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A Study of Vertical Load Capacity of Carbon Fiber Concrete Piles Reinforced with Geosynthetics.

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Abstract— *A compressive static load test was conducted on a total of thirteen end-bearing carbon fiber concrete piles reinforced with geosynthetics, which were divided into four groups and compared to traditional reinforced concrete piles. The tested piles included one reference concrete pipe pile reinforced with traditional steel reinforcement, four concrete pipe piles partially reinforced with carbon fiber bristles with different percentages of 0.75%, 1.00%, 1.25%, and 1.50% of cement weight, four piles partially reinforced with the same carbon fiber bristles percentages and confined with triaxial geogrid, and four piles partially reinforced with the exact carbon fiber bristle percentages and reinforced with carbon fiber bars. Thirteen vertical static loading tests (SLTs) were conducted on 1050-mm-long pipe piles with a diameter of 150 mm to obtain the behavior of these composite piles. Furthermore, the traditional method of stress-strain curves was analyzed. Comparisons between curves were conducted. It was concluded that the use of these composite piles significantly increased the ultimate vertical load capacity by up to 39%. Pile ductility was also significantly improved, and this composite material could be perfectly applied in geotechnical conditions. In addition, an economic analysis was conducted.*

Keywords— ***Geosynthetics, Carbon fiber bristles, Geogrid, Composite piles, Vertical Static Load***

I. INTRODUCTION

The pile foundation industry has problems associated with the use of traditional materials as reinforcement, especially when installed in corrosive and marine environments [1]. Recently, the use of geosynthetics and geogrids has been increasing significantly in civil engineering applications such as piles [2,3,4], which are constructed in a marine environment in place of conventional materials in piling systems to overcome these challenges. Using of composite piles reinforced with fiber-reinforced polymers (FRP) and geosynthetic can solve problems with traditional piles. Several investigations have been conducted to experimentally test the behavior of FRP composite piling under vertical axial loads [5], [6]. In comparison to conventional piles, their effective strength-to-weight ratio, durability, anti-corrosion capability, and bond strength make them an efficient and cost-effective alternative [7]. A study on precast concrete piles typically confined with carbon fiber reinforced polymers (CFRP) geogrid was made, and it was figured out that the confinement given by CFRP may provide equivalent levels of confinement as those achieved by steel spirals [8]. The geogrid systems have been proven to be an effective way to strengthen the stone column due to their high strength-to-weight ratio, high durability, high anti-corrosion ability, satisfactory fire endurance, and bond strength [9]. Under horizontal loading, the behaviour of RC pile models reinforced with composite materials was investigated. The results of the study indicated that the specimens exhibited a horizontal ultimate load that was 44% to 87% lower compared to the reference pile specimen that was reinforced using traditional reinforcing materials. The analysis of the specimens indicated that the implementation of composite piles has the potential to result in a cost reduction of up to 15.2%. [10]. Eleven lateral pile loading tests were conducted on concrete piles reinforced with various materials, such as FRP bars, geosynthetic geogrids, and composites of two materials, in order to evaluate their capacity to carry lateral loads [11]. The experimental results demonstrated that the lateral loads supported by piles were increased by up to 25.3% when FRP bars, biaxial geogrid, and uniaxial geogrid were utilized. A comparative analysis was conducted to assess the reinforcement expenses associated with all samples, revealing that the utilization of composite piles resulted in a cost reduction of up to 59%. The goal of the current study was to investigate the capacity of end-bearing piles reinforced by various materials. An axial loading test would be applied to reinforced concrete piles (RC) reinforced by various materials, for example, CFRP bars, CFRP grids, and carbon fiber bristles, to assess their efficiency by applying them to static vertical loads, then comparing the results with each other and making an economic comparison.

