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Utilizing vacuum bagging process to enhance bond strength between FRP sheets and concrete

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Abstract. This paper investigates the effect of utilizing vacuum bagging process to enhance the bond behavior between fiber reinforced polymer (FRP) composites and concrete substrate. Sixty specimens were prepared and tested using double-shear bond test. The effect of various parameters such as vacuum, fiber type, and FRP sheet length and width on the bond strength were investigated. The experimental results revealed that utilizing vacuum leads to improve the bond behavior between FRP composites and concrete. Both the ultimate bond forces and the maximum displacements were enhanced when applying the vacuum which leads to reduction in the amount of FRP materials needed to achieve the required bond strength compared with the un-vacuumed specimens. The efficiency of the enhancement in bond behavior due to vacuum highly depends on the fiber type; using carbon fiber showed higher enhancement in the bond strength compared to the glass fiber when vacuum was applied. On the contrary, specimens with glass fiber showed higher enhancement in the maximum slippage compared to specimens with carbon fibers. Utilizing vacuum does not affect the debonding failure modes but lead to increase in the amount of attached concrete on the surface of the debonded FRP sheet.

Keywords: vacuum; bond; concrete; FRP; slippage; fiber

1. Introduction

In the past few decades, the use of fiber reinforced polymer (FRPs) composites in civil engineering applications has increased steadily due to their remarkable properties such as lightweight, high specific strength, high corrosion resistance and easiness/flexibility to be attached on complex geometries and surfaces. The main use of the FRP composites in civil engineering is in strengthening or repairing new or damaged reinforced concrete structures. Several studies have been conducted on externally bonded FRPs to concrete structures. These studies showed that the use of FRP composites leads to improvement in the flexural and shear capacity of reinforced concrete structural elements (Yuan *et al.* 2004, Xue, Tan and Zeng 2010, You, Choi and Kim 2012, Ferrari, De Hanai and De Souza 2013, Zhou *et al.* 2015, Hadji *et al.* 2016, Godat *et al.* 2017). However, a major drawback was reported regarding the use of the FRP in constructional application, which is the debonding. Debonding or delamination is a serious failure mode in the FRP systems which implies a separation between the FRP and the concrete structure at the interface due to the weak interfacial adhesion (Lu *et al*. 2005, Yuan *et al*. 2004, Zhou *et al*. 2015, Hoque and Jumaat 2018). Several methods have been made to overcome the debonding problem and to enhance the interfacial bonding strength between the FRP and the concrete structure. These methods include: strengthening the polymer matrix by incorporating nanomaterials (Irshidat, Al-Saleh and Al-Shoubaki 2015, Irshidat and Al-Saleh 2016), varying the interfacial bond area between the FRP and concrete (Diab and Farghal 2014, Hosseini and Mostofinejad 2014), utilizing FRPs with different fabric and/or polymer strength capabilities/mechanical properties (Xue, Tan and Zeng 2010, Attari, Amziane and Chemrouk 2012, Hosseini and Mostofinejad 2013), and roughing the concrete interfacial surface (Ha, Na and Lee 2013, Wang, Li and Hu 2014). Irshidat and Al-saleh (Irshidat and Al-Saleh 2016) investigated the effect of incorporating carbon nanotubes (CNTs) in the epoxy matrix on the bond slip between FRP and concrete. Their results showed that incorporating CNTs in the epoxy matrix significantly enhances the bond strength and the maximum slippage of the tested specimens. The SEM revealed that CNT plays a significant role in improving the adhesion between the FRP and the concrete surface, which results in better load transfer between the two constituents. Wang *et al* (Wang, Li and Hu, 2014) were able to strengthen concrete by bonding it to FRP sheet without using any type of adhesive. They used lightweight aggregate to roughen the FRP sheet surface during the production process in order to assure better adhesion with concrete. In another attempt, Hawileh *et al* (Hawileh *et al.* 2014) investigated experimentally and analytically the effect of externally bonded carbon, glass and hybrid fiber reinforced polymer sheets at the reinforced concrete (RC) beam surfaces on their flexural behavior. Their results

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showed 30% to 98% increase in the flexural strength of the strengthened beams compared to the un-strengthened control ones. Also, higher ductility and fracture loads were reported in the beams strengthened with hybrid and glass FRPs compared to the ones strengthened with carbon or the control beams.

