RECYCLED CONCRETE AGGREGATE AND ITS APPLICATION IN NEW ZEALAND READY-MIX CONCRETE PRODUCTION

Wentao Zhang¹, Chris Munn² Jason M. Ingham³

Abstract

Motivations for adopting recycled concrete as an aggregate source include the preservation of natural resources, effective utilization of a growing waste stream, and financial and energy savings. Although current New Zealand practices include some use of crushed concrete in road construction, use of Recycled Concrete Aggregate (RCA) in low specification concrete is currently infrequent and the use of recycled concrete as an aggregate source in structural concrete applications is rare. To make such recycling feasible, the properties of RCA must be related to the properties of new concrete that utilizes the recycled aggregates. In response to this need, a study was undertaken to investigate the feasibility of using RCA as a viable alternative to Natural Aggregate (NA) in the production of concrete manufactured in a conventional New Zealand ready mix concrete plant. Aggregate properties and hardened and fresh concrete properties of RCA concrete were studied and compared with the associated properties derived from NA concrete. Results indicated that RCA is a viable alternative to NA in the production of concrete. Furthermore, it was confirmed that the properties of RCA dictate the hardened properties of the reconstituted concrete.

INTRODUCTION

Currently there is a lack of research on the performance of New Zealand recycled concrete aggregates (RCA) when the characteristics of the original concrete are known, and the general consensus within the New Zealand concrete industry is that recycled concrete can only be used in low-end, non-structural applications [1]. Land Transport New Zealand, the national transport agency in New Zealand, allows some use of RCA in pavement base courses but there are no standards for the prescription and widespread use of RCA in New Zealand [2]. Consequently, even though current New Zealand practices include some use of crushed concrete in road construction, use of RCA in low specification concrete is infrequent and the use of recycled concrete in structural applications is rare [3].

Numerous European demonstration projects have shown that RCA can be used in high strength applications [4], and reuse of concrete debris to produce new concrete is now practiced worldwide, with particularly extensive and standardized implementation in Japan and Europe [5]. Typically, experimental investigations have preceded the development of industry standards, such as the RILEM committee that conducted research commencing in the 1960’s and developed industry recommendations in the 1970’s [6]. Consequently, the study reported here was undertaken to address practical issues associated with determining the properties and behaviour of New Zealand RCA, specifically pertaining to the production of 20-60 MPa concrete, with a view to facilitating the implementation of RCA in New Zealand ready mix concrete plant.

LITERATURE REVIEW

In ordinary fresh concrete, due to the presence of a water film on the aggregates, an Interfacial Transition Zone (ITZ) is created between aggregate and cement paste where the w/c ratio may be significantly higher than that of the cement paste. The ITZ is widely regarded as the ‘weakest link’ in concrete [7-10], inhibiting the achievement of composite action in natural aggregate (NA) concrete. Obviously, the structure of RCA concrete is more complicated than NA concrete [11], with NA concrete consisting of only one ITZ, being the interface between the NA and the surrounding cement paste, whereas RCA concrete has two ITZ, located between the aggregate and old adhered mortar, and between the old adhered mortar and the new cement paste [12]. The strength of RCA concrete is usually dictated by the weaker of these 2 ITZs (see Figure 1). The presence of adhered mortar generally degrades the quality of RCA and negatively influences the fresh and hardened properties of concrete. In order to improve the properties of RCA concrete the Two Stage Mixing Approach (TSMA) was developed by Tam et al.

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where RCA and half of the mix water is combined and mixed for 60 seconds. Cement, the rest of the ingredients and the rest of the mix water is then added and mixed for a further 120 seconds.

RCA has high absorption due to the presence of adhered mortar. Kashino and Takahashi [15] suggested pre-soaking of RCA and Dhir et al. [16] also examined an RCA pre-treatment procedure and its effect on fresh concrete properties. Pre-soaking showed a slight improvement in the fresh properties of concrete containing 100% coarse and 50% fine RCA when compared to the corresponding mixes with dry RCA. In practical concrete production it is necessary to pre-soak RCA in order to produce workable concrete, and the soaking of aggregates for one hour before use proved to be effective [5]. Approximately 15% more free water was required when both fine and coarse RCA were used and most researchers agree that there is a gradual reduction in compressive strength as the RCA content is increased beyond 30% [4, 16]. The general consensus is that the substitution of NA with RCA produces concrete with 0-35% less strength [5, 8, 17]. Soshiroda [18] showed that increasing the recycled fines content negatively impacted on the resulting concrete strength.

