CFRP Strengthening of Circular Geo-Polymer Concrete Slabs with and without Openings

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Received: 29 December 2024 | Revised: 23 January 2025 | Accepted: 27 January 2025

 DOI: https://doi.org/10.48084/etasr.10072

ABSTRACT

The current study investigates the eco-friendly concrete and specifically Geopolymer Concrete (GPC), and its behavior in reinforced concrete circular slabs both with and without openings. It also examines GPC strength utilizing Carbon Fiber Reinforced Polymer (CFRP) sheets under punching shear. Slag-based GPC was used to cast the slabs. The experimental part included testing six circular slabs divided into two groups with a diameter of 700 mm and a thickness of 70 mm, and a cast circular column with dimensions of 150 x 150 mm at the top face in the middle. The slab components of these samples were strengthened with a distorted 8 mm diameter dispersed across the section of 75 mm c/c. The circular column was reinforced by 5Ø6mm bars, with a 2Ø6@50mm tie to prevent local failure in the column before the slab. The investigated experimental variables included the column location and the strengthening schemes. Measurements were made for the first cracking load, mid-span vertical deflections, and ultimate load capacity. Also, the crack patterns were marked, and the failure mode was observed. Furthermore, the mechanical properties of the slag-based GPC were studied. The results showed that the modulus of rupture and modulus of elasticity were about 3.2 and 29725 Mpa, respectively, and the compressive Strength (fcu) about 45 Mpa. Each slab's initial crack appeared at a load between 23 and 50 kN of its ultimate capacity.

Keywords-circular flat slabs; GPC; geopolymer concrete; strengthening; CFRP

I. INTRODUCTION

Reinforced concrete slabs can be supported directly by columns without beams, drop panels, or capitals, known as "flat plates." These structures maximize the usable space and have an appealing appearance while helping to reduce the construction costs. They simplify the formwork, flexural reinforcement placement, and they lower the building story heights, resulting in more usable space within a limited overall height. They also reduce the dead loads on columns and foundations [1].

Punching or two-way shear creates truncated pyramid-shaped cracks extending from the column through the flat slab. This results in a complete loss of the shear capacity at the joint, causing the slab to collapse and separate from the column. As loads redistribute, adjacent elements become overloaded, since they are not designed to handle these increased loads [2, 3]. This failure occurs quickly and unexpectedly, leading to a disruption of the entire system. Consequently, the punching shear failure is classified as catastrophic. In cases where flat slabs experience maximum moments under uniform load conditions, flexural cracks develop around each column. With additional loading, a fan-shaped crack begins to form. The failure mechanisms associated with the flexural and punching shear strength demonstrate that the slab exhibits significant ductility in the flexural failure mode [4]. On the contrary, limited ductility is obtained in the shear failure mode [2]. Openings near the columns can compromise the punching resistance of the flat slabs. This occurs because an opening reduces the critical perimeter of the slab by removing concrete and reinforcement, which in turn lowers its shear strength [5]. As a result, it is essential to accurately estimate the punching shear strength of flat slabs with openings. The current research focuses on the analysis and design of reinforced concrete slabs. Fiber-Reinforced Polymers (FRPs) provide significant advantages over traditional methods, like bolts, rebars, or drop panels to enhance the punching shear capacity of flat slabs. They are lightweight, strong, and easy to handle, which contributes to their growing popularity. Because of their ease of application, FRPs have proven effective in strengthening beams, columns, and slab-column connections while reducing labor costs [6, 7]. CFRP was selected as the preferred strengthening material because it offers exceptional tensile strength and stiffness, significantly outperforming other composite materials [8, 9]. This unique combination of properties makes CFRP particularly effective for applications where high strength-to-weight ratios are critical. Its lightweight nature, coupled with the ability to withstand substantial loads without deformation, ensures enhanced durability and performance in structural applications [10, 11].

II. EXPERIMENTAL WORK

The experimental procedure was carried out to investigate the strengthening of circular slabs with and without openings using CFRP sheets under a uniform distributed load. Slag-based GPC was used to cast the slabs, and many tests were carried out with control specimens in different shapes: prisms, cylinders, and cubes.