On the other hand, few studies focused on enhancing the interfacial bond between the FRP and the concrete structure by eliminating the effect of voids at the FRP/ concrete interface (Yu, Teng and Wong 2010). Voids are trapped air bubbles that emerge at the interface between the FRP and the concrete structure or inside the FRP during the manufacturing process. Voids formation sources include the air trapped inside the liquid polymer during the mixing process, the moisture from the surrounding, the emitted gases from the chemical reaction between the two parts of the polymer matrix, or the small spacing between the fabric tows that may not be fully saturated/wetted with polymer mixture (Dong 2016, Reddy, Krishna and Shanker 2017). Previous studies proved that voids affect the strength, stability, stiffness and service life of the FRP because they behave as stress risers and delamination initiation sites at the FRP/concrete interface (Bowles and Frimpong 1992, Olivier, Cottu and Ferret 1995, Suhot 2010, Sisodia *et al.* 2015, Abdelal and Donaldson 2017).

As clear in the above-mentioned literatures, the most common drawback of using FRP composites in RC strengthening is the debonding mode of failure. In order to solve this issue, most of the previous studies focused on either using epoxy with better properties or enhancing the epoxy properties by adding additives. In addition, all the aforementioned studies focused on techniques that are either expensive, difficult to apply in real life, or require special tools, equipment and specialized preparations in labs. Therefore, this research aims to utilizing an inexpensive and easy to apply method to achieve better adhesion at the interface between FRP and concrete surfaces. The idea of the current study emerged from two concepts: the well-known role of vacuum in eliminating voids in FRPs, and the role of vacuum as a pressure force to create better bonds between FRP and concrete during the curing process of the polymer matrix. A total number of 60 concrete blocks were casted, bonded to FRP sheets, and tested under double-shear test. The effect of applying vacuum during the curing process of the FRP polymer matrix on the bond strength between FRP and concrete substrate was investigated herein. The effect of various parameters on bond strength between FRP sheets and concrete were investigated such as applying the vacuum during the installation of FRP system, bond length, bond width and the type of fiber sheet. Moreover, scanning electron microscopic (SEM) analysis was conducted to investigate the microstructure at the interface of the damaged specimens.

2. Experimental procedure

2.1 Materials

Concrete with 28-day compressive strength of 34 MPa was used in this research to cast the concrete blocks. The

Table 1 Properties of fiber sheets and epoxy

Property	Carbon fiber	Glass fiber
Width (mm)	500	250
Fabric thickness (mm)	0.6	0.6
Tensile strength (MPa)	4900	4000
Tensile E-modulus (GPa)	230	81
Strain at break	2.1%	5.2%

Property	MBrace Saturant
Density (kg/lt)	1.13
Viscosity @ 25°C	4000 ± 500
Tensile strength (MPa)	17

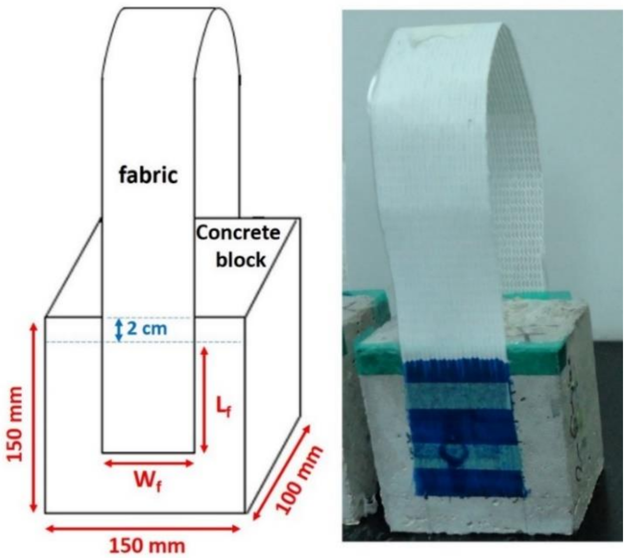

Fig. 1 Configuration of test specimen

FRP composites used in this study consist of two components: the fiber sheets and the epoxy resin. Two types of reinforcing fabrics were used: MBrace CF 230/4900 unidirectional carbon fibers supplied from BASF-Germany and Bruswick U-1301-13oz/yd² unidirectional fiber glass supplied from Fiber Glass Industries Inc-USA. In addition, MBrace Saturant epoxy resin system supplied from BASF-Germany was used. The properties of fibers and epoxy are summarized in Table 1.

2.2 Specimens preparation

The blocks of the fiber-reinforced concrete were fabricated on two stages. At the beginning, the concrete blocks were casted according to the ACI 211 procedure with the following mixed design: 505 kg/m3 Type I Ordinary Portland cement, 830 kg/m3 crushed coarse limestone with a maximum size of 12.5 mm, 110 kg/m3 silica sands, and 440 kg/m3 crushed fine limestone. The mixture was casted in wooden molds for 24 hours, followed by 28 days of wet curing in water to produce a total number of 60 of concrete

