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Bond Durability Characteristics of Glass FRP Bars Embedded in Concrete Exposed to Aggressive Environments

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الملخص العربى :

يُعتقد عمومًا ان الاسياخ البوليميرية المقواه بالألياف الزجاجية بديل مقبول للمنشئات الخرسانية المسلحة نظرا لمقاومتها للتآكل على عكس حديد التسليح حيث يكون التآكل مصدر قلق كبير لانخفاض مقاومه المنشئات للأحمال عبر الزمن. بسبب هذه الخاصية ، تم تحفيز المهندسين لاستخدام الاسياخ البوليميرية المقواه بالألياف الزجاجية في المنشئات الخرسانية المسلحة لمجموعة واسعة من التطبيقات. بالإضافة إلى مقاومة الاسياخ البوليميرية المسلحة بالألياف الزجاجية للتآكل فأنها توفر مقاومه شد عالية ، كما انها خفيفة الوزن (4/1 من وزن الحديد) وغير موصله للمجالات المغناطيسية .

في هذه الدراسة ، تمت مقارنة نتائج سلوك التماسك لجميع الاسياخ البوليميرية المسلحة بالألياف الزجاجية في الخرسانة مع اسياخ الحديد لها نفس قطر السيخ وطول السيخ الداخل في القطاع الخرساني. في ظل ظروف بيئية عدوانيه (محلول الكبريتات والكلوريدات).الاسياخ البوليميرية المقواه بالألياف الزجاجية مصنوعة يدويًا باستخدام الموارد المحلية والمواد الخام. وقد اجريت الدراسة الحالية علي تأثير سطح الاسياخ البوليميرية المختلفة (للسطح الناعم - مطلي بالرمل - سطح به نتوءات) على سلوك التماسك المعرضة لظروف بيئية عدوانيه (محلول الكبريتات والكلوريدات) في درجة حرارة الغرفة لمدة 60 يومًا.

وقد كشفت النتائج ان تحسين السطح الخاص بالأسياخ البوليميرية المقواه بالألياف الزجاجية التي لها نفس القطر المستخدم من اسياخ الحديد كان لها تأثير فعال في سلوك التماسك للخرسانة المعرضة لبيئة عدوانيه مقارنه بالعينات التي تم الحصول عليها من حديد التسليح .

Abstract

Fiber reinforced polymer (FRP) reinforcing bars are generally thought to be an acceptable replacement to standard steel reinforcing bars in concrete construction where corrosion is a major concern for the structure's long-term serviceability. Due to this property, engineers have been motivated to use FRP bars in concrete structural elements for a wide range of applications. High strength-to-weight ratios, electromagnetic transparency, and corrosion resistance are only a few of the advantages. In this study, the bond durability of all GFRP bar test specimens in concrete is compared to steel reinforcement of the same bar diameter and implanted length under accelerated hostile environmental conditions (sulfate and chloride solution). The GFRP bars are handmade using local resources and raw materials. The main parameters were the bars' surface enhancement (smooth surface, sand coating, and mechanical) exposed under two aggressive environmental conditions (sulfate and chloride solution) at room temperature for 60 days. The results reveal that the different surface treatments for the same nominal size GFRP rebars have a respectable effect on the bond durability of concrete exposed to aggressive environments, which enhances bond stress and modes of failure compared to specimens notched by steel reinforcement.

Keywords: Durability, Bond Strength, GFRP Bars, Surface enhancement, Pull Out and Aggressive environment.

1.INTRODUCTION:

