Article

Bond Strength Properties of GFRP and CFRP according to Concrete Strength

Jusung Kim 1, Sumi Jeong 1, Hojin Kim 1, Youngjin Kim 2 and Sungyu Park 1,*

1 Department of Architectural Engineering, Mokwon University, 88 Doanbukro, Daejeon 35349, Korea
2 Research Center, Korea Concrete Institute, Seoul 06130, Korea
* Correspondence: psg@mokwon.ac.kr; Tel.: +82-42-829-7712

Abstract: Reinforced concrete is the most commonly used material in the construction industry. However, one disadvantage of reinforced concrete is that environmental factors cause materials to penetrate the concrete and cause steel bar corrosion. Rebar corrosion increases its volume significantly by approximately 3–6 times, which lowers concrete–rebar adhesion. This severely affects the serviceability and durability of concrete structures. The economic and social impacts of such deterioration are extremely large. To reduce corrosion, glass fiber-reinforced plastics (GFRP) and carbon fiber-reinforced plastics (CFRP) can be applied to concrete. The rebar–concrete bond strength is an important factor to be considered while applying GFRP and CFRP. Thus, we experimentally investigated the adhesion strength of GFRP and CFRP in relation to the strength of concrete and water–cement ratio according to ASTM C 234 to correlate the data for the development of GFRP and CFRP as substitutes for deformed reinforcing bars. The results showed that a lower water–cement ratio yielded higher compressive strength and bond strength; the bond strength of GFRP was approximately 23% lower than that of CFRP. The coating of the rebar surface required for GFRP and CFRP application in reinforced concrete structures ought to be investigated in the future.

Keywords: GFRP; CFRP; corrosion; bond strength; surface shape; slip

1. Introduction

Reinforced concrete is the most commonly used construction material because the coefficient of thermal expansion values of the rebar and concrete are similar, and because the high tensile strength of rebar complements the limitations of concrete [1]. In Korea, the number of reinforced structures has increased since the 1980s due to rapid urbanization. The demand for coarse aggregate and fine aggregate has also increased, and the country faced a shortage of river gravel and river sand supply. Therefore, rubble and washed sea sand were substituted for coarse and fine aggregate. However, the salt content of sea sand accelerates the corrosion of rebar.

Simultaneously, concrete inhibits corrosion in reinforced structures through its strong alkaline properties; however, cracks on its surface caused by drying, shrinkage, and other factors are inevitable. Various deterioration factors permeate the concrete through these cracks and accelerate rebar corrosion [2,3]. Rebar corrosion causes the structure’s load carrying capacity to diminish. Corrosion damages the rebar’s rib, lowers bond strength, and eventually shortens its service life [4]. The bond strength reduction is affected by the strength of concrete, surface conditions of rebar, fiber reinforcement, cracks in concrete and anchorage length, cover thickness, and stress conditions around the concrete. The uncertainty caused by these factors increases the maintenance costs when addressing corrosion damage, which inhibits economic and social prospects [5]. To solve these problems, previous studies have suggested methods such as epoxy coating the surface of deformed reinforcing bars and increasing the concrete coating thickness [6]. However, difficulties have occurred during construction because of the cracking of the epoxy coating on the
rebar’s surface. Further, the increase in cover thickness leads to a heavier load. Subsequently, fiber-reinforced plastics (FRP) were developed to solve this problem [6]. FRP is a fiber-reinforced material used for specialized structures in many industries, such as the aerospace industry since the 1960s. It became a commonly used material in the construction industry in the 1990s. In the construction industry, short fibers are mixed in the concrete, whereas long fibers wrap the outside of the structure to reinforce it.

FRP benefits from the fiber’s high tensile strength and possesses noncorrosive and nonconductive properties [7]. Because of its high corrosion resistance, FRP is used as a replacement for rebar in structures that will potentially be exposed to salt damage. It is also a lightweight material, exhibiting one fourth the weight of steel, which effectively reduces the weight of the structure. This allows FRP to create a lightweight structure that possesses a high strength. However, FRP possesses engineering disadvantages such as low modulus of elasticity and brittle fracture. Furthermore, there is a limit on the increase of the diameter of reinforcing bars [8].

Glass fiber-reinforced plastics (GFRP) and carbon-reinforced plastics (CFRP) were developed to solve the problems of FRP; they have several independent benefits. First, GFRP is inexpensive; however, it is made of glass fiber and contains thorn-shaped protrusions on the surface [9], which pose a risk when used on site. Moreover, since GFRP has a small elastic modulus—approximately 0.2 times that of that of rebar—there is a possibility that a relatively large deflection may occur compared to a rebar with the same reinforcing ratio [10]. CFRP possesses a higher modulus of elasticity and tensile strength than GFRP. It is also lightweight and makes construction convenient. Moreover, CFRP exhibits a high corrosion resistance and economic feasibility due to advanced technology and increased demand [11,12].

