EXPERIMENTAL INVESTIGATION OF THE SEISMIC PERFORMANCE OF RECYCLED AGGREGATE CONCRETE BRIDGE PIERS

M. Al-Hawarneh¹, K. Tamanna² and S. Alam³

ABSTRACT

Most of the civil infrastructure facilities in Canada have passed their service lives, and are structurally or functionally deficient. Some of these infrastructures will need to be demolished and rebuilt. However, demolition will generate wastes whereas new construction will require a large amount of raw materials. Utilizing waste concrete as recycled coarse aggregates (RCA) could reduce the negative environmental impact associated with new concrete production. However, limited studies have investigated the performance of structural elements made of recycled aggregate concrete (RAC). This study experimentally investigates the seismic performance of reinforced concrete bridge piers made of RCA. The conducted test compares the performance of bridge piers made of 50% RCA replacement with that of conventional concrete (0% RCA) bridge pier. The bridge is a major route bridge located in Vancouver area and is designed as per Canadian standard (CSA 6-14). Then the specimen is scaled down to 1/3 scale. The scaled specimens had 300 mm diameter and 1730 mm height. The specimens were tested under quasi-static reverse cyclic loading. The performance of RAC piers was compared to that of the conventional piers in terms of cyclic response, ductility, moment-curvature relationship and failure mode. The results showed that the RAC specimen had similar cyclic response and failure mode. Moreover, the RAC specimen outperformed the control one in terms of ductility, moment-curvature relationship where it had 30% higher ductility and 20% higher moment capacity. Both specimens experienced flexural failure mode with similar cracking patterns. The results indicates that recycled aggregate concrete has the potential to be used as structural elements in seismic regions.

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Experimental investigation of the seismic performance of recycled aggregate concrete bridge piers

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ABSTRACT

Most of the civil infrastructure facilities in Canada have passed their service lives, and are structurally or functionally deficient. Some of these infrastructures will need to be demolished and rebuilt. However, demolition will generate wastes whereas new construction will require a large amount of raw materials. Utilizing waste concrete as recycled coarse aggregates (RCA) could reduce the negative environmental impact associated with new concrete production. However, limited studies have investigated the performance of structural elements made of recycled aggregate concrete (RAC). This study experimentally investigates the seismic performance of reinforced concrete bridge piers made of RCA. The conducted test compares the performance of bridge piers made of 50% RCA replacement with that of conventional concrete (0% RCA) bridge piers. The bridge is a major route bridge located in Vancouver area and is designed as per Canadian standard (CSA 6-14). Then the specimen is scaled down to 1/3 scale. The scaled specimens had 300 mm diameter and 1730 mm height. The specimens were tested under quasi-static reverse cyclic loading. The performance of RAC piers was compared to that of the conventional piers in terms of cyclic response, ductility, moment-curvature relationship and failure mode. The results showed that the RAC specimen had similar cyclic response and failure mode. Moreover, the RAC specimen outperformed the control one in terms of ductility, moment-curvature relationship where it had 30% higher ductility and 20% higher moment capacity. Both specimens experienced flexural failure mode with similar cracking patterns. The results indicates that recycled aggregate concrete has the potential to be used as structural elements in seismic regions.

Introduction

The Cascadia Subduction Zone is a region with an unusually highly earthquake exposure. For example, it has been reported that more than 100 earthquakes of magnitude 5 or greater have occurred during the past 70 years in the offshore region to the west of Vancouver Island [1]. Earthquake events damage buildings and infrastructures resulting in a constant need for repair and reconstruction. The reconstruction process produces a huge amount of debris, from collapsed buildings and subsequent demolition, that needs to be disposed leading to significant negative

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environmental impact. The current research investigates potential usage of debris materials in rebuilding efforts. Specifically, this study examines whether new concrete infrastructure produced with large amounts of recycled concrete aggregate (RCA) could meet performance criteria under natural hazards such as earthquake. The reuse of recycled concrete as aggregate could potentially reduce the environmental impact associated with disposal and reconstruction.

