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Durability of CFRP strengthened RC beams under wetting and drying cycles of magnesium sulfate attack

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Abstract. Durability of strengthened reinforced concrete (RC) beams with CFRP sheets under wetting and drying cycles of magnesium sulfate attack is investigated in this research. Accordingly, 18 RC beams were designed and made where 10 of them were strengthened by CFRP sheets at their tension side. Magnesium sulfate attack and wetting and drying cycles with water and magnesium sulfate solution were considered as exposure conditions. Finally, flexural performance of the beams was measured before and after 5 months of exposure. Results indicated that the bending capacity of the strengthened RC beams was reduced about 10% after 5 months of immersion in the magnesium sulfate solution. Wetting and drying cycles of magnesium sulfate solution reduced the bending capacity of the strengthened RC beams about 7%. Also, flexural capacity reduction of the strengthened RC beams in water and under wetting and drying cycles of water was negligible.

Keywords: durability; reinforced concrete beams; strengthening; CFRP; sulfate attack; wetting and drying cycles

1. Introduction

Most of the reinforced concrete structures have been destroyed due to the chemical and physical attacks such as sulfates and chloride attacks and other corrosive environments. Therefore, it is necessary to repair, reconstruct or replace the damaged member or structure which consequently creates engineering and social problems. When concrete structures are exposed to the sulfate solutions, cracks are formed in the concrete due to the precipitation of the expansive products such as ettringite or gypsum which increase the permeability of the concrete and as a result the permeation of the corrosive solutions is facilitated and consequently the damages are accelerated. Magnesium sulfate attack has a more destructive impact in comparison with the other sulfates, since in addition to the formation of gypsum and ettringite, calcium silicate hydrate can be decomposed during the attack (Mehta and Monteiro 1992). Also, wetting and drying cycles accelerate mechanism of the attack due to the salt deposition during the drying cycle which leads to formation of additional cracks in the concrete (Ferraris *et al*. 2006, Nehdi *et al*. 2014, Ouyang *et al*. 2014). Therefore, the lifetime of reinforced concrete structures is decreased in such corrosive environments.

Hence, maintenance of the damaged concrete structures is necessary. In addition, strengthening of concrete structures is inevitable due to upgrading of design codes, unsuitable construction and changing of the service loads (Duthinh and Starnes 2004). Using fiber reinforced polymers (FRPs) to repair the concrete members is a pretty effective method. Suitable properties of FRP materials such as resistivity to corrosion, very high tensile strength (up to 7 times higher than steel), resistivity to fatigue and creep, acceptable modulus of elasticity, low density and proper adhesion with concrete attract researchers to use FRP materials in the strengthening of the reinforced concrete structures (Chajes *et al*. 1995, Eldin *et al*. 2017).

Several researches have been carried out on the durability of FRP composites, during recent years (Al-Salloum 2011, Katsuki and Uomoto 1995, Dimitrienko 1999, Rostasy 1997, Kerr and Haskins 1982, Mufti *et al*. 2007, Uomoto and Nishimura 1999). For instance, Katsuki and Uomoto (1995) studied the FRP rebars performance under alkali attack. They expressed that GFRP rebars showed about 70% decrease in sodium hydroxide solution (1 mol/l) at 40℃ after 120 days of exposure. Rostasy (1997) reported considerable decrease in GFRP tensile strength after exposing GFRP sheets in sodium hydroxide (1 mol/l) at 23℃ after 100 hours.

Also, durability of concrete members strengthened with FRP composites has been studied under special environmental conditions (Bellakehal *et al*. 2013, Elkady and Hasan 2010, Duthinh and Starnes 2004, Chajes *et al*. 1995, Hamada *et al*. 1992, Ren *et al*. 2003, Naderi and Hajinasiri 2011, Silva and Biscaia 2008, Tang 2018, Tatar and Hamilton 2016, Toutanji and Ortiz 1997, Yun and Wu 2011, Zhou *et al*. 2015). Chajes *et al*. (1995) studied the flexural capacity of reinforced concrete beams strengthened with AFRP, CFRP and GFRP sheets under wetting-drying and freezing-thawing cycles. Results showed a 36%

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Table 1 Chemical composition of the cement

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O
%	62.15	21.91	5.05	4.45	2.27	2.19	0.31

