An Investigation of the Bond Performance of Reinforced Fly Ash-Based Geopolymer Concrete under Simulated Wet-Dry Environmental Conditions

Thien Thanh Nguyen
Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam | Vietnam National University, Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
ntthanh.sdh21@hcmut.edu.vn

Cao Thanh Tran Ngoc
School of Civil Engineering and Management, International University, Ho Chi Minh City, Vietnam | Vietnam National University, Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
tctngoc@hcmiu.edu.vn

Tan Hung Nguyen
Faculty of Architectural, Civil and Environmental Engineering, Nam Can Tho University, 94000, Can Tho City, Vietnam
nguyentanhung@nctu.edu.vn

Tan Khoa Nguyen
Institute of Research and Development, Duy Tan University, 550000, Da Nang, Vietnam | Faculty of Civil Engineering, Duy Tan University, 550000, Da Nang, Vietnam
nguyentankhoa@duytan.edu.vn

Anh Tuan Le
Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam | Vietnam National University, Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
latuan@hcmut.edu.vn (corresponding author)

Received: 30 May 2025 | Revised: 20 June 2025 | Accepted: 28 June 2025

ABSTRACT

This paper investigates the bond performance of fly ash-based Geopolymer Concrete (GPC) reinforced with steel bars under accelerated corrosion conditions. The study aimed to evaluate the bond strength of GPC when subjected to forced corrosion in a sulfate solution. Cylindrical specimens of three GPC mixtures, cured under different conditions, were prepared with 12 mm (d12) and 20 mm (d20) diameter rebars. These specimens were subjected to an accelerated corrosion test consisting of wet-dry cycles in a 1 M sodium sulfate solution for up to 8 weeks. The results indicated that the compressive strength of all GPC mixtures initially increased, peaking at 72 cycles, before steadily decreasing with a further exposure to corrosion. Similarly, the bond strength for both rebar diameters also showed an initial increase, peaking at 72 cycles, followed by a decline. The GPC cured for a longer duration exhibited higher compressive and bond strengths throughout the corrosion exposure. Furthermore, the 20mm diameter bars (d20) generally

demonstrated better bond strength retention and durability under corrosive attack than the 12mm diameter bars (d12).

Keywords-geopolymer concrete; fly ash; pull out; corrosion; wet-dry cycle; compressive strength; bond strength

I. INTRODUCTION

Fly ash-based GPC is an innovative and environmentally friendly alternative to traditional Portland cement concrete. Its popularity has grown due to its superior durability and sustainability [1, 2]. GPC is made using industrial by-products such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), rice husk ash, red mud, and metakaolin [3], which are activated by alkaline solutions, like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The resulting concrete exhibits excellent mechanical properties and strong resistance to chemical and acidic environments [4, 5], making it well-suited for construction in harsh conditions. One key property of GPC is its bond strength, the adhesion between reinforcing steel bars and the surrounding concrete matrix, which is crucial for the structural integrity of the reinforced concrete. In corrosive environments, such as marine areas or places exposed to deicing salts, steel reinforcement in conventional concrete can corrode, weakening the bond strength and compromising the structural performance. In contrast, GPC's unique chemical composition and microstructure offer better resistance to such degradation. It can maintain strong adhesion between steel bars and the concrete matrix, even in aggressive environments. Numerous studies have investigated the bond behavior of GPC under various corrosion conditions, with encouraging results. For instance, authors in [6] reported that GPC provides strong chemical adhesion at the bond interface, enhancing the bond strength. However, this interfacial adhesion can still be negatively affected by corrosion, especially in Slag-Based (SG) and Metakaolin-Based (MKG) GPC, where greater bond deterioration was observed with increased corrosion rates. The Hydrophobic Metakaolin-Based Geopolymer (HMKG) concrete showed a better performance by mitigating the corrosion effects and reducing the bond degradation.

