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REPAIR OF CORRODED RC BEAMS

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Twelve prototype rectangular RC beams (120 x 150 x 1000 mm) were constructed and evaluated using flexural test to investigate the employment of advanced composites in repairing corroded reinforced concrete (RC) beams. Three concrete mixtures with effective w/c ratio of 0.4 and cement content of 370 kg/m^3 were utilized in the study: control ordinary Portland cement concrete, silica fume (SF) and ground granulated blast furnace slag (GGBFS) concrete mixes. The RC beams (reinforced with two steel bars having diameter of 12 mm) were immersed (after 28 days of curing) in 2.5% NaCl solution and exposed to accelerated corrosion process using impressed electrical current. The corroded RC beams were repaired using advanced composite of carbon fiber reinforced polymer (CFRP) sheets. The CFRP sheets measuring 300-mm width by 0.131-mm thickness were used to rehabilitate and restore the mechanical behavior of the corroded and damaged RC beams. The investigation results confirmed that the corrosion of steel reinforcement caused significant deterioration and reduction of flexural capacity. The corroded SF and GGBFS beams showed higher flexural capacity compared to the corroded OPC beams. The repaired SF and GGBFS beams showed higher ductility and performance gain in the flexural capacity compared to the repaired OPC beams.

Keywords: Silica fume, Slag, Corrosion, Chloride, Concrete.

1 INTRODUCTION

Reinforcing steel is normally well protected against corrosion by embedment in high-quality concrete. The concrete high alkaline environment induces passive film around the steel reinforcement that protects the steel from corrosion. However, the penetration of chloride ions in sufficient amount (above threshold level) to the depth of the reinforcing steel breaks the passive film and initiates corrosion (Alonso *et al.* 2000). Different sources of chloride may come from deicing salts, seawater and some chemical admixtures (such as set accelerator). Marine structures such as bridges, piers, off-shore structures, etc. are exposed to high chloride environment that come from sea water that can penetrate with time into the reinforced concrete (RC) structures and causes severe corrosion (Scott and Alexander 2007). The development of corrosion products cause volume increase that consequently cause expansion, cracking and spalling of the concrete cover. Additionally, the corrosion cause reduction in the cross sectional area of the steel bars that jeopardizes the structural safety of the RC structures exposed to corrosion (Vu *et al.* 2005).

The penetration of chloride into the concrete depends on many factors including: permeability of concrete, w/c ratio, presence of mineral admixtures, and presence of cracks in the RC structure. Three factors should be present for the corrosion to occur including: moisture, oxygen and chloride. Variations in the amount of chloride, moisture, or oxygen at different points along the reinforcing steel bar, or between different steel bars, develop voltage differentials that greatly increase the rate of corrosion (Mechers and Li 2006)

The rehabilitation of damaged RC members such as beams, slabs and columns are well recognized to be practical and feasible solutions to restore the structural capacity of the deficient structural members. Many factors may induce damage and deterioration in the RC members including over-load, sulfate attack, alkali-silica reaction and corrosion of steel reinforcements. Several techniques may be applied to repair and retrofit the deteriorated structural members including: bonding of steel plate, enlarge the member's section, use of ferrocement and using advanced composites of fiber-reinforced polymers (FRP). The FRP is considered an innovative technique to repair, retrofit and restore the serviceability of the deteriorated structural elements (Chen and Teng 2003, Bousselham and Chaallal 2004, Adhikary and Mutsuyoshi 2006, Aslam *et al.* 2015).

The use of mineral admixtures such as silica fume (SF), pulverized fly ash (PFA) and ground-granulated blast furnace slag (GGBFS) in concrete mixtures is well established to have a very beneficial influence that improve significantly the mechanical properties and the durability of concrete. This study investigates the effect of SF and GGBFS on the performance and repair of corroded and deteriorated RC beams using advanced composite materials.

2 DESCRIPTION OF TEST PROGRAM

2.1 Materials

Type I Ordinary Portland cement (OPC) was used in the study. Micro-silica having specific gravity of 2.22 and Blaine fineness of 19,200 m^2/kg was employed in this study. The GGBFS used has specific gravity of 2.91 and specific surface area (using Blaine method) of 419 m^2/kg. Crushed limestone coarse aggregate with maximum aggregate size of 20 mm, bulk specific gravity of 2.62 and absorption of 2.3% was utilized in the study. Dune sand fine aggregate with bulk specific gravity of 2.6 and absorption of 2.2% was utilized in preparing the concrete mixture. High range water reducer (Superplasticizer) was used in all concrete mixtures (at 1.3% by weight of cement) to obtain workable fresh concrete with slump ranged from 22 to 26 cm. Steel reinforcement having diameter of 12 mm of Grade 60 steel was employed for the main reinforcement of the RC beams with yield stress of 420 MPa. An advanced composite material consists of carbon fiber reinforced polymers (CFRP) sheets measuring 300 mm width by 0.131 mm thickness were used to rehabilitate and restore the mechanical behavior of the corroded and damaged RC beams.

