

Experimental study of bond behavior of geopolymer concrete under different curing condition using a pull-out test

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ABSTRACT

Researchers recently have focused on geopolymer concrete as it has several advantages compared to traditional Portland cement, such as lower carbon footprint, high early strength, chemical resistance and long-lasting structural performance. This paper designed 192 pull-out specimens to investigate the influence of factors on the bond-slip behavior between geopolymer and steel bar such as curing condition (ambient and 80 °C for 7 hours), longitudinal rib angle, the position of longitudinal bar, bar diameter (12 mm and 24 mm), stirrup usage (with and without stirrup) and bond length (2d and 4d). The maximum bond strength, bond failure modes, and bond stress-slip relations were discussed. The test results showed that the longitudinal rib angle, and the position of rebar play a vital role in determining the bond strength as well as the bar diameter. In comparison with the specimens without the stirrup, the bond performance of specimens with stirrup increased more significantly, and this phenomenon became even more pronounced as the bar diameter increased. The stirrup usage in samples under ambient and heat cure increased the bond strength by an average of 45 % and %40, respectively. Moreover, it has been determined that the curing conditions have a significant effect on the bond performance, as especially the compressive and tensile strengths of the samples under heat cure improve. In samples exposed to both ambient and heat cure, doubling the bond length increased the bond strength by 70 %. Furthermore, increasing the bar diameter increased the bond strength of the samples exposed to ambient and heat curing by a maximum of 84 % and 79 %, respectively. The findings lay the groundwork for understanding the bond behavior of geopolymer, which is critical for the successful application of geopolymer-bonded rebar.

1. Introduction

The connection between steel and concrete determines the interaction of the two materials. Cracking, deformation and load-bearing capacity of reinforced concrete structures are greatly influenced by the bond performance. The most important factors affecting the bond performance between reinforcement and concrete are the diameter and surface shape of the steel bar, the constraints around the steel bar, the concrete strength and the position of the steel bar [1–3].

In the realm of reinforced concrete structural design, a crucial assumption is made regarding the presence of a reliable bond between the steel and concrete when the structural element is subjected to loads. This bond ensures that there is no slippage between the concrete and steel components. It is postulated that the tension caused by the load is

effectively resisted by the steel, and the resulting increased tension in the bars is transmitted to the concrete through a surface force known as bond stress. The strength of this bond is contingent upon three key factors: chemical adhesion, frictional resistance, and mechanical interlocking. In the case of deformed bars, the transfer of load between the concrete and reinforcement is primarily facilitated by mechanical interlocking. Conversely, for plain bars, the bond strength relies on chemical adhesion and friction. Inadequate bond strength leads to a significant reduction in both the stiffness and load-carrying capacity of the structure [4]. The bond stress (τ) is defined as the shear force exerted on each unit of nominal surface area of the reinforcing bar. Research on bond typically focuses on investigating the correlation between bond stress and the sliding of steel bars in pull-out specimens. The calculation of bond stress involves determining the shearing stress between the

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reinforcement and the surrounding concrete, as well as measuring the slip resulting from the relative displacement of the reinforcement from the concrete through experimental methods [4,5]. Srividya and Kannan Rajkumar [4] carried out an experimental study on four fly ash-GGBS blended GPC mixtures to evaluate the structural bond behavior. Srividya and Kannan Rajkumar reported that the 16 mm and 20 mm diameter bars failed with pull-out type of failure. Quadflieg and Stolyarov [6] reported that the utilization of glass, basalt and carbon enables a cost-effective utilization of concrete in the construction of various structures. Furthermore, an examination was conducted to assess the bonding effect between the coated roving and the matrix. Consequently, it was noted that the bonding strength within a matrix composed of fine-grained concrete surpasses that of a geopolymer. Bhutta et al. [7] carried out experimental program to investigate the effect of fiber type (steel and polypropylene), fiber shape, concentration of alkali solution in the geopolymer matrix and curing conditions on bond-slip performance. Test results have been shown that the evident improvements in equivalent strength, energy absorption, and the bonds of adhesion and friction can be attributed to the concentration of alkaline solution and the application of heat curing. Dahou et al. [8] reported that the bond strength between geopolymer concrete and reinforcing bars is found to be considerably higher than the bond strength calculated using the fib model code 2010, which is calibrated for OPC concrete, for all considered concrete compressive strengths. The traditional model, which assumes that bond strength is directly proportional to the square roots of the average compressive strength, seems to be highly effective for geopolymer concrete. Consequently, the fib model code 2010 has been adjusted to providing precise outcomes for both high and low calcium geopolymer concretes. Peng et al. [9] investigated the effect of strength of geopolymer (different mass ratios of fly ash and slag), bar embedded length (5, 10, and 15 times the bar diameter), fiber volume fraction in geopolymer (0, 1 %, and 2 %), and bar diameters (3 mm, 6 mm, and 10 mm) on bond performance. They reported that the using geopolymer concrete and adding the PVA fibers in geopolymer matrix improved the bond strength. Kanagaraj et al. [10] investigated the bond performance of self-compacting geopolymer concrete with three different materials (such as fly ash, metakaolin and GGBS) exposed the high temperature. They reported that the increasing temperature decreased the bond stress of self-compacting geopolymer concrete. Zhang et al. [11] carried out an experimental study to determine the effect of ambient temperature and after exposure to 100, 300, 500 and 700 °C and compressive strength (48 and 64 MPa) and bar diameter (10, 12, 14, 18 and 25 mm) on the bond behavior between geopolymer concrete and rebar. Test results showed that the geopolymer concrete can be an alternative to OPC concrete in reinforced concrete structures exposed the high temperature. Sarker [12] investigated the effect of concrete compressive strength, bar diameter and concrete cover on the bond strength of geopolymer concrete. Sarker [12] reported that the bond strength of geopolymer concrete than OPC concrete. Tobbala et al. [13] investigated that the effect of different temperatures up to 600 °C in the presence of ZRE coating on the bond performance. The test results showed that the residual bond strength of uncoated and zinc-rich epox-coated specimens in the silica fume mix was better than that of normal at temperatures up to 400 °C.

For centuries, concrete has been an important building material and the foundation of the construction sector. That means that as environmental concerns have grown and there is a need for more sustainable options, attention is being focused on novel materials like geopolymer concrete [14–20]. In fact, studies in the literature about not only normal strength but also high/ultra-high strength concrete [21–23] have been the focus of attention of researchers. A notable change from conventional Portland cement-based concrete is the use of geopolymer concrete. In order to create a more durable and environmentally friendly building material, alkali-activated materials like fly ash, slag, or other industrial by-products are included in its composition. Because of its own chemical composition and production method, geopolymer concrete stands out from its traditional cement-based competitors and is a

viable option for addressing structural and environmental issues in the building industry [24–27]. Kurtoglu et al. [28] investigated the short-term durability properties of fly ash and slag based geopolymer concrete. The test results showed that 100 % slag is stronger and durable than the geopolymer with fly ash due to more stable and strong cross-linked alumina silicate polymer structure. Moreover, geopolymer specimens with fly ash showed better durability resistance than the specimens with ordinary cement. Cevik et al. [29] reported that geopolymer concrete with fly ash showed superior performance than specimens with ordinary cement under chemical attacks due to low calcium content. Among the chemical environments, sulfuric acid (H_2SO_4) was found to be the most dangerous environment for all concrete types. The construction industry heavily relies on vast quantities of materials, including paving blocks, bricks, tiles, cement, and aggregates, for the development of new urban projects and the construction of new buildings. However, the production of these materials necessitates the consumption of natural resources and energy. Given these circumstances, the exploration of new sustainable materials emerges as a highly effective avenue for modernizing the construction sector. Among the most promising possibilities in this field is the development of pozzolanic materials derived from waste, which can serve as a viable alternative to traditional construction materials. Currently, pozzolanic materials find frequent application in the construction industry. In civil engineering, these materials are utilized as binders in soil stabilization techniques. Moreover, they play a crucial role in building construction as structural elements and building enclosures. The utilization of pozzolanic materials not only contributes to the economic growth and development of countries but also serves as an important indicator of their economic activity [30]. The geopolymer concrete (GPC) is comprised of a combination of industrial waste solids, such as ground granulated blast-furnace slag (SL) and fly ash (FA), along with alkaline activators like sodium hydroxide (SH), sodium silicates (SS), or sodium carbonates (SC) [30–32]. Additionally, aggregates and chemical admixtures may be included, although the effectiveness of these admixtures in GPC may not be as significant as in Portland Cement Concrete (PCC) [17,33]. The binder in GPC is formed through the reaction of aluminosilicates or calcium aluminosilicates materials with alkaline liquids. The complexity of mixture design in GPC arises from various factors, including inconsistent raw materials, alkali activators, and curing methods used in its manufacturing process. Consequently, the proportioning of GPC should be based on the desired performance, considering the impact of these constituents on the overall performance of the concrete [34]. For this reason, an experimental investigation based on pull-out tests has been planned and carried out, focusing on effect of different parameters on the adherence performance of geopolymer concrete. Zeyad et al. [35] investigated the effect of incorporating olive waste ash into high-strength geopolymer concrete by partially replacing fly ash and/or granulated blast furnace slag in the presence of rice husk ash. The test results of this research show that the inclusion of olive waste ash in high-strength geopolymer concrete mixtures resulted in a significant enhancement of the compressive strength. Specifically, adding 20 % olive waste ash to fly ash increased the compressive strength by 8,9 % at 28 days.

The effect of concrete cover on bond strength was discussed in a different and original way in present study. The effect of concrete cover was discussed in terms of the bar location, and the effect of the interaction of the reinforcement location with the curing condition, the stirrup usage, the bond length and the bar diameter on the bond strength was examined. In addition, another unique point of the study is that longitudinal rib angle is also considered as a parameter. In this experimental investigation, the results of 192 pull-out tests performed were presented with the aim of contributing to the experimental database and to a better understanding of the bond behavior between reinforcing bars and geopolymer concrete. Bonding behavior was extensively examined for different curing conditions, stirrup usage, bond length, position of rebar and longitudinal rib angles and rebar diameters to determine the

effects of the investigated parameters. The concrete specimens were grouped in two series: curing in the room temperature and curing in 80 °C at seven hours. 2d and 4d bond length (d is the bar diameter) were chosen for the tests. The reinforcing bar diameters were 12 and 24 mm. Moreover, the specimens with and without stirrup were manufactured to determine the effect of stirrup usage on the bond strength of geopolymer concrete. On the other hand, three different position of rebar and two various of longitudinal rib angles were conducted to evaluate the bond strength of geopolymer concrete. The significance of these experimental outcomes lies in their potential contribution to the utilization of geopolymer concrete in building applications, particularly when emphasizing the need for fire resistance as a critical design consideration.

2. Experimental program

The experimental investigation was carried out to investigate the effect of four main parameters on the bond strength between reinforcements and geopolymer mortar: position of rebar (center, middle bottom and corner), longitudinal rib angles (0°, 45° and 90°), curing condition (ambient and heat curing), rebar diameter (12 mm and 24 mm), bond length (2d and 4d) and stirrup usage. A total of 192 pull-out specimens were cast. Deformed reinforcements with two different diameters were embedded in geopolymer mortar cubes with dimensions of 150 mm×150 mm×150 mm.

2.1. Specimens

In this study, 192 specimens consisting of a steel bar embedded in a geopolymer cube specimen with a dimension of 150x150x150 mm were prepared. In this study, steel bars with different diameters (d) of 12 mm, and 24 mm were used for the preparation of specimens. Five primary specimen groups with rears embedded in geopolymer mortar were prepared. The five groups of geopolymer mortar were designed with different curing conditions (ambient and 80 °C for 7 hours), different position of rebar [center, 0°, 45°), different longitudinal rib angles, two different bond length (2d and 4d) and stirrup usage. Table 1 gives the specimen details. Each specimen type had three identical specimens. A name tab with four parts was developed for the specimens. As mentioned above, the first nomenclature represents the curing condition (e.g., C1). The second part describes the stirrup usage (S: with stirrup and E: without stirrup). The third part describes the diameter of the rebar (i.e., 12 mm, 24 mm). The bond length (2d and 4d) can be identified by the fourth part. The last Roma number (I, II, and III) is used to indicate the position of rebar (e.g. I, II and III represent the center, bottom side and corner, respectively). Moreover, the specimens positioned at bottom side were divided into two groups. In the specimens positioned at bottom, two different reinforcement directions (0° and 90°) were used. In order to investigate the effect of stirrups on bond behavior, stirrups with diameters of 8 mm were arranged in the middle of the embedded range in some specimens. In such case, C1/E/24/4d-I mean geopolymer composite cured at ambient curing condition; the diameter and embedded length of rebar are 24 mm and 4d, respectively; and the specimen is located the center of cube and the stirrup do not use. Fig. 1 shows the size and details of the specimens. In Series I, the steel rebars were located in the center of cube specimens ($x_1=x_2=75$ mm). For all specimens in series I, the longitudinal ribs of the steel rebars were uniformly placed horizontally ($\theta = 90^\circ$). In series II, the steel rebars were located in the bottom side of specimens ($x_1=30$ mm and $x_2=75$ mm). The longitudinal ribs of the steel rebars were placed with two different angle, 0° and 90°, respectively, in series II. In Series III, the steel rebars were located in the corner ($x_1=x_2=30$ mm) and the longitudinal ribs of the steel rebars were uniformly placed with 45°.