Mwasha and Lalla investigated the properties of concrete produced from recycled aggregate from demolition waste (DW) [2,3]. The results showed that concrete containing recycled aggregate had comparable properties to that of its source material which indicates a potential use of recycled aggregates as an aggregate substitute. However, they studied a limited range of properties such as compressive and splitting tensile strength.

Xiao et al. had found that some properties such as the compressive and tensile strength of recycled concrete could be lower than those of conventional concrete [4]. Rahal had examined the influence of (RCA) on wider range of concrete properties including compressive strength, modulus of elasticity, and workability [5]. He found that compressive strength and the indirect shear strength of RAC were about 90% compared to that of the conventional concrete. In addition to that, RCA and NCA showed similar trends in compressive strength development. Other pioneer studies examined the durability of recycled concrete [6, 7, 8, and 9]. They found that recycled concrete is less durable than conventional concrete and that it decreases with increasing RCA replacement percentage. Moreover, they showed that RCA concrete shrinkage could reach up to 100% more than NCA concrete and it increases with increasing RCA replacement percentages.

Despite lower mechanical properties of the recycled concrete compared to the conventional concrete, Xiao et al. suggested that recycled concrete could be applicable in structural elements as long as the concrete mix design and construction details are carried out properly [10]. Various studies investigated the influence of RCA replacement levels in structural elements using static testing [11,12]. For instance, Arezoumandi et al. investigated the effects of using 100% RCA on the shear strength with various longitudinal reinforcement ratios [11]. The results showed that 100% RCA beam had less shear strength by about 12% compared with conventional concrete. A more recent study conducted by Rahal and Alrefaei experimentally investigated the effects of RCA replacement levels on the shear strength of longitudinally reinforced concrete beams [12]. They used seven different replacement percentages ranging from 0% to 100%. They found that using up to 20% replacement has no significant effects, whereas 100% RCA replacement showed a reduction in shear strength up to 15%. Yet, they suggested that the current design code should be modified for RCA beams under shear [11] and [12].

However, relatively less researches have examined the seismic behavior of recycled concrete structures. Xiao et al. examined the seismic behavior of ½ scaled RCA plane frame under low cyclic loads [13]. The results showed similar failure patterns under low-frequency lateral loading regardless of RCA replacement percentages. Xiao et al. conducted a shake table test on a ¼ scaled model of a six-story recycled concrete frame [14]. The results indicated that it is feasible to use RCA frame structures less than six stories high in seismic regions. Furthermore Wang et al. studied the combined flexure-shear-torsion cyclic loading on RAC beams with and without fly ash [15]. It was observed that torsional energy dissipation capacity (EDC) of beams made of
RCA with 15% of fly ash was higher than that of RCA without fly ash. Soleimani et al. studied the seismic resistance of RCA columns under quasi-static cyclic testing using both seismic and non-seismic detailing [16]. They used 82% volumetric RCA replacement. The results showed that the seismically detailed RCA column experienced similar cyclic behavior as the one with NCA, however the non-seismically designed RAC column exhibited lower lateral capacity than one with NAC.

The principal objective of this study is to examine the applicability of using RCA as suitable substitute for NCA in construction of bridge piers in highly seismic regions. Two 1/3 scaled bridge piers with RCA replacement levels of 0%, and 50% were constructed and tested under combined constant axial and cyclic quasi static reverse loading.

