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Corrosion Resistance of Fiber-reinforced Geopolymer Structural Concrete in a Simulated Marine Environment

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ABSTRACT

The corrosion resistance of fly ash-based geopolymer structural concrete (GPC), with or without fibers, was investigated in a simulated marine environment, and compared with that of ordinary Portland cement structural concrete. The corrosion behavior is studied through an electrochemical method for inducing accelerated corrosion. The fiber reinforced beam specimens contained polyolefin fibers in the amounts of 0.1%, 0.3%, and 0.5% by volume. Several artificial corrosion conduits were introduced into the specimens reaching up to the rebars. This process enhanced the rate of laboratory corrosion in GPC, thus allowing faster and measurable evaluation of corrosion resistance. The corrosion-damaged beams were then analyzed through a method of crack scoring, and determination of steel mass loss and residual flexural load capacity. The fiber reinforced corroded GPC beams (with 0.1 - 0.5% fibers) showed a 24% reduction in crack scores, and a 109% increase in residual flexural load capacity, compared to unreinforced corroded GPC beams. This shows promise of fiber-reinforced GPC as a sustainable structural material in the marine environment.

Keywords: Geopolymer concrete, fly ash, sustainable, polyolefin fiber, corrosion resistance

1.0 INTRODUCTION AND BACKGROUND

Geopolymer paste was conceived by Davidovits (1991) as an inorganic polymer. Geopolymerization is an exothermic reaction, and involves the chemical reaction of aluminosilicate oxides (Si_2O_5 , Al_2O_2) with alkali polysilicates yielding polymeric Si-O-Al (Davidovits, 1989, 1991). Fly ash-based geopolymer concrete enables complete replacement of the cement content from the concrete matrix with fly ash. Geopolymer concrete uses the aluminosilicate in fly ash, which, combined with an alkali activator such as sodium hydroxide and/or sodium silicate, produces a crystalline structure comparable to, if not stronger than, cement paste (Duxson et al. 2007). To develop an idealized geopolymer concrete mix design, Hardjito and Rangan (2005)

investigated several mixtures as well as curing regimes. Singh et al. (2015) compared the mix-design and properties of fresh and hardened geopolymer concrete reported by various researchers such as Hardjito et al. (2004), Fernandez-Himenez et al. (2006), Sofi et al. (2007), Diaz-Loya (2011), and Pan et al. (2011). It was found that geopolymer concrete mixes with molarity ranging between 8-16, density between 1876-2555 kg/m³, and activator/binder ratio between 0.35-0.94, attained a compressive strength in the range of 30-80 MPa, flexural strength between 2.24-12 MPa, and the modulus of elasticity between 1.9-42 GPa. Several microstructural studies have identified a denser and stronger interfacial transition zone (ITZ) in geopolymer concrete (Lee and Van Deventure, 2004; 2007) that may contribute to higher splitting tensile strength, bond strength and durability. Other studies involved the diffusivity characteristics of multiple geopolymer mixes (Muntingh, 2006); the bond characteristics between geopolymer concrete mix and reinforcing steel (Sarker, 2011; Sofi et al. 2007); fire resistance of geopolymer concrete (Kong and Sanjayan, 2010; Zhao and Sanjayan, 2011); strength and durability studies such as alkali-silica reactivity (Meesala et al., 2020; Albitar et al. 2017; Patil and Allouche, 2013; Garcia-Lodeiro et al. 2007); effect of acid attack (Davidovits, 1991; Temuujin et al. 2011; Ariffin et al. 2013); and sulfate attack (Hardjito et al. 2004; Fernandez-Himenez et al. 2009; Ismail et al. 2013). Ali et al. (2018) recently studied the permeability indices, water penetration depth, and voids ratio of GPC and reported that GPC achieved higher permeability and corrosion resistance than OPC at the same compressive strength.

Summary of the above findings suggests that in general, the performance of geopolymer concrete in terms of strength and durability is comparable or better than ordinary Portland cement concrete, and accordingly, the fly ash based geopolymer concrete appears to offer promise as a sustainable construction material for structural applications.