For the past three decades [1], glass fiber reinforced polymer (GFRP) rebars have been successfully employed as an alternative to typical steel reinforcement for reinforced concrete construction. This is primarily due to corrosion resistance, as opposed to steel rebars. This is why numerous research investigations are focusing on developing this alternative technology for use in coastal applications, where corrosion is the primary cause of deterioration [2-3]. GFRP rebars have a high tensile strength, are lightweight (1/4 the weight of steel), and are magnetic field transparent [4]. GFRP rebars are pultruded composite elements produced from longitudinal glass fibers inserted into a resin matrix, which can be Vinyl Ester or Epoxy. The bond between the GFRP rebars and the concrete is achieved by a variety of surface treatments utilized by different manufacturers. One of the most major roadblocks to the proper development of this technology is the lack of standardization. Today, the GFRP rebar market is diverse, with different producers producing rebars with varying cross-sections (round, oval, quadratic, etc.) and surface modifications (sand coating, helical wrap, lugs, etc.) [1]. This last factor is one of the most significant during the design of GFRP reinforced concrete buildings because a proper bond is required for the composite action of the reinforced concrete system. Despite the fact that the bond coefficient has been evaluated and altered in prior work [6], bond durability and its effects on the system have yet to be addressed. To date, numerous studies have independently validated the durability of the concrete and the GFRP reinforcement in GFRP reinforced concrete structures [2, 5]. However, there isn't enough research to understand how the interface between the two elements deteriorates over time in aggressive conditions like salt solutions (sulfate and chloride). The goal of this study is to detect differences in the bond behavior of several GFRP rebar types (along with their related surface enhancements) and to evaluate the degradation of this mechanical feature over time in coastal areas with accelerated seawater conditions. The findings will provide important information on the long-term performance of GFRP reinforced concrete structures and will aid future studies in optimizing design coefficients while considering bond durability. This paper aims, first, to compare the bond strength of steel reinforcement of the same bar diameter and embedded length to the effect of rebar surface treatment (smooth surface, sand coating, and mechanical); Second, evaluate the bond-to-concrete property of all GFRB bar types test specimens over time under accelerated hostile environmental conditions (sulfate and chloride solutions) and compare the results to steel reinforcement of the same bar diameter and embedded length.

2.Experimental Program

2.1.Concept of Experimentation

The bond specimens were examined according to ASTM D7913 [7] by applying the "pullout" test procedure (ASTM International 2014). All three GFRP rebar types, as well as steel rebar, were divided into control and test groups to evaluate bond strength behavior with a focus on durability. Control group specimens were tested in their normal condition state, while test group specimens were tested after they were conditioned.