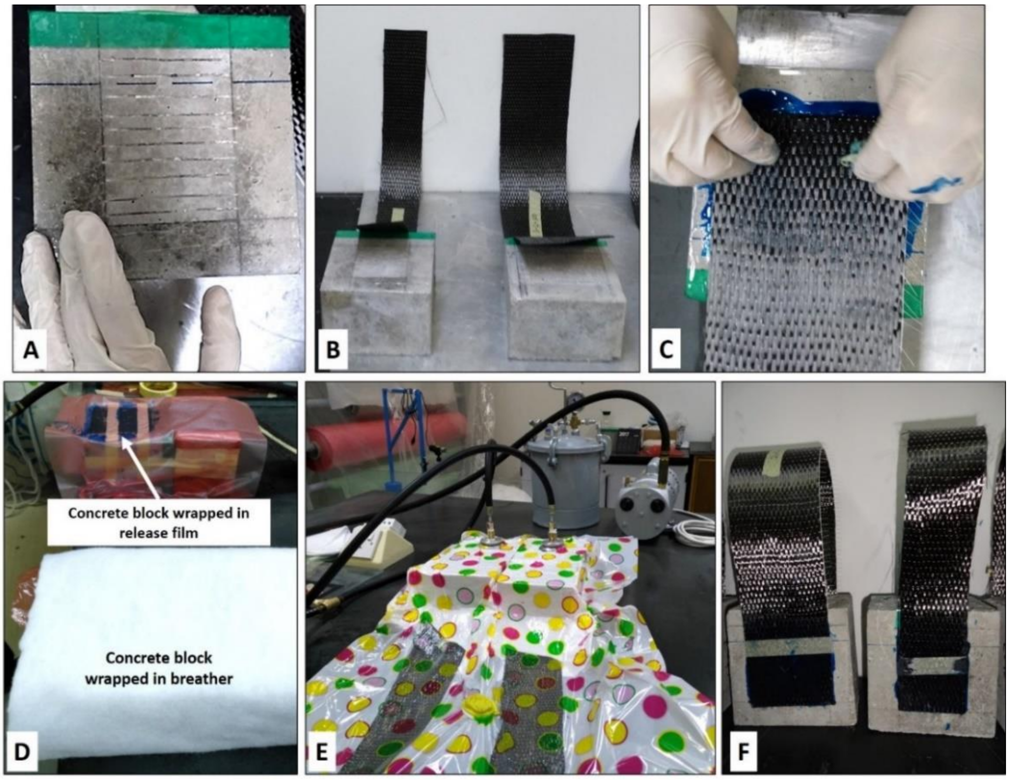

Fig. 2 Specimens preparation (A) Marking the block with dimensions and engraving it (B) Cutting the fabrics into strips (C) Applying epoxy (D) Wrapping the blocks with release film then breather (E) Vacuum bagging setup (F) Concrete blocks with FRP

blocks each with the dimensions of 150 X 150 X 100 mm. On the second stage, carbon and glass fabric strips with different lengths and widths were attached to both sides of the concrete blocks using epoxy mixture either with or without applying vacuum as shown in Figure 1.

The Lf and Wf represent the length and width of the fabric strip attached to the required area on the concrete block, respectively. To avoid stress concentration at the block edge, the bonded area started at 25 mm from the edge of the block as shown in Figure 1. To assure strong bonding/adhesion between the concrete block surface and the FRP, the weak layers of concrete were cleaned and the attachment area was engraved by a diamond grinding disk then cleaned using acetone and pressurized air hose as shown in Figure 2A. The carbon and glass fabric were cut into stripes as shown in Figure 2B. The epoxy was mixed with the curing agent at 100:50 ratio by weight as recommended by the manufacturer. Thin layer of epoxy was applied to the block engraved surface until fully saturated followed by applying the fabrics and pressing it firmly. Another layer of the epoxy mixture was applied to the exterior side of the fabrics until fully impregnated as shown in Figure 2C. To prepare the blocks for the vacuum bagging setup, the block was covered by a release film to prevent it from sticking to the remaining layers of the setup, and then it was wrapped with a breather cloth to allow better distribution of the vacuum as shown in Figure 2D. The entire setup was then inserted in a vacuum bag which was tightly sealed and attached to the vacuum pump through a vacuum port and hoses as shown in Figure 2E.

The setup was left under vacuum for 15 hours at room temperature to assure resin curing under vacuum. A vacuum gauge was connected between the vacuum pump and the setup to assure -27inHg vacuum was maintained during the curing process. After 15 hours, the vacuum bagging was removed, and the same process was repeated for the second side of the block. The block was left to cure under room temperature for 7 days before testing according to the manufacturer recommendations. For the FRP reinforced blocks fabricated with no vacuum, the first stage was the same, but the second stage was done without the vacuum bagging setup. Table 2 summarizes the test program and the specimens' designation.