In principle, an RCA concrete mix design is not dissimilar from the mix designs of conventional concrete. However, slight modification was required in practice [5]. A higher standard deviation must be employed when determining the target mean strengths of RCA concrete than when designing concrete with NA and due to higher free water requirement of RCA mixes, calculated cement content will also be higher.

EXPERIMENTAL PROGRAM

The experimental program consisted of 4 stages:

Stage I  Casting of three 15 m$^3$ concrete slabs having low (20 MPa), medium (40 MPa) and high (60 MPa) target compression strength NA concrete.

Stage II  Demolition and crushing of Stage I NA concrete slabs to produce RCA.

Stage III  Production of RCA concrete having target compression strengths of 20 MPa, 40 MPa and 60 MPa.

Stage IV  Commercial production of RCA concrete in a ready mixed concrete plant.

STAGE I  PREPARATION OF NA CONCRETE SLABS

Mix designs used to manufacture the low, medium and high strength NA concrete slabs were the standard mixes used by a commercial ready mixed concrete plant, having specified 28 day compressive strengths of 20 MPa, 40 MPa and 60 MPa and having a maximum aggregate size of 19 mm. The 19 mm, 13 mm and Pap 7 aggregates were crushed basalt, and the sand was sourced by suction dredges from Auckland’s offshore coastal deposits. Properties of the natural aggregate (NA) used in the slabs were assessed, and are reported in [19]. Compression strength tests were performed for each strength grade in accordance with NZS 3112:Part 2:1986 [20]. The slabs were cured by spraying an even coating of a synthetic hydrocarbon resin anti-evaporation compound onto the top surface of the slab. Figure 2 showed the three concrete slabs.

STAGE II  DEMOLITION AND CRUSHING OF NA CONCRETE SLABS

Demolition and crushing of the NA slabs determined the quality and gradation of the RCA. This process was achieved by using a Komatsu 20 tonne digger with D2500 hydraulic rock breaker (see Figure 3) to demolish the slabs into concrete pieces that had a maximum dimension of approximately 300 mm. The crushing and sorting process occurred at a mining quarry and involved a Lokotrack LT 1213S Impactor Crusher that broke the concrete pieces into one product with a maximum size of 20 mm. A Nordberg SW348 mobile screen then sorted the product according to size, which was necessary in order to obtain the 19 mm and 13 mm graded aggregate product (see Figure 4). The impact crusher’s sieve module was...
set at a maximum size of 20 mm and all oversized crushed material was returned to the front of the crusher for re-crushing. In practice, debris from demolished concrete structures will usually contain steel reinforcement and other contaminants, and additional steps to remove these deleterious contaminants would be required.

**STAGE III LABORATORY PRODUCTION OF RCA CONCRETE**

The experimental program is detailed in Table 1 and shows that at least 3 mixes were made for each RCA source strength and target strength combination. In addition, 2 mixes with Natural Aggregate (NA) were made for each strength designation and served as the control mixes for the experimental program. Figure 5 and Figure 6 show the ingredients used to produce RCA concrete and the pan mixer that was used to mix the concrete. RCA mixes contained approximately 5% more cement than the NA mixes, to account for loss of workability and strength as reported by previous researchers in the literature review. Each laboratory concrete mix had a volume of 50 L. Presoaking of RCA and the TSMA were adopted in the production of all RCA mixes, and 100% coarse aggregate replacement occurred for all RCA mixes.

**Figure 2:** The three concrete slabs with low medium and high strength concrete

**Figure 3:** Demolition of slabs into concrete pieces

**Figure 4:** Nordberg SW348 Mobile Screens sorted concrete pieces into RCA

**Figure 5:** Ingredients in the production of RCA concrete

**Figure 6:** Concrete mixing pan
Table 1: The experimental mix program

<table>
<thead>
<tr>
<th>RCA source Strength (MPa)</th>
<th>RCA Concrete Mix Strengths (MPa)</th>
<th>20</th>
<th>40</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA (Basalt)</td>
<td>Mix 12 Mix 15 Mix 8 Mix 19 Mix 10 Mix 20</td>
<td>Mix 22 Mix 33 Mix 11 Mix 23 Mix 21 Mix 28</td>
<td>Mix 16 Mix 17 Mix 1 Mix 5 Mix 25 Mix 27</td>
<td>Mix 31 Mix 3 Mix 2 Mix 6 Mix 32 Mix 37</td>
</tr>
<tr>
<td>20</td>
<td>Mix 36</td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>40</td>
<td>Mix 16 Mix 17 Mix 1 Mix 5 Mix 25 Mix 27</td>
<td>Mix 31 Mix 3 Mix 2 Mix 6 Mix 32 Mix 37</td>
<td>Mix 38 Mix 9 Mix 30 Mix 39</td>
<td>Mix 36</td>
</tr>
<tr>
<td>60</td>
<td>Mix 26 Mix 29 Mix 38 Mix 9 Mix 30 Mix 39</td>
<td>Mix 34 Mix 35</td>
<td>Mix 35</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: RCA density and absorption properties