The exposure of reinforced concrete structures such as high-rise residential buildings, bridges, and piers to saline environments, including exposure to de-icing salts, increases their susceptibility to the corrosion of the reinforcing steel leading to chemical/physical damage of the concrete.

The phenomena and mechanism of corrosion of steel in reinforced concrete have been well documented (Broomfield, 1997; Allen, 1998). It is known that the reinforcing steel is usually in a non-corroding (passive) state, but the ingress of chloride in aggressive environment disrupts the passive layer protecting the steel, resulting in rust or pitting corrosion. With the progress of the corrosion process, a solid corrosion product forms at the metal-concrete interface that absorbs water and expands in volume. This causes a tremendous increase in stresses in the surrounding concrete, resulting in cracking and spalling. As reported by Babaei and Castel (2016), information on the chloride ingress properties and subsequent corrosion of reinforcing steel in geopolymer concrete (hereafter called GPC) are quite limited, and therefore, the long-term durability of GPC remains a concern for the structural engineering community. While the highly alkaline pore system of fly-ash based GPC is expected to passivate (protect) the reinforcing steel, ingress of chloride ion can cause depassivation (disruption of the passive film) leading to corrosion damage in GPC (Babaei and Castel, 2016; Monticelli et al. 2016). Furthermore, Lloyd et al. (2010) reported that the presence of calcium in the matrix is important because it lowers the permeability of the pore system, thus preventing the leaching of alkali (lowering of the pH) leading to depassivation. Some of these studies also observed that the performance of fly-ash based geopolymer is similar to OPC in the passive state (i.e. in the absence of chloride ions). Therefore, it was interesting to evaluate the performance of low-calcium fly-ash (ASTM Class F) based GPC in the presence of chloride ions.

As corrosion induced cracking increases, more saline water can penetrate the structural element causing further corrosion and cracking. Limited studies are available in the literature for laboratory evaluation of the corrosion resistance of structural geopolymer concrete using accelerated electrochemical techniques (Olivia and Nikraz, 2012; Reddy et al. 2013, 2011). Therefore, a coordinated experimental program was undertaken at Florida Atlantic University to evaluate the corrosion resistance of structural geopolymer concrete (GPC) compared to structural ordinary Portland cement concrete (OPC) through accelerated electrochemical method (Nordtest, 1989; Sahmaran et al. 2008). The results of this research (Phase I) have been presented elsewhere (Reddy et al. 2013), and will be used in this paper for comparison purposes.

The lessons learned from Phase I (e.g. the corrosion current behavior) were then used in Phase II to (i) suggest modifications to the accelerated corrosion testing procedure by creating artificial corrosion conduits for better evaluation of the corrosion resistance of GPC; and (ii) to determine the effects of fiber addition on the propagation of corrosion cracks and residual strength after corrosion damage has initiated. It is well known that fibers are used in concrete as secondary reinforcement to aid in arresting crack propagation (Bentur and Mindess, 2007), and some researchers have found that fiber addition in concrete can also delay corrosion damage by preventing crack formation and propagation (Kakooei et al. 2012).

2.0 OBJECTIVES

The main objective of this research was to evaluate the corrosion resistance of GPC in comparison with OPC, with and without fiber reinforcement, in a simulated marine environment. This was accomplished by determining (i) the effect of crack-arresting properties of polyolefin fibers using a crack scoring analysis, (ii) the rebar mass loss of autopsied specimens, and (iii) the residual flexural strength after being subjected to corrosion damage. Additionally, the effectiveness of

creating artificial corrosion conduits in laboratory specimens to induce and further accelerate the corrosion process in GPC was proposed and evaluated in this study.