The mechanical properties and corrosion resistance of GPC made with fly ash, GGBS, and metakaolin were compared to those of conventional concrete. The results indicated that GPC exhibited superior corrosion resistance, contributing to better bond strength under corrosive conditions [7, 8]. The use of alkaline solutions as activators played a crucial role in achieving these properties, as they facilitated the formation of a dense and durable matrix that protected the steel reinforcement from corrosion. Furthermore, the bond performance of Self-Compacting Geopolymer Concrete (SCGC) reinforced with Basalt Fiber-Reinforced Polymer (BFRP) bars was investigated in [9]. This study examined the bond behavior of BFRP-reinforced SCGC specimens with variables, such as the bar diameter and embedment lengths. The results demonstrated that SCGC reinforced with BFRP bars exhibited an excellent bond strength and corrosion resistance, making it a viable option for reinforced concrete structures. Even though several studies have evaluated the bond behavior under corrosion conditions, there is a lack of research on the bond strength of fly ash-based GCP under accelerated corrosion conditions. To investigate the bond performance, three different GPC mixtures were tested in combination with two types of reinforcing bars: d12 (12 mm diameter) and d20 (20 mm diameter). The specimens were subjected to a wet-dry cyclic test by immersing them in a 1 M sodium sulfate (Na_2SO_4) solution. Both the compressive strength and bond strength were measured at various stages of the exposure. The results from these tests were then compared with the findings from previous studies to evaluate the performance under accelerated corrosion conditions.

II. MATERIALS AND METHODS

A. Material and Specimen Preparation

This study chose geopolymer binders, such as fly ash, Na_2SiO_3, and Na_2O. The fly ash "Class F" was used with a 2.5 g/cm^3 density. The chemical compositions of fly ash are shown in Table I. Na_2SiO_3 and NaOH were combined in a mass ratio of 2.5 to create an alkaline activator solution. The components of the Na_2SiO_3 solution were Na_2O and SiO_2 (Na_2O = 10%, SiO_2 = 29%). The concentration of Na_2O was 13 M. The mass ratio between the alkaline solution and the fly ash was 0.56. Fine Aggregates (FA) and Coarse Aggregates (CA) were both used in this experiment, along with a Saturated Surface Dry (SSD) condition. The amount of CA to FA was 70% to 30%. For CA, the density was 2.7 g/cm^3, and for FA, it was 2.65 g/cm^3. Two kinds of reinforcing bars were used to evaluate the bond behavior of the reinforced GCP. Ribbed steel bars were employed, with a diameter (d_b) of 12 mm and 20 mm. For the samples used for the pullout test, the rebars were carefully covered by a PVC tube to control the embedded length l_d, which was chosen to be 5 d_b.

TABLE I. CHEMICAL COMPOSITION OF FLY ASH

Oxide	(%)
SiO_2	53.5
Al_2O_3	34.8
Fe_2O_3	4.1
CaO	1.2
K_2O & Na_2O	0.3
MgO	0.83
SO_3	0.25
LOI	8.87

LOI: Loss of ignition

Fly ash-based GCP consists of CA, FA, fly ash, and alkaline solutions. The mixing procedure followed that of [10]. Firstly, the fly ash and alkaline solution were mixed approximately five min after measuring. Then, CA and FA were added to a slurry and were stirred for five min. Fresh GCP was cast and compacted into two types of cylindrical molds: 100 mm × 200 mm for the compressive strength test and 150 mm × 300 mm for the pullout test. Later, the specimens were sent to an oven for curing in three different conditions. The details of the mixing process are presented in Figure 1, and the mix proportions used in this study are shown in Table II.

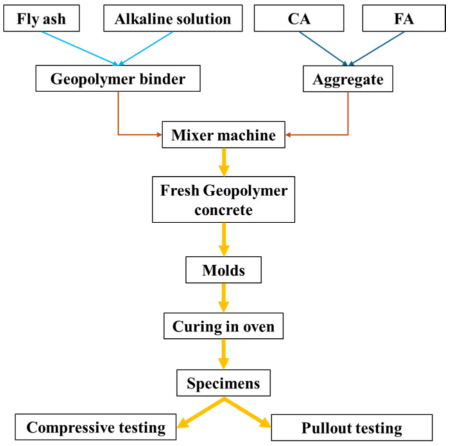

Fig. 1. Experimental process of this study.