A. Details of Specimens

Six circular slabs were tested, which were divided into two groups with a diameter of 700 mm and a thickness of 70 mm. The first group included three reinforced GPC slabs without openings and a column at the center. The second group included three reinforced GPC slabs with openings and a column at the center, as can be seen in Table I.

TABLE I. DETAILS OF TESTED SLABS

Group	Slab Designation	Column location	Opening	CFRP
A	SC11	Center	Without opening	-
	SC12	Center	Without opening	CFRP in the Punching shear area
	SC13	Center	Without opening	CFRP around the column and punching shear area
B	SC21	Center	With opening	-
	SC22	Center	With opening	CFRP in the punching shear area
	SC23	Center	With opening	CFRP around the column and punching shear area

Figure 1 presents the dimensions and reinforcement details of the tested slabs.

B. Materials

1) Materials of Geopolymer Concrete and Mix Properties

The materials of the GPC mixture are:

- Ground granulated blast furnace slag (S95) [12], which was tested according to the standard in [13].
- A fine aggregate with a maximum size of 4.75mm in which the sieve analysis test was performed according to the Iraqi specification in [14].
- Natural gravel with a maximum size of 19 mm, which was tested according to the Iraqi Standard Specification in [14].
- NaOH solid flakes, which were provided from a local company, had molar mass (M) 10, and were prepared using 314 g of flakes per 1 kg of solution [15]. The flakes were melted to create a solution, and varying amounts were used to adjust the concentration.
- A commercially available material, known as sodium silicate, Na2SiO3, was used. The liquid itself is dense and can range from being clear to off-white. The substance has a distinctive odor. Based on mass, the company's product consists of 55% water. It can be treated by hand for different types of work.
- A liquid high-performance GLENIUM 51 ether-based superplasticizer was utilized to reduce the workability loss. This plasticizer can be found in types A and F according to the classification given in [16].
- CFRP of type Sika Wrap®-300 C/60 with a roll width of 50 cm [17].

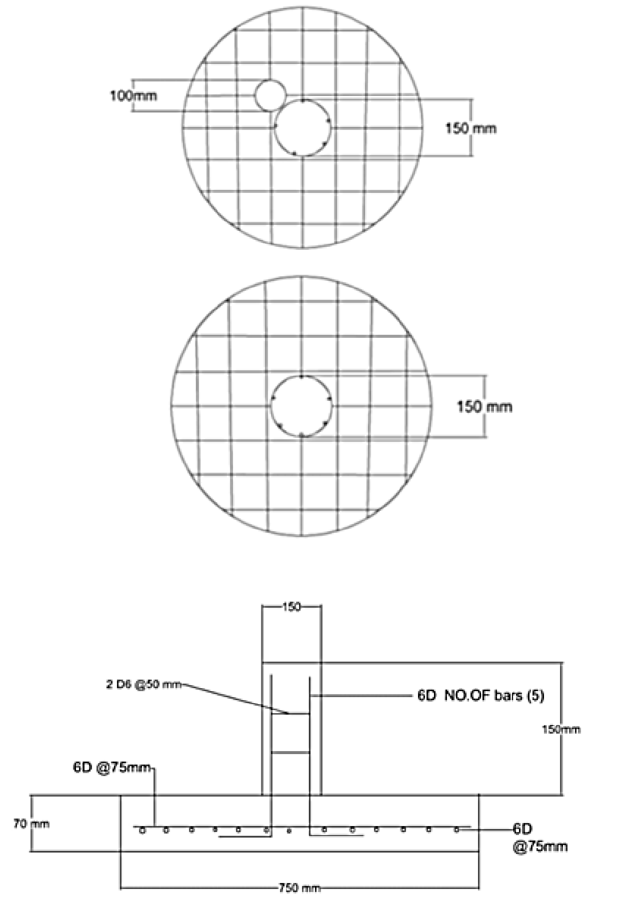

Fig. 1. Reinforcement details of slabs.

Several trial mixes were carried out to obtain a cubic compressive strength higher than 35 MPa at 28 days. Six trials and mixes were made to prepare the appropriate mixture. The percentage of sand and gravel weight was constant for all mixes. Table II outlines the final quantities by weight of the materials used to prepare GPC per cubic meter for the different mixes adopted.

