DURABILITY OF GFRP IN LOW-HEAT HIGH-PERFORMANCE CONCRETE

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ABSTRACT

Reinforced concrete structures are typically exposed to harsh environments, such as de-icing salts, which could be extremely harmful to the steel reinforcements. Corrosion of steel causes spalling of concrete and therefore increase the maintenance costs of structures. As a result, the use of fibre reinforced polymer (FRP) as a replacement for conventional steel reinforcement has greatly increased over the last decade. The non-corrosive and relatively high strength-to-weight characteristics of glass fibre reinforced polymer (GFRP) are also attractive characteristics which could increase the service life of structures subjected to highly corrosive environments.

However integrity of glass fibres depend on a 3-dimensional network of silica-oxygen-silica bonds, which are highly susceptible to hydroxyl attack, commonly known as alkali attack. The high pH value of normal conventional concrete (NCC) pore water could create a potentially damaging environment for GFRP reinforcement. Several methods to reduce GFRP degradation under such environments have been investigated including the use of different concrete mix designs. Low heat high performance concrete (LHHPC) is concrete with low cement content. Consequently the low alkalinity of LHHPC may reduce deterioration of GFRP and therefore significantly increase the benefits of their use as reinforcement.

A comparative study on the durability of GFRP in LHHPC and NCC at 60°C solution was undertaken at the University of Manitoba. Long-term measurements indicate higher tensile strengths for GFRP bars embedded in LHHPC as opposed to NCC. The structural behaviour, in terms of strength and ductility of LHHPC and NCC beams reinforced with GFRP or steel is also presented.
INTRODUCTION

Low heat high performance concrete is a concrete mix design that was patented by Atomic Energy of Canada Limited in July of 1996. Aside from having a considerably low heat of hydration, this type of concrete has a relatively low alkalinity level of pH 9, which may be convenient for concrete structures reinforced with materials such as GFRP reinforcements, which are susceptible to deterioration in highly alkaline environments. The durability of GFRP rods in LHHPC as well as NCC was investigated and the results are discussed in this paper. The structural behaviour of LHHPC beams reinforced with steel and GFRP was also investigated and compared to that of NCC beams.

EXPERIMENTAL PROGRAM

Materials

Low heat high performance concrete (LHHPC):

Low heat high performance concrete is characterized by a relatively low alkalinity in comparison to conventional concrete due to its low cement content. To reduce the cement content while maintaining high performance, four percent of silica fume and eight percent of silica flour by weight were used. Silica flour generally acts as a filler material to improve the density and impermeability of concrete while silica fume has the additional property of acting as a pozzolan to improve the compressive strength of the concrete. A sulphate-resistant Portland cement (Type 50) was used in this study while a water reducing agent (superplasticizer) was added as a chemical admixture to improve the workability of the concrete prior to casting. Fine and coarse aggregates were also included in the mix design of LHHPC at 37 percent and 43 percent by weight, respectively. The mix proportions are shown in Table 1. Using this low cement content, the water cementitious ratio of the mix is 0.54.

The average 28-day elastic modulus, strength and ultimate strain of standard 150 by 300 mm LHHPC cylinders tested under compression were found to be 37.0 GPa, 69.2 MPa, and 2,380 micro-strains respectively. Test results over time indicated the ultimate strength increase beyond 100 MPa. The test procedure for determining the modulus of elasticity was conducted according to ASTM C469 (1994).

Table 1- Mix Proportions

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Quantity (kg/m³)</th>
<th>Composition by Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>97.02</td>
<td>4.00</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>97.02</td>
<td>4.00</td>
</tr>
<tr>
<td>Silica Flour</td>
<td>193.85</td>
<td>8.00</td>
</tr>
<tr>
<td>Aggregates, Fine</td>
<td>894.74</td>
<td>36.93</td>
</tr>
<tr>
<td>Aggregates, Coarse</td>
<td>1039.59</td>
<td>42.90</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>10.32</td>
<td>0.43</td>
</tr>
<tr>
<td>Water</td>
<td>90.54</td>
<td>3.74</td>
</tr>
</tbody>
</table>
Normal conventional concrete (NCC):

The cement content of conventional concrete was found to produce a pH level ranging from 12 to 13. Presence of highly alkaline nature derived from this pH creates a potentially damaging environment for GFRP reinforcement.