2.3 Test setup

Double-shear tests were conducted using a computer controlled universal testing machine as shown in Figure 3 to measure the bond-slip behavior between the concrete blocks and the FRP composite system. Three samples of each category were tested under displacement control mode at 0.3 mm/min rate. The force measurements were directly collected by the machine data acquisition system where as the linear variable displacement transducers (LVDTs) were used to collect the displacement readings. After testing, the microstructure of the FRP/concrete interface was characterized on representative specimens from each category using Quanta 450 FEG Environmental scanning electron microscope (ESEM).

Table 2 Test program and specimens designation

Designations	No. of specimens	Fiber Type	Fiber bond length (cm)	Fiber bond width (cm)	Vacuum/No Vacuum
C-No-10-7.5	3	Carbon	10	7.5	No vacuum
C-No-10-10	3	Carbon	10	10	No vacuum
C-No-10-12.5	3	Carbon	10	12.5	No vacuum
C-No-7.5-10	3	Carbon	7.5	10	No vacuum
C-No-12.5-10	3	Carbon	12.5	10	No vacuum
C-V-10-7.5	3	Carbon	10	7.5	Vacuum
C-V-10-10	3	Carbon	10	10	Vacuum
C-V-10-12.5	3	Carbon	10	12.5	Vacuum
C-V-7.5-10	3	Carbon	7.5	10	Vacuum
C-V-12.5-10	3	Carbon	12.5	10	Vacuum
G-No-10-7.5	3	Glass	10	7.5	No vacuum
G-No-10-10	3	Glass	10	10	No vacuum
G-No-10-12.5	3	Glass	10	12.5	No vacuum
G-No-7.5-10	3	Glass	7.5	10	No vacuum
G-No-12.5-10	3	Glass	12.5	10	No vacuum
G-V-10-7.5	3	Glass	10	7.5	Vacuum
G-V-10-10	3	Glass	10	10	Vacuum
G-V-10-12.5	3	Glass	10	12.5	Vacuum
G-V-7.5-10	3	Glass	7.5	10	Vacuum
G-V-12.5-10	3	Glass	12.5	10	Vacuum

3. Results and discussion

The experimental results are divided based on the parameters taken into consideration in this study and affecting the FRP-concrete bond strength. The effect of vacuum, type of fiber, FRP bond length and width on the ultimate bond force and maximum slippage are discussed in the following sections. Failure modes and scanning electron microscopic (SEM) analysis are presented to explore the effect of vacuum process on the failure mechanisms and bond strength enhancement.

3.1 Effect of vacuum

To explore the effect of vacuum on the bond behavior between concrete substrate and FRP strengthening system; the bond force versus slippage curves of representative samples reinforced with carbon and glass fiber sheets are shown in Figure 3. The ultimate force and maximum slippage are summarized in Table 3.

It is clear that there are two regions in each bond force-slip curve; the linear region where the force-slip follow a linear relationship until the initiation of the debonding which is the beginning of a steady state region where there is no significant increase in the bond force with increasing the slippage. In addition, Figures 3A and 3B show that the specimens strengthen with FRP under vacuum have higher bond force and maximum slip compared to the ones without vacuum for both carbon and glass fibers. For instance,

Table 3 Response parameters for tested specimens

Specimen	Ultimate force (KN)	Maximum slippage (mm)
C-No-10-7.5	11.91	0.1998
C-V-10-7.5	24	0.315
C-No-10-12.5	28	0.4128
C-V-10-12.5	44.41	0.495
G-No-10-7.5	13	0.24
G-V-10-7.5	20	0.4
G-No-10-12.5	25.39	0.3792
G-V-10-12.5	33	0.585
C-V-10-10	28	0.405
G-V-10-10	27.2	0.5069
C-V-12.5-10	34	0.485
G-V-12.5-10	36	0.535
C-V-7.5-10	19.12	0.315
G-V-7.5-10	24.65	0.3351

Figure 3A shows that utilizing vacuum lead to 54% and 30% increase in the bond force and 67% and 54% increase in the maximum slippage when using glass fiber with dimensions of 10cm x 7.5cm and 10cmx 12.5cm, respectively. Moreover, Figure 3B shows that utilizing vacuum lead to 102% and 59% increase in the bond force and 58% and 20% increase in maximum slippage when using carbon fiber with dimensions of 10cm x 7.5cm and 10cmx 12.5cm, respectively. It is important to mention that specimens strengthened with both glass and carbon fiber sheets with a total area of 75 cm^2 under vacuum sustain ultimate bond force similar to the ones with 125cm^2 area with no vacuum. That highlights the role of vacuum on reducing the amount of needed materials to achieve same bearing load; thus the cost of strengthening process could be reduced. This behavior can be attributed to the fact that when vacuum is applied during the curing process of the epoxy, it results in a better adhesion and compaction between the FRP and the concrete surface. In addition, vacuum minimizes void content as shown later in the SEM images, which act as crack initiators and debonding sites, thus eliminating debonding, crack initiation and propagation between the FRP and the concrete.