II. EXPERIMENTAL WORK

2.1. Test specimens

The experimental program included testing concrete piles reinforced with geosynthetics and subjected to concentric axial compression loads applied at the top section of the piles. Thirteen concrete piles, divided into four groups, were tested for failure. The specimens had a 150-mm circular cross-section with an overall height of 1050 mm, a width-height ratio of 1:7, and a clear concrete cover of 20 mm. The first group was composed of one specimen reference concrete pipe pile (PS) reinforced with traditional steel reinforcement of four 8mm steel bars confined with 6mm circular steel spirals with a 10 mm pitch. The second group was composed of four concrete pipe pile specimens (PC) partially reinforced with carbon fiber bristles with a different percentage from 0.75% - 1.00% - 1.25% -1.5% of cement weight. The third group was composed of four concrete pipe pile specimens which were partially reinforced with carbon fiber bristles from 0.75% to 1.5% of cement weight and confined with triaxial geogrid (PCG). The fourth group contained four concrete pipe pile specimens partially reinforced with carbon fiber bristles ranging from 0.75 to 1.5% of cement weight, reinforced with four 8mm carbon fiber bars, and confined with 6mm circular steel spirals with a 10 mm pitch. Table (1) provides details for all tested specimens. There are cross-section details for all pile groups in figure (1).

Table 1: Details of all tested specimens.

Group	Group Code	Pile Code	Material	Fibre bristles %
First Group (Reference)	PS	PS 1	Steel Rft.	______
Second Group	PC	PC 1	Carbon fibre bristles	0.75
		PC 3		1
		PC 5		1.25
		PC 7		1.5
Third Group	PCG	PCG 1	Carbon fibre bristles with Tri-Axial Geogrid Rft.	0.75
		PCG 3		1
		PCG 5		1.25
		PCG 7		1.5
Fourth Group	PCC	PCC 1	Carbon fibre bristles with carbon fibre bars Rft.	0.75
		PCC 3		1
		PCC 5		1.25
		PCC 7		1.5

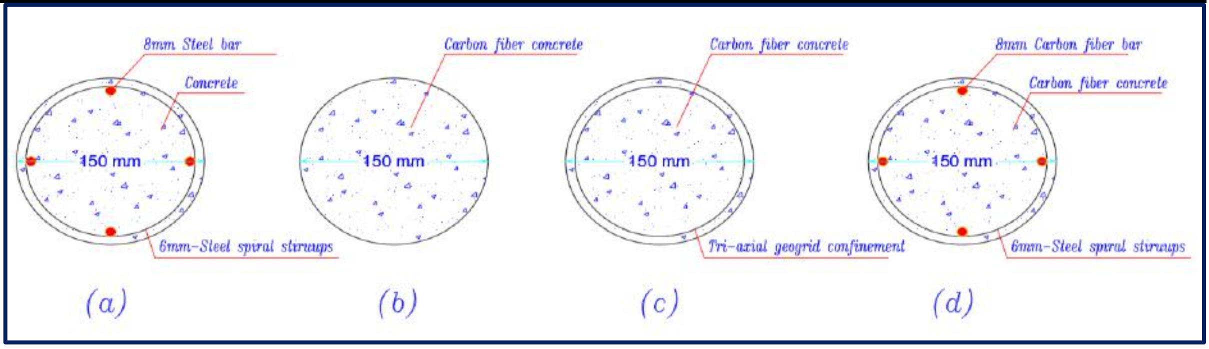

Fig.1: Typical cross-section details for all pile groups: (a) first group (reference pile), (b) second group, (c) third group, (d) fourth group.