**Design and Geometry**

The bridge pier is assumed to be a part of a typical two span single pier bridge located in Vancouver, British Columbia, Canada, and was seismically designed using a forced-based design (FBD) approach following the Canadian highway bridge design code [CHBDC], 2014. W400 steel bars with a yielding strength of 415 MPa and 30 MPa concrete strength were considered for the design. Figure 1 shows the geometry of the bridge pier considered in this study. The diameter of the pier was 900 mm with longitudinal reinforcement ratio of 1.91%, which incorporated 18-30M reinforcing bars and 15 M steel spirals at a pitch of 70 mm (transverse reinforcement ratio of 1.52%) for plastic hinge region and 15 M steel spirals at 100 mm pitch for the rest. The effective pier height was 5.2 m with an aspect ratio of 5.8, which ensured the domination of flexure behavior. A constant mass of 22.6 tons, representing the weight of the superstructure, was applied at the top which is approximately 10% of the gross pier capacity. The bridge pier was scaled down by 1/3 while preserving the same stresses in scaled pier as in the prototype pier. The effective scaled down pier height was 1.73 m with 300 mm diameter. The scaled pier longitudinal reinforcement ratio was calculated to be 1.98%, which is 14-10M reinforcing bars and 10M steel spirals at a 75 mm pitch (transverse reinforcement ratio of 2.2%). Figure 2 shows the detailing for the scaled pier. A comparative summary for the prototype and the scaled down pier is shown in Table 1.
Two RC bridge pier specimens were constructed using various RCA replacement ratios, the control specimen was built using 100% NAC (control), where the other specimen used 50% RCA replacement ratio. Figure 3 illustrates compressive strength gaining for the two mixes up to 56 days. The concrete mixes were designed by CSA A23.1-14 to achieve the desired
compressive strength. The compressive strength of the NCA mix was about 31 MPa whereas the 50% RCA had about 29 MPa. Elastic moduli were 24, and 20 GPa for the control, and 50% RCA specimen, respectively. This result supports the conclusion suggested by [17, 18] that RCA typically has lower elastic modulus than NCA. Table 2 summarized concrete properties of each mix.

<table>
<thead>
<tr>
<th>RCA replacement (%)</th>
<th>Ec'(GPa)</th>
<th>Poisson Ratio</th>
<th>$f'_c$(MPa)</th>
<th>$f_s$(MPa)</th>
<th>$f_t$(MPa)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>24</td>
<td>0.1821</td>
<td>30.92</td>
<td>3.29</td>
<td>3.96</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>0.1787</td>
<td>28.86</td>
<td>2.87</td>
<td>3.38</td>
</tr>
</tbody>
</table>

Figure 3. Compressive strength development of concrete mixtures.

**Test Setup and Layout**

Figure 4 shows the test set-up. The specimens were anchored to the strong floor by post-tensioning the four corners of the footing using 35 M High Strength Steel (HSS) rebars. The 10% axial load effect was simulated by post-tensioning a 25 M HSS rebar going through the center duct/hole of the specimen to 190 kN and bolting it at the bottom of the base and top of the column. The applied axial load on top of the pier was monitored using a calibrated load cell. A hydraulic actuator with $\pm$250 kN load capacity and $\pm$125 mm displacement capacity was mounted to a reaction frame which was assumed to have insignificant deformation during the test procedure. The actuator was placed in such a way that enabled it to reach its maximum displacement range during both push and pull. The lateral cyclic load was transferred to the specimen using a steel plate fixed to the column head through four strong bolts. The lateral loading was gradually applied to the specimens in the cases of both pull and push as per the specified loading protocol. Deflections and loadings at the point of lateral load application were recorded by a MTS controller.
Test Results

Hysteretic behavior and backbone curves

Figure 5 represents the hysteretic behavior of the tested specimens (0% RCA and 50% RCA) piers. The 50% RCA pier specimen showed similar cyclic behavior as the 0% RCA pier. Figure 5(a) represents hysteretic behavior of 50% RCA pier, the hysteresis on pulling side reached its maximum strength of 55.0 kN at 6.10% drift. After that significant strength degradation occurred on the second cycle of 6.1% drift where the strength dropped by 12.4% of the peak strength. Then, strength degradation continued but with a lower rate to drop by 16.82% of the peak strength at 6.90% drift. This sudden deterioration in pier lateral performance is due to longitudinal bar rupturing. Whereas, the pushing side showed more stable behavior, as it reached its maximum strength of 47.5 kN at 3.50% drift. After that the strength deteriorated slightly by 8.7% of peak strength at 6.94%.