3.2 Effect of bond length

The effect of bond length on the bond strength improvement using vacuum is discussed herein. Figures 4A and 4B show the bond force versus slippage curves of specimens strengthened with glass and carbon fiber sheets with 10 cm width and varied lengths (7.5cm, 10cm, and 12.5cm), respectively. Both figures show an increase in the bond force and maximum slippage with increasing the bond length. For example, Figure 4A and Table 3 show 10% and 46% increase in the bond force when the length of the glass fiber sheet increases from 7.5cm to 10cm and to 12.5 cm, respectively, whereas the ultimate slippage increases by 51% and 60% for the same dimensions. Moreover, carbon

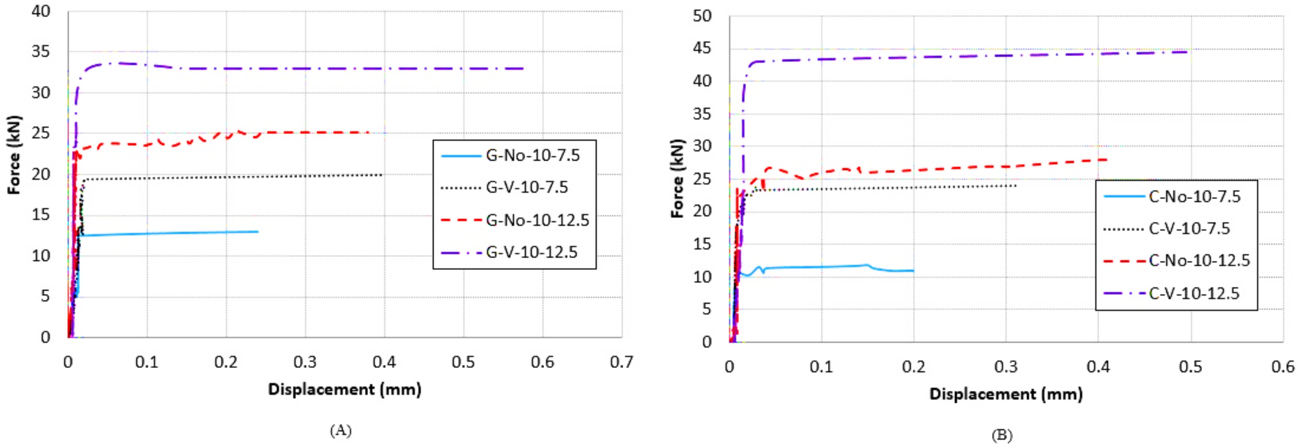

Fig. 3 Effect of vacuum on bond force versus slippage behavior using (A) Glass and (B) Carbon FRP

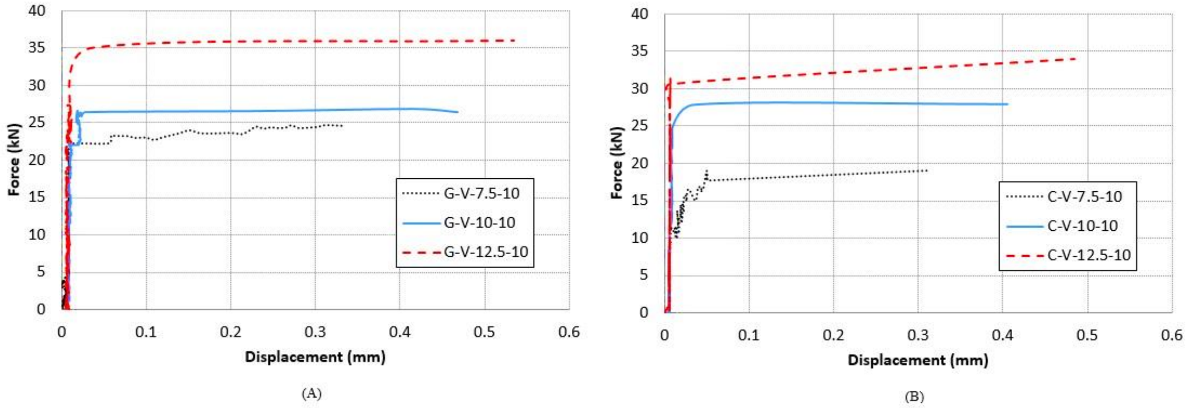

Fig. 4 Effect of bond length on bond force versus slippage behavior using (A) Glass and (B) Carbon FRP

