plant when the old concrete was produced. If insufficient water was applied during batching then the cement would not have fully bound to the aggregates. When water was added during the Micro Deval test, further binding would have occurred. This reduces the tendency to abrade.

FUTURE RESEARCH

This research has examined the abrasion loss of recycled concrete aggregates and recycled masonry brick. The abrasion loss of recycled concrete aggregates has been seen to conform to overseas standards. The abrasion loss of recycled masonry brick has been shown to exceed the standards set by Western Australia and Winnipeg, Canada. It is recommended that future research determines the abrasion loss of recycled concrete aggregates with increasing percentages of masonry brick to determine when the overall percentage of abrasion is unacceptable.

The quality of fines produced by the recycled aggregates after being subjected to the Micro Deval or Los Angeles test should be examined. This will determine whether the increased abrasion loss, seen from a comparison of the recycled aggregates with virgin M4 aggregate, will harm the pavement.

The research conducted in this study determined the percentage of abrasion loss for three different constituents in recycled crushed concrete. It is important to determine what percentage of abrasion loss relates to high quality aggregates and poor quality aggregates when interpreting these results. Currently overseas standards have been used to compare to our research, however the environment in New Zealand may lead to a different threshold being acceptable. Following the procedure used by Rangaraju and Edlinski (2008), the performance of recycled concrete and virgin aggregates needs to be monitored in the field and determined as poor, fair or good based on their performance. Samples of the same aggregates should also be subjected to a series of Micro Deval and Los Angeles tests. The abrasion loss can then be related to the field performance to determine the maximum percentage of abrasion loss that distinguishes a poor quality aggregate from a high quality aggregate.

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