2.2 Concrete Mixtures

Three concrete mixtures with effective water to binder (w/b) ratio of 0.40 were prepared and utilized in the study. The cement content was 370 kg/m^3, the coarse aggregate content was 1100 kg/m^3 and the fine aggregate content was 70% of the coarse aggregate content. Table 1 shows the concrete mixture components per cubic meter.

Table 1. Concrete mix design, slump, and strength.

Mix	Cement (kg)	SF (kg)	GGBFS (kg)	Water (kg)	CA (kg)	FA (kg)	Slump (cm)	f_c' (MPa)
OPC	370	0	0	147	1100	765	22	30
SF	333	37	0	147	1100	765	23	42
GGBFS	148	0	222	147	1100	765	26	24

CA = Coarse aggregate, FA = Fine aggregate, f_c' = compressive strength at 28 days

2.3 Corrosion Exposure

An accelerated corrosion procedure using impressed electrical direct current (DC) of 2 mA/cm^2 of the surface area of the reinforcing steel was utilized. The beams were immersed in a water tank containing 2.5% NaCl solution. The steel bars were connected to the positive DC current and a steel plate immersed in the tank was connected to the negative DC current. The corrosion process was monitored periodically every 12 hours using visual observations of the beam.

2.4 Repairing Procedure

The rehabilitation process of the corroded beams was pursed as following: The concrete surface was cleaned thoroughly using a brush. The CFRP fabric sheets were cut into pieces of one meter in length. The epoxy resin was prepared by mixing two parts using laboratory mixer for two minutes. The epoxy was spread over the bottom surface and the sides of the beam. The CFRP fabric sheets were placed onto the resin coating and squeezed using a plastic roller until the epoxy was distributed evenly over the whole CFRP fabric surface. A thin layer of the epoxy was spread over the surface of the fabric sheets. The epoxy was cured at laboratory temperature of about 21 C for 3 days.

3 RESULTS AND DISCUSSION

3.1 Concrete Strength Properties

As shown in Table 1, the SF concrete compressive strength increased significantly from 30 MPa for the OPC to 42 MPa with percent increase of 40%. However, the GGBFS concrete compressive strength reduced from 30 MPa to 24 MPa with percent reduction of 20%. The increase in the strength of SF concrete is due to the high reactivity of the SF. Nevertheless, the decrease in the strength of the GGBFS is due to the low reactivity of GGBFS as pozzolanic material and the high content of GGBFS (60%) as a replacement of cement used in the concrete mix.

3.2 Intact Beams

Figure 1 shows the load-deflection behavior of the intact RC beams before exposed to corrosion. As shown in the figure, both the SF and GGBFS reinforced concrete beams showed higher flexural capacity performance compared to the OPC beams. The stiffness of the SF and GGBFS beams increased significantly compared to that of OPC beams. Also, the SF beams reached higher ultimate load of 46 kN compared to the GGBFS that reached 39 kN and the OPC that reached 40 kN which is about 1.15 times the results of OPC and GGBFS. This behavior may be due that the SF concrete has higher 28 days compressive strength (42 MPa) compared to that of the OPC concrete (30 MPa) and GGBFS concrete (24 MPa). Both the OPC and GGBFS reached almost the same ultimate maximum load. The SF beams were also more ductile and reached higher ultimate deflection of 4.3 mm compared to 4 mm for the OPC and 3.6 mm for the GGBFS beams.

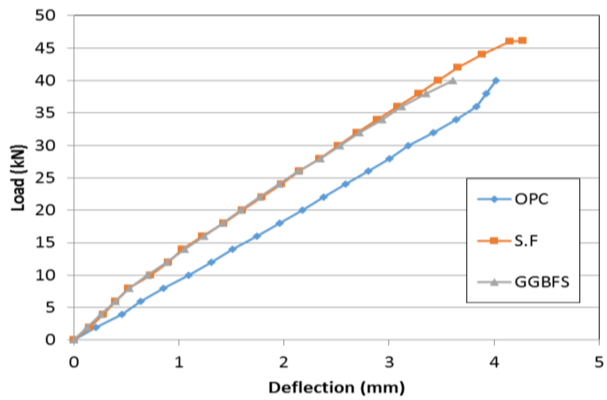

Figure 1. Load-deflection behavior for the RC beams before corrosion.