2.2. Materials and specimen preparations

Fig. 2 shows the strain-stress curves of 8 mm, 12 mm and 24 mm

Table 1
Specimens details.

Specimen IDs	Curing condition	Diameter (mm)	Stirrup usage	Bond length	Longitudinal rib angles
C1/S/12/2d-I,II,III	Ambient	12	Ø8	2d	90°, 0°, 45°
C1/S/12/4d-I,II,III	Ambient	12	Ø8	4d	90°, 0°, 45°
C1/E/12/2d-I,II,III	Ambient	12	/	2d	90°, 0°, 45°
C1/E/12/4d-I,II,III	Ambient	12	/	4d	90°, 0°, 45°
C1/S/24/2d-I,II,III	Ambient	24	Ø8	2d	90°, 0°, 45°
C1/S/24/4d-I,II,III	Ambient	24	Ø8	4d	90°, 0°, 45°
C1/E/24/2d-I,II,III	Ambient	24	/	2d	90°, 0°, 45°
C1/E/24/4d-I,II,III	Ambient	24	/	4d	90°, 0°, 45°
C1/S/12/2d-II	Ambient	12	Ø8	2d	90°
C1/S/12/4d-II	Ambient	12	Ø8	4d	90°
C1/S/24/2d-II	Ambient	24	Ø8	2d	90°
C1/S/24/4d-II	Ambient	24	Ø8	4d	90°
C1/E/12/2d-II	Ambient	12	/	2d	90°
C1/E/12/4d-II	Ambient	12	/	4d	90°
C1/E/24/2d-II	Ambient	24	/	2d	90°
C1/E/24/4d-II	Ambient	24	/	4d	90°
C2/S/12/2d-I,II,III	80 °C	12	Ø8	2d	90°, 0°, 45°
C2/S/12/4d-I,II,III	80 °C	12	Ø8	4d	90°, 0°, 45°
C2/E/12/2d-I,II,III	80 °C	12	/	2d	90°, 0°, 45°
C2/E/12/4d-I,II,III	80 °C	12	/	4d	90°, 0°, 45°
C2/S/24/2d-I,II,III	80 °C	24	Ø8	2d	90°, 0°, 45°
C2/S/24/4d-I,II,III	80 °C	24	Ø8	4d	90°, 0°, 45°
C2/E/24/2d-I,II,III	80 °C	24	/	2d	90°, 0°, 45°
C2/E/24/4d-I,II,III	80 °C	24	/	4d	90°, 0°, 45°
C2/S/12/2d-II	80 °C	12	Ø8	2d	90°
C2/S/12/4d-II	80 °C	12	Ø8	4d	90°
C2/S/24/2d-II	80 °C	24	Ø8	2d	90°
C2/S/24/4d-II	80 °C	24	Ø8	4d	90°
C2/E/12/2d-II	80 °C	12	/	2d	90°
C2/E/12/4d-II	80 °C	12	/	4d	90°
C2/E/24/2d-II	80 °C	24	/	2d	90°
C2/E/24/4d-II	80 °C	24	/	4d	90°

rebar. 12 mm and 24 mm diameter rebar were used as main reinforcement in pull-out tests. In all specimens with stirrups, 8 mm diameter rebar were used. The mechanical properties of the rebar with different diameters were given in Table 2. The yield and tensile strength of 24 mm diameter reinforcement is higher than that of 12 mm diameter reinforcement. However, the ultimate strength of 12 mm diameter reinforcement is higher than that of 24 mm diameter reinforcement. The

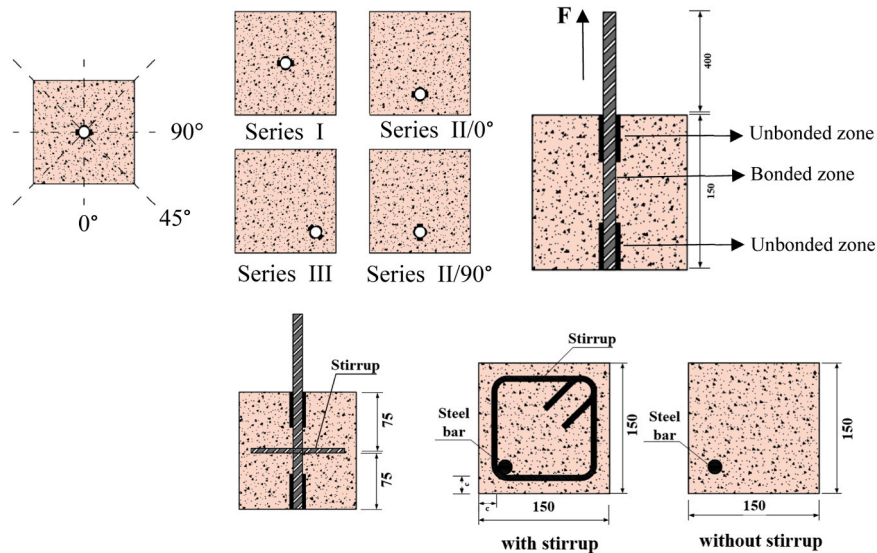


Fig. 1. Specimen dimensions (units: mm).

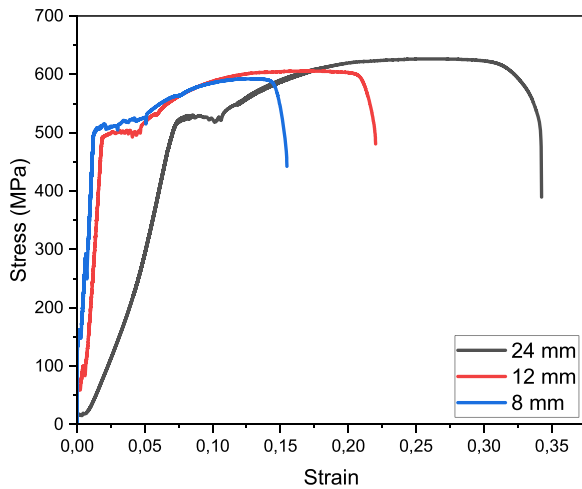


Fig. 2. Strain-stress curve of rebar.

Table 2
Mechanical properties of rebar.

	8 mm	12 mm	24 mm
Nominal diameter (mm)	8	12	24
Measured diameter (mm)	8.1	12.3	24.5
Tensile strength (MPa)	592.51	605.75	626.40
Strain at tensile point	0.127	0.169	0.256
Yield strength (MPa)	508.16	495.94	522.48
Strain at yield point	0.0145	0.0213	0.0783
Ultimate strength (MPa)	422.33	480.64	389.82
Ultimate strain	0.154	0.220	0.342

ultimate strain of 24 mm reinforcement is also 55 % higher compared to 12 mm reinforcement. Differences in the mechanical properties of reinforcement with two different diameters also affected the adherence tests.

Table 3
Mix proportions of geopolymer mortar (kg/m³).

GGBS	Metakaolin	Quartz powder	Quartz aggregate	NaOH	Na ₂ SiO ₃
800	100	700	200	140	350

The geopolymer mortar mix proportions are shown in Table 3. In this experiment, ground granulate blast furnace slag (GGBS) and metakaolin were utilized as the precursors. Moreover, quartz powder (0–0.5 mm) and quartz aggregate (1–3 mm) were used as the aggregate in geopolymer mortar. The particle sizes of GGBS, metakaolin, quartz powder and quartz aggregate are shown in Fig. 3. On the other hand, the XRD pattern and photos of GGBS, MK and quartz are shown in Fig. 4 and Fig. 5. The chemical and physical properties of GGBS, metakaolin, quartz is listed in Table 4. The sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) were used as the alkaline activator. The sodium silicate had a SiO₂/Na₂O molar ratio of 3.2. The SiO₂ and Na₂O in sodium silicate were 28.2 % and 8.2 %, respectively. The sodium hydroxide contained NaOH of 99 %. The ratio of alkaline activators (NaOH+Na₂SiO₃) to binder (GGBS+MK) is designed to be 55 % for workability.

PVC moulds were prepared for casting the geopolymer mortar cylinder with dimensions of $\Phi 150 \text{ mm} \times 220 \text{ mm}$, according to ACI 440–1R–15 [36]. The mixing of geopolymer mortar can be divided into two steps, (i) the solid materials, including GGBS, metakaolin, quartz powder and quartz aggregate, were pre-mixed for 5 min; (ii) the alkali activators, sodium silicate and sodium hydroxide, was added with the additional 3 min of the mixing process. The preparation stage of specimens is shown in Fig. 6. The workability of the geopolymer mortar was tested following ASTM C1437–20 [37]. The average flow diameter was 205 mm. The geopolymer concrete mix with a high slump of 205 mm has excellent workability, which is essential for effective compaction and application in complex shapes. The mix consists of GGBS, MK, quartz, sodium silicate and sodium hydroxide and enables robust geopolymerization through optimal alkaline activation and raw material reactivity. The right curing conditions, especially elevated temperatures, further promote this process and ensure the stability of the concrete. The use of GGBS and MK helps to reduce shrinkage. Overall, the well-designed mix and controlled curing indicate successful geopolymerization, resulting in a stable, workable and durable concrete. After the casting of processing, all types of geopolymer mortars were set within 2 h. All specimens were subjected to pull-out test 7 days after manufactured. Specimens in C1 group were air cured in the laboratory conditions until the test day (7 days). Specimens in group C2 was cured at consist temperature 2 hours after manufacturing. The temperature cure was applied at 80 °C for 7 hours. In order to conduct pull-out tests on specimens that have been exposed to high temperatures, the specimens were initially heated in an electrical furnace. The heating process was carried out gradually, with a heating rate of 15 °C per minute. Once

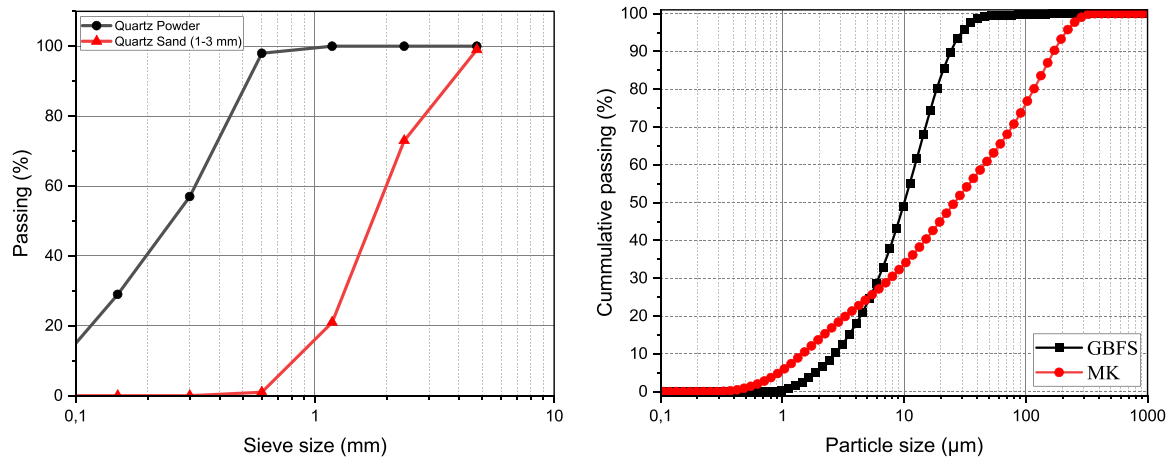


Fig. 3. The particle size of GBFS, metakaolin, quartz powder and quartz sand.

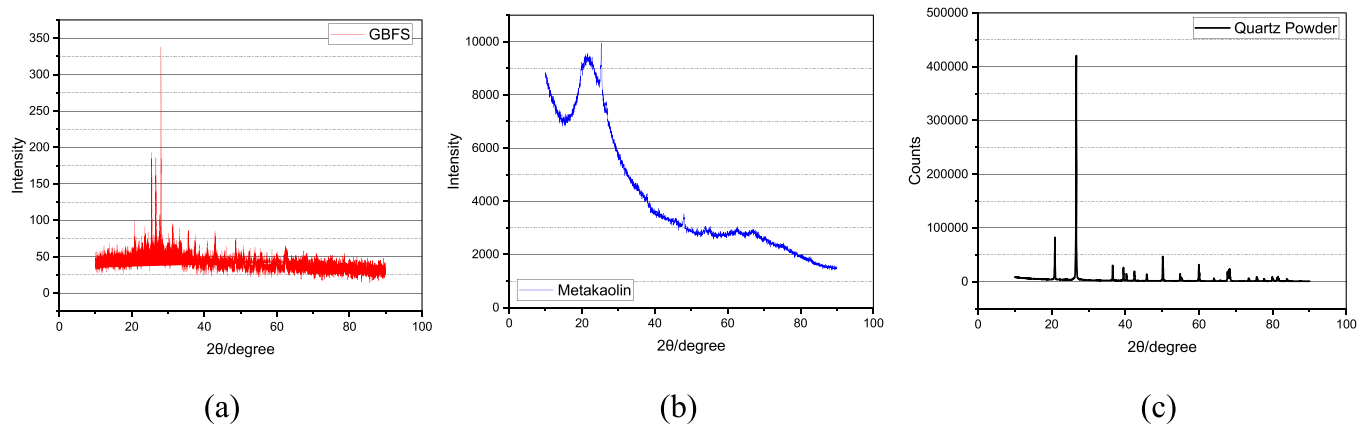


Fig. 4. XRD pattern of (a) GBFS (b) MK (c) quartz.