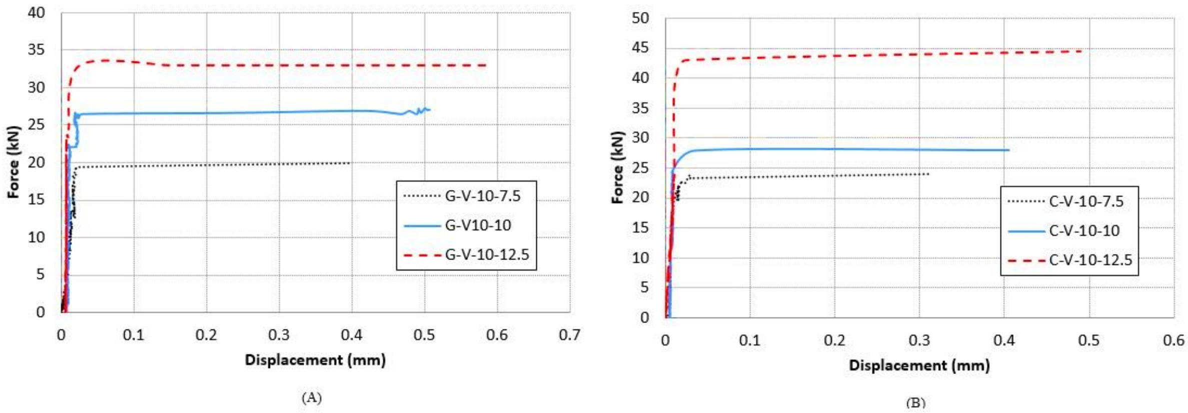

Fig. 5 Effect of bond width on bond force versus slippage behavior using (A) Glass and (B) Carbon FRP

fiber sheet with the same dimensions show 46% and 78% increase in the bond strength and 29% and 54% increase in the ultimate slippage, respectively, as shown in Figure 4B. The improvement in the bond force and ultimate slippage is associated with the larger contact area between the FRP and the concrete (Irshidat and Al-Saleh 2016).

3.3 Effect of bond width

The effect of bond width on the bond strength improvement using vacuum is discussed herein. Figures 5A and 5B show the bond force versus slippage curves of specimens strengthened with glass and carbon fiber sheets with 10 cm length and varied widths (7.5cm, 10cm, and 12.5cm), respectively. Both figures show an increase in the bond force and maximum slippage with increasing the bond width. For example, Figure 5A show 36% and 65% increase in the bond force when the length of the glass fiber sheet increases from 7.5cm to 10cm and to 12.5 cm, respectively, whereas the ultimate slippage increases by 27% and 46% for the same dimensions. Moreover, carbon fiber sheet with

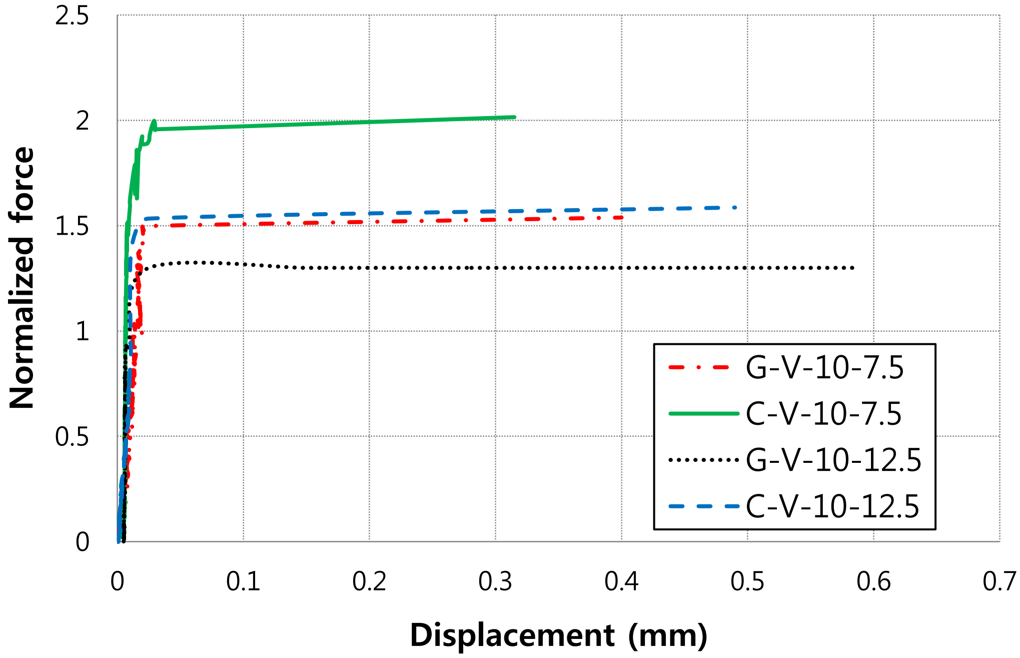

Fig. 6 Effect of fiber type of vacuum process efficiency to enhance the bond behavior between concrete substrate and FRP system

the same dimensions show 17% and 85% increase in the bond strength and 29% and 57% increase in the ultimate slippage, respectively, as shown in Figure 5B The improvement in the bond strength and ultimate slippage is associated with the larger contact area between the FRP and the concrete (Irshidat and Al-Saleh 2016).