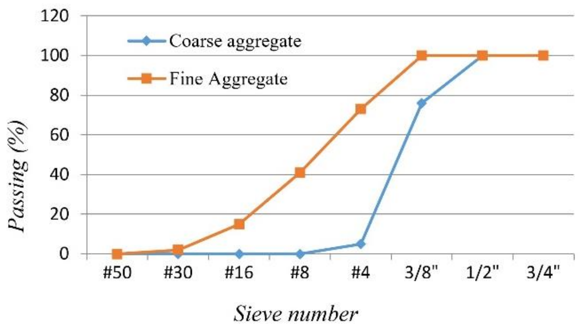

Fig. 1 Coarse and fine aggregate grading curves

Table 2 Aggregate properties

Aggregate type	Specific gravity (kg/m^3)	Water absorption (%)	Fineness modulus
Coarse	2670	1.26	-
Fine	2620	0.78%	3.0

Table 3 Properties of the CFRP materials

Fiber Type	Fiber nominal thickness (mm)	Modulus of elasticity (GPa)	Tensile strength (MPa)	Weight per unit area (gr/m^2)
CFRP	0.17	230	3900	306

Table 4 Resin properties

Resin Type	Tensile strength (MPa)	Strain at failure point (%)	Flexural modulus (MPa)
Epoxy	30	0.9	3800

decrease in the bending capacity of the strengthened beams with AFRP and GFRP and 19% decrease in the bending capacity of the strengthened beams with CFRP after 100 wetting and drying cycles. Bending capacity reduction of the strengthened beams with AFRP, GFRP and CFRP sheets after 100 freezing and thawing cycles was reported to be 21, 27 and 9 percent, respectively. Zhou *et al*. (2015) have used a high-temperature sulfate solution with dry-wet cycle to simulate the external sulfate attack on the externally bonded FRP-strengthened concrete elements and the mechanical performances of the concrete, FRPs, adhesive and the bond performance deterioration of an FRP-to-concrete interface were tested and analyzed. They have developed bond-slip models of FRP-to-concrete interface based on the materials-degradation and the sulfate-induced corrosion in the depth of concrete.

In the present study, resistance of CFRP strengthened RC beams under magnesium sulfate attack is studied. Therefore, the reinforced concrete beams were strengthened with CFRP sheets after 28 days of curing and kept 5 months in 4% magnesium sulfate solution and water. Also wetting and drying cycles of water and magnesium sulfate solution for 5 months are carried out separately. Finally, all beams were tested through the 3 point flexural test set-up.

2. Materials

2.1 Cement

Locally sourced ordinary Portland cement type II was used in this research. Table 1 presents the chemical composition of the cement.

2.2 Aggregates

The maximum nominal size of the coarse crashed aggregates was considered to be 11 mm regarding to the cover of the reinforcements on the stirrups (see Fig. 2). Locally sourced washed sand is used as fine aggregate to make the fresh concrete. The grading curves of the aggregates are presented in Fig. 1. Table 2 presents additional properties of the aggregates which were determined according to ASTM standard test methods.

2.3 Steel

Longitudinal steel bars and stirrups with 12 and 8 mm of diameters were used in the reinforced concrete beams, respectively. Their yield and ultimate stress were 400 and 600 MPa, respectively.

2.4 FRP and resin

CFRP sheets, which have a suitable resistance to alkali and acidic environments and other corrosive conditions (Uomoto and Nishimura 1999), were used for the strengthening of the reinforced concrete beams. Also, two parts of epoxy resin were mixed by hand with 1:2 ratio and then used for strengthening. Tables 3 and 4 present CFRP and the resin properties, respectively.

2.5 Corrosive environments

Reinforced concrete beams strengthened with CFRP sheets and cubical samples were kept in water and 4% magnesium sulfate solution for 5 months. Four kilograms of solid magnesium sulfate was dissolved in 100 liters of water to prepare 4% magnesium sulfate solution as the corrosive environment. In addition, wetting and drying cycles are separately considered to accelerate corrosion process.