Fig. 5. The photo of used materials in GPC blends.

Table 4
The chemical and physical properties of GBFS, metakaolin (MK), quartz.

	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	SO ₃	SG*	SSA**	SS***
GBFS	37.7	11.4	34.4	5.3	6.9	0.8	2.90	-	5090
MK	54.3	43.2	<0.5	<0.8	<0.2	<0.1	2.60	20****	
Quartz	98.2	11.4	-	0.2	<0.1	<0.1	2.71	-	

*Specific gravity.
**Specific surface area.
***Specific surface (blain)(cm²/gr).
****BET method (m²/g).

the desired test temperature was reached, the furnace temperature was maintained at a constant level for a duration of 7 hours. Subsequently, the heating in the furnace was turned off and the specimens were allowed to cool naturally. Once the specimens had cooled down to the ambient temperature, they were removed from the furnace and pull-out

tests were conducted using the same procedures as those employed during ambient tests. In order to safeguard the interface from potential damage resulting from the rapid increase in temperature of the steel bar during the heating procedure, a protective measure was taken by enveloping the exposed steel bars of the specimens with refractory

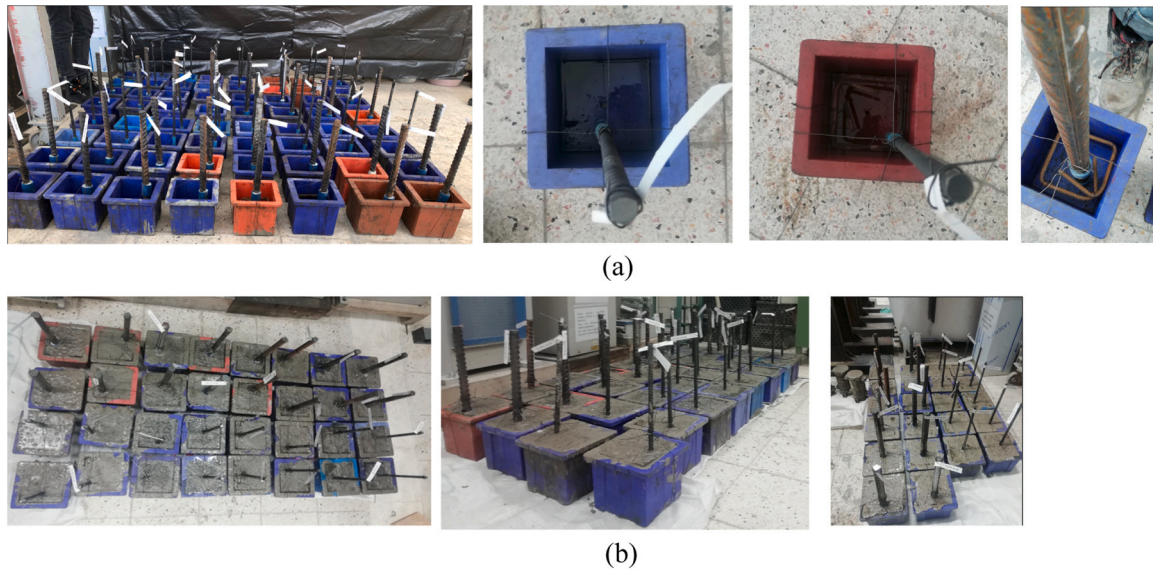


Fig. 6. Preparation of concrete specimens (a) preparation phase of the molds (b) concrete poured samples.

cotton. The rebar used in the pull-out specimen had a total length of 450 mm (including a free end and an embedded part). A steel tube filled with epoxy was sleeved outside the loading part to protect the bar from gripping failure. The small PVC covers achieved the desired embedded length at two ends of the rebar to prevent the contact between the rebar and the geopolymer mortar.

2.3. Test procedures

The test setup is illustrated in Fig. 7 the loading end of the bars was gripped to the machine and the specimen was clamped on a reaction rig. A displacement-controlled loading mode with a rate of 0,2 mm/min was adopted. The bar loading end movements and the applied loads were recorded by the loading machine.

The average bond stress along a discrete length was calculated according to Eq. (1)

$$\tau = F/(\pi dL) \quad (1)$$

where τ = Bond stress (MPa), F = Tensile load (N), d = Bar diameter (mm), and L = Bond length (mm).

3. Experimental results and discussion

3.1. Compressive, splitting tensile and flexural strengths

The comparative result of compressive and splitting tensile strength

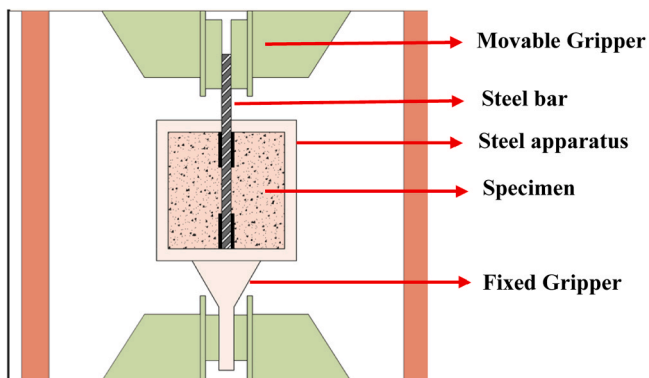


Fig. 7. Experimental setup for the direct pull-out test.

of geopolymer concrete at ambient temperature (C1) and exposure to temperature cure (C2) is shown in Table 5. The relationship between compressive strength and strain is shown in Fig. 8a in which the flexural strength and mid-span curves are shown in Fig. 8b. It can be seen that increase in compressive and flexural strength of C1 and C2 concretes is significant till the exposure temperature is up to 80 °C. The average compressive strength of samples exposure to temperature cure is approximately 2 times higher than that of samples cured at ambient temperature since it is similar with that reported in Ref. [38–40]. The higher compressive strength and flexural strength of the samples exposed to 80 °C temperature caused the geopolymer concrete to have a denser structure due to the temperature cure affecting the geopolymerization process. Thus, this situation caused the formation of a stronger and tighter chemical bond in the internal structure of geopolymer concrete. The geopolymerization process of geopolymer concrete samples exposed to ambient curing occurred slower. On the other hand, geopolymerization in the internal structure of the samples cured at 80 °C occurred faster. In other words, the dissolution of aluminosilicates and the formation of molecular chains by the alkali solution occurred more effectively and rapidly in C2 concrete samples. Geopolymer concrete C1 exhibits the similar level of tensile strength as that of C2 after exposure to elevated temperatures, but the relatively higher splitting tensile strength than that of C2 concrete. Metakaolin and quartz materials in the geopolymer mixture (C2) reacted with activators and formed extra bonds with the effect of temperature cure, causing an increase in strength.

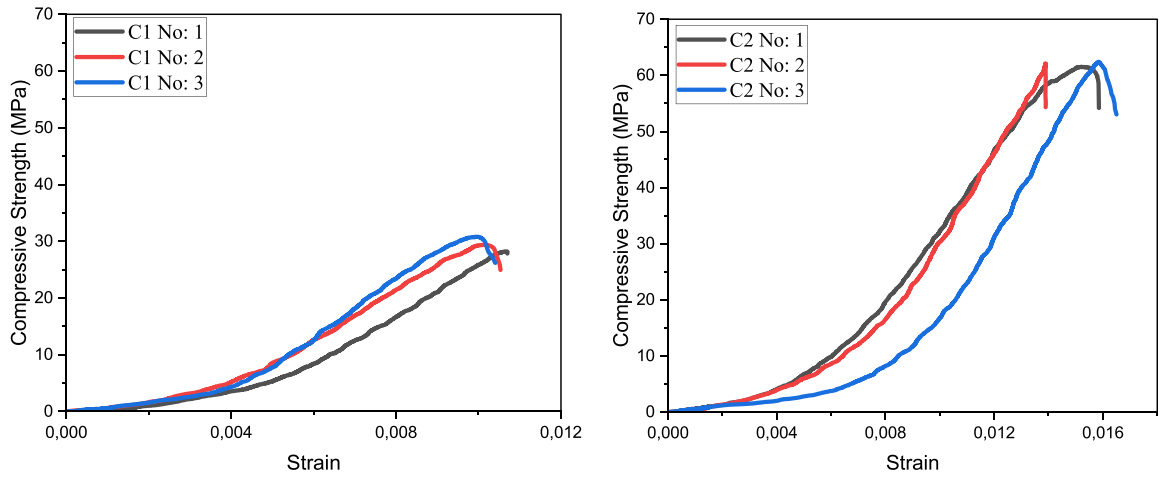
3.2. Pull-out tests results

Pull-out tests are an important method for evaluating the bond strength between reinforcement (usually steel) and concrete. Pull-out tests primarily measure the local bond stress at the interface between concrete and reinforcing steel. This is crucial because in practical loading scenarios, the bond strength determines the ability of the concrete to transfer stresses in the reinforcement and thus ensures structural integrity. While real structures are subjected to complex stress distributions (bending, shear, torsion), pull-out tests focus on the pull-out force (tensile force). Despite this simplification, the test results are important as they provide a conservative estimate of bond performance under more complex stress conditions. The test helps to understand the interaction between geopolymer concrete and steel reinforcement. Pull-out tests offer a simplified representation of stress conditions when

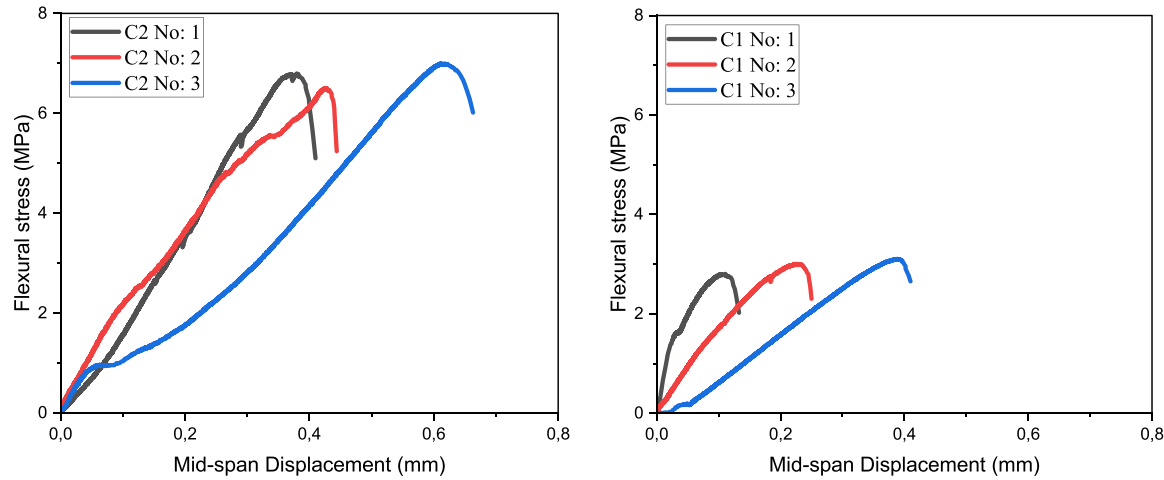
Table 5

Compressive and splitting tensile strength of geopolymer concrete.

Type of concrete	Curing temperature (°C)	Comp. strength f_{cu} (MPa)	Average comp. strength	Tensile strength f_t (MPa)	Average Tensile strength	Flexural strength (MPa)	Average flexural strength
C1	Ambient	28.20	29.44	3.05	2.55	3.00	2.96
	Ambient	29.36		2.11		2.80	
	Ambient	30.78		2.50		3.10	
C2	80 °C	61.49	61.98	2.80	3.11	6.80	6.76
	80 °C	62.09		3.74		6.99	
	80 °C	62.36		2.79		6.50	



(a) Compressive strength and strain relationship



(b) Flexural strength and mid-span relationship

Fig. 8. Mechanical results of C1 and C2.

compared to real-life loading scenarios. However, these tests play a crucial role in assessing the bond strength and overall performance of reinforced geopolymer concrete. The findings from these tests provide valuable insights into the behavior of anchorage, which in turn contribute to the development of safer and more efficient structural designs. Furthermore, these insights help in promoting the wider acceptance and use of geopolymer concrete in the construction industry.

The experimental results are presented here in terms of measured average bond strength, normalized bond strength, average load, slip corresponding maximum bond strength, energy dissipation capacity and failure mode. A summary is given in Table 6. The results are grouped by

Series (according to the cure condition, C1 and C2), each value. Therefore, represents the average of three specimens tested under the same conditions. The influence of the position of rebar (center, middle bottom and corner), longitudinal rib angles (0°, 45° and 90°), curing condition (ambient and heat curing), rebar diameter (12 mm and 24 mm), bond length (2d and 4d) and stirrup usage on the bond behavior is analyzed in this section. In the pull-out test, the stress distribution is not constant along the embedment length. Hence, an average bond stress is defined as Eq. (1). The experimental results obtained from the bond tests, as well as the mode of failure, are given in Table 6, for C1 series and for C2 series. In this table, P_{max} is the maximum load, τ_{max} is

Table 6
Summary of test results.