3.0 MATERIALS AND MIX DESIGN

The experimental program used a GPC mix design similar to that suggested by Wallah and Rangan (2006) for 8 Molar and 14 Molar geopolymer concrete. The GPC and OPC mix designs are shown in Table 1. The coarse and fine aggregates constituted 75-80% of the mixture. The coarse aggregate used in the mixture was pearock, in a saturated surface dry condition (SSD). The fine aggregate used was a “medium coarse” sand. A low-calcium Class F fly ash (ASTM C618), obtained from Cemex Corporation, was used in this study, having chemical compositions shown in Table 2. The choice of alkali activators, namely a mix of sodium hydroxide and sodium silicate, was originally used by Hardjito and Rangan (2005) to produce geopolymer concrete with desirable durability characteristics. The sodium silicate, with product designation D, was obtained in solution from PQ Corporation. The composition is made up of 55.9% water and 44.1% sodium silicate with a 2.0 weight ratio ($\text{Na}_2\text{O}=14.7\%$, $\text{SiO}_2=29.4\%$). The sodium hydroxide was obtained from Fisher Scientific in solid pellet form. The pellets were composed of 99% assay sodium hydroxide, and were prepared into a solution as suggested by Wallah and Rangan (2006). The sodium hydroxide and sodium silicate solutions were prepared and mixed together 24 hours prior to specimen preparation. It is to be noted that the dissolution of sodium hydroxide pellets is an exothermic reaction, and proper cooling is needed prior to its use so that the geopolymerization process is not affected. The ratio of sodium silicate solution to sodium hydroxide solution was 2.5, and the ratio of activator solution to fly ash was 0.3. To increase the workability of the geopolymer concrete without adding more water, ADVA 120 superplasticizer was added to the mixture. Type 50/63 Polyolefin Fibers from 3M Corporation were used for the fiber reinforcement of GPC. The

polyolefin fibers had a length of 50 mm and a diameter of 0.635 mm. According to the 3M Product Data Sheet, these Polyolefin fibers are corrosion resistant, non-rusting, chemically inert (excellent resistance to salt, chemicals and alkalinity), and non-magnetic. The specific gravity, tensile strength and modulus of elasticity are 0.91, 275 MPa and 2,647 MPa, respectively. Fibers were added to the geopolymer concrete beams in three different percentages by volume: 0.1%, 0.3%, and 0.5%. The materials used in the geopolymer concrete mix were obtained from locally available sources, and Class F fly ash was used as the principal binder material in the mix.

Phase I of the experimental program included 12 OPC cylinders (100 mm x 200 mm) for compressive strength testing. In addition, 18 beam specimens (150 x 150 x 525mm) were prepared for accelerated corrosion testing (six OPC, six 8M GPC and six 14M GPC). All beams were centrally reinforced with 12.5 mm rebars. Details are available in the reference (Reddy et al. 2013). In Phase II of the experimental program, three 100 mm x 200 mm cylinders, for each of the three fiber mixes (0.1%, 0.3%, and 0.5% by volume), and one control mix without fibers, were cast for compressive and splitting tensile strength tests at 7 and 28 days. Three 150 mm x 150 mm x 525 mm centrally reinforced beam specimens with 12.5 mm steel rebar, for each of the three fiber mixes, and three control mix without fibers, were prepared to evaluate the corrosion resistance of fiber and non-fiber-reinforced GPC in a simulated marine environment. Only 14 Molar solution was used for GPC beams. The 12 GPC beams were labeled as follows: GPC beam# - % fiber. Accordingly, the three control beams were labeled GPC 1-0, GPC 2-0 and GPC 3-0, while the nine fiber reinforced beams were labeled GPC 4-0.1, GPC 5-0.1, GPC 6-0.1, GPC 7-0.3, GPC 8-0.3, GPC 9-0.3, GPC 10-0.5, GPC 11-0.5, and GPC 12-0.5. The OPC and GPC beams were cast into molds and allowed to set for 24 hours prior to removal. The specimens were then heat-cured in an oven at 60°C for a period of 24 hours (Wallah and Rangan 2006), and then left at room temperature

until their testing time. Figure 1 shows several GPC beam specimens and the process of heat curing in the laboratory oven.