<table>
<thead>
<tr>
<th>Aggregate Products</th>
<th>SSD Density. (kg/m³)</th>
<th>Dry Density(kg/m³)</th>
<th>Absorption (%)</th>
<th>Ratio of NA Absorption to RCA Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA 13 mm</td>
<td>2864</td>
<td>2804</td>
<td>2.1</td>
<td>1.00</td>
</tr>
<tr>
<td>20 MPa RCA 13 mm</td>
<td>2470</td>
<td>2280</td>
<td>7.6</td>
<td>3.62</td>
</tr>
<tr>
<td>40 MPa RCA 13 mm</td>
<td>2500</td>
<td>2320</td>
<td>7.4</td>
<td>3.52</td>
</tr>
<tr>
<td>60 MPa RCA 13 mm</td>
<td>2510</td>
<td>2330</td>
<td>7.2</td>
<td>3.43</td>
</tr>
<tr>
<td>NA 19 mm</td>
<td>2887</td>
<td>2838</td>
<td>1.8</td>
<td>1.00</td>
</tr>
<tr>
<td>20 MPa RCA 19 mm</td>
<td>2630</td>
<td>2510</td>
<td>4.6</td>
<td>2.56</td>
</tr>
<tr>
<td>40 MPa RCA 19 mm</td>
<td>2640</td>
<td>2520</td>
<td>4.6</td>
<td>2.56</td>
</tr>
<tr>
<td>60 MPa RCA 19 mm</td>
<td>2650</td>
<td>2530</td>
<td>4.4</td>
<td>2.44</td>
</tr>
</tbody>
</table>

Table 3: Slump loss (mm/min)

<table>
<thead>
<tr>
<th>Aggregates</th>
<th>Mix Strength</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 MPa</td>
<td>40 MPa</td>
</tr>
<tr>
<td>NA</td>
<td>0.83</td>
<td>0.40</td>
</tr>
<tr>
<td>20 MPa RCA</td>
<td>0.60</td>
<td>0.67</td>
</tr>
<tr>
<td>40 MPa RCA</td>
<td>0.56</td>
<td>0.77</td>
</tr>
<tr>
<td>60 MPa RCA</td>
<td>0.50</td>
<td>0.89</td>
</tr>
<tr>
<td>Average</td>
<td>0.55</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 2 shows that the RCA had higher absorption values than the NA. Furthermore, the dry densities of 19 mm RCA were markedly higher than the dry densities of 13 mm RCA. The higher absorption and lower dry densities exhibited in RCA 13 mm, when compared to 19 mm RCA, was attributed to the higher percentage of adhered mortar on the 13 mm RCA. Because adhered mortar is more absorbent and less dense, it results in increased absorption and reduced density. For both aggregate sizes, the dry density of the RCA increased slightly with increased strength of the original concrete. The measured properties of RCA were in agreement with findings from other researchers as reported in the literature review.

Table 3 shows the rate of slump loss of the concrete mixes expressed as millimetre of slump loss per minute (mm/min). On average, RCA mixes exhibited a greater rate of slump loss when compared to mixes with NA. In addition, all concrete mixes with RCA experienced slump loss at a similar rate. In all cases, it was found that concrete mixes produced from 20 MPa RCA had slump characteristic that closely resembled those of concrete mixes with NA. Slump results indicated that in the production of 20 MPa concrete, RCA produced concrete having comparable or better workability than NA concrete. However, in the production of 40 MPa and 60 MPa concrete all RCA concrete performed relatively poorly when compared to concrete produced from NA. Generally, there was no significant difference in workability for the different source strengths of RCA.

Cylinders were made for each RCA mix type, and were crushed on day 1, 3, 7, 14, 28 and 56. Figure 7(a) show the compression strength gain curves of mixes with target strength of 20 MPa, indicating that all RCA produced 20 MPa concrete with equal or greater 28 day strengths than the 20 MPa NA concrete and that the use of 40 MPa and 60 MPa RCA to produce 20 MPa concrete led to higher strengths than obtained for the 20 MPa NA concrete.
From Figure 7(b) it can be seen that when producing 40 MPa concrete, compression strengths depended on the strength of the RCA source. In addition, Figure 7(b) shows that 20 MPa, 40 MPa and 60 MPa RCA lead to the production of RCA concrete having 28 day compression strengths of 40 MPa, 48 MPa and 52 MPa respectively. Consequently it may be concluded that both 40 MPa RCA and 60 MPa RCA can produce concrete that has compressive strength equal to or greater than the target 28 day strength for a 40 MPa mix.