3. Experimental program

3.1 Reinforced concrete beams

The strengthened and un-strengthened reinforced concrete beams were designed according to Iranian national building regulations considering 1000 mm of length and 14 mm of reinforcement cover. The regulations suggest 0.0035 for the ultimate compressive strain of the concrete and use Whitney’s equivalent rectangular block to calculate the

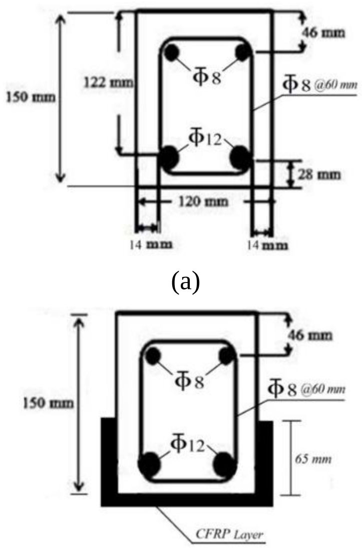

Fig. 2 Cross section of the reinforced concrete beams, (a)Un-strengthened, (b)Strengthened

Table 5 Details of the mix design

w/c	Water (kg/m^3)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Slump (cm)
0.45	225.4	500	716.1	843.5	15

Table 6 Beams categorization

Beams group	Number	Strengthening system	Exposure condition
B1	2	Without strengthening (Control beams)	Immersed in water for 28 days
B2	2	Strengthened by a U-shaped CFRP layer after 28 days of water curing	-
B3	2	Without strengthening	Immersed in water for additional 5 months
B4	2	Strengthened by a U-shaped CFRP layer after 28 days	Immersed in water for additional 5 months
B5	2	Strengthened by a U-shaped CFRP layer after 28 days	Immersed in magnesium sulfate for 5 months
B6	2	Without strengthening	Immersed in magnesium sulfate for 5 months
B7	2	Strengthened by a U-shaped CFRP layer after 28 days	Wetting and drying cycles of magnesium sulfate solution for 5 months
B8	2	Without strengthening	Wetting and drying cycles of magnesium sulfate solution for 5 months
B9	2	Strengthened by a U-shaped CFRP layer after 28 days	Wetting and drying cycles of water for 5 months

flexural strength. The cross section of the beams is shown in Fig. 2. In order to prevent shear failure and regarding to the design regulations, the distance between stirrups along the reinforced concrete beams was considered to be 60 mm as shown in Fig. 2.

3.2 Mix design and preparation of the samples

In this research, ACI method was applied to obtain a mix design by assuming the specific strength of 28 MPa and maximum nominal aggregate size of 11 mm. Table 5 presents the details of the mix design. The mixture was mixed two minutes after all materials were added to the mixture in order to reach a uniform mixture. The prepared concrete mixture was placed in three layers in the wooden moulds of the beams and compacted using a rebar with a diameter of 12 mm. Also 8 cubical samples of 10×10×10 cm were casted to investigate the compressive strength and weight loss of the concrete under sulfate attack. After 24 hours of curing, the beams and the cubical samples were demoulded and kept in water for 28 days. Then, the beams were categorized into 9 groups according to Table 6.

For strengthening of the beams, first, a dry surface of the beams was achieved by keeping them in the laboratory environment for 48 hours. Next, the surface of the tensile part of the beams and also 65 mm of the beams height in the shape of a ‘U’ was roughened and cleaned to insure a good adhesion between the adhesive and the concrete surface. Then, the surface of the tensile part of the beams and also 65 mm of the beams height were covered with adhesive with a thickness of 1 mm (see Fig. 2(b)). Subsequently the CFRP sheets were gently adhered to their tensile surface. The length of the CFRP sheets was considered 70 cm in the middle of the beams (see Fig. 3). In order to dry up the epoxy adhesive, the strengthened beams were kept in the laboratory environment for 48 hours.

3.3 Exposure condition

Some of the strengthened and un-strengthened reinforced concrete beams were exposed to 4 percent magnesium sulfate solution for 5 months and some were exposed to wetting and drying cycles of magnesium sulfate in order to simulate tidal conditions. Also, in order to better comparison of the results, similar strengthened and un-strengthened beams were exposed to water and wetting and drying cycles of water for 5 months. Wetting and drying cycles were carried out in 1 day or 24 hours, where the wetting and drying cycles were considered 18 and 8 hours, respectively.

3.4 Experiments

Compressive strength test: The compressive strength test of 10×10×10 cm cube samples was carried out in accordance with BS standard at the ages of 7, 14, 28 and 180 days. The average compressive strength of the samples was reported as the concrete compressive strength.