4.0 EXPERIMENTAL PROCEDURE

Following the compressive and split tensile strength testing of cylindrical specimens, the OPC and GPC beams were tested for corrosion in artificial seawater (salinity 3%), with induced current. The procedure used followed that of Sahmaran et al. (2008) and the Florida Department of Transportation (2000). A schematic of the setup is shown in Figure 2, while Figure 3 shows several GPC specimens undergoing accelerated corrosion in the laboratory. Each beam was connected to the positive terminal of a D.C. power supply of 30 volts, and the current was measured with a multimeter. The corrosion current reading was taken every day during the testing period. The corrosion current value showed a direct relationship to the corrosion resistance of each beam. A rise in the current would indicate the initiation of a crack in the concrete, increasing the access of seawater to the rebar. The beams were monitored for cracking, both through the changes in corrosion current behavior and visual inspection.

The GPC specimens did not show any signs of corrosion even after 60 days of accelerated corrosion testing. This observation was consistent with Phase I of the research in which only the OPC beams suffered corrosion damage, while the GPC beams remained intact after the corrosion testing (Reddy et al. 2013). In order to evaluate the performance of GPC beams after corrosion cracks have been initiated, it was decided to facilitate (accelerate) the induced corrosion by introducing artificial corrosion conduits in the form of three 6 mm holes drilled to reach up to the steel rebar, Figure 4. This created an environment favorable to “depasivation” of the steel through ingress of chloride ions and possible reduction in alkaline content due to leaching. In the presence of chloride, the

corrosion process initiated and as more cracks developed, the corrosion performance of GPC could be measured and evaluated.

Exposure was continued for 30 days, when significant cracking occurred. The specimens were then removed from the seawater, and the amount of cracking (length and width) was recorded. Following the accelerated corrosion testing, the beams were tested for residual flexural load capacity through third-point loading. The final step was to autopsy the concrete to measure the mass loss of the rebar to evaluate the corrosion damage.

5.0 EXPERIMENTAL RESULTS AND DISCUSSION

The average compressive strengths for the OPC cylinders were 22 MPa and 33 MPa for 7 and 28 days, respectively. For GPC cylinders, these values were 36.5 MPa and 41.6 MPa at 7 and 28 days, respectively. The splitting tensile strength tests for GPC cylinders showed average values of 2.78 MPa and 2.97 MPa at 7 and 28 days, respectively. The experimental data were analyzed through four criteria: (1) corrosion current, (2) crack score, (3) mass loss and (4) (3) residual flexural load capacity.

5.1 Corrosion Current Behavior

Comparing the corrosion current behavior of the GPC beams to the OPC beams shown in Figure 5 (Phase I), it is apparent that no corrosion of the reinforcement took place in the GPC beams during the 300 hours of testing, as no rise in corrosion current was observed. The OPC beams, however, had a rapid increase in current, eventually showing cracks after 60 hours of testing. Therefore, it was concluded that GPC has significantly better corrosion resistance than OPC. A similar corrosion current behavior of GPC beams was observed in Phase II of the experimental program, where no rise in current was evidenced for a period of nearly 60 days, which was a much longer period of exposure compared to the first phase. At that time, in an effort to induce corrosion cracking, a modification to the usual accelerated corrosion testing procedures was adopted by drilling three 6

mm (1/4 in.) holes into the specimen reaching up to the rebar, enabling the access of seawater, Figure 4. Only two out of every three beams were drilled, leaving samples GPC 3-0, GPC 6-0.1, GPC 8-0.3, and GPC 12-0.5 intact.

After about 20 additional days following the drilling of the holes, spikes in the corrosion currents indicated that cracking had commenced. This was also established by the observation of small longitudinal cracks. The cracking was allowed to continue for 10 more days (resulting in a total of 90 days of corrosion testing), after which the beams were removed from the seawater. Figures 6 and 7 show the behavior of corrosion currents of the GPC beams throughout the duration of the experiment. Analysis of experimental data for the GPC beams was done separately for beams without drilled holes, and beams with drilled holes. The evaluation addressed the corrosion behavior in two successive stages: crack initiation stage followed by crack propagation stage. The rise of corrosion current indicates the sequence of crack initiation followed by propagation.