TABLE II. MIXTURE PROPORTIONS OF THIS STUDY

Name	**GB1**	**GB2**	**GB3**
CA (kg)	1294	1294	1294
FA (kg)	554	554	554
Fly ash (kg)	300	300	300
Na_2SiO_3 solution (kg)	120	120	120
NaOH solution (kg)	48	48	48
AL/Fly ash	0.56	0.56	0.56
Curing conditions	80 °C, 4 hours	80 °C, 8 hours	80 °C, 12 hours

B. Test Methods

This study conducted an experimental program to evaluate the bond behavior of reinforced GCP under accelerated corrosion conditions, focusing on both the compressive strength and pullout performance. For the compressive strength test, three specimens 100 mm × 200 mm were prepared from each mixture group. The test was performed on 150 mm × 300 mm cylinders using axial loading at a rate between 0.15 MPa/s and 0.35 MPa/s until failure, following the procedure in [11]. The direct pullout test setup and specimen preparation followed the methodology described in [10], as illustrated in Figure 2.

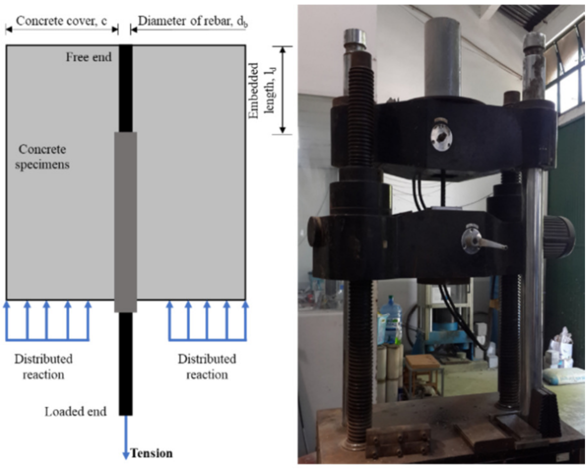

Fig. 2. Schematic of pullout testing.

The bond stress is calculated by assuming that it is uniformly distributed along the embed length of the bar:

$$\tau_{max} = \frac{P_{max}}{\pi d_b l_b} \qquad (1)$$

where τ_{max} is the maximum bond stress, P_{max} is the corresponding applied force at failure, d_b is the bar diameter, and l_d is the bar embedded length; in the current work $l_d=5d_b$.

In this study, an accelerated corrosion test was conducted to assess the durability of reinforced GCP. An 1 M Na_2SO_4 solution was used to simulate the exposure to typical rural and urban atmospheric conditions. After curing for 28 days, the specimens were subjected to a wet-dry cyclic testing program consisting of two stages. First, each specimen was immersed in the Na_2SO_4 solution for 30 min. Then, it was dried in an oven at a constant temperature of 40 °C for 60 min. Each test cycle lasted 90 min (30 min wetting and 60 min drying), with six cycles performed per day, six days a week, over a period of eight weeks. The compressive strength and pullout tests were conducted at four intervals: after 2 weeks (72 cycles), 4 weeks (144 cycles), 6 weeks (216 cycles), and 8 weeks (288 cycles). The wet-dry cycle parameters are summarized in Table III.

TABLE III. CHARACTERISTICS OF THE WET-DRY CYCLIC TEST

Wet/dry cyclic test	**Cycle characteristics**			
	Cycle/day	**Wet**	**Dry**	**Duration**
	6	30 min	60 min	90 mins/cycle
Number of cycles (t)	**t_1**	**t_2**	**t_3**	**t_4**
	72	144	216	288

III. RESULTS AND DISCUSSION

A. Influence of Wet-Dry Cycles on the Compressive Strength of Reinforced GCP

The influence of wet-dry cycles on the compressive strength of GCP was investigated. Three mixtures, GB1, GB2, and GB3, were prepared for the wet-dry cyclic test, which was followed by the testing program presented in Table III. The results are shown in Figure 3.

