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Bond Deterioration of GFRP Concrete Enhanced with Steel Fibers Subjected to External Sulfate Attack

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Abstract—**Concrete structures are exposed to sulfate and chloride attacks when are used in different environments such as seawater, deicing salts or industrial waste. Sulfate corrosion is considered one of the most important factors that responses for deterioration of construction materials performance. When sulfate attacks concrete, sulfate ions interact with cement materials to form chemical compounds inside the concrete. These compounds result volume increase and create internal stresses causing cracks, spalling and reduction in concrete strength. In this paper, the effect of external sulfate attack on properties of concrete samples enhanced with and without steel fibers (SF) and on bond damage between glass fibers reinforced polymer GFRP bar and concrete were investigated. Samples were completely immersed in 10% magnesium sulfate solution for two different exposure periods (60 & 120 days) to compare with control samples. Compressive and tensile strengths, density and pulse velocity were experimentally investigated. Push-out test was also carried out to study the damage in bond between concrete and GFRP rod. The results of concrete samples immersed in magnesium sulfate solution for 60 days showed an increase in compressive strength, tensile strength and density, while the results decreased for samples immersed for 120 days.**

Index Terms: **Sulfate, Crack, GFRP, Steel fibers, Strength.**

I. INTRODUCTION

Sulfate attack is one of the most widespread and common forms of damage to concrete [1]. It is adverse environmental factor on service of concrete structures and reinforcement corrosion [2]. Marine concrete structures frequently suffer from sulfate attack causing deterioration of structural performance (Figure. 1).

External sulfate attack occurs when there is high permeability of cement-based material and sulfate environment presence (Fig. 2) [3]. Sulfate ions penetrate into internal pores and react with cement hydration products to form expansive products of Gypsum and Ettringite leading to expansion, cracking, and degradation of concrete [4-5].

sKanaujia *et al*. [6] examined the influence of different sulfates on concrete properties (compressive and flexural strengths, weight analysis, density loss and visual appearances. Different concrete strength (25. 30 35 MPa) were investigated. Concrete samples were immersed in different sulfate concentrations (4.0pH, 5.0pH and 6.0pH).

They concluded that the reduction in compressive strength loss was noticed when the strength was increased from 25 to 35 MPa. The weight and density analysis also confirmed the compressive strength loss and flexural strength. Discoloration of concrete was clear on the concrete surface when immersed in sulfate solution for 75 and 90days.

Figure 1. Cracking in bridge due to sulfate attack

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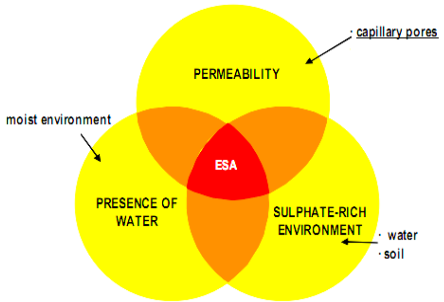

Figure 2. Representation of European Requirements

Guo *et al.* [7] examined the effect of dry–wet cycle periods on properties of concrete due to sulfate attack. Dry–Wet cycle periods (3, 7, 14, and 21 days) were selected with erosion solution prepared with 5% sodium sulfate by weight. After 252 days of sulfate dry–wet cycles, the flexural strength for of the single-cycle specimens (400 × 100 × 100 mm) decreased by 1.05%, 2.7%, 4.2%, and 5.6% on average, respectively.

Microstructural analysis indicated that, with an increase in the dry–wet cycle period, the corrosion depth of sulfate attack increased inside the concrete. However, excessively longing the dry–wet periods does not significantly further the deterioration of concrete's performance. Specimens (100 × 100 × 100 mm) was an initial increase in mass and then decrease; in the early stages, the weight of specimen increased at a rate that increased with longer dry–wet cycles. For dry–wet cycle period of 7 days, the mass was the largest, at about 0.49% compared with the initial value.