Specimens	P _{max} (kN)	τ_{max}^* (MPa)	τ_n^{**} (MPa)	SD ^{***}	S _{max} (mm)	SD	E (MPa. mm)	FM
C1-C-E-12-2D	15.64	8.65	1.59	1.10	2.21	1.08	11.25	S
C1-C-E-12-4D	10.25	11.33	2.09	1.08	2.21	1.04	25.28	S
C1-C-S-12-2D	10.55	11.66	2.15	1.08	2.27	1.05	15.99	S
C1-C-S-12-4D	24.51	13.54	2.49	1.06	2.53	1.01	29.15	S
C1-0-E-12-2D	8.34	4.61	0.85	1.11	2.26	1.06	6.07	S
C1-0-E-12-4D	13.27	7.33	1.35	1.05	2.11	1.08	9.65	S-B
C1-0-S-12-2D	15.31	8.46	1.55	1.10	3.27	1.09	16.53	S
C1-0-S-12-4D	7.89	8.72	1.60	1.07	2.01	1.05	11.94	S
C1-45-E-12-2D	3.81	4.21	0.77	1.08	1.85	1.04	5.93	S
C1-45-E-12-4D	11.04	6.10	1.12	1.07	2.02	1.06	8.92	S
C1-45-S-12-2D	3.93	4.35	0.80	1.12	1.15	1.04	3.52	S
C1-45-S-12-4D	12.59	6.96	1.28	1.09	3.13	1.05	17.08	S
C1-90-E-12-2D	5.02	5.55	1.02	1.09	1.30	1.03	8.19	S-B
C1-90-E-12-4D	16.06	8.87	1.63	1.02	2.51	1.04	13.04	S-B
C1-90-S-12-2D	9.13	10.10	1.86	1.06	2.56	1.04	23.57	S
C1-90-S-12-4D	21.21	11.72	2.16	1.07	3.35	1.05	33.15	S
C1-C-E-24-2D	9.64	1.33	0.24	1.07	3.68	1.08	2.64	S-B
C1-C-E-24-4D	17.80	4.92	0.90	1.08	2.74	1.06	7.90	S-B
C1-C-S-24-2D	52.55	14.52	2.67	1.06	7.03	1.07	71.86	S
C1-C-S-24-4D	68.75	18.99	3.50	1.12	15.01	1.09	160.64	S
C1-0-E-24-2D	13.52	1.86	0.34	1.07	6.20	1.011	5.07	S
C1-0-E-24-4D	17.73	4.90	0.90	1.08	3.31	1.07	10.07	S
C1-0-S-24-2D	49.89	6.89	1.27	1.07	6.54	1.06	45.38	S
C1-0-S-24-4D	32.85	9.07	1.67	1.06	9.43	1.05	52.48	S
C1-45-E-24-2D	7.62	2.10	0.38	1.09	2.16	1.07	2.98	S
C1-45-E-24-4D	18.27	2.52	0.46	1.07	2.13	1.07	3.26	S
C1-45-S-24-2D	51.97	7.18	1.32	1.03	8.68	1.08	35.29	S
C1-45-S-24-4D	41.99	11.60	2.13	1.04	8.40	1.02	70.41	S
C1-90-E-24-2D	29.44	3.53	0.65	1.07	2.67	1.04	6.98	S
C1-90-E-24-4D	30.17	4.16	0.76	1.07	4.46	1.06	10.31	S-B
C1-90-S-24-2D	57.41	7.93	1.46	1.08	5.28	1.03	24.91	S
C1-90-S-24-4D	33.82	9.34	1.72	1.08	5.16	1.07	36.26	S
C2-C-E-12-2D	16.97	9.38	1.19	1.08	1.76	1.07	9.29	S
C2-C-E-12-4D	15.39	17.01	2.16	1.13	2.92	1.05	32.61	S
C2-C-S-12-2D	27.85	15.39	1.95	1.09	3.79	1.07	62.59	S
C2-C-S-12-4D	16.37	18.09	2.29	1.13	2.58	1.07	48.58	S
C2-0-E-12-2D	15.20	8.40	1.06	1.08	2.16	1.04	9.58	S
C2-0-E-12-4D	10.96	12.12	1.54	1.09	1.71	1.04	24.27	S
C2-0-S-12-2D	27.11	14.98	1.90	1.11	4.05	1.04	63.41	S
C2-0-S-12-4D	14.84	16.40	2.08	1.11	2.28	1.02	25.33	S
C2-45-E-12-2D	19.14	7.57	0.96	1.07	2.80	1.04	16.14	S
C2-45-E-12-4D	15.13	8.36	1.06	1.11	5.16	1.07	24.36	S
C2-45-S-12-2D	8.90	9.84	1.25	1.07	2.70	1.08	16.03	S
C2-45-S-12-4D	12.36	13.67	1.73	1.08	3.04	1.06	25.43	S
C2-90-E-12-2D	4.69	5.18	0.65	1.12	1.42	1.05	5.94	S
C2-90-E-12-4D	16.66	9.20	1.17	1.06	2.37	1.07	11.63	S
C2-90-S-12-2D	8.66	9.57	1.21	1.08	1.64	1.04	16.99	S
C2-90-S-12-4D	20.39	11.27	1.43	1.07	7.82	1.08	54.61	S
C2-C-E-24-2D	58.70	8.11	1.03	1.06	9.55	1.03	26.20	S-B
C2-C-E-24-4D	42.20	11.66	1.48	1.03	8.70	1.04	35.81	S-B
C2-C-S-24-2D	55.40	15.31	1.94	1.08	11.40	1.06	83.36	S
C2-C-S-24-4D	97.29	13.44	1.70	1.02	11.21	1.02	77.59	S
C2-0-E-24-2D	11.84	3.27	0.41	1.12	4.53	1.07	8.82	S
C2-0-E-24-4D	44.82	6.19	0.78	1.13	6.44	1.09	18.41	S
C2-0-S-24-2D	61.01	8.43	1.07	1.12	6.60	1.09	45.52	S
C2-0-S-24-4D	34.42	9.51	1.20	1.11	4.85	1.05	63.04	S
C2-45-E-24-2D	11.28	1.56	0.19	1.09	4.50	1.07	4.55	S
C2-45-E-24-4D	18.83	5.20	0.66	1.12	3.45	1.03	10.92	S
C2-45-S-24-2D	38.27	5.28	0.67	1.05	6.32	1.05	17.67	S
C2-45-S-24-4D	29.21	8.07	1.02	1.13	4.58	1.07	37.04	S
C2-90-E-24-2D	10.94	3.02	0.38	1.05	7.79	1.05	11.25	S
C2-90-E-24-4D	33.69	4.65	0.59	1.08	5.34	1.06	11.99	S
C2-90-S-24-2D	33.37	9.22	1.17	1.04	6.78	1.09	29.61	S
C2-90-S-24-4D	89.23	12.32	1.56	1.05	13.81	1.03	78.52	S

*Average bond strength; **Normalized bond strength ($\tau_n = (\tau_{nmax})/(\sqrt{f_{cu}^t})$); ***Standard deviation; S = Splitting; B = Bond failure; S-B = Splitting and failure; Y = Bar yielding.

the average maximum bond strength of three samples, τ_n is the normalized average bond strength of three samples ($\tau_n = (\tau_{nmax})/(\sqrt{f_{cu}})$; f_{cu} is the concrete compressive strength), s_{max} is the slip corresponding maximum bond strength and E is the energy dissipation capacity. Energy dissipation capacity was calculated from the area under of bond-slip curve.

It can be seen from the table that the test parameters are effective on the bond strength. It is seen that the application of temperature cure in samples produced from geopolymer concrete increases the bond strength. Moreover, increasing the diameter of the reinforcement is one of the most important parameters on the bond strength. Increasing the diameter of the reinforcement also reduced the bond strength whereas the stirrup usage positively affected the bond performance. The effect of test parameters on bond strength is explained in detail in the following sections.

Figs. 9, 10, 11 and 12 present typical bond stress- slip curves of specimens in Groups C1 and Groups C2 respectively, at different curing conditions. As shown in Figures, the bond behavior of these samples can be described in three stages: an initial stage with a sharp rise in bond stress and minimal slippage, a subsequent stage with a rapid drop in bond stress and a quick rise in slippage, and a final stage with no notable change in bond stress but a substantial increase in slippage. The load is then primarily controlled by the mechanical interlocking between the geopolymer mortar and rebar, for which the geopolymer mortar

properties play essential roles. Afterward, the peak average bond stress is reached, and subsequently the load is declined. This declining segment is due to the cracks in the concrete or/and the damage in the surface layer in the rebar. Particularly, the average bond stress-slip curves for some specimens exhibit a post-peak sharp descending segment (e.g., C2-C-E-24-2D, C2-C-E-24-4D, C2-90-E-12-4D, C2-0-E-12-2D). This is because the stress concentration in around the cracks. The sharp decrease in average bond stress rebounds during the subsequent pull-out loading. Following this rebound, the bond-slip curve shows a consistent residual section resembling the third segment seen in typical bond-slip curves.

3.3. Effects of different parameters

3.3.1. Rebar diameter

The rebar diameter is one of the most parameters on the bond strength between concrete and rebar. It is believed that the increasing rebar diameter generally decreases the bond strength, when the specimen sizes are kept constant [41–45]. However, there are few studies in the literature [46–50] which indicate that the increasing rebar diameter increases the bond strength between concrete and rebar. The bond strength of specimens under different curing conditions with different rebar diameters is presented in Fig. 13. Although increasing the rebar diameter decreased the bond strength in some samples under ambient

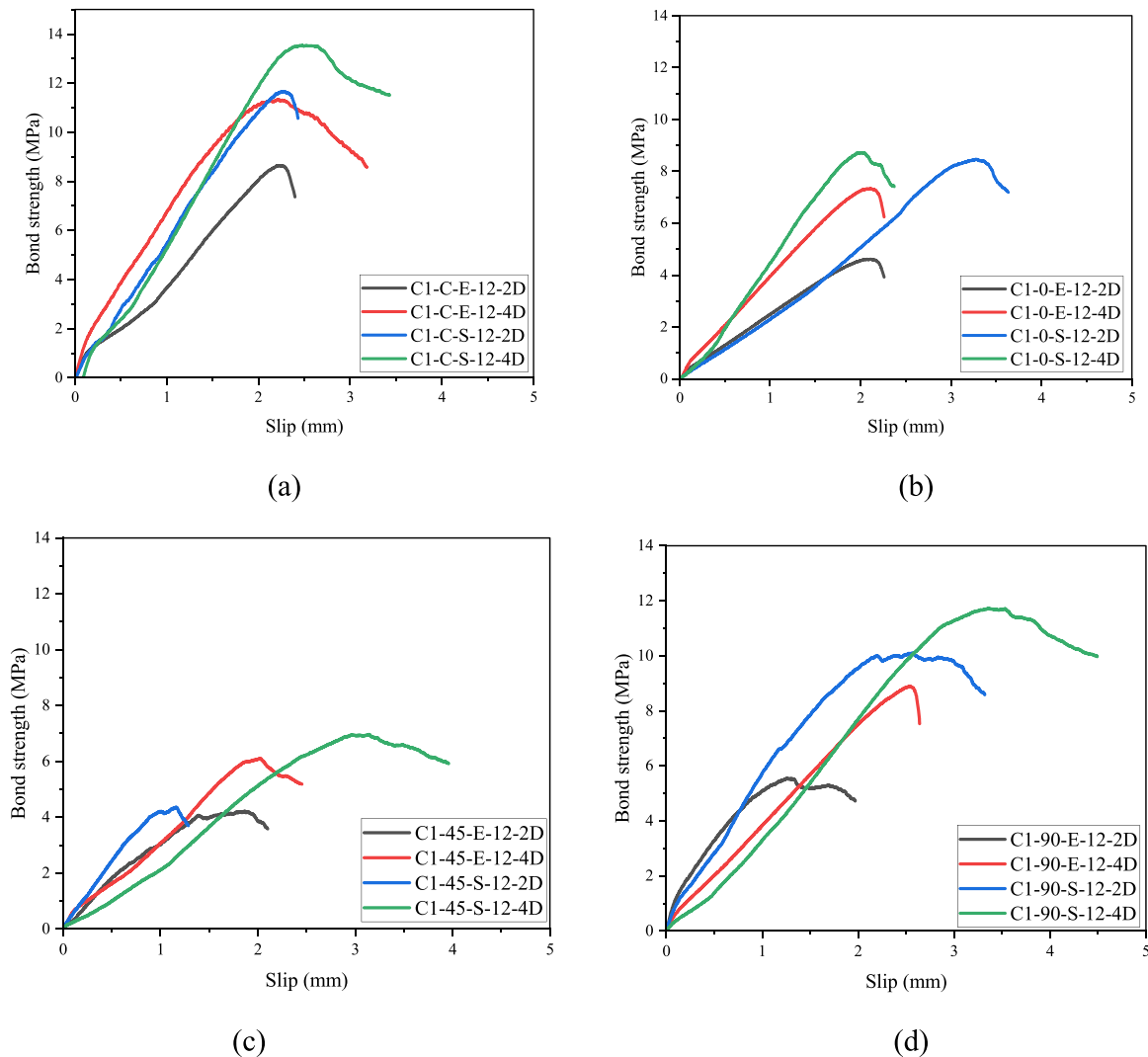


Fig. 9. Bond strength-slip curves of samples with 12 mm diameter rebar under ambient cure (a) center (b) middle bottom 0° (c) corner (d) middle bottom 90°.