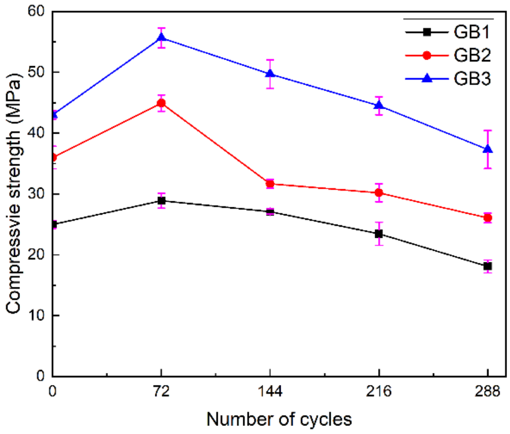

Fig. 3. Relationship between compressive strength of GCP and number of cycles.

As portrayed in Figure 3, the specimens exhibited a clear initial hierarchy in compressive strength. GB3 had the highest initial strength at approximately 43 MPa, followed by GB2 at around 36 MPa, and GB1 with the lowest at about 25 MPa. During the first 72 wet-dry cycles, all mixtures showed a notable increase in the compressive strength. GB3 rose by 30.2%, reaching a peak of about 55.6 MPa. GB2 followed with a 25% increase, peaking at approximately 44.9 MPa. GB1 showed a more modest 16% gain, reaching around 28.9 MPa. However, this increase was short-lived. After 72 cycles, all mixtures experienced a steady decline in the compressive strength as the number of corrosion cycles increased. GB1 and GB3 gradually decreased after peaking, while GB2 showed a sharp drop at 144 cycles, followed by a slower decline. By the end of the 288-cycle period, GB3 maintained the highest strength at about 37.3 MPa, GB2 dropped to around 26.1 MPa, and GB1 to roughly 18.1 MPa. Across all three mixtures, the compressive strength declined by approximately 44%–46% from their peak values at 72 cycles. This initial strength gain may be attributed to the wet-dry cycling and the presence of Na_2SO_4. The elevated temperature during drying (60 °C) may have provided additional energy to sustain the geopolymerization process, while sulfate ions likely filled the micro-pores in the matrix, enhancing the strength. Over time, however, the repeated moisture fluctuations caused expansion and shrinkage, leading to microcracking and strength loss. In summary, fly ash-based GCP showed an early improvement in compressive strength during the corrosion test, but the prolonged exposure to wet-dry cycles ultimately led to significant deterioration.

B. *Influence of Wet-Dry Cycles on the Bond Strength of Reinforced GCP*

The mixtures GB1, GB2, and GB3 were combined with two types of reinforced bars (d12 and d20) to evaluate the effect of wet-dry cycles on the bond strength of reinforced GCP. Figure 4 (for d12) and Figure 5 (for d20) show the relationship between the bond strength of reinforced GCP and the number of wet-dry cycles.

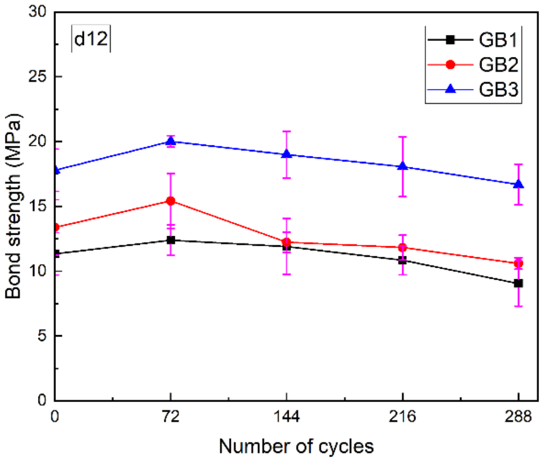

Fig. 4. Relationship between bond strength of reinforced GCP and number of cycles in the case of d12.