As shown in table 1

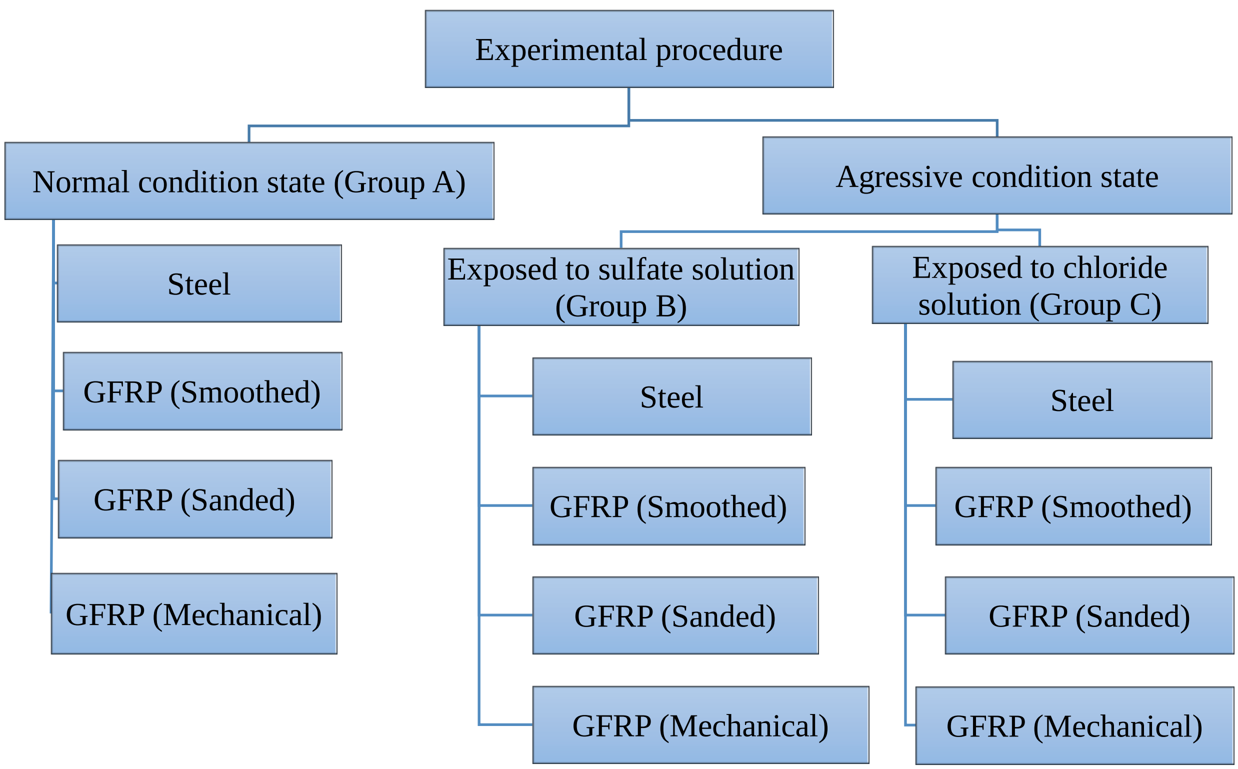


Table 1. Experimental Procedure Flow Chart for pull out test

2.2 GFRP Bar Manufacturing Methodologies

The GFRP bars were handmade using glass fiber roving. [8, 9]. A continuous fiber thread is tensioned between two hooks that are 2.20m apart at first. As illustrated in Fig. (1), to make bars with a length of 2.0 m and a nominal diameter of 12 mm, one hook is fixed, while the other is moveable and connected to a handle. The arm is pushed out and turned after the fibers have been gently wetted out to twist the strands and squeeze out any excess resin. The operation is repeated until there is a clear space of 2.0 m between the hooks, as shown in Fig. (2).

The manufactured GFRP bars are given three different surface treatments. The first type was left untreated, with the bar surface cleaned of any resin buildup to ensure it was entirely smooth. The second type is sand-coated (sanded). The last type was processed by roughing the Sikhs' surface in two directions to raise the process roll fiber inclination angle of 45° on the GFRP bar surface, as illustrated in Figure (3).

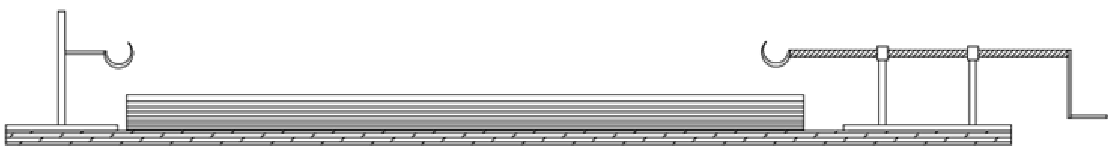


Fig.1. the device for manufacturing

Fig.2. the fiber is rolled in the resins and leaves to harden.

		
Mechanical	**Sanded**	**Smooth**

Fig. 3. Various GFRP surface coatings.

PREPARING THE SPECIMEN

A total of 12 specimens were prepared for the ASTM D7913 [7] ‘pullout' test technique, and another 9 specimens were prepared to determine the compressive strength of the concrete mix. Three cubes for each group were exposed to the same curing process and conditioning exposure as the pullout specimens. The bond specimens were prepared with concrete that has a compressive strength of 35 MPa.

For example, as shown in Figure (4), a250 mm long steel pipe was used to cover the loaded end of the rebar (the end where the load was placed). Along the 250 mm length of the steel tube, a commercial epoxy named "Sikadur-31" was employed. The mixture was poured into the gap between the bars and the steel tubes and allowed to harden for seven days. Due to the poor transverse strength of the FRP rebars, this was necessary.

The opposite end of the rebar, on the other hand, was embedded in a concrete cube of 150 x 150 x 150 mm. The contact (bonded) surface between the concrete and the FRP bar was placed in the center of the concrete cube, 100mm above the bottom surface and the cube's concrete cover. To accomplish the desired embedment length and to ensure no contact between the FRP bar and the concrete at the top region, PVC tubes were placed at the top face of the specimen, above the 8dB contact length. As illustrated in Figures (5) and (6).

Figure (4) Concrete cubes that have been tested.]