Bond strength is a crucial factor for the bearing strength of reinforced concrete structures. When bond strength is reduced, it affects the monolithic behavior of rebar and concrete, resulting in a decline in structural capacity [13]. Similar to the process of verifying the bond strength of deformed bar and FRP, the examination of bond strength between reinforcing bar and concrete is required in the case of GFRP and CFRP before they are used in a reinforced concrete structure. The application of GFRP and CFRP is severely limited because the current structural design standards cannot be adopted for GFRP and CFRP owing to the difference in the mechanical behaviors such as tensile, compression, and adherence performance from existing deformed rebars [14]. In this study, a bond strength experiment was conducted based on ASTM C 234, which was used in a previous study, to examine the bond strength of GFRP and CFRP. The water–cement ratio was set at 40%, 50%, and 60%; GFRP and CFRP rebars with a diameter of 13 mm were used to test the concrete strength.

2. Manufacturing Process of GFRP and CFRP

The GFRP and CFRP used in this experiment were produced through the pultrusion process as shown in Figure 1. The pultrusion process is designed to form various types of fibers similar to the shape of rebar in the rebar production process.
The first step is unwinding the loaded yarn and impregnating it on the hardening body. The impregnated yarn is molded into a bar shape, and winding is carried out by constantly snaking a rib wire that forms a knot shape on the bar. The yarn with ribs is hardened to the inside, cooled in water and air, undergoes the caterpillar process, and cut at certain lengths in the production process. This process makes stronger products than those produced by the method of simply twisting and bonding fibers.

3. Experimental Procedure

The experiment plan is shown in Table 1. The water–cement ratio was set at 40%, 50%, and 60% to compare and analyze the bond strength of the GFRP and CFRP according to the level of concrete strength. Figure 2 shows the test specimens that were made to check the bond strength of the GFRP and CFRP. For each specimen, form removal was performed 1 day after setting, and water curing was performed at 20 ± 2 °C for 28 days.

| Factors                  | Levels                              |
|--------------------------|-------------------------------------|
| W/C (%)                  | 40%, 50%, 60%                       |
| bar type                 | CFRP, GFRP                          |
| curing condition         | temperature 20 ± 2 °C               |
| aggregate type           | river sand and crushed gravel       |
| test item                | compressive strength (28 days), bond strength (28 days) |

Figure 2. Bond strength test specimen.

3.1. Materials

The GFRP and CFRP used in this experiment were developed as shown in Figure 3 by N company. Their physical properties are listed in Tables 2 and 3. The cement used was Type 1 Ordinary Portland Cement manufactured by H company, and its physical properties are shown in Table 4. The fine aggregate used was river sand, procured from E company, and the physical properties are shown in Table 5. The coarse aggregate used was crushed stones, and its physical properties are shown in Table 6.

Figure 3. Reinforcement bars. (A) Glass fiber-reinforced plastic (GFRP) and (B) carbon fiber-reinforced plastic (CFRP).
Table 2. Physical properties of GFRP.

| Diameter (mm) | Fiber          | Tensile Strength (MPa) |
|---------------|----------------|------------------------|
| 13            | glass fiber 4400TEX | 1106                   |

Table 3. Physical properties of CFRP.

| Diameter (mm) | Fiber | Tensile Strength (MPa) |
|---------------|-------|------------------------|
| 13            | carbon fiber 24K | 1714                   |

Table 4. Physical properties of cement.

| Type | Specific Gravity | Blaine (cm²/g) | Setting Time (h:m) | Compressive Strength (MPa) |
|------|------------------|----------------|--------------------|---------------------------|
|      |                  |                | Initial  | Final  | 3 Days | 7 Days | 28 Days |
| 1    | 3.14             | 3,750          | 4:30     | 6:20   | 36.9   | 49.1   | 60.6    |

Table 5. Physical properties of sand.

| Type     | Density (g/m³) | Fineness Modulus (g/cm²) | Absorption (%) |
|----------|----------------|--------------------------|----------------|
| river sand | 2.56           | 2.57                     | 0.94           |

Table 6. Physical properties of gravel.

| Type       | Density (g/m³) | Fineness Modulus (g/cm²) | Absorption (%) |
|------------|----------------|--------------------------|----------------|
| crushed gravel | 2.63         | 7.531                    | 0.8            |

3.2. Experimental Test Methods

The mix formulation used in this experiment is shown in Table 7. A twin-shaft mixer was used for concrete tempering, and fluidity was secured by using superplasticizing admixture (SP) water reducing agent for smooth concrete application. Three compressive strength test specimens were made for each water–cement ratio using a cylindrical mold of 100 mm × 200 mm based on KS F 2405, and the mean of the three specimens was used. Bond strength test specimens were made using a cube mold with an inner diameter of 150 mm × 150 mm × 150 mm, as shown in Figure 4, based on ASTM C 234 [15]. To form a non-adhesive surface in the bond strength experiment, PE foam was used in areas except for four times the diameter of the buried length (4d). Three specimens were made for each water–cement ratio, and the mean of the three specimens was used.