3.4 Effect of fiber type

Two types of unidirectional fibers, glass and carbon were used in this study to investigate the effect of fiber type on the efficiency of using vacuum process to enhance the bond behavior between concrete substrate and FRP strengthening system. Normalized bond force versus slippage curves were plotted for vacuum specimens strengthened using either glass or carbon fiber sheets with different bond lengths as shown in Figure 6. The curves were normalized by dividing the load values of the vacuum specimens by the ultimate load of the identical un-vacuum ones. It is clear in Figure 6 that using carbon fiber showed higher enhancement in the bond strength compared to the glass fiber when vacuum was applied. In addition, Table 3 shows that the ultimate load of specimen with carbon fiber (C-V-10-7.5) enhanced by 102% under vacuum, whereas the enhancement was equal to 54% when using the glass fiber (G-V-10-7.5) under vacuum. Moreover, Figure 4 and Table 3 reveal that specimen with carbon fiber shows 78% improvement in the bond strength when changing the bond length from 7.5cm to 12.5cm, whereas specimens with glass fiber show 46% improvement. On the contrary, Figure 6 shows that specimens with glass fiber shows higher enhancement in the maximum slippage compared to specimens with carbon fibers. This behavior could be attributed to the fact that glass fibers have lower stiffness than carbon fiber as shown in Table 1.

3.5 Failure modes and SEM analysis

Figure 7 highlights the effect of applying vacuum process on the failure mode of double-shear bond test specimens. It is clear from the figure that the main failure mode was debonding between the concrete substrate and the FRP system. However, applying vacuum leads to increase the amount of attached concrete on the surface of the debonded FRP sheet. This feature implies a stronger bond between the FRP and concrete under vacuum compared to the one with no vacuum. This behavior may be attributed to the enhancement in the adhesion between the FRP system and concrete when the vacuum was utilized which lead to increase the amount of concrete fragments that attached to the debonded fiber sheet as shown in the SEM images (Figure 8).

4. Conclusion

The effect of utilizing vacuum bagging process on the bond strength between FRP strengthening system and concrete substrate was investigated in this study. Sixty specimens were prepared and tested under double-shear bond test. The results were presented and analyzed to highlight the effect of variable parameters such as applying vacuum, bond length and width, and type of fibers on the bond strength. Failure mode was presented and discussed using scanning electron microscopic imaging. The following conclusions could be drawn.