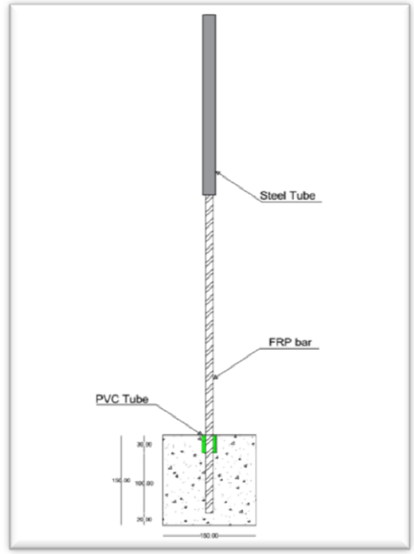


Fig.5 The bars used in this study

Figure 6:Detail of a specimen

Environmental exposure conditions

The bond specimens were exposed to two aggressive environmental conditions to accelerate the degradation of the bond between the GFRP rebars and the concrete. Four samples (one per specimen type) of the total 12 were tested in their normal condition state to provide bench mark values as shown in Figure (7), while the other eight samples were exposed to two different aggressive environments. Four of them (one per specimen type) were submerged in an individual plastic tank containing sulfate solution as shown in Figure (8), at room temperature, for 60 days after they were moist cured for 28 days. To accelerate the sulfate effect, the saline solution consisted of 4.0% sodium sulfate (Na_2SO_4) and 4.0% magnesium sulfate ($MgSO_4$). The solution was replaced every two weeks .The remaining four specimens after the curing process were immersed in a saline solution containing a 3% concentration of sodium chloride (NaCI) [10], which was used to simulate the marine environment in warmer climates, as seen in fig. (9).

Figure (7): Exposure of specimens to tap water

Figure (8): exposure of specimens to a sulfate solution

Figure (9): Exposure of specimens to saline solution

2.6 Testing methods

2.6.1 Compression test

9 specimens were prepared to determine the compressive strength of the concrete mix. Three cubes for each group were exposed to the same curing process and conditioning exposure as the pullout specimens as shown in fig 10.

Fig. 10 the machine for compressive strength testing

2.6.1 Tension test of GFRP bars

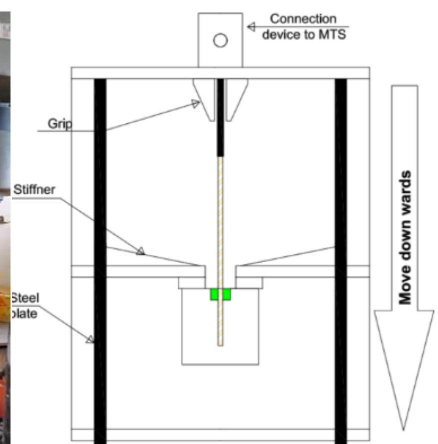
Tensile test were carried out on three GFRP bars as well as one steel bar specimens, in the Housing and Building National Research Center's laboratories using an MTS machine

(HBRC). As shown in Fig. 11, the tension test is set up. The maximum capacity of the MTS machine is 200 KN. The stress –strain curve was measured using the machine's electronic data logger.

Figure (11): Tension testing machine of GFRP bars

2.6.3 The pullout test

The pullout test was carried out in the Housing and Building National Research Center's laboratories using an MTS machine (HBRC). As shown in Fig. 12 (a), the pullout test is set up. The maximum capacity of the MTS machine is 200 KN. Figure 12 (b) shows a schematic representation of the test set up. The load was measured using the machine's electronic loading cell.



(a) (b)

Fig. (12) (a)MTS machine pull-out tests of tested cubes, 200 KN capacity. (b) Pullout specimens are held in a test device.

2.6 Test results and discussion

2.6.1 Compression test results for unconditioned and conditioned specimens

As obtain in Table (2) average compressive strength (MPa) results for unconditioned and conditioned specimens.

condition state	Normal condition state	Exposed to sulfate solution	chloride solution
average compressive strength (MPa)	33.73	16	22

Table (2) average compressive strength (MPa) results

2.6.2 Tension test results of GFRP Bars.

The average tensile strength of GFRP bars with a diameter of 12 mm was experimentally determined to be 607.4 MPa using the testing approaches of ACI committee 440 [11], as shown in Fig. (13).