TABLE II. THE MIXING PROPORTION FOR GPC

Mix No.	M1
Slag (kg/m^3)	400
Sand (kg/m^3)	720
Gravel (kg/m^3)	1100
Alkaline Solution (L/m^3)	180
Super Plasticizer %	3
Water (L/m^3)	40
Compressive Strength (MPa)	45

2) *Reinforcement Beams*

Deformed steel bars with a diameter of 6 mm were used and the testing outcomes are illustrated in Table III. The standards reported in [18] were followed during the current work at the construction material laboratory of the civil engineering department at the Mustansirya University.

TABLE III. TENSION TEST RESULTS FOR STEEL BARS

Nominal Diameter (mm)	**Actual Diameter (mm)**	**Yield Stress (MPa)**	**Yield strain (mm/mm)**	**Ultimate Strength (MPa)**	**Ultimate strain (mm/mm)**
6	5.92	435	0.0023	0.0023	0.0023

3) *CFRP System Installation*

Before welding the CFRP to the slab, all faces of the slab were milled to remove any weak, loose materials by an electrical hand grinder, and all corners of the specimen were rounded according to [19]. As a first step of the CFRP installation, the two parts Sikadure-330 (Compound A and Compound B) were mixed in a 4:1 proportion by using an electric mixer until the color was grey. Then the epoxy mixer was applied to the surface of the concrete position of the CFRP strips to fill any possible cavities. Applying the CFRP strips to their designated place, a rubber roller was used in the direction of the fiber to remove air bubbles and to avoid any distortion of the fiber orientation. Subsequently, the CFRP was coated with a thin layer of epoxy, as portrayed in Figure 2. After completing the application process, the slab was left inside the laboratory for 7 days to allow the epoxy to set.

Fig. 2. Applying CFRP sheet to the specimens.

4) *Test Slabs Under Applied Load*

The testing was conducted using the Magnetic Flux Leakage (MFL) system of the hydraulic universal testing machine type EPP300, as depicted in Figure 3, with a maximum capacity of 3000 kN, available in the structural engineering lab. Before testing, a thin layer of white emulsion paint was applied to the surface of the specimen to aid in detecting cracks. Without a factor, the loading rate was 10 kN. Because of the inability to transfer the load directly to the flat slab column, a steel beam was used to transfer the load from the MFL to the column. The load P was analyzed to get a decrement factor of 50% load P.

Fig. 3. Slabs under applied load.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Mechanical Properties of Hardened Concrete*

The mechanical properties of hardened concrete for 28 days are listed in Table IV.

TABLE IV. RESULTS OF CONCRETE PROPERTIES

Compressive Strength (fcu)	**Modulus of Rupture (fr)**	**Splitting Tensile Strength (fct)**	**Modulus of Elasticity (EC)**
45 Mpa	3.2 Mpa	2.94 Mpa	29725 Mpa

B. *General Behavior*

All specimens were designed with a flexural reinforcement ratio of 0.0051 with a clear cover to the reinforcement of 15 mm, which is higher than the minimum reinforcement ratio required 0.0018 by the ACI building code in [20].

C. *Cracking Load and Crack Pattern*

The initial crack of each slab occurred at a load between 23 and 50 kN of its ultimate capacity, as evidenced in Table V. Relative to the reference sample (SC1-1), the cracking load was 37% of the ultimate load capacity. For the specimen with an opening and no CFRP (SC2-1), in the tension face, the initial crack emerged near the perimeter around the column and extended across the slab's edges. The first crack appeared at 40% of the ultimate load. However, for the collar head samples, the cracks connected the edges of the opening on the tension face. The crack propagation continued with loading from the testing machine, and the cracks increased, having delineated the cracking zone at the extending end of the support column on the tension face of the test slabs (Figure 4).