In the case of the bond strength of rebar d12 illustrated in Figure 4, at the initial cycle, GB1 steadily increased, reaching the peak of 12.4 MPa (increased by 8.6%) at 72 cycles. However, the bond strength gradually decreased beyond this point, dropping by 4% to 144 cycles. Then, the bond strength kept decreasing by 12.6% at 216 cycles compared with the peak strength. By the final cycle at 288, GB1 had lost approximately 27% of its peak strength (9 MPa compared with 12.4 MPa). Ultimately, its last recorded bond strength was lower than its initial value, confirming a substantial degradation over time. GB2 followed a similar trend but reached a higher peak, achieving 15.4 MPa at 72 cycles. Following this peak, the bond strength decreased by 20.7% at 144 cycles. At 216 cycles, the bond strength kept reducing by 24%. By the final cycle at 288, GB2 had lost about 34.4% of its peak strength but maintained a slightly better resistance than GB1. Its last recorded value, although reduced, remains higher than GB1, indicating a better resistance to corrosion, GB3 demonstrated the highest bond strength throughout the test, peaking at 20 MPa at 72 cycles. After reaching the maximum strength, it gradually decreased by 5.1% after 144 cycles. At 216 cycles, the bond strength further dropped by 9.9%. By the final cycle at 288, GB3 lost about 17.6% of its peak strength but retained a higher bond strength than the other specimens.

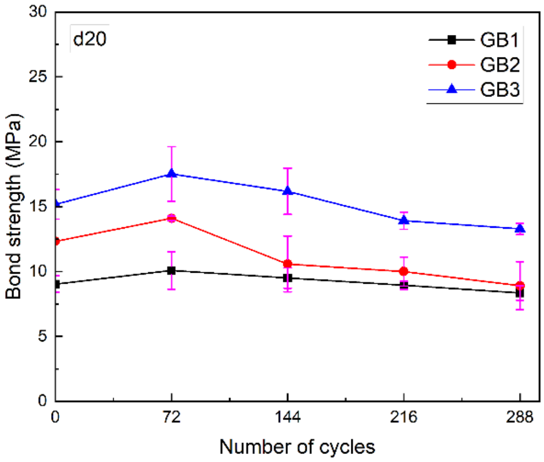

Fig. 5. Relationship between the bond strength of reinforced GCP and number of cycles in the case of d20.

In the case of d20 presented in Figure 5, GB1 started with an initial bond strength of 9 MPa, rising to 10.1 MPa at 72 cycles, marking a 10.5% increase. The bond strength remained stable between 72 and 144 cycles before gradually decreasing to 8.3 MPa at 288 cycles, indicating a 10% reduction from the initial value. The bond strength of GB1 was lower than its initial value by the final cycle, indicating susceptibility to corrosion. GB2 began with a bond strength of 12.3 MPa, reaching 14.1 MPa at 72 cyclists, representing a 14.4% increase. The bond strength stabilized from 72 to 144 cycles, showing a minimal change. However, after 144 cycles, it steadily decreased, dropping to 8.9 MPa at 288 cycles, about a 41.4% decrease from its initial value. By the end, GB2 exhibits more strength retention than GB1. GB3 reached the highest bond strength with a 15.4% increase at 72 cycles. Like GB2, it remained stable until 144 cycles. After 144 cycles, the bond strength of GB3 reduced by 14% at 216 cycles, followed by a 26.2% total decrease from its initial value at 288 cycles. Despite this decrease, GB3 still had the highest bond strength among the three mixtures, reinforcing its durability against extended exposure. For both the d12 and d20 specimens, the bond strength initially increased, reaching a peak around 72 wet-dry cycles. This early improvement is likely due to the mechanical interlocking and surface roughness generated by the initial stages of corrosion. However, after this peak, the bond strength began to decline as the prolonged exposure to the 1 M Na_2SO_4 solution weakened the bond interface. The d12 specimens showed a more rapid reduction in bond strength compared to d20. This is likely because their higher surface-area-to-volume ratio made them more vulnerable to crack development and corrosion penetration. In contrast, d20 specimens demonstrated better durability, retaining their bond strength for a longer period. This can be attributed to their larger contact area with the geopolymer matrix and a more favorable stress distribution. Overall, while both rebar sizes experienced bond degradation over time, the d20 bars proved to be more resilient under aggressive wet-dry cyclic conditions, maintaining a higher bond strength and offering a greater resistance to corrosion-induced damage.