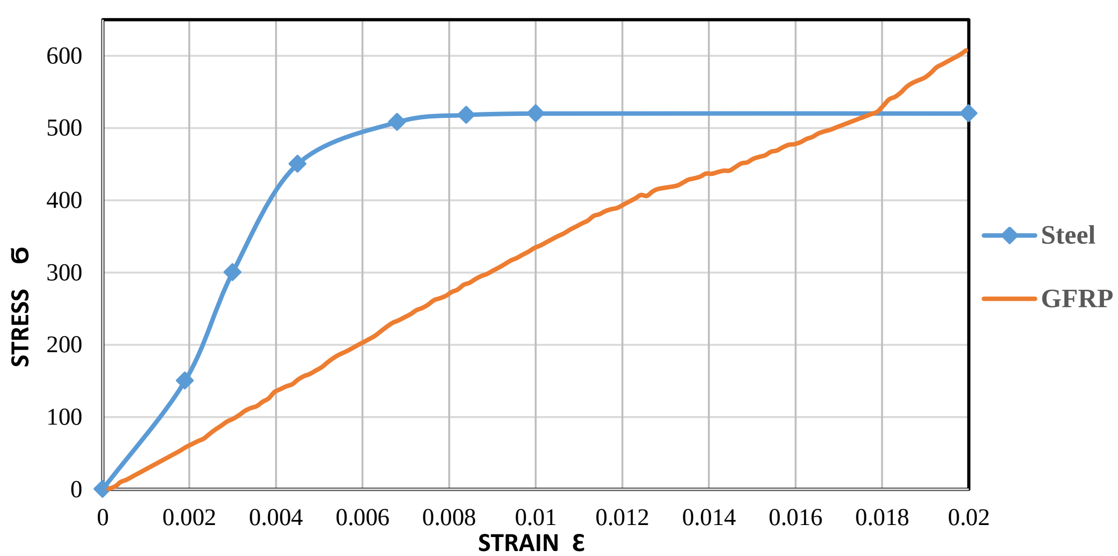


Fig. 13. Stress –strain curve for average tensile strength of GFRP bars and steel bars

2.6.3 Pull out test results of GFRP specimens that have been tested

Table 3.Obtain the pull out test results of GFRP specimens that have been exposed to various environmental conditions.

specimen	Group	Rebar Type	Surface treatment	P_U KN	Δ_U mm	Failure mode	τ MPa
C1	A	Steel	Ribbed	54.5	6.5	slip	14.46
C2	A	GFRP1	Smoothed	27.5	2.5	slip	7.29
C3	A	GFRP2	Sanded	32.7	5.4	slip	8.67
C4	A	GFRP3	Mechanical	45.2	6	splitting	11.98
C5	B	Steel	Ribbed	24.7	5	slip	6.55
C6	B	GFRP1	Smoothed	21.3	2.1	slip	5.65
C7	B	GFRP2	Sanded	33.5	4.8	slip	8.89
C8	B	GFRP3	Mechanical	40.5	5.2	splitting	10.74
C9	C	Steel	Ribbed	31.7	6	splitting	8.4
C10	C	GFRP1	Smoothed	28	2.2	slip	7.43
C11	C	GFRP2	Sanded	42.2	5	slip	11.19
C12	C	GFRP3	Mechanical	52	5.4	splitting	13.8

This test included a total of 12 GFRP-concrete specimens. Because the stress along the embedment length in the pullout test is not evenly distributed, the average bond stress is defined as: $\tau = \frac{P}{\pi \, d_b \, l_d}$

Where P is the tensile load, the experimental results obtained from the pullout test are detailed in Table 1, where P_{max} is the maximum tensile load, and Δ_U is the ultimate displacement of GFRP alimined with the maximum tensile load. Although failure mode has also been mentioned,

By comparing the values mentioned in table 3, it shows that the specimens of notched steel C1, C5, and C9 have an ultimate load equal to 54.5, 24.7, and 31.7 KN, an ultimate displacement equal to 6.5, 5, and 6 mm, and an average bond strength equal to 14.46, 6.55, and 8.4, respectively. It can be said that the ultimate load and an average bond strength for conditioned specimens exposed to sulfate solution C5 decreases from that of unconditioned specimens C1 by about 54.6%, and the ultimate load an average bond strength for conditioned specimens exposed to chloride solution C9 decreases from that of unconditioned specimens C1 by about 42%.

While the value of displacement shows that the specimen of notched steel C1 has a higher displacement than C5, C9 by about 23.1% and 7.7%, respectively.

The mode of failure of C1 and C5 was slip failure, as shown in fig. 14 (a). As for sound, no sound was heard, whereas for splitting failure, a loud sound was heard and occurred in specimens C9 as demonstrated in fig. 14 (b).

(a) (B)

Fig. 14 (a) slip failure for C1, C5 - (b) splitting failure for C9

By analysis of the values mentioned in table 3, it shows that the specimens with a smooth GFRP bar C2, C6, and C10 have an ultimate load equal to 27.5, 21.3, and 28 KN, an ultimate displacement equal to 2.5, 2.1, and 2.2 mm, and average bond strength equal to 7.29, 5.65, and 7.43, respectively. It can be said that the ultimate load for unconditioned specimens C2 has a higher ultimate load and average bond strength than conditioned specimens exposed to sulfate solution C6 by about 22.6%, and a lower ultimate load and an average bond stress than conditioned specimens exposed to chloride solution C10 by about 1.8%.