This paper presents the effect of external sulfate attack on properties of concrete samples enhanced with and without SF and on bond damage between concrete and GFRP bar.

II. EXPERIMENTAL PROGRAM

Effect of external sulfate attack on plain concrete samples and samples enhanced with SF were experimentally investigated. Samples were completely immersed in 10% magnesium sulfate solution for two different exposure periods (60 & 120 days) to compare with control samples (no exposure). The purpose of using a high concentration of the magnesium solution (10%) is to speed up the reaction process and to get early results. Compressive strength, density and ultrasonic pulse velocity tests using 100 mm cube and tensile strength (100x200 mm cylinder) were experimentally investigated. A push-out test was also carried out on 100 mm cube samples with and without SF and reinforced with one 12 mm-GFRP bar located at the center of the concrete section and fully immersed in 10% magnesium solution for 60 & 120 days. This is to study damage in bond between concrete and GFRP rod.

III. EXPERIMENTAL MATERIALS

The cement used in this study was Portland cement manufactured by Al-Fattaih Cement Factory (Darna – Libya), conforming to BS 12: 1996 [8]. Natural sand with specific gravity of 2.7 and absorption of 2.4% was used [9]. Crushed limestone aggregates were mixed and designated as type 1 and 2 with sizes of (10-20) mm and (5-10) mm, respectively. The properties were; specific gravity (2.6), absorption (2.5%), impact value (10%) and crushing (25%). Properties are measured in accordance with BS 812: Part 2: 1995 [10], BS 812: Part 110: 1990 [11] and BS 812: Part 112: 1990 [12]. The water used in the mixing and curing is potable water.

Hooked-end steel fiber with length of 55 mm, equivalent diameter of 1.0 mm, hook length 2.5 mm and hook height 40 mm (Fig. 3) were used in this research. Steel fiber percentages were added to concrete at 0 and 0.75 by volume of concrete. Fibers are introduced to concrete to increase its tensile capacity (Fig. 3) [13].

Figure 3. Steel fibers added to Concrete

Glass Fiber Reinforced Polymer (GFRP) rebar with 12 mm was selected (Fig. 4). GFRP significantly improves the longevity of civil engineering structures [14] and is the lower cost effective. Other benefits are that they are lightweight; have greater tensile strength than steel; they do not influence to magnetic fields and radio frequencies; they are thermally non-conductive and they are non-corrosive [15]. The bar surface deformation is induced so that mechanical bonding is developed between FRP rebars and concrete. Properties of the GFRP used are given in Table 1.

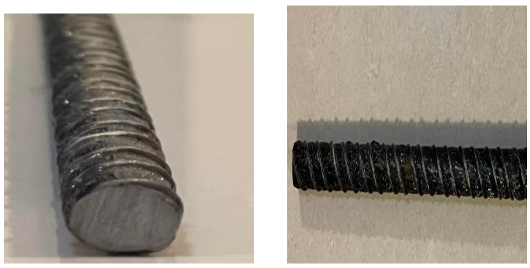

Figure 4. 12 mm GFRP reinforcing bar

Table 1. Properties of GFRP reinforcing bars

Property	GFRP
Density (g/cm^3)	1.25 – 2.1
Nominal Yield Stress, MPa	N/A
Tensile Strength, MPa	483-690
Elastic Modulus, GPa	35-51

IV. CONCRETE MIX DESIGN

Mix design proportioning is designed in accordance with the Building Research Establishment (British Method). Proportioning of concrete mixtures is shown in Table 2. All mixtures were mixed in a laboratory pan mixer with a capacity of 56 liters. The mix ingredients placed in the mixer was in the following order; dry aggregates and cement were mixed in the mixer for 30 seconds. Then, steel fibers were added for 30 seconds and water added gradually (in 15 seconds) and the mixing was continued for 2 minutes, with total mixing time of 3 minutes for each concrete mixture. After mixing, the molds were filled with the two types of concrete (with and without steel fibers) and properly compacted by vibrating table. The top surface was leveled and finished by trowel.