The average 28-day elastic modulus and strength of 150 mm diameter NCC cylinders tested under compression were found to be 33.2 GPa and 44.3 MPa, respectively. The test procedure for determining the modulus of elasticity of NCC used in this study was conducted according to ASTM C469 (1994).

Reinforcement:

The GFRP reinforcement used in the durability phase of the study is 15 mm diameter ISOROD™ bar. The measured tensile strength of this bar is 674 MPa, and the modulus of elasticity in tension is 42 GPa. This bar is manufactured using a modified vinyl-ester matrix and 75 percent volume fraction of glass fibres.

The GFRP reinforcement used in the structural behaviour phase of the study was 12 mm nominal diameter C-BAR™. The bars consisted of E-glass fibres embedded in an epoxy resin matrix. The maximum tensile strength of the GFRP bars was recorded as 532 MPa with a modulus of elasticity of 34.3 GPa.

The conventional steel reinforcement used in the structural behaviour phase of the study was 15 mm in diameter. The measured yield stress of this reinforcement was 425 MPa with an elastic modulus of 177 GPa. The test samples were tested according to ASTM A 370-97a (1997).

Specimens

Flexural tests:

A total of six concrete beams were tested for each type of reinforcement, four of which were cast with LHHPC and two of which were cast with NCC. The beams are 150-mm in width and 350-mm in height with a total length of 4 meters. For each type of reinforcement, two separate reinforcement ratios were investigated. Tables 2 and 3 summarize the details of beams reinforced by conventional steel and GFRP, respectively. The test setup can be found in Fig. 1.

Durability tests:

The testing program included a total of 20 LHHPC and 20 NCC specimens concentrically reinforced with a 15 mm GFRP rod as shown in Fig. 2. The specimens measured 500 mm in length with a corresponding width and height of 125 mm.
Figure 1– Schematic Drawing for Beams Reinforced by Steel and GFRP

<table>
<thead>
<tr>
<th>Concrete</th>
<th>b  (mm)</th>
<th>d  (mm)</th>
<th>$f'_c$ (MPa)</th>
<th>$E_c$ (GPa)</th>
<th>$f_y$ (MPa)</th>
<th>$E_s$ (GPa)</th>
<th>$A_s$ (mm$^2$)</th>
<th>$\rho$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHHPC</td>
<td>150</td>
<td>300</td>
<td>80</td>
<td>39.5</td>
<td>450</td>
<td>177</td>
<td>800</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1200</td>
<td>2.7</td>
</tr>
<tr>
<td>NCC</td>
<td>150</td>
<td>300</td>
<td>40</td>
<td>33.6</td>
<td>450</td>
<td>177</td>
<td>800</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1200</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table 3– GFRP Reinforced Beams

<table>
<thead>
<tr>
<th>Concrete</th>
<th>b  (mm)</th>
<th>d  (mm)</th>
<th>$f'_c$ (MPa)</th>
<th>$E_c$ (GPa)</th>
<th>$f_u$ (MPa)</th>
<th>$E_s$ (GPa)</th>
<th>$A_s$ (mm$^2$)</th>
<th>$\rho$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHHPC</td>
<td>150</td>
<td>300</td>
<td>82</td>
<td>39.5</td>
<td>532</td>
<td>34</td>
<td>226</td>
<td>0.5</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>678</td>
<td>1.5</td>
</tr>
<tr>
<td>NCC</td>
<td>150</td>
<td>300</td>
<td>38</td>
<td>33.6</td>
<td>532</td>
<td>34</td>
<td>226</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>678</td>
<td>1.5</td>
</tr>
</tbody>
</table>
The deterioration of GFRP by alkali is a very slow process especially if the fibres are protected by resin, therefore each GFRP rod was machined at mid-span to expose the glass fibres to the alkaline environment, and therefore accelerate the degradation process. The transition section was designed to reduce the stress concentration caused by an abrupt change in section. The cross-sectional area of the GFRP rod was reduced to half of its initial area along a length of 80 mm.