The Weight loss of the cubical samples in magnesium sulfate solution: In order to measure the weight loss of the concrete samples due to the magnesium sulfate attack, 2 of 10×10×10 cm cube samples were weighed after 28 days of curing in the saturated surface dry (SSD) condition and then

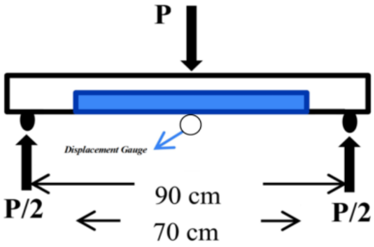

Fig. 3 Schematic loading of the strengthened beam

(a)

(b)

Fig. 4 Beams failure mode (a) Un-strengthened beam (b) Strengthened beam

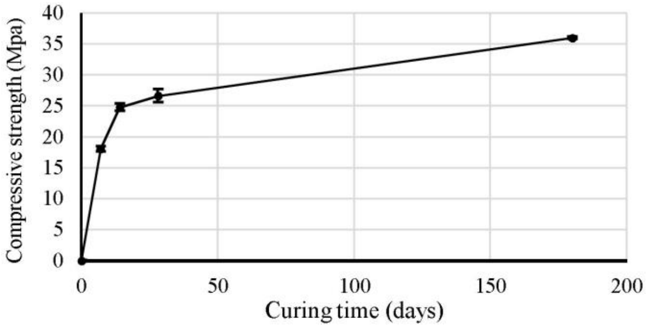

Fig. 5 Increase in compressive strength over curing time

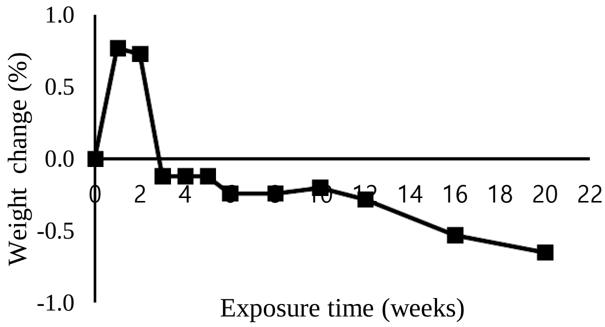

Fig. 6 Weight loss of the concrete samples over exposure time

the samples were immersed in 4 percent magnesium sulfate solution for 5 months. Subsequently, the samples were taken out of the solution at the first, second, third, fourth, fifth, sixth, eighth, tenth, twelfth, sixteenth and twentieth weeks, and washed gently by brush and then were weighed in the SSD condition to calculate their weight loss.

Flexural capacity of the beams: Fig. 3 presents the schematic of 3 point flexural test set-up for a strengthened beam. The beams deflection and the automatic applied load by rate of 0.86 MPa/min were coordinated by embedding a displacement gauge at the middle of the beam and the load was continuously applied and recorded together with the corresponding mid span deflection until the beams were failed.

4. Results and discussions

4.1 Visual observations

No significant degradation on the specimens and beams were seen since the maximum weight loss of the specimens were less than 1%. Failure mode of the control beams was in the flexural mode according to the design of the beams. Flexural or vertical and diagonal cracks were formed in the middle of the beams after applying the maximum load (see Fig. 4(a)). In the strengthened beams, which were in the various environmental conditions, debonding of CFRP sheets were occurred in the form of separation of the end of the strengthened layer of CFRP sheets (see Fig. 4(b)). Formation of the flexural cracks at the middle zone of the beams, increasing the crack width and short height of U-shaped strengthening sheets result in such failure mode.

4.2 Compressive strength test results

Fig. 5 presents increasing of the compressive strength with curing time. In fact, chemical reactions between unhydrated cement particles and water is going on during the curing time and such reactions generate new C-S-H gels and other hydrated products. Those new products fill pores and defects in concrete and consequently improve the compressive strength of the concrete (Yu and Chen 2018). The diagram suggests that the compressive strength of the concrete is about 27 MPa after 28 days of curing.

4.3 Weight loss of the samples exposed to magnesium sulfate solution

Fig. 6 presents the weight loss of the concrete samples where the samples showed an increase in the weight during the first two weeks exposure due to the formation of gypsum. Then, the samples showed a decrease in the weight due to the destructive effect of magnesium sulfate solution.