While the value of displacement shows that the specimen with a smooth GFRP bar C6, which is subjected to sulfate exposure, has a lower displacement than C2, C10by about 16% and 4.6%, respectively.

The mode of failure of C2, C6, and C10 was slip failure, as shown in fig. 15.

Fig. 15 slip failure for C2, C6, and C10

As shown in Table 3. The specimens with sanded GFRP bar C3, C7, and C11 have an ultimate load equal to 32.7, 33.5, and 42.2 KN, an ultimate displacement equal to 5.4, 4.8, and 5 mm, and average bond strength equal to 8.67, 8.89, and 11.19, respectively. It can be said that the ultimate load for conditioned specimens exposed to chloride solution C11 increases from that of unconditioned specimens C3 and that exposed to sulfate C7 by about 22.6%, 20.3, respectively.

While the value of displacement shows that the specimen with a sanded GFRP bar C3, which is unconditioned, has a higher displacement than C7, C11 has by about 12% and 7.3%, respectively. Average bond stress shows a higher value in conditioned specimens C11 exposed to chloride solution than in unconditioned specimens C3 and conditioned specimens exposed to sulfate C7, by about 22.6% and 20.3%, respectively.

The mode of failure of C3, C7, and C11 was slip failure, as shown in fig. 16.

fig. 16 slip failure for C3,C7,C11

By analysis of the values mentioned in table 3, it shows that the specimens with mechanical GFRP bar C4, C8, and C12 have an ultimate load equal to 45.2, 40.5, and 52 KN, an ultimate displacement equal to 6, 5.2, and 5.4 mm, and average bond stress equal to 11.98, 10.47, and 13.8, respectively. It can be said that the ultimate load and average bond stress for conditioned specimens exposed to chloride solution C12 increases from that of unconditioned specimens C4 by about 13.1% and from specimens exposed to sulfate C8 by about 22.2%.

While the value of displacement shows that the specimen with mechanical GFRP bar C4, which is unconditioned, has a higher displacement than C8, C12 has about 13.4% and 10%, respectively.

By comparison, the value of specimens C2, C3, and C4 reinforced by GFRP (smooth, sanded, and mechanical) in an unconditioned state is that specimen C4 shows a higher average bond stress than C2 and C3 by about 39.2%, 27.7%, and displacement (58.4%, 10%), respectively.

The mode of failure of C4, C8, and C12 was splitting failure, as shown in fig. 17.

Fig. 17 splitting failure for C4, C8, C12

By analysis of the values mentioned in table 3, it shows that the unconditioned specimens C1, C2, C3, C4 It can be said that C1, which is reinforced by a steel bar, has a higher ultimate load value and an average bond stress than the other specimens, which are reinforced by GFRP bars (smooth, sanded, or mechanical) by 49.6%, 40.1%, and 17.1%, and respectively.

While the value of displacement shows that the specimen of notched steel C1 has a higher displacement than C2, C3 and C4 have by 61.6%, 17%, and 7.7%, respectively.

By analysis of the values mentioned in table 2, it shows that the conditioned specimens exposed to sulfate solution C5, C6, C7, C8 It can be said that C1, which is reinforced by a steel bar, has a higher ultimate load value and an average bond stress than specimen C6, which is reinforced by a smooth GFRP bar by about 13.8%, and also has a lower ultimate load and an average bond stress than specimens C7 and C8, which are reinforced by (sanded and mechanical) GFRP bars by about 26.27% and 39.1%, respectively.

While the value of displacement shows that the specimen of notched steel C5 has a higher displacement than C6, which is reinforced with smooth and sanded GFRP bar, by about 58% and 4%, respectively. On the other hand, specimen C5 has a lower displacement value by about 3.9% than specimen C8, which is reinforced with a mechanical GFRP bar.

By analysis of the values mentioned in table 3, it shows that the conditioned specimens exposed to chloride solution C9, C10, C11, C12 It can be said that C9, which is reinforced by a steel bar, has a higher ultimate load value and an average bond stress than specimen C10, which is reinforced by a smooth GFRP bar by about 11.7%, and also has a lower ultimate load and an average bond stress than specimens C11 and C12, which are reinforced by (sanded and mechanical) GFRP bars by about 24.9% and 40%, respectively.