5.1.1 Measured current in GPC beams with drilled holes (artificial corrosion conduits)

Figure 6 shows the results of the corrosion currents measured during the accelerated corrosion testing for beams with drilled holes. It can be seen that, on the average, the GPC beams without fiber reinforcement showed some of the highest readings for the currents, followed by beams with 0.5% fibers. The lowest rise (propagation) occurred in the 0.1% fiber reinforced beams, indicating the possible existence of an optimum fiber dosage for maximizing corrosion resistance. This can be attributed to the lower permeability associated with the lower fiber volume content (Miloud, 2005).

5.1.2 Measured current in GPC beams without drilled holes

The corrosion currents for beams without holes did not show any noticeable change in current throughout the testing period, when compared to the beams with holes (in the same scale). In the

magnified scale of Figure 7, some changes in the current behavior are observed for specimens with 0.1% and 0.3% fibers (still negligible compared to GPC beams with holes), while those with no-fiber and 0.5% fiber reinforcement never showed any change in corrosion current. Therefore, no conclusions could be drawn regarding the influence of fibers in the corrosion current behavior of GPC beams without the drilled holes.

5.2 Cracking Evaluation

Once the beams were removed from the seawater, the cracks on each beam were measured to the nearest millimeter. A method of crack scoring (Reddy et al. 2012) was used to analyze the amount of cracking on each beam. Crack scoring takes into account the number of cracks on each beam, the average crack length of all the cracks, and the average maximum width of each crack, Eq. (1). The number of cracks is multiplied by the average widths and lengths of the cracks to obtain a beam’s approximate total cracked area. This evaluation was done separately for beams with holes and without holes. Crack scores for beams with the same fiber amounts were added together to give a final crack score, and a rank from 1 to 4 (1 being the best) was assigned, as shown in Tables 3 and 4.

$$Crack\ Score = \sum [(No.\ of\ cracks) \times (Avg.\ crack\ length) \times (Avg.\ crack\ width)] \dots\dots\dots(1)$$

5.2.1 Crack score of GPC beams without drilled holes

For specimens without drilled holes, the crack scoring gave an indication of the resistance to corrosion of the geopolymer concrete cover, with and without fibers (Table 3). The GPC beams with 0.1% fiber reinforcement showed the most amount of cracking. This was followed by the beam with 0.3% fiber reinforcement, which only showed small amounts of corrosion-induced cracking. The beams with no fiber and 0.5% fibers showed no cracking, consistent with the measured corrosion current behavior (Figure 7).

5.2.2 Crack score of GPC beams with drilled holes (artificial corrosion conduits)

For GPC specimens with drilled holes, the crack scoring can help determine the effects of fibers in arresting cracks once corrosion has begun to take place (Table 4). Based on the crack scores, the GPC beams that showed the least amount of cracking were the ones with 0.1% and 0.3% fiber reinforcement. GPC beams with no fiber reinforcement suffered the greatest amount of cracking on the surface. These observations indicate that fiber reinforcement can be beneficial in arresting the propagation of corrosion cracks in GPC.

5.3 Mass Loss

The amount of mass loss to the rebar could be used to analyze the corrosion resistance of each mix, since more the specimen cracks, the greater the amount of seawater solution that can reach the rebar, allowing for greater corrosion. The steel rebars, which were weighed before casting into each beam, were weighed again after autopsy. In Phase I, it was found that only OPC beams experienced corrosion of the reinforcement, with an average mass loss of about 60%, while the GPC beams did not experience any corrosion and had no mass loss (Reddy et al. 2013). In Phase II, in which corrosion of the reinforcement was induced in some beams, the mass loss is indicative of how fibers affected the initiation of corrosion and the crack propagation in GPC beams. Figure 8 shows typical rebars retrieved from the beams. The mass loss of each beam is shown in Figure 9.