C. Comparison of Experimental Test with Previous Research

Authors in [12] defined a formulation to obtain the bond strength of reinforced GCP as:

$$\tau_u = 3.83\sqrt{f_c'} \tag{2}$$

where τ_u is the bond strength (MPa), and f'_c is the compressive strength of GCP (MPa). Authors in [13] proposed an equation for calculating the bond strength of reinforced GCP from the compressive strength:

$$\tau_u = 2.58\sqrt{f_c'} \tag{3}$$

where τ_u is the bond strength (MPa), and f'_c is the compressive strength of GCP (MPa).

The experimental and predicted data of the bond strength using (2) and (3) are shown in Figure 6.

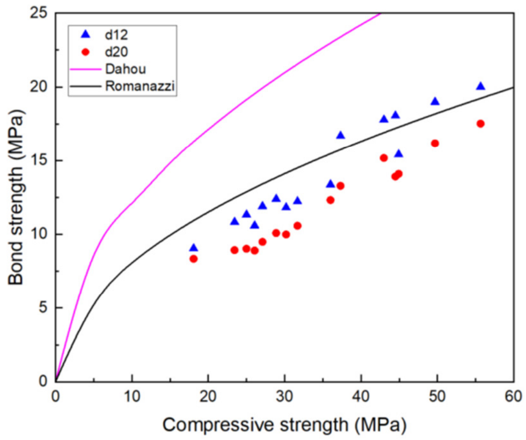

Fig. 6. Relationship between the bond strength of GCP and number of cycles in the case of d.

Figure 6 provides a comparative analysis between the experimentally measured bond strengths for d12 and d20 reinforced GCP specimens and the predicted values from two existing models proposed in [12, 13], based on varying compressive strengths of concrete. A general trend observed across all datasets is that the bond strength increases with the compressive strength. However, the model proposed in [12] significantly overestimates the bond strength compared to the experimental results. For both d12 and d20 bars, the predicted values were 23%-47% higher than those measured in the experiments, indicating a substantial deviation from the actual performance. In contrast, the model from [13] aligned more closely with the experimental data, particularly for the d12 specimens. The predicted bond strengths for d12 generally fell within a narrow margin, ranging from a 10% overestimation to a 6.25% underestimation suggesting a good fit. Most of the d12 data points were located near the curve generated by this model. While the model in [13] performed better overall, it still tended to overestimate the bond strengths for the d20 bars, with deviations ranging from 7.7% to 23.1%. The experimental results also showed that, for a given compressive strength, the d12 bars typically achieved slightly higher bond strengths than the d20 bars. In summary, the model in [13] provides a more accurate prediction of the bond strength based on the compressive strength, particularly for smaller diameter bars (d12). Nevertheless, further research is necessary to develop a more precise model that accounts for the effects of corrosion and varying bar diameters on the bond performance.

IV. CONCLUSIONS

This study examines the bond performance of reinforced fly ash-based GCP under accelerated corrosion conditions, using wet-dry cycles in a Na_2SO_4 solution. The main findings are:

- The compressive strength of all mixtures GB1, GB2, and GB3 increased during the first 72 wet-dry cycles. However, beyond this peak, the strength steadily declined up to 288 cycles, likely due to the crack formation caused by the volume changes from the repeated moisture fluctuations.
- Among the three mixtures, the longer cured GCP (GB3), showing higher compressive and bond strengths during the corrosion exposure. When comparing the reinforcing bar diameters, the 20mm diameter bars (d20) generally demonstrated a better bond strength retention and durability under corrosive attack compared to the 12mm diameter bars (d12), which experienced a more rapid degradation. This difference is likely due to the larger contact area and better stress distribution in the d20 bars.
- The current study compared experimental bond strengths with predictions from previous studies. The model of [12] significantly overestimated the bond strength, while the model of [13] provided a closer approximation, particularly for the d12 specimens, though it still tended to overestimate values for the d20 bars. These findings highlight the complex nature of the bond behavior in GCP under corrosive environments. Therefore, further research is essential to develop a more accurate predictive formulation for the bond strength of reinforced GCP, especially

considering the detrimental effects of the prolonged exposure to corrosive conditions.

AKNOWLEDGEMENTS

The authors acknowledge Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for supporting this study.

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