Several reports state that the usual reaction produce gypsum in hardened concrete during the magnesium sulfate attack according to Eq. (1). Magnesium sulfate solution can

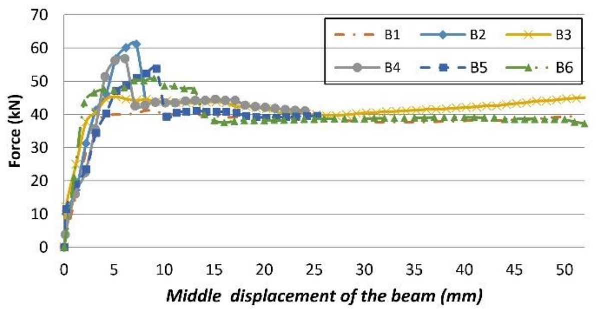

Fig. 7 Load-displacement diagram of un-strengthened and strengthened beams

correspondingly react with C_3A, hydrated C_3A and monosulfate hydrate in hardened concretes to form ettringite. Eq. (2) shows usual ettringite formation, where gypsum ($CaSO_4.2H_2O$) is created by Eq. (1). Also, magnesium sulfate be able to dissolve C-S-H crystals according to Eq. (3). Ettringite formation is responsible for cracking and spalling of concrete elements as a result of expansion (Collepardi 2001, Santhanam *et al*. 2003, Monteny *et al*. 2000). These reactions lead to weight loss of the samples. Moreover, some researchers reported thaumasite formation during the magnesium sulfate attack when carbonate sources are available in the hardened concrete (Iden and Hagelia 2003, Justnes 2003). More details of the magnesium sulfate attack on hardened concretes can be find in the literature.

$$\mathrm{Ca(OH)_2{+}MgSO_4{+}2H_2O \rightarrow CaSO_4.2H_2O + Mg(OH)_2} \quad (1)$$

$$3CaO.Al_2O_3 + 3(CaSO_4.2H_2O) + 26H_2O \rightarrow 3CaO.Al_2O_3.\mathrm{3CaSO_4.32H_2O} \quad (2)$$

$$3CaO.2SiO_2.2H_2O + 3MgSO_4.7H_2O \rightarrow \mathrm{3(CaSO_4.2H_2O) + 3Mg(OH)_2}{+}2SiO_2 \quad (3)$$

4.4 Flexural test results

Results of the flexural tests for the un-strengthened and strengthened beams under various environments are shown in Table 7. Also, increase in the maximum flexural loads in comparison with B1 is calculated to better evaluations. It can be observed that the strengthened beams whether exposed to various environments or not have had a drastic increase (about 34.0-50%) in the flexural capacity in comparison with the control beam. The average of the maximum load for B1 and B2 beams was 41.2 kN and 61.2 kN, respectively, which means the strengthening of the beams with a layer of CFRP has increased the flexural capacity up to 50%. Sudden drop in the applied loads was seen in the strengthened beams due to the separation of CFRP sheets from the concrete beams (see Fig. 4(b)). Results can be discussed in two aspects, first one is the effect of magnesium sulfate solution and the second one is the wetting and drying cycle's effect.

4.4.1 Effect of water and magnesium sulfate solutions

Fig. 7 presents the load-displacement diagrams of the beams were kept in water (B1, B2, B3 and B4) and the beams were exposed to magnesium sulfate solution (B5 and B6). Also, related comparisons of the maximum flexural loads of the beams regarding exposure condition and CFRP strengthening is calculated to better evaluations and are shown in Table 8. Maximum loads of B6 (50.8 kN) and B3 (48.5 kN) (un-strengthened beams under sulfate and water solution), shows 4.7% increase in the flexural capacity and indicates that the effect of magnesium sulfate solution on the flexural capacity of the un-strengthened RC beams after 5 months of exposure can be ignored. However this trend is entirely different for the strengthened beams where the maximum load for B4 (strengthened and kept in water) and B5 (strengthened and immersed in 4 percent magnesium sulfate solution) were 59.5 kN and 55.2 kN, respectively. Considering the fact the failure mode of all strengthened beams is the same, 9.8 and 7.2 percent decrease in the maximum load of B5 in comparison to B2 and B4, respectively, indicates the destructive effect of magnesium sulfate solution on the bond region of CFRP sheets and concrete surface. Moreover, 2.8 percent decrease in the maximum load of B4 in comparison to B2 shows the negligible effect of water saturated on the flexural performance of strengthened beams.