Table 7. Mix proportion of concrete.

| W/C (%) | Air (%) | S/a (%) | Water (kg/m³) | Unit Weight (kg/m³) | Unit Volume (L/m³) |
|---------|---------|---------|---------------|---------------------|--------------------|
|         |         |         |               | C   | S   | G   | C   | S   | G   |
| 40      | 5       | 46      | 175           | 438 | 743 | 910 | 139 | 293 | 344 |
| 50      | 5       | 46      | 175           | 350 | 776 | 950 | 111 | 305 | 359 |
| 60      | 5       | 46      | 175           | 299 | 797 | 977 | 93  | 314 | 369 |
Table 7. Mix proportion of concrete.

| W/C (%) | Air (%) | S/a (%) | Water (kg/m³) | Unit Weight (kg/m³) | Unit Volume (L/m³) |
|---------|---------|---------|--------------|---------------------|-------------------|
| 40      | 5       | 46      | 175          | 438                 | 743               |
| 50      | 5       | 46      | 175          | 350                 | 776               |
| 60      | 5       | 46      | 175          | 299                 | 797               |

Figure 4. Bar bond strength mold.

The bond strength experiment was conducted as shown in Figure 5. After the bond strength test specimens were placed horizontally on the jig, linear variable differential transformers (LVDT) were installed at the bottom of both sides to check the slip between the concrete and rebar according to the load. Moreover, to prevent the rebar from splitting during the experiment, a sufficient length of action was secured in the clamping jaw. The bond strength experiment was conducted at a strain rate of 0.001 mm/s using the universal test machine (UTM) with a maximum load of 300 ton.

Figure 5. Test equipment.

4. Results and Discussion

4.1. Compressive Strength

The results of the compressive strength of the concrete at 28 days are shown in Figure 6, and the fracture shape during measurement is shown in Figure 7. The compressive strength was 54.9, 35.8, and 25.1 MPa for water–cement ratios of 40%, 50%, and 60%, respectively.
Figure 6. Compressive strength of concrete.

Figure 7. Fracture shape of concrete specimen.

4.2. Bond Strength

Average bond strength was calculated using Equation (1). In Equation (1), \( u \) is the average bond stress, \( p \) is the maximum load applied to the test specimen, \( d_b \) is the diameter of the rebar, and \( l_d \) is the embedded length of the rebar (4\( d_b \)).

\[
u = \frac{p}{\pi d_b l_d}
\]

(1)

The bond strength results of the test specimens at 28 days are shown in Figures 8 and 9. The GFRP bond strength was 11.81, 8.72, and 7.29 MPa for water–cement ratios of 40%, 50%, and 60%, respectively. The CFRP bond strength was 16.41 MPa with the 40% water–cement ratio, 11.18 MPa with 50%, and 8.76 MPa with 60%. The GFRP and CFRP showed higher bond strength in lower water–cement ratios. This suggests that a lower water–cement ratio generates more hydrate between the concrete and rebar, which increases the strength of the surface between the rebar and concrete, thereby showing high bond strength. These test results show that the attachment strength tended to increase with a decreasing water–cement ratio, which is consistent with the trend observed for deformed rebar attachment strength in previous studies [16,17].
4.3. Bond Strength and Slip Relationship

Table 8 summarizes the experimental data of the bond strength of the GFRP and CFRP according to the water–cement ratio. The notation of the test specimens is as follows: free end slip is represented by the mean of the LVDTs installed at the bottom of both sides measured at maximum bond strength.

| CW_D#N | C = type of rebar used in the test specimen |
|--------|--------------------------------------------|
| W      | water–cement ratio                          |
| D      | diameter of rebar used in the test specimen  |
| N      | number of test specimens                    |

Figure 10 shows the relationship between bond strength and slip of the GFRP. It was found that the increase in bond strength of the GFRP also led to the increase in slip. At the water–cement ratio of 40%, the bond strength increased after maximum bond strength. This may be because the high compressive strength cracked the ribs on the surface of the GFRP, and the ribs remaining on the bonded surface between the concrete and GFRP led to the increase in bond strength. For the water–cement ratio of 50%, the bond strength increased slightly after maximum bond strength. On the other hand, for the water–cement ratio of 60%, the bond strength showed a gentle slope after maximum bond strength and then declined. Moreover, a lower water–cement ratio led to more slip of maximum bond strength.
Table 8. Bond strength and slip.