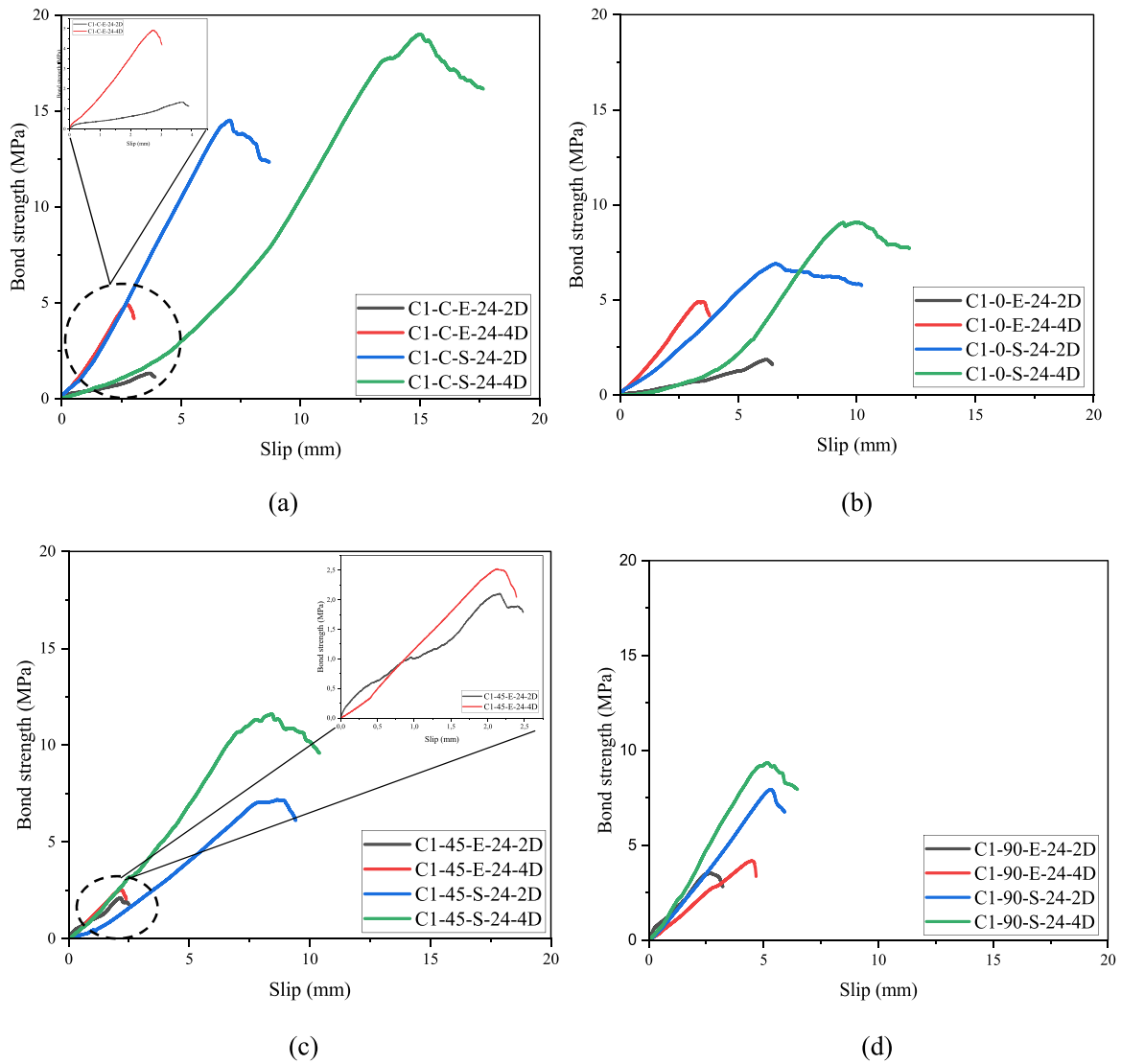


Fig. 10. Bond strength-slip curves of samples with 24 mm diameter rebar under ambient cure (a) center (b) middle bottom 0° (c) corner (d) middle bottom 90°.

curing. Nevertheless, the increase in the rebar diameter generally decreased the bond strength. Increasing the rebar diameter decreased the adherence strength in the C1-C-S-2D, C1-C-S-4D, C1-O-S-4D, C1-45-S-2D and C1-45-S-4D samples. The bond strength increase in these samples is between 4 % and 66 %. In other samples under ambient curing, increasing the diameter of the reinforcement decreased the bond strength. Among the samples subjected to heat cure, increasing the rebar diameter increased the bond strength only in the C2-90-S-12-4D sample. In these samples, as the rebar diameter increased, the interface between the reinforcement and the concrete also increased. At the interface, the high interlocking ability between reinforcement and concrete in these samples increased the bond strength. Moreover, larger diameter reinforcements may have caused tensile stresses to be distributed more homogeneously within the geopolymer concrete phase. Therefore, the stress can be distributed more evenly between the concrete and the reinforcement, and thus the bond strength increases. The another reason for this phenomenon that occurs at the interfacial transition zone between the reinforcement and concrete. It is identified by a greater concentration of geopolymer particles that can connect with the reinforcement surface. This improves the mechanical connection between the reinforcement and the matrix, leading to a higher bond strength. Increasing the rebar diameter of samples under ambient cure increased the bond strength between 18 % and 84 %, in which

increasing the rebar diameter of samples under heat cure increased the bond strength between 0.52 % and 79 %. It can be seen that the most of specimens' bond strength with rebar diameters of 12 mm is higher than that of 24 mm, both at ambient and heat cure. As the diameter of the reinforcement increases, the contact surface between the concrete and the reinforcement increases, thus increasing the defect rate in this region. An increase in the imperfection rate may also cause the chemical bond between concrete and reinforcement to weaken. Hence, stress concentrations increase crack formation and crack propagation at the interface between concrete and reinforcement. Therefore, increasing the diameter of the reinforcement decreased the bond strength in these samples.

3.3.2. The position of longitudinal bar and longitudinal rib angles

To examine the effect of the position of the longitudinal bar on the bond strength, the reinforcements were placed in the square section sample in three different ways; center (C), middle bottom (0 and 90) and corner (45). To investigate the effect of longitudinal rib angles on bond strength, the ribs of the rebar placed at the middle bottom point were positioned at two different angles (0° and 90°). The effect of the position of longitudinal bar and longitudinal rib angles is shown in Fig. 14. Placing the longitudinal reinforcement at the middle bottom and corner points, contrary to the center position, significantly reduced the bond

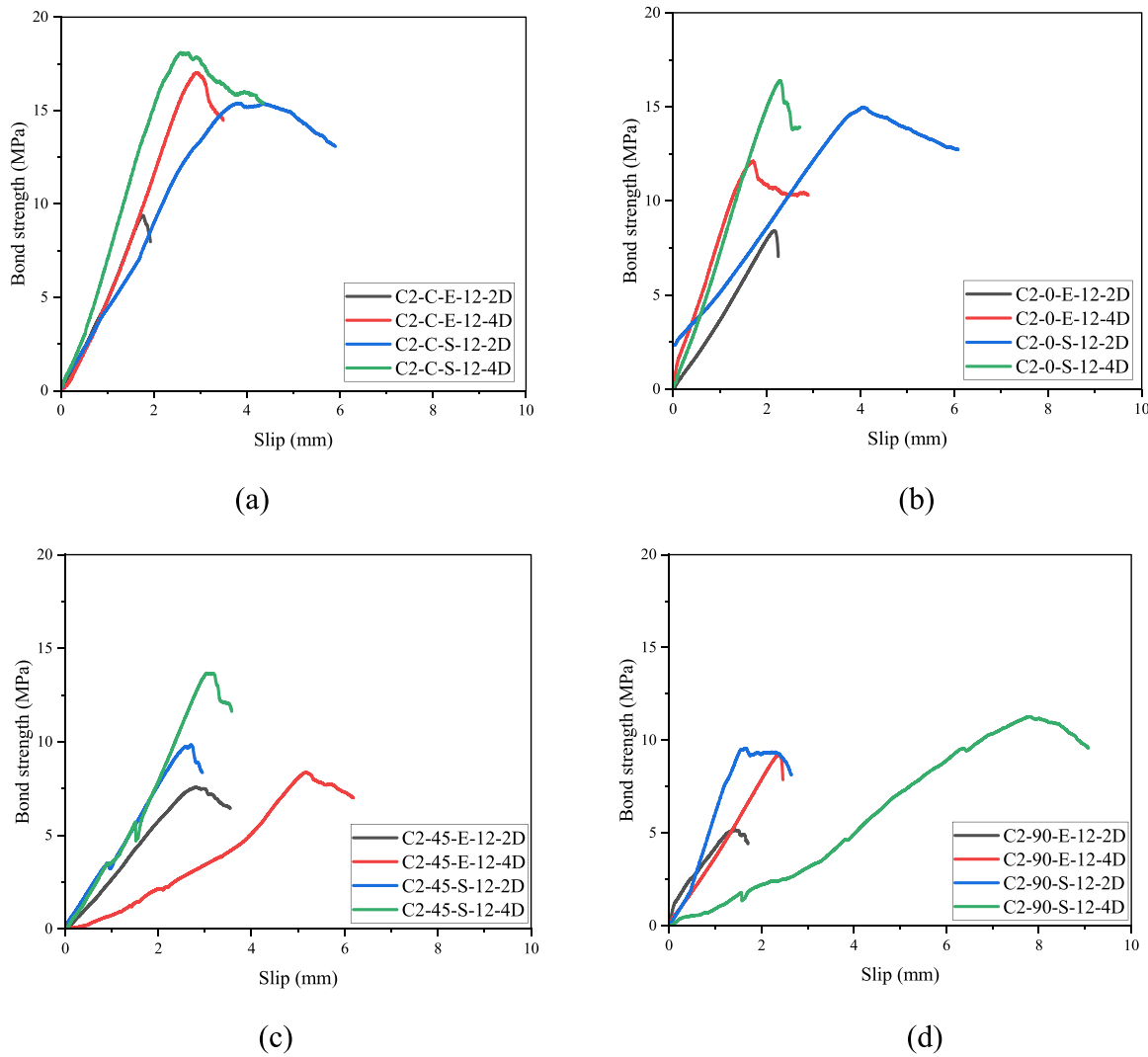


Fig. 11. Bond strength-slip curves of samples with 12 mm diameter rebar under heating cure (a) center (b) middle bottom 0° (c) corner (d) middle bottom 90°.

strength. In samples under ambient cure, when the reinforcement was placed from the center position to the middle bottom (comparing C and 0 samples), the bond strength decreased by 27–52 % in which the bond strength of samples under heat cure decreased by 2–59 %. The reason for this is that although the distance of the reinforcement placed in the center position to the edge points of the sample is 75 mm, the distance of the reinforcement placed in the middle bottom to the edge point of the sample is 30 mm and 75 mm. Therefore, in 0 samples, excessive stress concentrations in the region close to the edge weakened the characteristic properties of the concrete. This negatively affected the adhesion mechanism between the reinforcement and concrete. The bond strength of the samples (under ambient cure) in the central position (C) of the reinforcement is 38–62 % less than the samples in the edge position (45) of the reinforcement, except for the C1–45-E-24–2D sample, in which bond strength of samples (under heat cure) in the central position (C) of the reinforcement is 19–80 % less than the samples in the edge position (45) of the reinforcement. As the position of the reinforcement was moved to the middle bottom, the mechanical connection between the reinforcement and the geopolymer concrete was weakened, thus the adherence strength of the samples (0 and 45) decreased. In addition, there have been significant changes in the concrete cover by positioning the reinforcement at the corner and middle bottom. In other words, the concrete cover of samples 0 and 45 has decreased significantly. As the concrete cover decreased, the adhesion between the reinforcement and geopolymer concrete also weakened. Therefore, the location of the

reinforcement is very important to increase the bond strength of the reinforcement, especially in structural elements that may be exposed to chemical effects, corrosion or similar effects. On the other hand, in the literature few studies [51–53] reported that the increasing concrete cover decreased the bond strength.

To investigate the effect of longitudinal rib angles on bond strength, when 0 and 90 samples are compared, it is seen that changing the longitudinal rib angles affects bond strength. However, this effect is increasing in some samples and decreasing in some samples. In samples under ambient cure, changing the longitudinal rib angles from 0 degrees to 90 degrees reduced the bond strength by 2–89 %, except for the C1–90-E-24–4D sample. In heat cured samples, changing the longitudinal rib angles from 0 degrees to 90 degrees increased the bond strength between 7 % and 38 %, except for C2–90-S-24–2D and C2–90-S-24–4D samples.