Table 7 Flexural test results

Beam Name	B1	B2	B3	B4	B5	B6	B7	B8	B9
Average of the maximum load (kN)	41.2	61.2	48.5	59.5	55.2	50.8	56.8	45.6	60.5
Increase in the maximum load comparing to B1 (%)	-	48.5	17.7	44.4	34	23.3	37.9	10.7	46.8

Table 8 Effect of magnesium sulfate solution on the flexural strength of the beams

Beam Name	B2	B3	B4	B5	B6
Solution/CFRP strengthening*	-/Y	Water/N	Water/Y	Sulfate/Y	Sulfate/N
Average of the maximum load (kN)	61.2	48.5	59.5	55.2	50.8
Decrease in the maximum load comparing to B2 (%)	-	-	2.8	9.8	-
Decrease in the maximum load comparing to B4 (%)	-	-	-	7.2	-
Decrease in the maximum load comparing to B3 (%)	-	-	-	-	-4.7

*Y for strengthened beams and N for un-strengthened beams

4.4.2 Effect of the wetting and drying cycles of water

Fig. 8 presents the load-displacement diagram of the strengthened beams were kept in water (B2 and B4) and the strengthened beams were exposed to wetting and drying cycles (B9). It is clearly seen that the differences between the maximum loads of the strengthened beams were negligible.

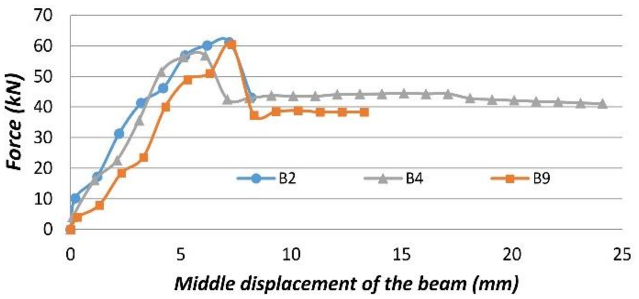

Fig. 8 Load-displacement diagram of strengthened beams under wetting and drying cycles

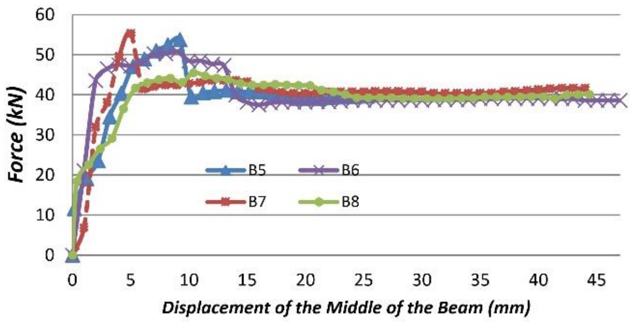

Fig. 9 Load-displacement curve of the strengthened beams under wetting and drying cycles of magnesium sulfate solution

4.4.3 Effect of the wetting and drying cycles of magnesium sulfate solution

Fig. 9 presents the load-displacement diagram of the beams were exposed to magnesium sulfate solution (B5 and B6) and the beams were exposed to wetting and drying cycles of magnesium sulfate solution (B7 and B8). Nevertheless, magnesium sulfate solution decrease the flexural capacity of the strengthened beams about 7.2%, however, the wetting and drying cycles of magnesium sulfate solution does not change the strengthened beams performance in comparison to magnesium sulfate attack (see Table 7 and compare B7 with B5). But, wetting and drying cycles significantly accelerate magnesium sulfate attack on the un-strengthened beams, where B8 beams (exposed to wetting and drying cycles of magnesium sulfate solution) were shown 10.2 percent decrease in the flexural capacity in comparison to B6 Beams (exposed to magnesium sulfate solution). Absorption process is additionally occurred when the wetting and drying cycles of magnesium sulfate are added to the sulfate solution attack which consequently accelerate the penetration process into the substrate of concrete that leads to more decrease in flexural strength of un-strengthened beams.

5. Conclusions

Strengthened and un-strengthened reinforced concrete beams were exposed to magnesium sulfate solution and wetting and drying cycles for 5 months. Then, the flexural capacity of the beams was measured and compared with each other and consequently the following results were obtained:

- The flexural strength of the beams significantly increased after strengthening of the beams with a CFRP layer on the tensile surface.
- The failure mode of all strengthened beams was in the form of CFRP de-bonding at the end of the strengthened region.
- Magnesium sulfate attack decreases the flexural capacity of the strengthened beams. However, wetting and drying cycles did not accelerate magnesium sulfate attack.
- The effect of water and wetting and drying cycles of water on the strengthened beams performance are insignificant.
- Wetting and drying cycles significantly accelerate the magnesium sulfate attack on the un-strengthened beams.

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