Table 2. Proportioning of concrete mixes (kg/m^3)

Mix	Cement	Water	Sand	Fiber volume	Coarse Aggregate	
					10-20	5-10 mm
SF-0	320	190	720	0	648	432
SF-0.75	320	190	720	59.025	648	432

V. CURING OF TEST SPECIMENS

After casting, the specimens were covered with burlap sheet and left for 24 hours in the molds at 20±2°C (laboratory temperature). After 24 hours, specimens were removed from the molds and kept in water curing for 28 days at 20°C. Thereafter, concrete specimens were fully immersed in magnesium sulfate solution (MgSO4) with concentration of 10% by mass, for (60 &120) days (Figure. 5).

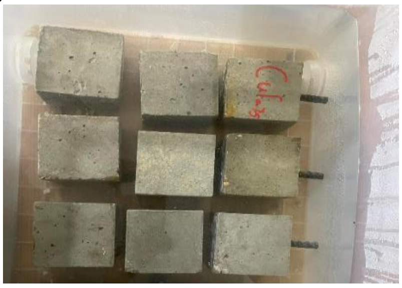

Figure 5. Specimens immersed in 10% MgSO4 solution

VI. RESULTS AND DISCUSSIONS

A. Fresh Mix Properties

Wet density of concrete sample without steel fiber CUF0 (2399 kg/m^3) is lower than concrete enhanced with steel fiber CUF0.75 (2421 kg/m^3) (Figure. 6). The slump decreases with the addition of steel fiber to concrete sample from 65 to 50 mm, respectively (Figure. 7). This is because adding steel fibers in the mix causes better resistance against compaction.

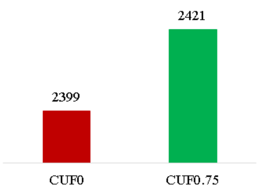

Figure 6. Wet Density of concrete samples (kg/m^3)

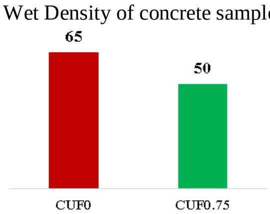

Figure. 7 Slump values (mm)

B. Compressive Strength

Figure 8 shows compressive strength of concrete samples subjected to 10% magnesium sulfate attack. It can be seen from the figure that compressive strengths increase for both plain concrete samples (CUF0) and samples enhanced with steel fibers (CUF0.75) at exposure period of 60 days. Then, the compressive strength slightly decreased at 120 days. This results were also noted by Zhou *et al*. [7].

The increasing and decreasing in compressive strengths are related to reaction of sulfates with hydrated calcium aluminate which produce expansive products, such as ettringite and gypsum. Thus, concrete becomes more compact and its strength is slightly increased in the initial stage of the reaction process. However, with the gradual formation of an expansive stress on concrete through continuous accumulation of expansive products, tensile stress is developed in concrete. When stress exceeds concrete tensile strength, cracks are formed resulting in reduction of compressive strength [16-18].

In comparison to plain concrete samples (CUF0), a higher compressive strength with the addition of steel fibers was observed at all exposure times (Fig. 8). According to study done by Yazıcı et al. [19], the use of steel fiber in concrete increases the compressive strength of concrete by about 4–19%.