5.3.1 Mass loss in GPC beams without drilled holes

For GPC beams without drilled holes, the mass loss followed a similar pattern to the crack scoring, where the beam with 0.1% fiber reinforcement had the greatest mass loss. Unlike the observation in the crack scoring, the beam with no fiber reinforcement did experience some mass loss, which indicates that corrosion may have taken place. The beam with 0.5% fiber reinforcement did not

experience any mass loss, which may indicate that corrosion of the steel rebar had not begun to take place in this beam.

5.3.2 Mass loss in GPC beams with drilled holes (artificial corrosion conduits)

For beams with drilled holes, the corrosion process was purposely induced, with corrosion occurring primarily at the points where the holes were drilled. Based on the mass loss data for these specimens, beams with no fiber reinforcement had the greatest mass loss. The lowest mass loss was seen in specimens with 0.1% fiber reinforcement. This again indicates the need for identifying the optimum amount of fiber reinforcement that would be the most effective for reducing the effects of corrosion-induced damage in GPC.

5.4 Residual Flexural Load Capacity

At the completion of accelerated corrosion testing, residual load capacities were determined by testing corroded beams in third-point flexural loading until failure, as shown in Figure 10. The measured flexural load capacities during the test are shown in Table 5. From Phase I data it is clearly observed that the average residual flexural capacity for GPC beams were significantly higher (more than double) than the OPC beams. Comparing data for GPC beams with no drilled holes in Phase II show that addition of 0.3 to 0.5% fibers significantly increased the residual load carrying capacity. In general, the average capacity of specimens with drilled holes (subjected to modified corrosion testing procedure) was lower than that of the corresponding beam with no drilled holes (which was expected). Corroded beams with fiber reinforcement were able to maintain their integrity for a longer period before reaching failure load possibly due to fiber bridging action that is known to delay crack propagation in concrete. Specimens with 0.5% fiber reinforcement, on the average, reached the highest flexural load. The results indicate that fiber reinforcement in GPC

can significantly improve the residual flexural load carrying capacity after corrosion damage has taken place.

6.0 CONCLUSIONS

The purpose of this research was to study the corrosion properties of fly ash-based geopolymer concrete, with or without fiber reinforcement, as a sustainable and alternative structural material in the coastal/marine environment. It is to be noted that the need for heat curing may limit the energy saving benefits and the use of GPC in large practical applications. As reported by Meesala et al. (2020), some information is available in the literature on the effects of curing temperature, duration of curing, and the molarity of NaOH on the strength and durability properties of GPC; however, there is a need for design optimization studies to achieve a target GPC strength. Similarly, more research is needed on the properties of GPC under ambient temperature for widespread use of this promising material in cast-in-situ field applications. In the recent years, researchers have been developing more user-friendly activators with near-neutral salts with promising benefits. For example, Bernal (2016) described the advances in the use of near-neutral salts as activators for producing alkali-activated slag cements with reduced alkalinity, thus minimizing the risk associated with handling highly alkaline materials in routine construction.

The process of corrosion in embedded steel reinforcement in actual field conditions can be quite different from the processes in the accelerated corrosion tests (simulated aggressive environment) used in the laboratory. However, since the depassivation of steel in the accelerated laboratory tests can be achieved in days, rather than years or even decades, that could be needed in the field environment, there is significant motivation behind developing accelerated testing protocols that can potentially save time and resources. Moreover, numerous variations in materials, mix-designs, activator selections, and curing conditions can be evaluated rather quickly using accelerated tests,

similar to what was used in this study. It needs to be emphasized that due to the difference in the field and laboratory mechanisms, the results of laboratory tests should not be used for the estimation of remaining life of corroded reinforced concrete structures, until further studies are conducted to develop better correlations between the field and laboratory corrosion behavior.