The value of displacement shows that the specimen of notched steel C9 has a higher displacement than C10, C11, and C12, which are reinforced with (smooth, sanded, mechanical) GFRP bar by about 63.4%, 16.7%, and 10%.

By comparison, the value of specimens C2, C3, and C4 reinforced by GFRP (smooth, sanded, and mechanical) in an unconditioned state is that specimen C4 shows a higher average bond stress than C2 and C3 by about 39.2%, 27.7%, and displacement (58.4%, 10%), respectively.

By comparison, the value of specimens C6, C7, and C8 reinforced by GFRP (smooth, sanded, and mechanical), respectively, the specimens were conditioned by exposing the specimens to sulfate solution is that specimen C8 shows a higher average bond stress than C6 and C7 by about 47.5%, 17.3%, and displacement (60%, 7.7%), respectively.

By comparison, the values of specimens C10, C11, and C12 reinforced by GFRP (smooth, sanded, and mechanical), respectively, the specimens were conditioned by exposing them to a chloride solution. Specimen C12 shows a higher average bond stress than C10 and C11 by about 46.2%, 19%, and displacement (60%, 7.4%), respectively.

2.7 Conclusion

- When compared to commercial products, the handmade GFRP bars have reasonable mechanical qualities in terms of fiber volume fraction (70%), tensile strength (607.4MPa), and elastic modulus (30370 MPa).
- Test specimens with embedded GFRP mechanical rebars offer the highest bond stresses, followed by sanded coated GFRP rebars after they are conditioned by exposure to (sulfate and chloride) solutions. On the other hand, steel bars and smooth GFRP bars have inferior bond stress after they are conditioned. The last two may lead to 40% and 47.46% weaker bond stresses as compared to mechanical GFRP bars in the state in which the specimens are exposed to sulfate solution and (39% and 48%) in the state in which the specimens are exposed to chloride solution.

- The specimens were conditioned and unconditioned, exhibiting a minor change in displacement compared to specimens notched by steel bars, except the specimens reinforced by GFRP smooth bars, which exhibited a major change of about 62%

REFERENCES :

1. Ruiz Emparanza A, Kampmann R, De Caso F. State-of-the-Practice of Global Manufacturing of FRP Rebar and Specifications. In: ACI Fall Convention, Anaheim. 2017.
2. Robert M, Benmokrane B. Combined effects of saline solution and moist concrete on long-term durability of GFRP reinforcing bars. Constr Build Mater; 38.
3. Chen Y, Davalos JF, Ray I, et al. Accelerated aging tests for evaluations of durability performance of FRP 260 reinforcing bars for concrete structures. Compos Struct 2007; 78: 101–111.
4. Nanni A, Luca A De, Zadeh HJ. Reinforced Concrete with FRP Bars: Mechanics and Design. CRC Press, 262 pp. 23–33.
5. Micelli F, Nanni A. Durability of FRP rods for concrete structures. Constr Build Mater 2004; 18: 491–503.
6. El-Nemr A, Ahmed EA, Barris C, et al. Bond-dependent coefficient of glass- and carbon-FRP bars in 266 normal- and high-strength concretes. Constr Build Mater 2016; 113: 77–89.
7. ASTM International. ASTM D7913 - Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing. 2014. Epub ahead of print 2014.
8. Safaan. ,2004,’’Mechanical Properties of Locally Produced GFRP Concrete Reinforcement”, International conference: Future Vision and Bars as Challenges for Urban Development, HBRC Journal, Vol. 1, No. 1,20-22 D i ISSN 12478/(2004), Cairo, Egypt, pp.1-13.
9. HamdyShehabEldin, Mohamed Hussein, Khalid fawzy Khalil, Shady Khaiiy “Pullout bond behavior of GFRP bars and concrete”, Journal of Al Azhar University Engineering Sector (JAUES), ISSN: 1110-6409, Cairo, Egypt, August (2013).
10. Dong Z, Wu G, Xu B, et al. Bond durability of BFRP bars embedded in concrete under seawater conditions and the long-term bond strength prediction. Mater Des 2016; 92: 552–562.
11. Antonio Nanni,Vernon and Maralee Jones Professor of Civil Engmeering,2004 /‘North American design guidelines for concrete reinforcement and strengthening using FRP: principles, applications and unresolved issues” .Center for Infrastructure Engineering Studies, 1870 Miner Circle, University of Missouri-Rolla, Rolla, USA.