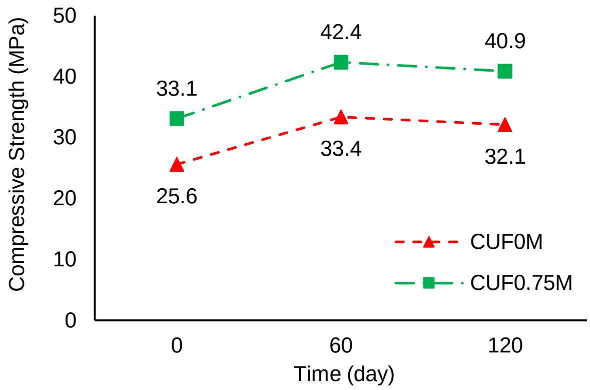

Figure 8 Compressive Strength versus magnesium exposure time

C. Splitting Tensile Strength

Figure 9 shows 10% magnesium sulfate effect on tensile strength of concrete cylinder samples for both plain concrete (CYF0) and concrete enhanced with fibers (CYF0.75). At 60 days of exposure, tensile strength for CYF0.75 sample increased by 34% compared to CYF0 sample without steel fibers (2.9 MPa). At 120 days, the tensile strength of both samples with and without steel fiber decreased to 3.3 & 2.6 MPa compared to values at 60 days. However, the tensile values are still higher the control samples 3.2 & 2.3 MPa, respectively.

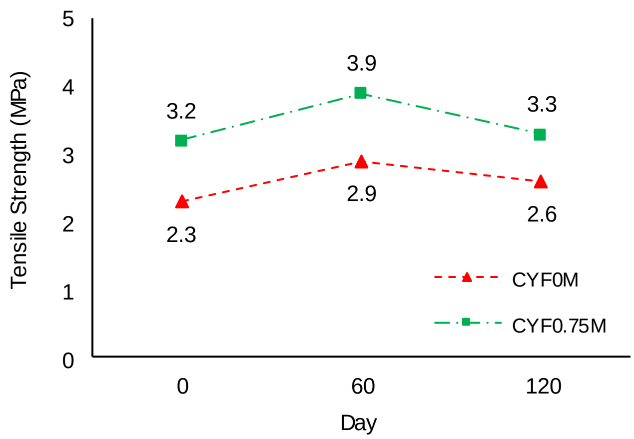

Figure 9 Tensile strength versus magnesium exposure time

Samples with steel fibers (CYF0.75) show higher strength values at all exposure times (0, 60 & 120 days) compared to CYF0 plain samples. This is because the steel fibers significantly increase splitting tensile strength compared to plain concrete as Figure 9 demonstrates [13].

Figure 10 shows plain concrete sample (CYF0) and sample enhanced with steel fibers (CYF0.75) both were exposed to 10% magnesium sulfate for 60 days. It is noted that steel fibers affect failure mode of concrete cylinder samples. It is also noticed that all plain concrete samples exposed to magnesium sulfate or not had a complete splitting (separation of the sample into two parts) at the failure load (Figure. 10), while the samples containing steel fibers did not have a separation despite their cracking and continued to hold together as a result of the effect of fibers that worked to bind the components of the concrete mixture.

CYF0 CYF0.75

Figure 10. Samples after exposed to magnesium (60 days)

D. Density

The weight of control and attacked concrete specimens was monitored for different exposure times (0, 60 & 120 days). Figure 11 shows the effect of magnesium sulfate attack on density for both concrete samples with and without steel fibers. It can be seen for the figure that density of samples without steel fibers (CUF0) increases when immersed in magnesium sulfate up to 60 days compared to control sample (2161 kg/m^3). As mentioned previously, this is due a deposition of corrosion products in the pore spaces at the initial stage of corrosion, which made the concrete more compact [20-21]. At 120 days, the density gradually decreases to 2253 kg/m^3. This is because of stress due to reaction of sulfates with hydrated calcium aluminate exceeds concrete tensile strength and causes cracks resulting in reduction of compressive strength [16-18].

Samples with steel fibers (CUF0.75) show higher density than CF0 plain samples by about 3.3 – 4.9% at exposure periods of 60 and 120 days, respectively, as figure shows.