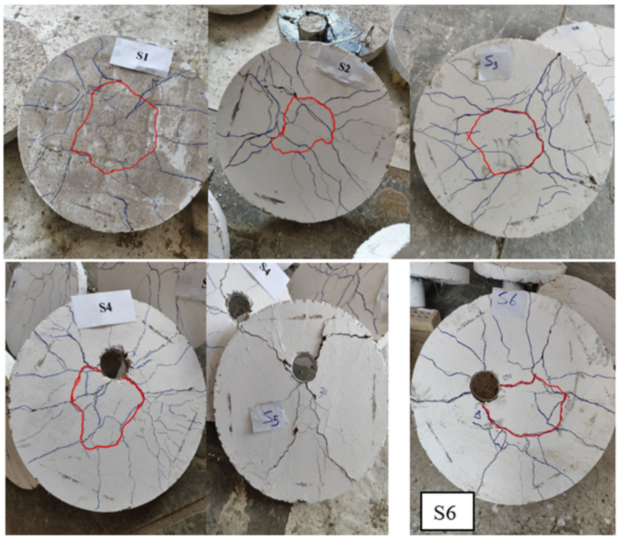

Fig. 4. Load-deflection curve of slabs of group A.

TABLE V. EXPERIMENTAL RESULTS OF GROUP A

Samples	First Crack Load (Pcr) (kN)	Ultimate Load (Pu) (kN)	(Pcr/Pu) %	(Pcr/Pcr_0) %	(Pu/Pu_0) %	Mode of Failure
SC1-1	37	100	37	-	-	Punching
SC1-2	45	118	38.4	121.6	118	Punching
SC1-3	50	130	39	135	130	Punching
SC2-1	23	72	31.9	62.1	72	Punching
SC2-2	30	84	35.7	81	84	Punching
SC2-3	35	95	36.8	94.6	95	Punching

Pcr_0 and Pu_0 correspond to the reference sample SC1-1

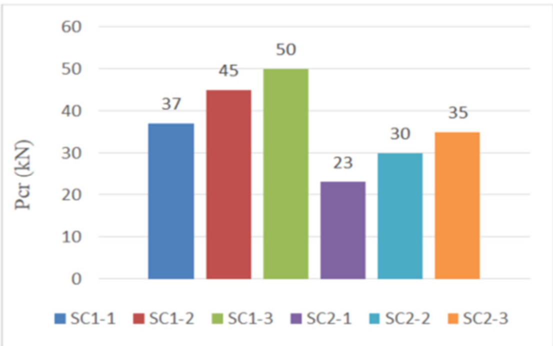

Fig. 5. Cracking load for tested samples.

The first cracking load value in the reference specimen SC1-1 was 37 kN, which decreased to 75.6% in the specimen with apertures adjacent to the column SC2-1. When the CFRP sheet was at the critical zone without opening, this percentage increased to 108.1% in the SC1-2 specimen. Still, when the same strengthening was used with an opening in the slab, the percentage decreased to 81% in SC2-2, and reached 117% when using the CFRP sheet at the critical zone and around the column in SC1-3. Moreover, when utilizing the CFRP sheet at the critical zone and around the column with an opening, this percentage decreased to 94.6% in SC2-3, as shown in Figures 5, 6.

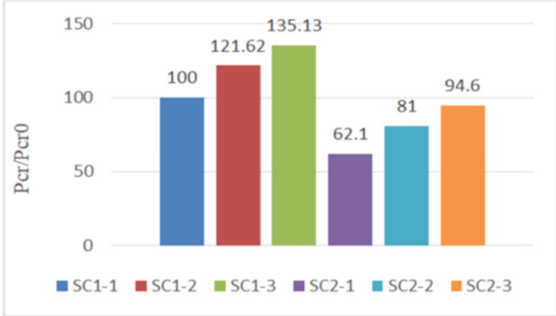

Fig. 6. Percentage of the sample cracking load to the reference sample cracking load for the specimens (column in center of slab).

D. Ultimate-Load Capacity

The primary goal of this research was to examine the effect of the CFRP sheet designs on the specimens with and without openings close to columns, considering the maximum allowable load for the samples that have been strengthened for punching shear and then to compare the results to those obtained from the reference specimen (without opening and shear reinforcement). Table VI presents the slab failure loads in order of examination.