| Specimen Name | Ultimate State | Bond Strength (MPa) | Free End Slip (mm) | Load (kN) |
|---------------|----------------|---------------------|--------------------|-----------|
| G40_13#1      |                | 11.29               | 11.67              | 23.96     |
| G40_13#2      |                | 10.69               | 11.01              | 22.69     |
| G40_13#3      |                | 13.48               | 9.13               | 28.61     |
| G50_13#1      |                | 8.45                | 6.43               | 17.94     |
| G50_13#2      |                | 8.75                | 8.63               | 18.57     |
| G50_13#3      |                | 9.00                | 6.38               | 19.10     |
| G60_13#1      |                | 7.85                | 10.11              | 16.66     |
| G60_13#2      |                | 7.11                | 5.25               | 15.09     |
| G60_13#3      |                | 6.95                | 11.56              | 14.75     |
| C40_13#1      |                | 18.72               | 10.41              | 39.74     |
| C40_13#2      |                | 15.84               | 8.14               | 33.62     |
| C40_13#3      |                | 14.70               | 23.19              | 31.20     |
| C50_13#1      |                | 12.33               | 6.38               | 26.17     |
| C50_13#2      |                | 8.89                | 6.10               | 18.87     |
| C50_13#3      |                | 12.35               | 11.21              | 26.21     |
| C60_13#1      |                | 10.34               | 6.05               | 21.95     |
| C60_13#2      |                | 7.71                | 16.13              | 16.37     |
| C60_13#3      |                | 8.24                | 12.22              | 17.49     |

G = GFRP, C = CFRP

Figure 10. Bond strength and slip of GFRP.

Figure 11 is a graph showing the relationship between bond strength and slip of the CFRP. For the water–cement ratio of 40%, similar to GFRP, high compressive strength cracked the ribs on the surface of the CFRP, and the ribs remaining on the bonded surface between the concrete and the CFRP led to an increase in bond strength. In addition, the concrete with 50% and 60% water–cement ratio showed a similar trend as the GFRP.
Figures 13–15 show graphs comparing the relationship between slip and bond strength of the GFRP and CFRP by water–cement ratio. The CFRP was 17–28% higher than the GFRP because the CFRP had about 35% higher tensile strength than the GFRP. Overall, bond strength and slip of the GFRP and CFRP showed similar trends despite the different water–cement ratios. Figures 16 and 17 show the fracture shapes of the bonded surface of the GFRP and CFRP. The upper part of the image shown is the part clamped by the concrete and reinforcing bar in the GFRP experiences stress concentration, which reduces the attachment strength of the GFRP.
clamping jaw, and the lower part is the bonded surface of the concrete and rebar. Both the GFRP and CFRP failed to withstand the bearing pressure, and the surface coating cracked, resulting in low adhesion strength. On comparing the results of the adhesion strength of concrete, GFRP, and CFRP in this study with a previous study, it was found that the trend of the slip relationship according to the adhesion strength of the GFRP and CFRP exhibited a similar overall pattern [19–23].

Figure 13. Bond strength and slip by FRP type(W/C 40).

Figure 14. Bond strength and slip by FRP type(W/C 50).

Figure 15. Bond strength and slip by FRP type(W/C 60).
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5. Conclusions

The following conclusions were drawn from the experiment on the bond strengths of GFRP and CFRP by concrete strength based on the scope of the study.

(1) While investigating the relationship between bond strength and slip, bond strength tended to increase after rib failure in the concrete with a 40% water–cement ratio. This can be attributed to the increased bond strength in the remaining intact concrete–rebar ribs under high compressive strength.

(2) For all water–cement ratios, it was found that higher the compressive strength of the concrete, the better the adhesion strength between the concrete, and the CFRP or GFRP. This could be attributed to the effect on the increase in strength.

(3) When comparing the bonding strength of the GFRP and CFRP, the bonding strength of the CFRP, which has higher tensile strength, was greater than that of the GFRP. This could be attributed to the resistance offered by the reinforcing bar with high tensile strength against the pull-out load even under the same frictional force.

This experimental study was aimed toward investigating the adhesion strength of GFRP and CFRP at three levels of W/C and the same reinforcement diameter. Other parameters affecting adhesion strength between concrete, and CFRP or GFRP could not be explained through the results of this study. In the future, research on GFRP and CFRP according to the concrete mixing level and rebar diameter ought to be investigated.

Figure 16. Fracture shape of the GFRP surface.

Figure 17. Fracture shape of the CFRP surface.
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