Four threaded rods were also cast for each concrete specimen to allow gripping the specimens into the testing frame. To ensure cracking of the concrete and eventual failure of the GFRP rod at its reduced section, a 10 mm gap was provided at the mid-span of each threaded rod. Two steel spirals at each end of the specimen were used to prevent cracking at gripping end.

![Figure 2 – Detailed drawing of tension sample](image)

**FLEXURAL TESTS**

**Test Method**

All beams were simply supported and tested in flexure on the basis of ASTM C 78 (1994) under a third-point loading. The distance between the end supports was set at 3.7 meters and the constant moment zone at 1.1 meters. Beam specimens were painted with a latex white paint to facilitate locating and mapping crack initiation and propagation. All cracks were marked and crack widths were measured at each load increment.

The beams were instrumented by three electrical strain gauges mounted on the longitudinal tensile reinforcement in the constant moment zone. A Pi gauge was also located in the compressive zone and constant moment region of the concrete beam to measure strain. Two Linear Variable Displacement Transducers (LVDT) were located at mid-span to measure the deflection.
A servo-hydraulic closed loop cyclic testing machine was used. The machine applied the load to the beam specimens at a stroke control rate of 0.5 mm/min. A 16-channel data acquisition system to record the strains in the reinforcement was also used.

**Test Results and Discussion**

The load-deflection behaviour was found to be similar in nature for beams cast in both LHHPC and NCC. It was observed for both reinforcement types, that the beams tested had a similar stiffness prior to initial cracking. After cracking the stiffness of LHHPC beams was higher than the stiffness of NCC beams for both reinforcement ratios.

The ductility index, which is the ratio of the deflection at ultimate to the deflection at yield of the reinforcement, was computed for beams reinforced with steel. The index was not computed for beams reinforced with GFRP since they do not yield. The ductility was found to be approximately 70 percent greater for beams cast in LHHPC as compared to beams cast from NCC for both steel reinforcement ratios.

The ultimate load for the steel reinforced beams cast in LHHPC was also found to be consistently higher than that for beams cast in NCC. These results therefore suggest that LHHPC generally exceeds the performance of NCC in both strength and ductility at the two steel reinforcement ratios. Fig. 3 shows the load-deflection behaviour of LHHPC and NCC beams reinforced by steel.

Fig. 4 shows the load-deflection behaviour of LHHPC and NCC beams reinforced by GFRP. The short-term results for GFRP reinforced beams show that LHHPC beams have slightly lower strength and deflection at ultimate load than their corresponding NCC beams. However, these results do not necessarily suggest any trend in behaviour between LHHPC and NCC since an insufficient number of specimens have been tested. Further details of the flexural test program can be found in Jawara (1999).

**DURABILITY TESTS**

**Test Method**

The specimens were stripped from their forms three days after casting and submerged into a water bath maintained at a temperature of 60°C. The samples were tested after 1, 3, 6, 9, 15 and 24 months. After each specified curing period, three specimens were taken out of the water bath and subjected to axial tension to measure the level of deterioration of GFRP bars.
Figure 3 - LHHPC and NCC Beams Reinforced by Steel

Figure 4 - LHHPC and NCC Beams Reinforced by GFRP
Figure 5 – Test setup

Fig. 5 shows the test setup and the tension specimen in the testing frame prior to load application. The specimens were tested in axial tension using a servo-hydraulic machine with a capacity of 1000 kN and maximum stroke of 100 mm. The stroke rate used for all tension tests was 0.5 mm/min. In order to provoke GFRP failure, a 40 mm deep notch was introduced along the middle section of the specimen coinciding with the reduced section of the GFRP rod. This considerably reduced the cross sectional area of the specimen and induced cracking of the concrete. The concrete was forced to crack in the zone of reduced bar cross-section to evaluate the effect of aggressive environment on the strength of the bar.