3.3.3. Bond length

The relationship between the embedded length and the average bond strength for specimens with different cure condition is shown in Fig. 15. It is evident that for specimens with increasing embedded length, the average bond strength increase. Increasing the bond length increased the bond strength both in the samples under ambient and heat cure. Increasing the adherence length from 2D to 4D to the samples under ambient curing increased the adherence strength by 3–73 %, in which, increasing the bond length reduced the bond strength of samples under

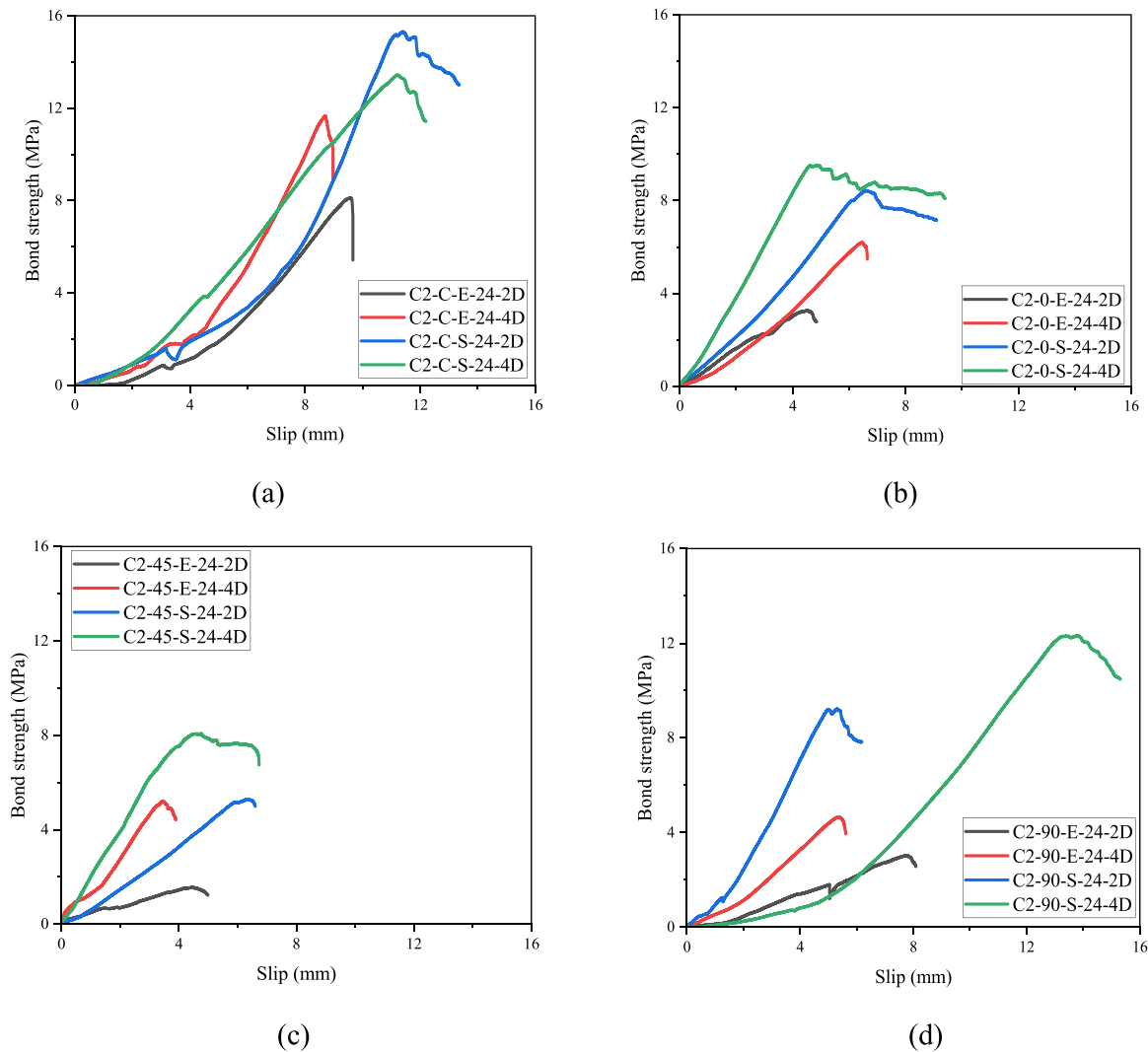


Fig. 12. Bond strength-slip curves of samples with 24 mm diameter rebar under heating cure (a) center (b) middle bottom 0° (c) corner (d) middle bottom 90°.

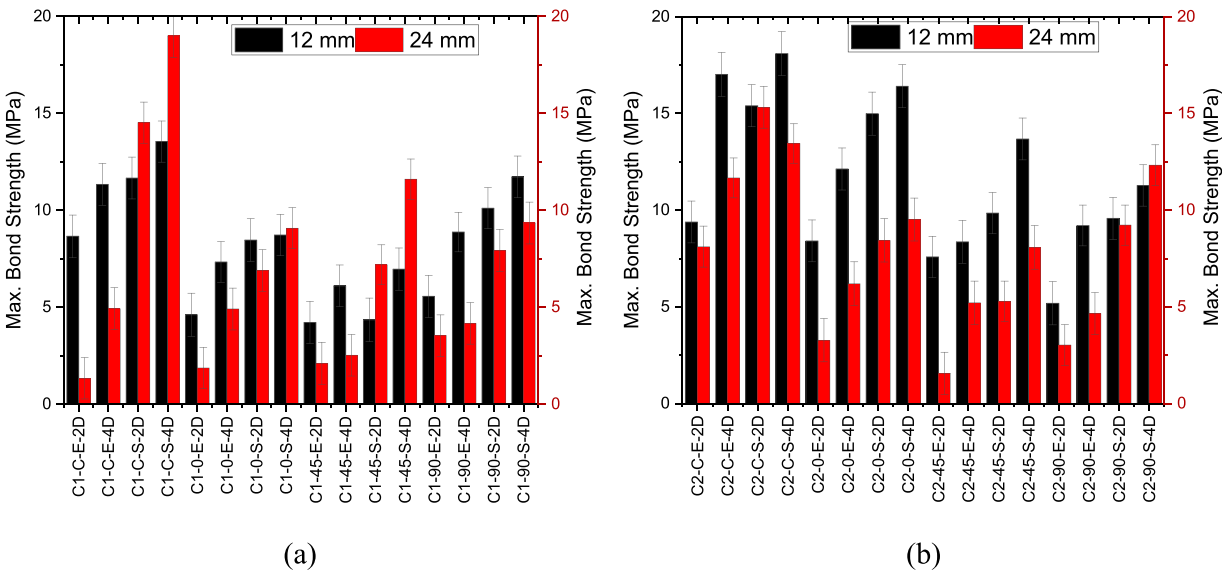


Fig. 13. Effect of bar diameter on the bond strength (a) under ambient cure (b) under heat cure.

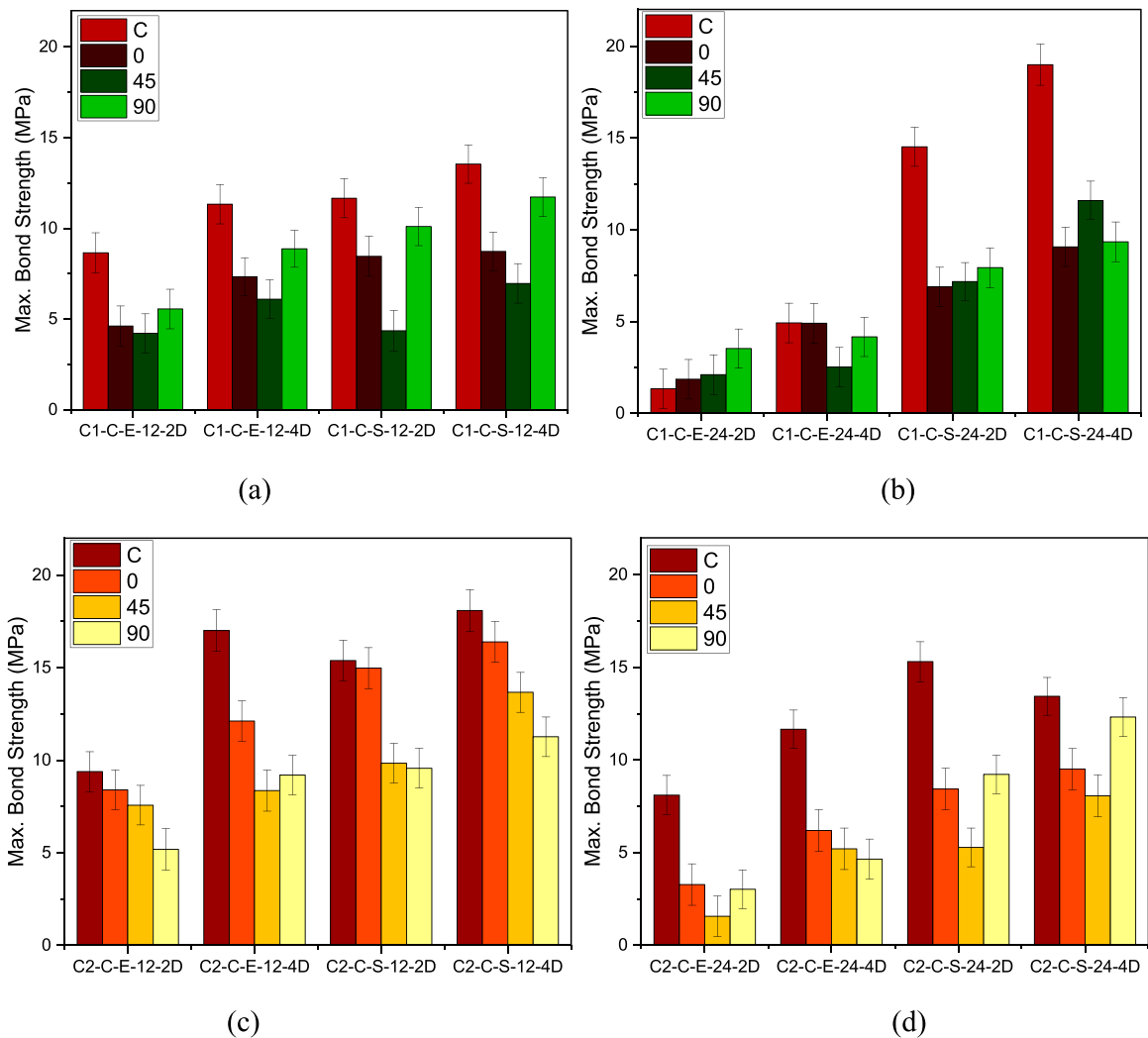


Fig. 14. Effect of position of longitudinal bar and longitudinal rib angles on the bond strength (a) under ambient cure and 12 mm rebar diameter (b) under ambient cure and 24 mm rebar diameter (c) under heat cure and 12 mm rebar diameter (d) under heat cure and 24 mm rebar diameter.

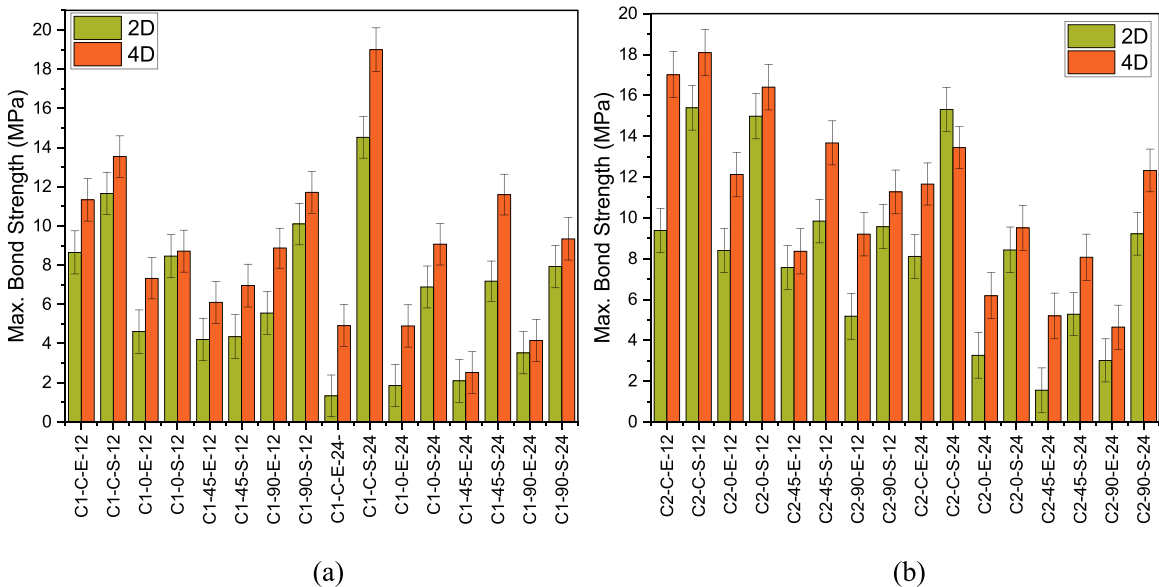


Fig. 15. The effect of embedded length on the bond strength (a) under ambient cure (b) under heat cure.

heat cure by 8–70 %. The phenomenon has been reported by few studies in the literature [54–56]. The reduction of bond strength is due to the nonlinear distribution of the bond stress along the rebar embedded in the geopolymer matrix. Consequently, the increase in load is not effectively distributed to the geopolymer mortar located close to the unrestrained end of the reinforcement bar. This heightened stress in one area could lead to cracks in the geopolymer mortar and premature detachment. In addition, the stresses were compensated by the mechanical adhesion between the concrete and the reinforcement at a longer bond length. The stress distribution on the reinforcement is shown schematically in Fig. 16. Since the stress concentration around the reinforcement increased with the decrease in the bond length, these stresses caused micro cracks to form between the concrete and the reinforcement. With increasing stress, micro cracks spread and the crack width increases. In samples with high bond length, the stress distribution between concrete and reinforcement was more homogeneous, causing stress concentrations to decrease. During the rebar pull-out process, the rebar slid along the geopolymer matrix. The main source of bond resistance came from the mechanical interlock between the rebar ribs and the matrix. The rib bearing forces caused radial components, generating tension stress fields around the rebar, as illustrated in Fig. 16. In this stress environment, splitting cracks began in the matrix near the rebar and spread outward towards the surface of the concrete.