The 0% RCA pier specimen, (Figure 5(b)) shows symmetric cyclic behavior for both sides. The hysteresis on the pushing side reached its maximum strength of 53.6 kN at 3.47% drift and was slightly reducing until 5.2% drift. After that, significant strength degradation occurred at 6.10% drift due to one longitudinal bar rupturing. A rapid strength deterioration continued until 6.94% drift when a second longitudinal bar ruptured and the pier was considered to be failed under lateral loading. Figure 5(b) shows that the strength deteriorated from its maximum capacity by 11.6% at 5.20% drift and then the strength quickly degraded by 20.7% at 6.10% drift and by 34.6% at 6.94% drift. A similar behavior was observed in the pulling side, where it reached its maximum strength of 50.9 kN at 4.34% drift and was slightly reducing until 4.50% drift. After
that, significant strength degradation occurred at 6.10% drift to reach 18.7% reduction of the peak strength due to one longitudinal bar rupturing. Then the rapid strength deterioration continued until 6.94% drift to reach 35.1% reduction compared to peak strength, as a second longitudinal bar ruptured, at that point the lateral strength degradation exceeded the threshold, which is 20%, considered as failure.

To assess the influence of RCA replacement percentages on the cyclic performance of piers, a lateral force-displacement backbone curve for each specimen was constructed as shown in Figure 6. The backbone curves of the two specimens were almost parallel to each other which indicated similar general behavior. However, the difference between them was in the load values. In the pull side 50% RCA had higher flexural strength than 0% RCA with about 8.1% and yet, in the push side 50% RCA showed slightly lower flexural strength comparing to 0% RCA with about 11% reduction. Figure 6 showed that the initial stiffness of the tested specimens were the same, however 50% RCA showed slightly lower post cracking stiffness. In addition, there was slight difference in the stiffness degradation rates between the tested specimens. The stiffness degradation rate is the decrease in the specimen load with the displacement increase.

**Moment-Curvature Response**

The plastic hinge region curvature (ϕ) was measured using a pair of linear variable displacement
transducers (LVDTs) that were mounted on the extreme sides of the specimen located 100 mm above the base of piers, under combined constant axial loading and variable cyclic lateral loading as presented in Figure 7. The moment-curvature curves for the two specimens are almost parallel until the curvature value of 0.000281 rad/mm but with different values indicating similar moment-curvature behaviors (Figure 7). The control specimen (0% RCA) experienced a significant deterioration in moment capacity after reaching a peak moment capacity of 87.5 kN-m at curvature value of 0.000281 rad/mm until curvature value of 0.000608 rad/mm whereas the reduction in the moment capacity reached 34.5% of the peak. 50% RCA specimens reached peak moment capacity of 94.56 kN-m at the curvature value of 0.000382 per mm. Unlike the 0% RCA specimen, 50% RCA specimens experienced more stable behavior after reaching the maximum moment capacity where the reduction in moment capacity was 11.6% of the peak. This could be attributed to the lower elastic modulus of concrete with RCA replacement.

Ductility Analysis

This study used two types of ductility measures, displacement and curvature ductility. The ductility values of the tested specimens were calculated using yielding and ultimate points of the test. The yield force was found from strain response of rebar and corresponding displacement was obtained from hysteresis curves (Figure 5). After that, the ultimate and yield moments were calculated from the corresponding forces. Then, the corresponding curvature was obtained from the moment-curvature relationships (Figure 7) obtained from tests. The result summary of the ductility analysis is shown in Table 3. All the tested specimens showed good ductility performances for both displacement and curvature ductility. However, the specimen with 50% RCA replacement outperformed the control specimen with about 32% and 52% increase in displacement ductility and curvature ductility, respectively. To specify, the displacement and curvature ductility for the specimen with 50% RCA were 7.78 and 17.62, respectively. Table 3 shows that 0% RCA specimen had the lowest yielding force and displacement. However, the specimen with 50% RCA replacement had the smallest yielding curvature with a value of 2.17x10⁻⁵ per mm at a moment of 35.5 kN-m. Unlike the yielding measurements, the ultimate measurements showed that 0% RCA specimen had the smallest moment and curvature values (Table 3). This difference between yielding and ultimate results could be attributed to earlier
yielding of the 50% RCA compared to the control specimen leading to lower moment and curvature values, thus higher ductility values.