A steel plate was bolted to the threaded rods on either side of the specimens for load application. In order to avoid eccentricity during load application, wooden spacers were placed between the steel plate and the test specimens to maintain the sample parallel to the test machine.
Results and Discussion

There were two failure modes observed, all of which occurred through fracture of the GFRP rod at its reduced section. Some of the GFRP rods failed at the notched section while several other rods failed away from the notch inside of the specimen. Fig. 6 shows fracture of a GFRP rod at the edge of a notched section.

A total of three to four LHHPC and NCC test specimens containing GFRP reinforcement were subjected to axial tension at each curing period. Fig. 7 shows a typical load-stroke curve for LHHPC and NCC samples tested after 15 months of exposure to the selected environment.

The measured cracking load was 7 and 4 kN for LHHPC and NCC concrete, respectively. The initial stiffness of LHHPC sample was larger than the stiffness of NCC sample. The ultimate loads were recorded, averaged and plotted against their respective curing periods. The objective was to obtain a trend of the reduction in tensile resistance of GFRP reinforcement with duration of exposure to the selected environment and different concrete mix designs.

Table 4 contains test results of the durability test and their corresponding standard deviations. The tensile capacity of the GFRP has reduced with their exposure duration for both LHHPC and NCC concrete. Test results indicate slight increase for the exposure period of 9 and 24 months. These could be due to quality control of the GFRP bars or/and instrumentation errors. Fig. 8 shows the reduction in tensile resistance of GFRP rods.
Table 4– Tension Test Results

<table>
<thead>
<tr>
<th>Exposure Duration (Month)</th>
<th>LHHPC</th>
<th>NCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave. Tensile Load (kN)</td>
<td>St. Deviation</td>
</tr>
<tr>
<td>1</td>
<td>55.1</td>
<td>0.416</td>
</tr>
<tr>
<td>3</td>
<td>46.0</td>
<td>2.095</td>
</tr>
<tr>
<td>6</td>
<td>36.3</td>
<td>4.050</td>
</tr>
<tr>
<td>9</td>
<td>40.0</td>
<td>0.540</td>
</tr>
<tr>
<td>15</td>
<td>32.7</td>
<td>1.933</td>
</tr>
<tr>
<td>24</td>
<td>35.2</td>
<td>0.689</td>
</tr>
</tbody>
</table>

embedded in LHHPC as opposed to NCC as a function of exposure to the selected environment. The measured data for LHHPC and NCC test specimens are plotted using a power function in Fig. 8. In addition to clarifying the relationship between the tensile resistance and the duration of exposure, the curves revealed effect of using two concrete mix designs into which the GFRP rods were embedded. Tensile resistance was found to be consistently higher for GFRP rods embedded in LHHPC as opposed to GFRP rods embedded in NCC.

![Figure 7– Load versus Stroke](image-url)
At the end of two years exposure to the selected environment, the tensile resistance of GFRP rods embedded in LHHPC is 14 percent higher than the tensile resistance of GFRP rods embedded in NCC.

![Graph showing the effect of environment on ultimate strength](image)

**Figure 8- The Effect of Aggressive Environment on Ultimate Strength**

**CONCLUSIONS**

The alkaline environment in concrete (NCC) may negatively affect the long-term performance of GFRP-reinforced concrete. The objective of this study was to investigate the feasibility of using LHHPC as a replacement for regular concrete (NCC) and eliminate GFRP deterioration. The investigation consisted of examining the deterioration of GFRP rods embedded in LHHPC and observing the structural behaviour of LHHPC as a material for concrete beams. Similar tests were imposed to corresponding NCC specimens in order to create a benchmark for comparison. The following are conclusions supported by this experimental program:
Flexural Tests
1) Flexural strength of beams cast with LHHPC was similar to those using NCC, therefore, LHHPC can be used for construction.
2) The performance of steel reinforced LHHPC beams in terms of strength and ductility, was superior to NCC beams.

Durability Tests
1) Tensile resistance of GFRP rods embedded in LHHPC and NCC was found to reduce by 35 to 45 percent during the period of twenty-fourth month of exposure to the selected environment. Such reductions in tensile resistances were linked to the alkaline nature of both concrete mixes and eventual degradation of glass fibres.
2) Degradation of GFRP rods embedded in LHHPC was found to be lesser with time than that of GFRP rods embedded in NCC.

REFERENCES


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