3.3.4. Curing condition

The effect of curing condition on the bond strength of samples is shown in Fig. 17. It appears that heat cure has a significant effect on the bond strength of the samples. Application of heat cure to samples produced from geopolymer concrete increased the adherence strength. The application of heat cure increased the adherence strength of the samples up to 85 %. Although the application of heat cure increased the bond strength by an average of 26 % in 12 mm diameter reinforcement, it increased the bond strength by an average of 10 % in 24 mm diameter samples. Heat curing was more effective in samples with the smaller reinforcement diameter. The most important reasons why temperature curing increases the adherence strength is its effect on the compressive and tensile strengths of geopolymer concrete. The compressive and tensile strengths of samples under heat cure are 110 % and 22 % higher, respectively, than those of samples under ambient cure (from Table 5). The use of temperature in the curing process speeds up the geopolymerization process, leading to more effective chemical reactions between the aluminosilicate source and alkali activators. This results in the formation of a more uniform and dense geopolymer matrix, enhancing the mechanical properties of the concrete. The accelerated geopolymerization under higher temperatures promotes improved crystallization and a consistent microstructure, which in turn enhances interlocking and bonding within the material, ultimately boosting compressive and tensile strength. The elevated temperature during curing allows for a stronger bond between the geopolymer, aggregate, and reinforcement, thereby improving the overall mechanical properties of the concrete. The enhanced bonding and interlocking of the geopolymer matrix with aggregates and reinforcements significantly contribute to increase compressive and tensile strength. Precise temperature control during curing is vital for enhancing the mechanical properties of geopolymer concrete without compromising other

characteristics. Curing geopolymer concrete at specific temperature levels for an appropriate duration results in a denser, more uniform, and stronger geopolymer matrix. This optimized matrix promotes better mechanical interactions, microstructure development, and overall improved compressive and tensile strength of the concrete. For these reasons, an increase in adherence strength was detected due to the improvement of the mechanical properties of the geopolymer matrix with temperature curing. Due to the increase in the tensile strength of geopolymer concrete, it was more effective in resisting the principal tensile stresses. Crack formation and crack propagation caused by principle tensile stresses were slower due to the high-tensile strength. Thus, the interlocking between geopolymer concrete and reinforcement is more effective in samples under temperature curing. This is another important factor that increases adherence strength.

3.3.5. Stirrup usage

The bond strength rises as the lateral pressure increases. Stirrups offer lateral confinement stress, holding back the expansion of crack width, and are linked to the stress in stirrups caused by their deformation and crack width. The effect of stirrup usage on the bond strength is illustrated in Fig. 18. The figure shows that for samples under ambient and heat cure, the bond strength between the reinforcements and concrete can be significantly improved when stirrups were used. For example, the stirrup usage in samples under ambient curing increased the adherence strength between 3 % and 90 %, in which the bond strength of samples under heat cure increased between %5 and %70 because of stirrup usage. The stirrup usage in samples under ambient and temperature curing increased the adherence strength by an average of 46 % and 40 %, respectively. Confining stirrups in reinforced concrete elements significantly contribute to ductility and bond strength. Typically, adding lateral or transverse confinement in concrete improves the bond strength by countering the forces exerted by the stirrups. Another reason why stirrup usage increases adherence strength that the stirrup usage has the potential to decrease crack propagation and boost shear resistance. This enhanced shear transfer can indirectly help in maintaining the connection between the reinforcement and the concrete, especially in areas exposed to stress. Stirrups typically enlarge the effective bonding surface between the reinforcement and the concrete, particularly in the compression section of the sample. This enlarged bonding surface can improve the bond strength and enhance the load transfer between the reinforcement and the geopolymer concrete. Proper placement and design of stirrups can optimize the stress distribution within the geopolymer concrete element. This optimized stress distribution can result in a consistent bond stress throughout the reinforcement's length, thus bolstering the bond strength of geopolymer concrete.

3.4. Failure mode

During pull-out tests conducted on geopolymer concrete specimens, four distinct types of failure modes were observed. These included the typical splitting failure (S), bond failure (B) (also known as pull-out failure), a combination of splitting and bond failure (S-B) (referred to as splitting-bond failure), and rebar fracture (Y). The typical failure mode after pull-out tests of some specimens is shown in Fig. 19. In the case of typical splitting failure, one can observe the development of radial cracks originating from the rebar surface. These cracks then propagate rapidly in the longitudinal direction, ultimately resulting in the abrupt failure of the geopolymer concrete with minimal slippage of the rebar. On the other hand, bond failure is characterized by shear failure at the interface between the geopolymer concrete and the reinforcing bar. This failure mode is accompanied by significant slippage of the rebar, although no visible splitting cracks are observed. It was observed that the splitting collapse mode was generally dominant in the test samples that reached the failure mode.

Photographs of the samples that reached the failure mode after the

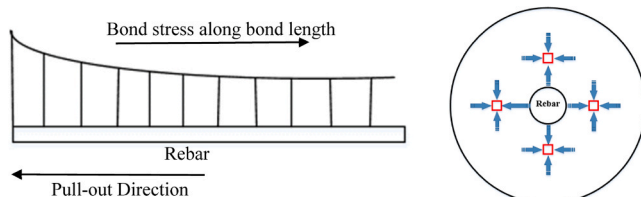


Fig. 16. Stress distribution along bond length.

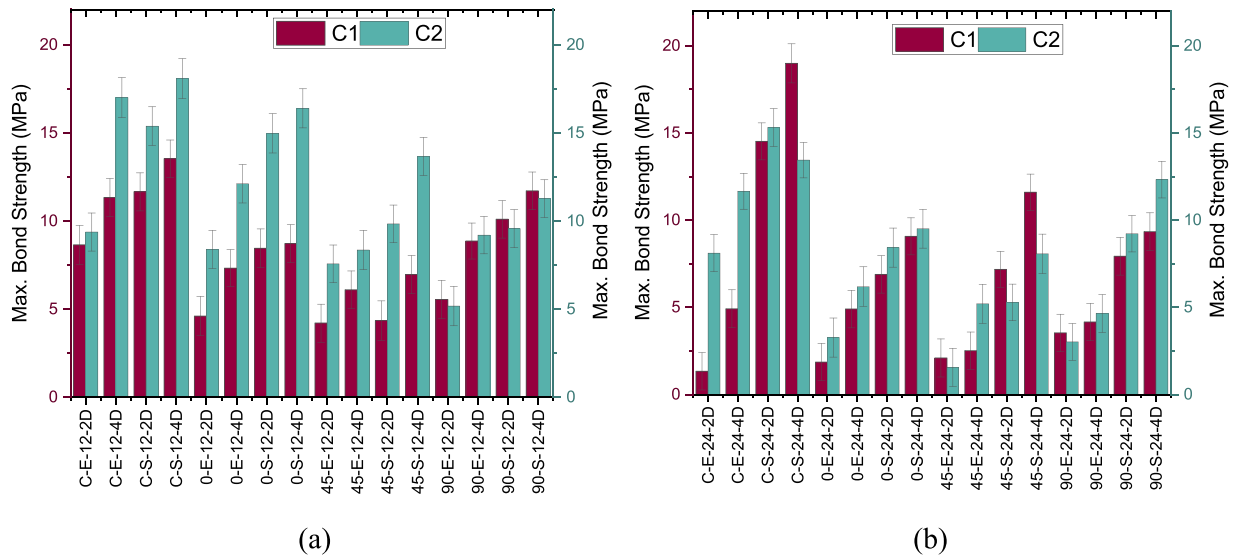


Fig. 17. Effect of curing condition on the bond strength (a) 12 mm rebar diameter (b) 24 mm rebar diameter.

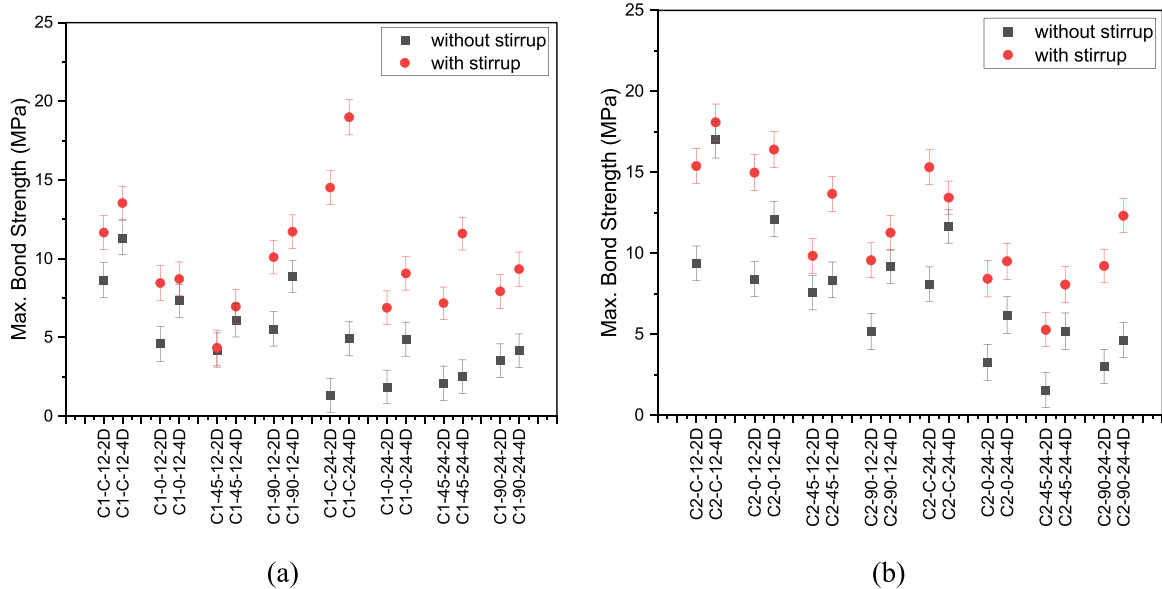


Fig. 18. Effect of stirrup usage on the bond strength (a) ambient cure (b) heat cure.

pull-out test are presented in Figure A1. Although cracks were observed in the samples with stirrups under ambient cure, very small crack widths were observed in the samples using stirrups. However, it was observed that the stirrup usage had an effect on crack distribution under ambient curing and in samples where 12 mm diameter reinforcement was used. Among these samples, crack distribution and crack width decreased in the samples using stirrups. The stirrup usage under heat curing and on samples with a diameter of 12 mm significantly reduced the crack width and crack distribution. Although no concrete spalling was observed in the samples under ambient cure and where the reinforcement was positioned at the corner point, concrete spalling was observed at the corner points of the samples under the same conditions but with the temperature cure. It was also observed that increasing the diameter of the reinforcement had a significant effect on the failure mode. Increasing the reinforcement diameter significantly increased the crack width.

4. Conclusion

To evaluate the effect of curing condition on bond characteristics of geopolymer concrete, pull-out tests were conducted on the large number of specimens with different longitudinal rib angle, the position of longitudinal bar, bar diameter, stirrup usage and bond length. Based on the test results, the following conclusions can be drawn:

- The bond strength was primarily related to the strength of geopolymer mortar. When the heat cure was applied to geopolymer samples, the compressive and tensile strength was improved, and an increase of up to 83 % was achieved on the bond strength of the samples under heat cure.
- The using stirrup in geopolymer significantly had the effect on the bond strength. The use of stirrups in geopolymer concrete samples resulted in an average 45 % increase in bond strength. Confining stirrups in reinforced concrete elements significantly contribute to ductility and bond strength.

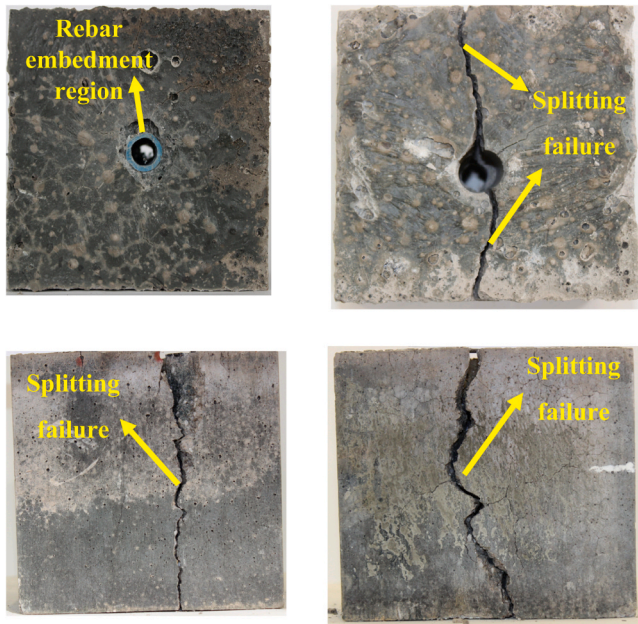


Fig. 19. Typical failure mode after pull-out tests.