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>0% RCA</th>
<th>50% RCA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yield</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force (kN)</td>
<td>18.62</td>
<td>20.46</td>
</tr>
<tr>
<td>Dis (mm)</td>
<td>10.21</td>
<td>11.55</td>
</tr>
<tr>
<td>Moment (kN-m)</td>
<td>32.02</td>
<td>35.50</td>
</tr>
<tr>
<td>Curv. (1/mm)</td>
<td>2.43x10^{-5}</td>
<td>2.17x10^{-5}</td>
</tr>
<tr>
<td><strong>Ultimate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force (kN)</td>
<td>50.88</td>
<td>54.98</td>
</tr>
<tr>
<td>Dis (mm)</td>
<td>60.01</td>
<td>89.98</td>
</tr>
<tr>
<td>Moment (kN-m)</td>
<td>87.51</td>
<td>94.56</td>
</tr>
<tr>
<td>Curv. (1/mm)</td>
<td>2.81x10^{-4}</td>
<td>3.82x10^{-4}</td>
</tr>
</tbody>
</table>

**Failure Mode**

All of the specimens were tested up to the maximum displacement capacity (±120 mm or 6.98% drift) of the hydraulic actuator. The failure modes for both the specimens were characterized by the presence of horizontal cracks distributed around and along the specimen’s surface. After reaching the maximum lateral capacity, horizontal cracks width started to increase, and cover concrete started to spall off for all specimens at about 90 mm displacement which initiated the buckling of longitudinal reinforcement and eventually rupture of some longitudinal bars. For 0% RCA, four longitudinal bars ruptured, two at each loading side at 105 mm displacement whereas, only one longitudinal bar ruptured for each specimen, at about 120 mm displacement at pulling side for the 50% RCA specimen. This resulted in losing the restoring force of pier and increased the residual drift and energy dissipation as discussed earlier. At this point, there was a sudden drop in the lateral load capacity of all piers. The observed failure modes were flexural failure modes for all specimens as shown in Figure 8. Figure 8(b) shows the plastic hinge region of the tested specimen where it was observed that the specimen experienced concrete spalling, horizontal cracks and reinforcement buckling. Furthermore, Figure 8(a) shows locations where steel bars experienced rupture. Figure 9 shows the cracking patterns for all specimens. It was observed (Figure 9(a),and (b)) that the 0% and 50% RCA specimen had similar number of cracks with crack spacing of about 150 mm for both specimens. Moreover, 50% RCA specimen experienced similar crack width as the 0% RCA specimen.
Conclusions

In this study, two 1/3 scaled bridge piers containing 0% and 50% RCA replacement were tested under combined axial load and lateral cyclic quasi-static loading. The tested specimens had similar compressive strengths of about 30 MPa. The experimental results showed that specimen with RCA replacement had very similar strength behavior and sustained flexural and shear capacities at large lateral displacement ratios at about 4.3% drift. However, specimen with RCA replacements showed higher ductility performance than the conventional concrete specimen. All tested specimens experienced flexural failure mode and similar cracking patterns with almost identical crack widths. In addition to that, the average crack spacing was about 150 mm. Based on the test results, it is concluded that RAC can be used as alternative material for NAC in bridge piers in highly seismic region without significant changes on the seismic behavior.
References