60 MPa concrete produced using 60 MPa RCA was found to only reach 60 MPa at 28 days, and failed to attain the target 28 day mean strength of 69 MPa. This represented a 10 MPa strength reduction when compared to the corresponding concrete mix using NA (see Figure 7(c)). At 56 days, the 60 MPa RCA concrete compressive strength results were comparable to those from the 60 MPa NA concrete, indicating that the concrete produced from 60 MPa RCA exhibited a delayed strength gain when compared to the NA concrete.

Results from compression testing confirmed the influence of the RCA source strength on the resultant concrete produced from the recycled aggregates. Figure 7(c) shows that independent of cement content, 20 MPa RCA reached a ceiling strength of about 52 MPa at 56 days, indicating that it is not feasible to use 20 MPa RCA in the production of higher strength concrete.

Compression strength results indicated that a higher source strength of RCA is required in order to produce higher strength RCA concrete. This finding was in agreement with previously reported findings, which identified that the strength of RCA concrete is governed by the weaker of the interface between the stony particle and adhered mortar, and the interface between the adhered mortar and the new cement matrix. It was determined that all source strengths of RCA can produce 20 MPa RCA concrete, but that only the 40 MPa RCA and 60 MPa RCA can produce 40 MPa RCA concrete.
The purpose of this component of the study was to confirm that laboratory results could be replicated at commercial scale using truck batching. As there are no provisions in the relevant New Zealand concrete manufacturing standards pertaining to the use of RCA to manufacture concrete, it was determined that initial implementation was limited to driveway and sidewalk applications (see Figure 9). Recognising that most concrete debris should have compression strengths ranging between 20 MPa and 40 MPa, it was decided that the two mixes that had most practical application were the 40 MPa mix with 40 MPa RCA and the 20 MPa mix with 20 MPa RCA. A “specials bin” was used at the ready mix plant to contain the RCA, with quantities determined by the batcher who observed the weight of the specials bin from the computer read out (see Figure 8). For full scale batching, the TSMA that was employed in the previous stage was again adopted. Concrete workers noted that the concrete finished well and was workable, and it was concluded that the 20 MPa RCA concrete was indistinguishable from NA concrete.

Figure 8: Specials bin

Figure 10(a) shows the average slump of concrete mixes with mix strengths of 20 MPa at 28 days, with the data associated with ‘field trial mix with 20 MPa RCA’ being the average of two truck mixes. The figure shows that all mixes exhibited similar slump life, including those for NA concrete. However, Figure 10(b) showed that for 40 MPa concrete there was greater variation in slump loss and the rate of slump loss was higher than for comparable 20 MPa concrete. Figure 11 indicates that the 20 MPa field trial mixes produced comparable concrete strengths to mixes with NA Basalt, whilst the 40 MPa field trial mixes produced concrete strengths that were satisfactory but still lagged behind the corresponding control values.
CONCLUSION

Following a review of previously published literature, it was determined that the use of RCA for concrete production in New Zealand ready-mixed concrete plant was feasible, and that a study was necessary to understand the resultant material properties when using recycled concrete aggregates having a variety of characteristics. Recycled aggregates were intentionally manufactured from concrete that had been specially manufactured and cured to ensure that all relevant characteristics of the original concrete were known. Demolition, crushing and sorting was performed using conventional commercial equipment, and the properties of the resultant recycled aggregates were compared with those from natural aggregates, with variations primarily attributed to the effect of adhered mortar. A matrix of mix types was developed to investigate the outcome when using a range of recycled aggregate strengths to produce low (20 MPa), medium (40 MPa) and high strength (60 MPa) concrete. It was confirmed that all strength grades of recycled concrete aggregates were suitable to produce low strength concrete, but that the production of medium and high strength concrete required the RCA to have a source strength matching or exceeding the strength of the new concrete. The study concluded with field trials, where results and anecdotal evidence indicated that RCA concrete was indistinguishable from NA concrete. It is hoped that the results from this study will contribute to a positive cycle of increased confidence in the use of recycled concrete aggregates and eventually lead to the development of standard specifications enabling widespread use of RCA in New Zealand concrete production.

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