- iii. With increasing embedded length, the bond strength of samples with 12 mm and 24 mm reinforcement diameters increased by 72 % and 70 %, respectively. In addition, the increase in bar diameter caused a distinct decrease in bond strength.
- iv. The failure mode of the pull-out specimen was related to the curing condition, the position of the longitudinal bar, and bar diameter. It was observed that the stirrup usage had a significant effect on the crack distribution of the samples. The crack width decreased significantly in the samples using stirrups.
- v. The longitudinal rib angle and the position of the longitudinal bar have an influence on the bond performance. The bond strength of reinforced samples positioned at the center point was higher than other location configurations. Although the bond strength decreases when the reinforcement is positioned at the middle bottom point, this decrease is less than when the reinforcement is positioned at the corner point. On the other hand, it has been determined that changing the reinforcement rib angle also has a significant effect on bond strength.
- vi. The increase of steel bar diameter from 12 mm to 24 mm resulted in samples under ambient and heat cure average 44 % and %37 reduction in bond strength, respectively.
- vii. The application of heat cure increased the adherence strength of the samples up to 85 %. Although the application of heat cure increased the bond strength by an average of 26 % in 12 mm diameter reinforcement, it increased the bond strength by an average of 10 % in 24 mm diameter samples. Heat curing was more effective in samples with the smaller reinforcement diameter.

5. Recommendations

- i. It is recommended to conduct studies on the bond strength of geopolymer concretes produced by using different types of waste materials in future studies. It is also recommended by the authors to conduct studies on the bond performance of hybrid fiber geopolymer concrete produced by combining different types of fibers.
- ii. It is recommended to conduct future studies on the bond performance of different types of geopolymer concrete. For example, the adherence strength of self-compacting geopolymer concrete, high/ultra-high strength geopolymer concrete types, and the interaction of reinforcement diameter, reinforcement type, etc. can be emphasized.
- iii. It is recommended by the authors to investigate the effect of using FRP bars, which are preferred in construction applications, in geopolymer concrete on bond strength.

CRediT authorship contribution statement

Oguzhan Celebi: Validation, Resources, Investigation. **Haluk Gökem Alcan:** Resources, Methodology, Investigation. **Abdulkadir Cüneyt Aydın:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Gökhan Kaplan:** Visualization, Resources, Conceptualization. **Barış Bayrak:** Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Conceptualization. **Mahmut Kılıç:** Methodology, Investigation, Data curation. **Oguzhan Akarsu:** Resources, Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. . Failure modes of teste specimens

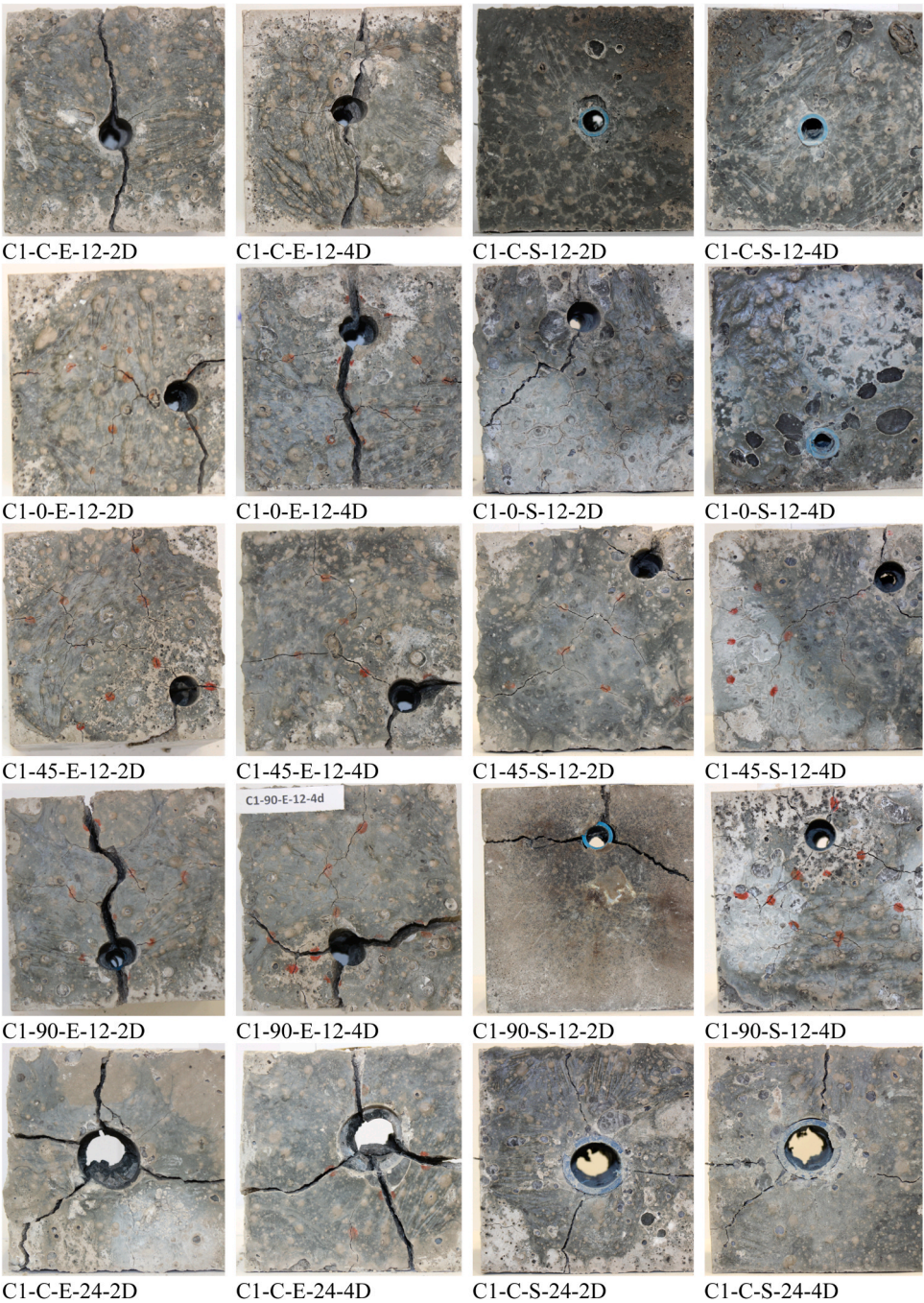


Figure A1. Failure modes of tested specimens.

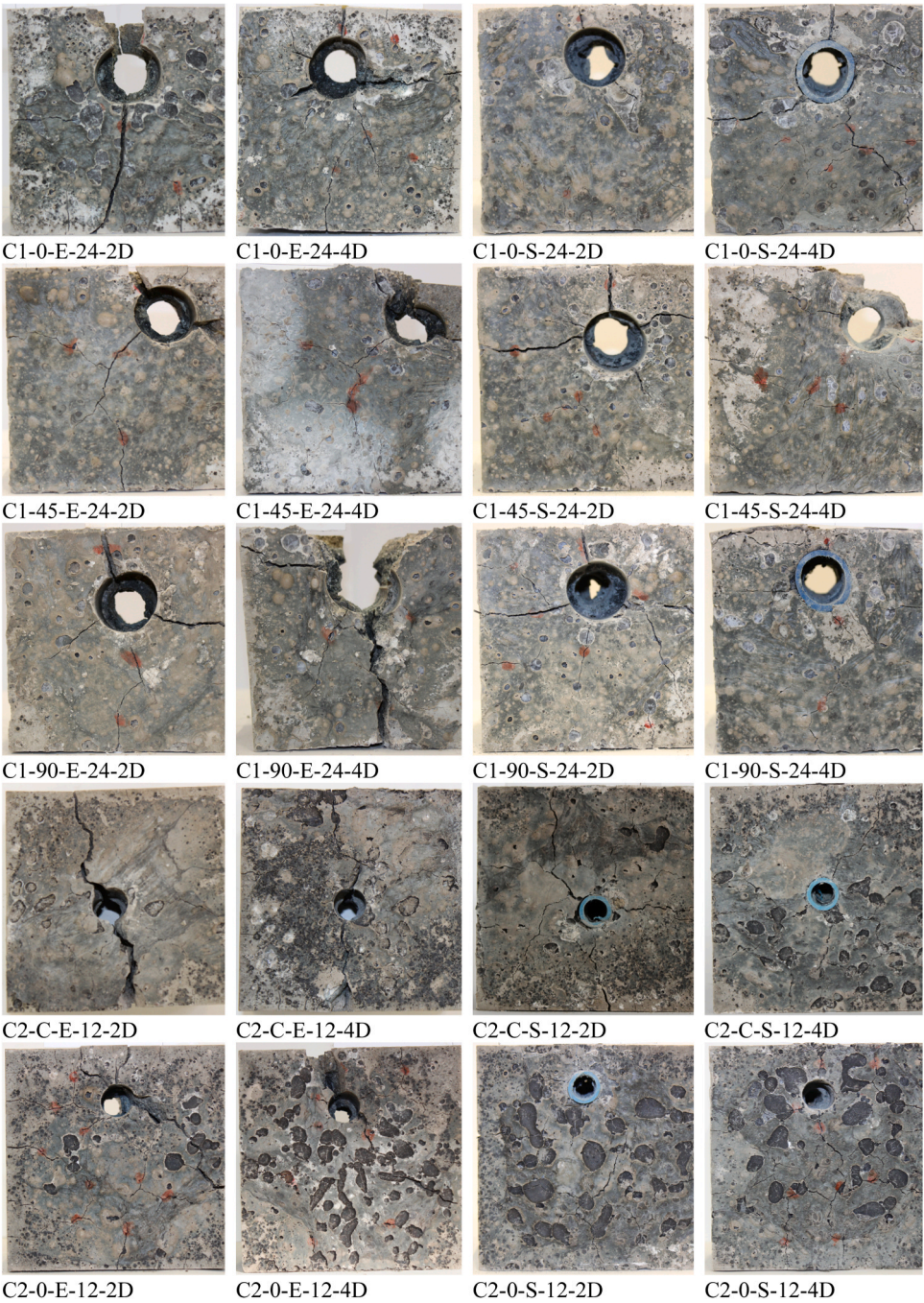


Figure A1. (continued).

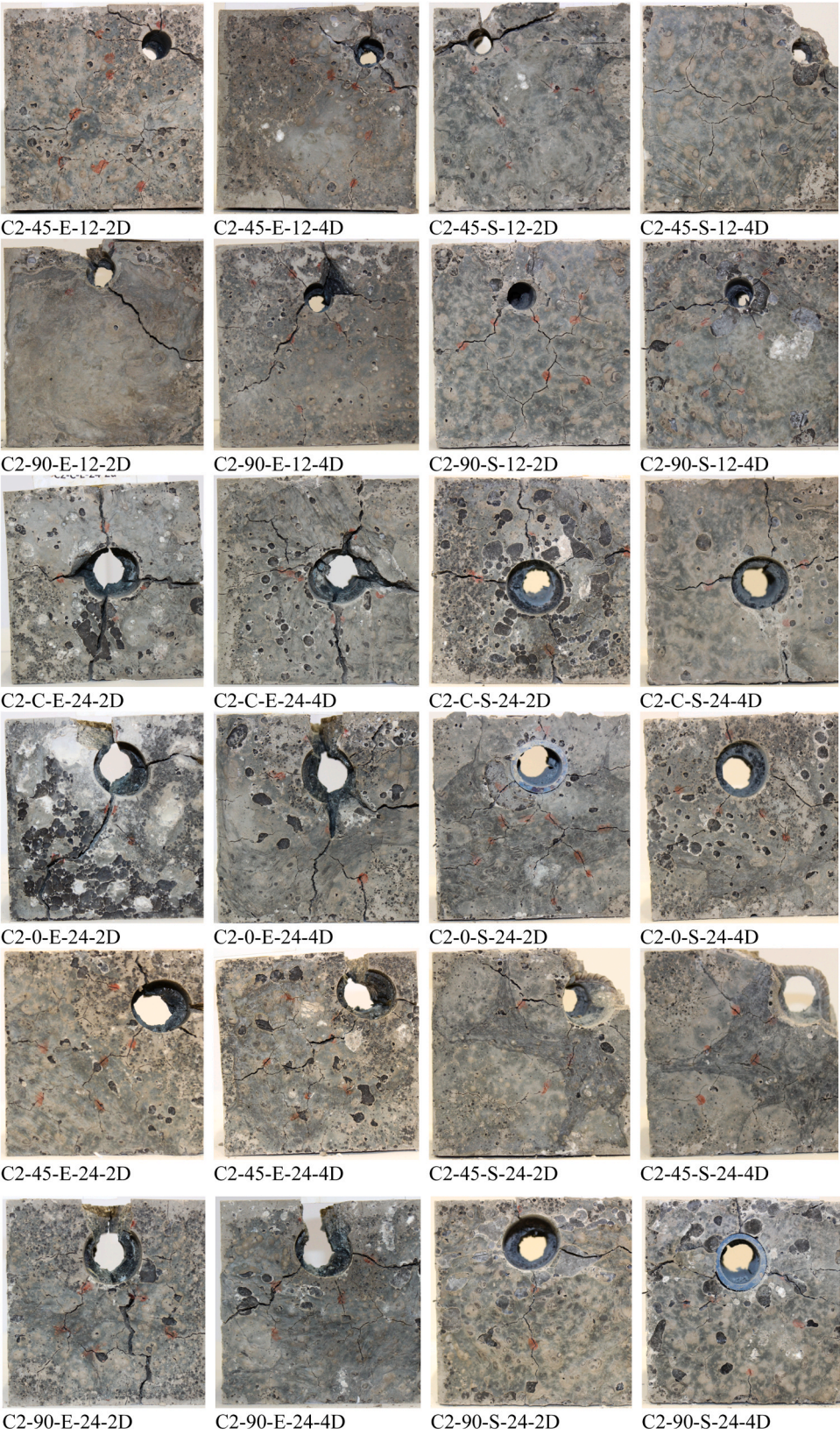


Figure A1. (continued).

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