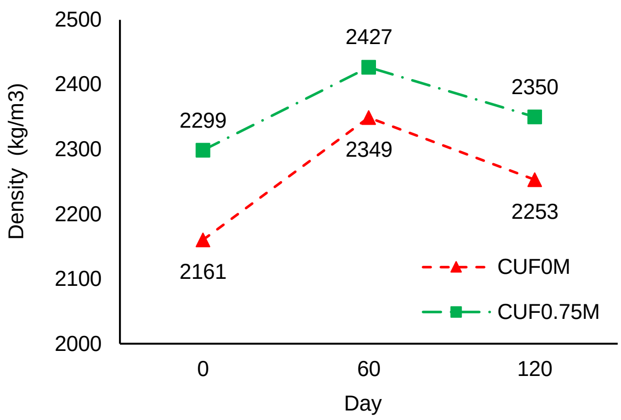

Figure 11. Density versus magnesium exposure time

E. Ultrasonic Velocity

Figure 12 shows magnesium sulfate effect on pulse velocity of plain concrete samples (without steel fibers). It can be seen from figure 12 that the ultrasonic velocity increases at 60 day of corrosion time and then deceases later at 120 days. It is also noted that the ultrasonic velocity has the same shape as the curve obtained from the compressive and tensile strengths of concrete samples. As mentioned previously, when concrete exposed to magnesium sulfate solution, the reaction processes produce ettringite. As a result, concrete volume expands and pores inside concrete are filled with ettringite, concrete compactness increase, and thus the ultrasonic velocity increases. However, with extended sulfate exposure, ettringite and other expansive products accumulate and micro cracks of different sizes are formed inside the concrete samples. The cracking increases the porosity of the concrete and reduces the ultrasonic velocity gradually [22].

The results of ultrasonic velocity for samples enhanced with steel fibers could be affected by steel fibers and do not give an accurate indication of the cracks resulting from the magnesium sulfate attack. This behavior may be interpreted through the fact that the velocity is faster in minerals than in non-metallic materials [23].

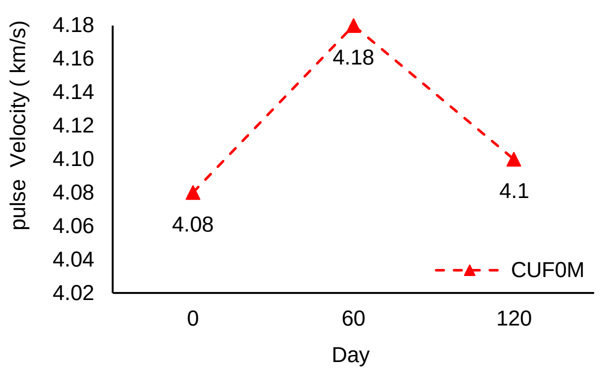

Figure. 12 Ultrasonic velocity versus magnesium exposure time

F. Influence on Mass under Wetting Cycles

The plain concrete samples and concrete samples enhanced with SF were completely immersed in 10% sulfate solution for different exposure times (0, 60 & 120 days), and only SF sample is presented in figures 13, 14 & 15, respectively. After each exposure period, the sample was inspected for any deterioration or damage. It can be seen from figures that edges and surfaces of concrete specimen were peeled and damaged. In addition, some stones inside concrete were exposed, and different degrees of cracks on sample surface were noted. A yellow layer was also observed on the outer surface of concrete samples at exposure time of 60, 120, 180 and 240 days.

G. Effect of sulfate on BOND between GFRP & concrete

a. Load-displacement Curve

The push out test was carried out to study damage in bond between concrete and GFRP rod (Figure. 16). The load-displacement curves for control concrete samples enhanced with and without steel fibers (CPF0 & CPF0.75) are shown in figure 17. The same samples but fully immersed in 10% magnesium sulfate (CPMF0 & CPMF0.75) for 60 days are also shown in figure 16 for compression. It can be seen from figure 17 that all samples show linear behavior increase up to maximum loads. However, the immersed samples (CPMF0 & CPMF0.75) have lower values of ultimate load (Figure. 17).