TABLE VI. MAXIMUM LOAD CAPACITY SAMPLES TESTED

Samples	Ultimate Load (Pu) (kN)	Pu/Pu_0%
SC1-1	100	-
SC1-2	117	117
SC1-3	128	128
SC2-1	72	72
SC2-2	84	84
SC2-3	95	95

The maximum load for the SC1-1 reference slabs was 100 kN. This value dropped to 72 kN for SC2-1 in the other slabs because of the opening being already there. Using the CFRP sheet increased the maximum load in the SC1-3 sample by 128% compared to the reference sample.

E. Load-Deflection Behavior

The deflection profile was measured using a dial gauge with an accuracy of 0.01 mm, and the measurements from this gauge were recorded for each load increment. Measurements were taken at the center of the slabs and on the side of the column, with a distance of 2 d from the face of the column. These data, displayed in Table VII, were used to illustrate the measured values of the deflection in Figures 7 and 8, where each curve represents the state of the slab in each 5 kN increment.

TABLE VII. LOAD-DEFLECTION TESTED SAMPLES

Group	Samples	Ultimate Load (Pu) (kN)	Deflection at Ultimate Load (mm)	
			Center	Side
Group 1	SC1-1	100	7.9	5.25
	SC1-2	108	7.1	5.67
	SC1-3	117	6.5	5.89
Group 2	SC2-1	72	8.4	4.66
	SC2-2	84	6.3	4.93
	SC2-3	95	5.4	5.15

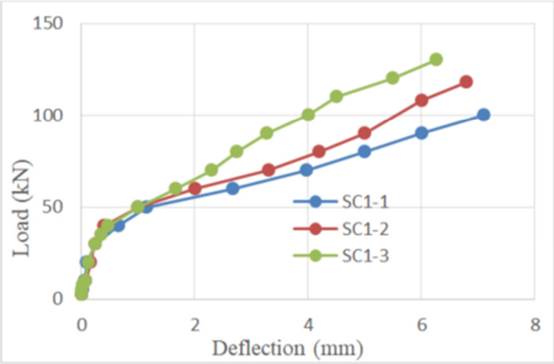

Fig. 7. Load-Central deflection curve of group 1.

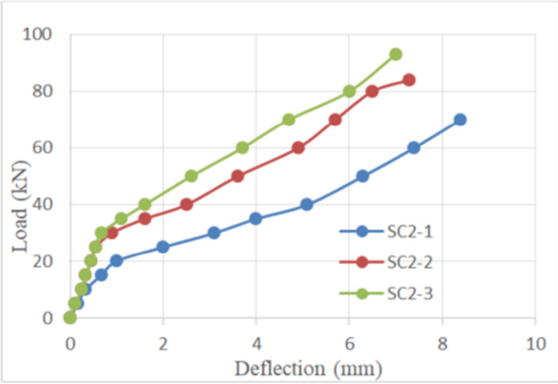

Fig. 8. Load-Central deflection curve of group 2.

IV. CONCLUSIONS

The results of the research can be summarized as follows:

- The general punching shear behavior of the circular reinforced Geopolymer Concrete (GPC) slabs was decreased by the presence of transverse web holes because of the reduction of concrete within the GPC section.
- The largest cracking load noticed was 50 kN for the samples that were cast without opening and with a column in the center slab using Carbon Fiber Reinforced Polymer (CFRP) sheet at critical zone and around the column.
- The presence of an opening in the plates accelerated their cracking load. The largest percentages of cracking load to ultimate load capacity belonged to the SC1-3 specimen.
- All specimens with CFRP sheet had a value of percent cracking load greater than that of the reference specimen (SC2-1), whose spans did not have a CFRP sheet.
- All samples with a column at the center of the slabs had an ultimate load capacity of between 72 and 128 kN. The SC1-3 and SC1-2 slabs were the strongest among all samples because they used a CFRP sheet and the slabs without opening.
- The specimen SC2-1, which had an opening without a CFRP sheet, achieved the lowest value of the ultimate load, and this loss was because of the presence of an opening adjacent to the column.
- The specimens containing CFRP sheet achieved higher ultimate load values than the specimens containing a span without using a CFRP sheet and those not containing a CFRP sheet and a span. It can be thus concluded that the use of CFRP sheet increases the ultimate load.

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