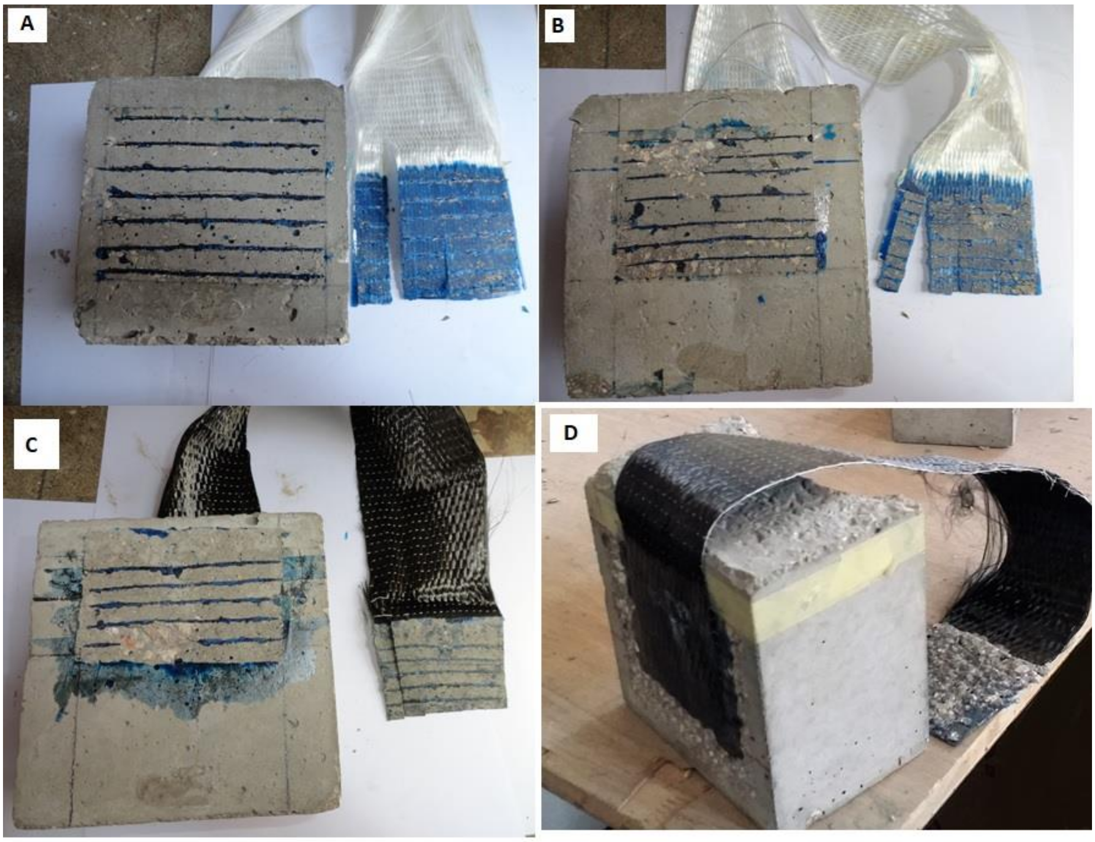

Fig. 7 Failure modes of selected specimens (A) Glass with no vacuum (B) Glass with vacuum (C) Carbon with no vacuum (D) Carbon with vacuum

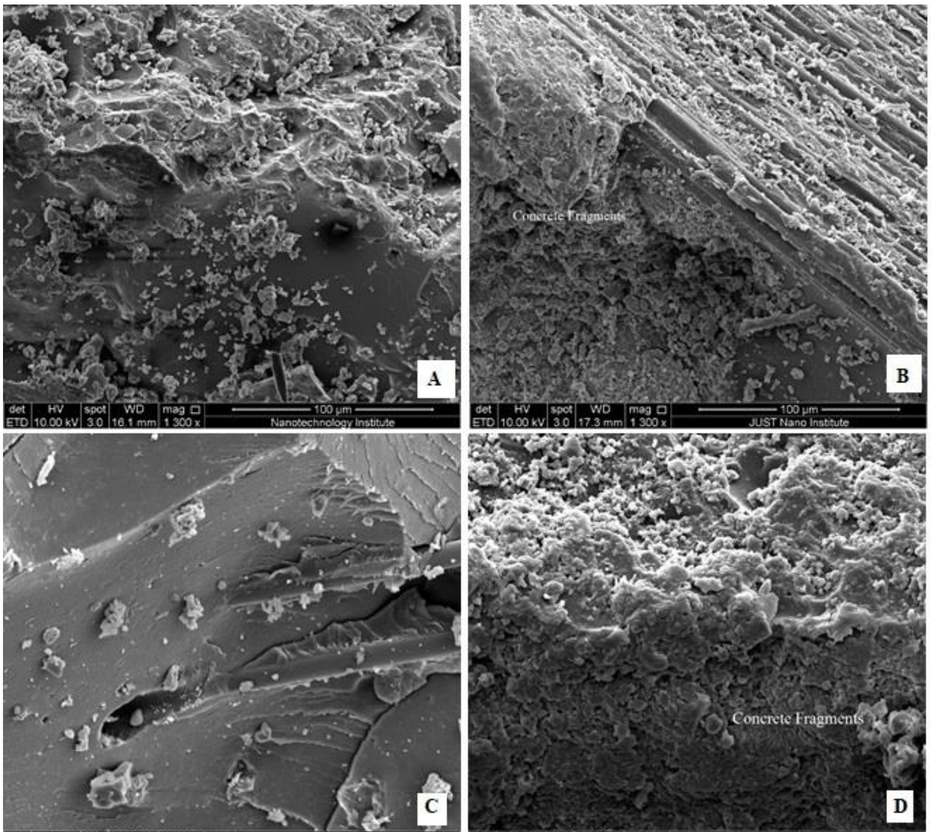

Fig. 8 SEM images of selected specimens (A) Glass with no vacuum (B) Glass with vacuum (C) Carbon with no vacuum (D) Carbon with vacuum

- Utilizing vacuum bagging process when binding FRPs to concrete leads to enhancing the bond behavior between FRP composites and concrete. The ultimate bond force and maximum slippage were increased when applying the vacuum process which leads to reduction the amount of FRP materials needed to achieve the required bond strength.
- The bond force and the maximum slippage increased with increasing the bonded length and width.
- Using carbon fiber as the reinforcement in the FRP/concrete bond showed higher enhancement in the bond strength compared to the glass fiber when vacuum was applied. On the contrary, specimens with glass fiber showed higher enhancement in the maximum slippage compared to specimens with carbon fibers.
- The main failure mode was debonding between the concrete substrate and the FRP system. However, applying vacuum leads to increase in the amount of attached concrete on the surface of the debonded FRP sheet.

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