Significant conclusions from the study are as follows:

- GPC has a greater electrical resistivity than ordinary Portland cement concrete (OPC), due to reduced permeability in the GPC.
- Based on the crack scoring ranks for GPC beams with artificial corrosion conduits, the fiber-reinforced specimens in general showed greater resistance to corrosion, while the GPC beams with no fiber reinforcement suffered the greatest amount of cracking on the surface. The fiber reinforced corroded GPC beams (with 0.1 to 0.5% fibers) showed a 24% reduction in average crack scores, compared to unreinforced corroded GPC beams (Table 4).
- Although GPC specimens (with artificial corrosion conduits) began to show signs of steel rebar corrosion faster, the mass loss of beams containing fibers was less than that for beams without fibers (Figure 9). This indicates that fiber addition can help reduce corrosion damage.
- Residual flexural load carrying capacity for corroded GPC beams were significantly higher (more than double) than the OPC beams. Addition of 0.1 to 0.5% fibers increased the residual average load carrying capacity of corroded GPC beams by as much as 109% (Table 5).
- Modification of the accelerated corrosion test procedures by introducing artificial corrosion conduits (drilled holes) allowed the evaluation of the corrosion resistance of GPC beams and the effect of fiber reinforcement on crack propagation. In contrast, the GPC beams without drilled holes (Phase I) suffered no mass loss as reported by Reddy et al. (2013). As future studies are undertaken on the corrosion resistance of GPC, the simple method of creating

artificial corrosion conduits may be useful for comparative evaluations of the impact of various supplementary materials, mix designs, and fibers or other synthetic inclusions. More research is needed to assess the impact and design of the artificial corrosion conduits in laboratory

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Table 1: OPC and GPC mix design

Materials		GPC Mix	OPC Mix (kg/m ³)	
		Weight (kg/m ³)		
Coarse aggregate	12.7 mm	272	Portland Cement	449
	9.5 mm	368		
	6.35 mm	641		
Fine sand		545	Water	256
Fly ash		400		
Sodium silicate solution		103	Coarse Aggregate	1,297
Sodium hydroxide solution		40.8 [8M], [14M]		
Superplasticizer		6	Fine Aggregate	561
Polyolefin fibers (by volume)		0.1%, 0.3%, 0.5%		

Table 2: Composition of fly ash

Chemical Composition (%)	Fly Ash
Silicon Dioxide (SiO ₂)	52.90
Aluminum Oxide (Al ₂ O ₃)	28.21
Calcium Oxide (CaO)	3.00
Magnesium Oxide (MgO)	5.21
Ferric Oxide (Fe ₂ O ₃)	5.31
Sulfur Trioxide (SO ₃)	0.68
Loss On Ignition	3.90
Specific Gravity	2.31

Table 3: Crack scoring for GPC without drilled holes (Notation: GPC (sample#)-%fiber)

Specimen	Average maximum crack width, in (mm)	Average crack length, in (mm)	Number of cracks	Crack area per specimen, in ² (mm ²)	Crack score per group, in ² (mm ²)	Rank
GPC 3-0	0.000	0.000	0	0.000	0.000	1
GPC 6-0.1	0.040 (1.013)	25.098 (63.750)	8	0.800 (516.375)	0.800 (516.375)	4
GPC 8-0.3	0.002 (0.050)	27.559 (70.000)	1	0.005 (3.500)	0.005 (3.500)	3
GPC 12-0.5	0.000	0.000	0	0.000	0.000	1

Table 4: Crack scoring for GPC with drilled holes (Notation: GPC (sample#)-%fiber)