Figure. 13 Sample with no exposure

Figure 14. Sample after exposed to 10% magnesium (60 days)

Figure 15. Sample after exposed to 10% magnesium (120 days)

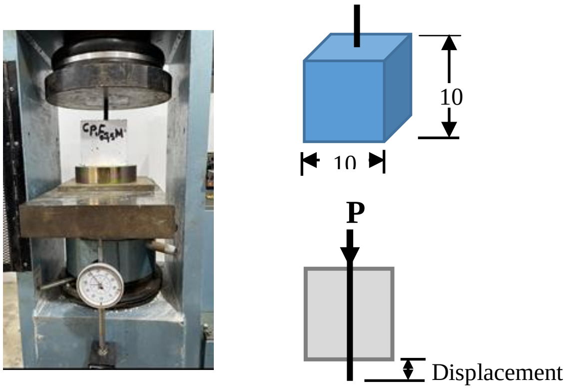

Figure. 16 Push-out Test setup

This behavior may be interpreted to internal damage to concrete due to magnesium sulfate attack. When sulfate attacks concrete, sulfate ions interact with cement materials to form chemical compounds inside the concrete. These compounds result volume increase and create internal stresses causing cracks, spalling and reduction in concrete strength.

Control sample (CPF0.75) having 0.75% steel fibers shows relatively largest toughness (area under curve) compared to control sample without steel fibers (CPF0), and this applies to the same samples, but immersed in 10% magnesium sulfate. This is because of the short discrete fibers delay the propagation of micro-cracks, due to the fact that fibers bridge these cracks and restrain their widening [24] and thus improve in the bond of concrete component.

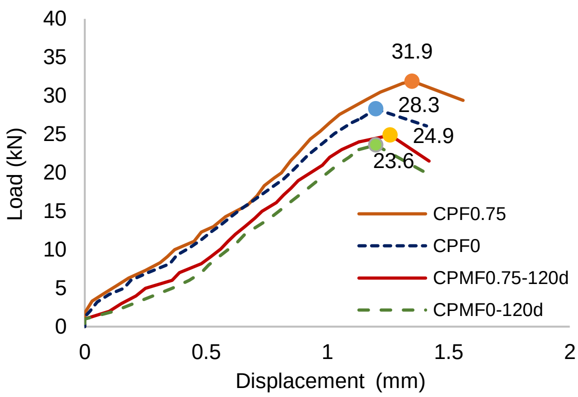

Figure. 17 Load versus displacement

H. Failure Mode

Figure 18 shows plain concrete sample (CPF0, Fig. 18a) and sample enhanced with steel fibers (CPF0.75, Figure. 18b), and figure 19 displays the same two samples but they were exposed to 10% magnesium sulfate for 120 days. It can be seen from figures that plain concrete samples either exposed to magnesium sulfate attack or not failed by splitting at maximum load (figure.18a & figure. 19a). However, samples containing steel fibers did not have a separation into two parts (figure.18b & figure. 19b), and continued to hold together as a result of the effect of fibers that worked to bind the components of the concrete mixture.

a) CPF0 b) CPF0.75

Figure. 18 Control sample (no exposure)

a) CPF0 b) CPF0.75

Figure. 19 Sample after exposed to 10% magnesium (120 days)

VII. CONCLUSIONS

The main findings are:

- Adding steel fibers improved resistance against compaction, and thus the slump decreased.
- Increasing in concrete properties was noted in all samples at shorter attack (60 days), then they slightly decreased at longer exposure (120 days). This is due to expansive products resulted more compacted concrete. Furthermore, with continuous accumulation of products, cracks formed resulting reduction in properties.
- Adding fibers did improve compressive and tensile strengths and density.
- Plain samples exposed to magnesium or not had complete splitting at the failure load, while the SF samples did not have separation despite their cracking and continued to hold together due to fibers.
- All magnesium-treated samples showed that edges and surfaces of samples were peeled and different degrees of cracks on sample surface were also noted.
- In push out test, all magnesium-treated samples had lower ultimate bond loads compared to control samples.
- Plain samples either exposed to magnesium or not failed by splitting at bond failure load. However, SF samples did not have a separation into two parts.

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