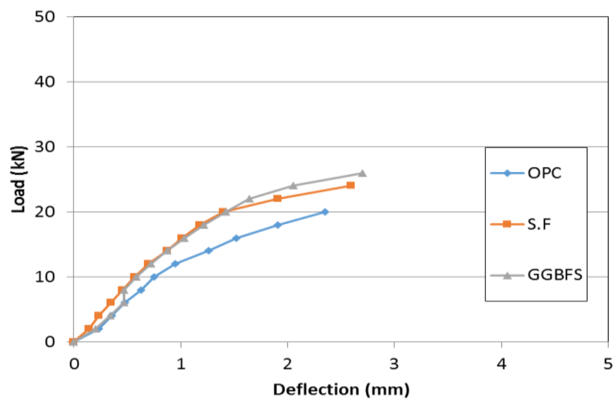

Figure 2. Load-deflection behavior for the corroded RC beams.

3.3 Corroded Beams

Figure 2 shows the load-deflection behavior of the corroded RC beams under flexural loading test. It is obvious that the RC beams containing SF and GGBFS showed higher performance to corrosion compared to the OPC beams. The ultimate load of the GGBFS and SF beams reached 26 and 24 kN, respectively, compared to 20 kN for the OPC beams. The percent reduction in the ultimate flexural load capacity for the OPC, SF and GGBFS were 50%, 48% and 33%, respectively. The use of 60% GGBFS replacement by cement concrete improved the performance of RC beams against corrosion compared to the OPC and SF concrete. The superiority performance of GGBFS in resisting the corrosion of reinforcing steel may be explained that the GGBFS particles effectively bind the chloride ions that initiate the corrosion of the steel bars.

3.4 Repaired Beams

Figure 3 presents the load-deflection behavior of the repaired beams. The RC beams containing mineral admixtures shows higher ultimate flexural load capacity compared to the OPC beams. The ultimate load capacity of the SF and GGBFS beams were 22 and 18 kN compared to 14 kN for the OPC beams. The GGBFS beams showed the highest deflection value of 3 mm compared to 1.9 mm for the OPC beams and 2.5 mm for the SF beams. The repaired SF and GGBFS beams showed higher ductility compared to the OPC beams. The SF beams exhibited the highest ultimate flexural load of 22 kN with percent gain of 48% from the intact original flexural load (before corrosion and deterioration) compared to 18 kN ultimate flexural capacity for the GGBFS with percent gain of 45% and 14 kN for the OPC with percent gain of 35%. The repaired SF and GGBFS beams showed higher performance gain in the flexural capacity compared to the repaired OPC beams.

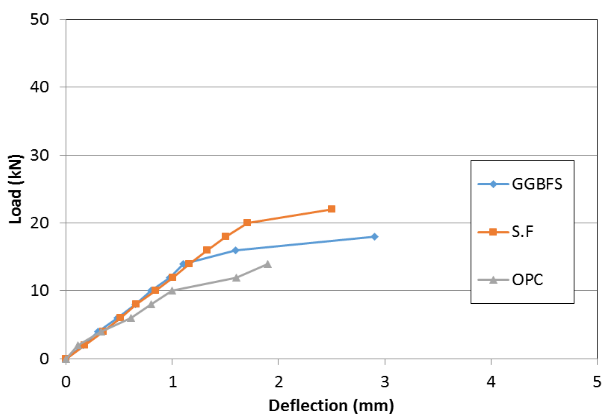

Figure 3. Load-deflection behavior for the repaired RC beams.

4 CONCLUSIONS

The followings can be concluded from the results of the study:

1. Both the SF and GGBFS reinforced concrete beams showed higher flexural capacity performance compared to the control beams. The stiffness of the SF and GGBFS beams increased significantly compared to those of the control beams.
2. The GGBFS beams showed the highest performance to corrosion with 33% reduction in the ultimate load, then the SF beams with 48% reduction. The control RC beams had 50% reduction in the ultimate flexural load capacity.

3. The rehabilitated SF and GGBFS beams exhibited higher ductility and flexural capacity gain of 48% and 45%, respectively, compared to the rehabilitated OPC beams that gained 35% of the ultimate flexural load capacity.

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