Specimen	Average maximum crack width, in (mm)	Average crack length, in (mm)	Number of cracks	Crack area per specimen, in ² (mm ²)	Crack score per group, in ² (mm ²)	Rank
GPC 1-0	0.037 (0.933)	4.243 (107.772)	9	1.413 (911.611)	1.945 (1254.836)	4
GPC 2-0	0.013 (0.338)	5.118 (130.000)	8	0.532 (343.225)		
GPC 4-0.1	0.018 (0.450)	6.468 (164.286)	7	0.815 (525.805)	1.470 (948.385)	2
GPC 5-0.1	0.015 (0.388)	10.925 (277.500)	4	0.655 (422.579)		
GPC 7-0.3	0.007 (0.179)	7.424 (188.569)	7	0.363 (234.193)	1.221 (787.740)	1
GPC 9-0.3	0.020 (0.514)	6.131 (155.727)	7	0.858 (553.547)		
GPC 10-0.5	0.030 (0.763)	8.071 (205.000)	4	0.968 (624.514)	1.740 (1122.578)	3
GPC 11-0.5	0.018 (0.450)	10.728 (272.500)	4	0.772 (498.063)		

Table 5: Residual flexural load capacities for GPC specimens

Specimen	Maximum flexural load (kN)	
Phase I		
OPC (avg.)	13.5	
GPC 8M (avg.)	31.4	
GPC 14M (avg.)	33.6	
Phase II		
GPC 1-0	24.9	Drilled holes
GPC 2-0	26.2	Drilled holes
GPC 3-0	72.9	No hole
GPC 4-0.1	12.6	Drilled holes
GPC 5-0.1	40.8	Drilled holes
GPC 6-0.1	34.6	No hole
GPC 7-0.3	67.4	Drilled holes
GPC 8-0.3	91.4	No hole
GPC 9-0.3	33.2	Drilled holes
GPC 10-0.5	31.5	Drilled holes
GPC 11-0.5	76.4	Drilled holes
GPC 12-0.5	94.3	No hole

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Sulfur Trioxide (SO ₃)	0.68
Loss On Ignition	3.90
Specific Gravity	2.31

Table 3: Crack scoring for GPC without drilled holes (Notation: GPC (sample#)-%fiber)

Specimen	Average maximum crack width, in (mm)	Average crack length, in (mm)	Number of cracks	Crack area per specimen, in ² (mm ²)	Crack score per group, in ² (mm ²)	Rank
GPC 3-0	0.000	0.000	0	0.000	0.000	1
GPC 6-0.1	0.040 (1.013)	25.098 (63.750)	8	0.800 (516.375)	0.800 (516.375)	4
GPC 8-0.3	0.002 (0.050)	27.559 (70.000)	1	0.005 (3.500)	0.005 (3.500)	3
GPC 12-0.5	0.000	0.000	0	0.000	0.000	1

Table 4: Crack scoring for GPC with drilled holes (Notation: GPC (sample#)-%fiber)

Specimen	Average maximum crack width, in (mm)	Average crack length, in (mm)	Number of cracks	Crack area per specimen, in ² (mm ²)	Crack score per group, in ² (mm ²)	Rank
GPC 1-0	0.037 (0.933)	42.432 (107.778)	9	1.403 (905.333)	1.947 (1256.333)	4
GPC 2-0	0.013 (0.338)	51.181 (130.000)	8	0.544 (351.000)		
GPC 4-0.1	0.018 (0.450)	64.679 (164.286)	7	0.802 (517.500)	1.469 (947.625)	2
GPC 5-0.1	0.015 (0.388)	109.252 (277.500)	4	0.667 (430.125)		
GPC 7-0.3	0.007 (0.179)	74.241 (188.571)	7	0.365 (235.714)	1.234 (796.286)	1
GPC 9-0.3	0.020 (0.514)	61.305 (155.714)	7	0.869 (560.571)		
GPC 10-0.5	0.030 (0.763)	80.709 (205.000)	4	0.969 (625.250)	1.729 (1115.750)	3
GPC 11-0.5	0.018 (0.450)	107.284 (272.500)	4	0.760 (490.500)		

Table 5: Residual flexural load capacities for GPC specimens

Specimen	Maximum flexural load (kN)	
Phase I		
OPC (avg.)	13.5	
GPC 8M (avg.)	31.4	
GPC 14M (avg.)	33.6	
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GPC 1-0	24.9	Drilled holes
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