2.2. Material properties

The concrete mixture used to cast all of the pile specimens was normal-weight concrete consisting of filter stones with aggregate sizes ranging from four to nine mm in size, ordinary Portland cement (grade 42.5), and natural sand, in addition to different percentages of carbon fiber bristles from 0.75% to 1.5% of the cement weight. The measured average compressive strength at the time of testing (after 28 days) was approximately 20 MPa. Concrete compressive strength was measured according to ECP 203-2020 [12]. The pile models have been kept and subjected to a curing process. Pile models and curing conditions were represented in figure (2). High-tensile steel bars 8 mm in diameter with a yield stress of 400 MPa were used in longitudinal reinforcement in the reference pile, and 6 mm mild steel bars with a yield stress of 360 MPa were used as confinement spiral stirrups. The used CFRP bars in this study were fabricated from Sika Wrap-300C as a product of the Sika company [13]. The bars were fabricated via carbon fiber-reinforced polymer (CFRP) strands that were rolled and bonded together using epoxy Sikadur-330. Subsequently, the CFRP strips were positioned into a mould, and the epoxy was poured and left to cure, resulting in solidification, Fig. 3(a). As per the manufacturer's specifications, table (2) presents the mechanical properties of carbon fiber. Carbon fibre bristles used in this study were fabricated from Sika Wrap-330C as a product of Sika company [14]. The bristles were fabricated via CFRP strands that were cut in lengths from 2 to 3 cm, Fig. 3(b). The geosynthetics geogrids utilized in this study were produced by Tensar International Corporation [12]. Geogrids TX130 was used, Fig. 3(c). The mechanical properties of geogrids are listed in table (2).

(a) **(b)**

Fig.2: (a) curing conditions, (b) pile models.

Table 2: Mechanical properties and dimensions of CFRP bars and used geogrids.

Materials	Dimension (mm)		Tensile strength		Modulus of elasticity (MPa)	Failure Strain %
	Diameter	Thickness	(MPa)	(N/mm)		
CFRP bar	8	-	1060	-	120000	0.5
Geogrids (TX130)	-	1.3	-	10	200000	0.5

(a) **(b)** **(c)**

Fig.3: Typical types of used materials: (a) CFRP bars, (b) Carbon fibre bristles, (c) Tri-Axial geogrid.

2.3. Testing machine set-up

The Piles specimens were tested using a 1000 KN capacity compression machine and were loaded concentrically to failure, figure (4). The specimens were capped using a steel plate cap to form parallel loading surfaces and ensure uniform distribution of the applied load to the bearing surfaces. The compression machine was operated in a displacement mode, maintaining a rate of loading of 5 KN/sec. Electrical resistance strain gauges were attached to the outer surfaces of the columns to measure the axial and lateral strain of the concrete.

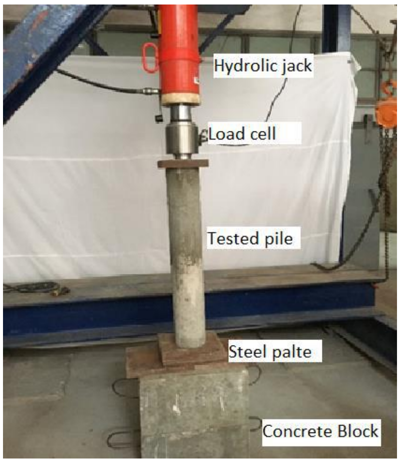

Fig.4: Testing machine set-up and concentrically loading of the tested pile.

III. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Piles reinforced with carbon fibre bristles (PC).

The maximum axial stress, strain at the maximum axial stress, and maximum strain of the reference pile and PC piles, table (3). Based on the findings, it is obvious that the PC piles exhibited a maximum capacity ranging from 76.7% to 93.60% when compared to the reference pile. Additionally, the strain at the maximum axial stress ranged from 73.20% to 88.20%, while the maximum strain observed ranged from 67.20% to 77.20%.

Table 3: Results summary of Reference pile and PC piles.

Group	Pile Code	Max. Axial Stress (MPa)	Strain at Max. stress *10-6 (mm/mm)	Max. Strain *10-6 (mm/mm)
First Group (Reference)	PS 1	13.19	3069	4022

Second Group	PC 1	10.12	2245	2702
	PC 3	11.59	2706	3035
	PC 5	12.35	2394	3104
	PC 7	11.29	2630	3102

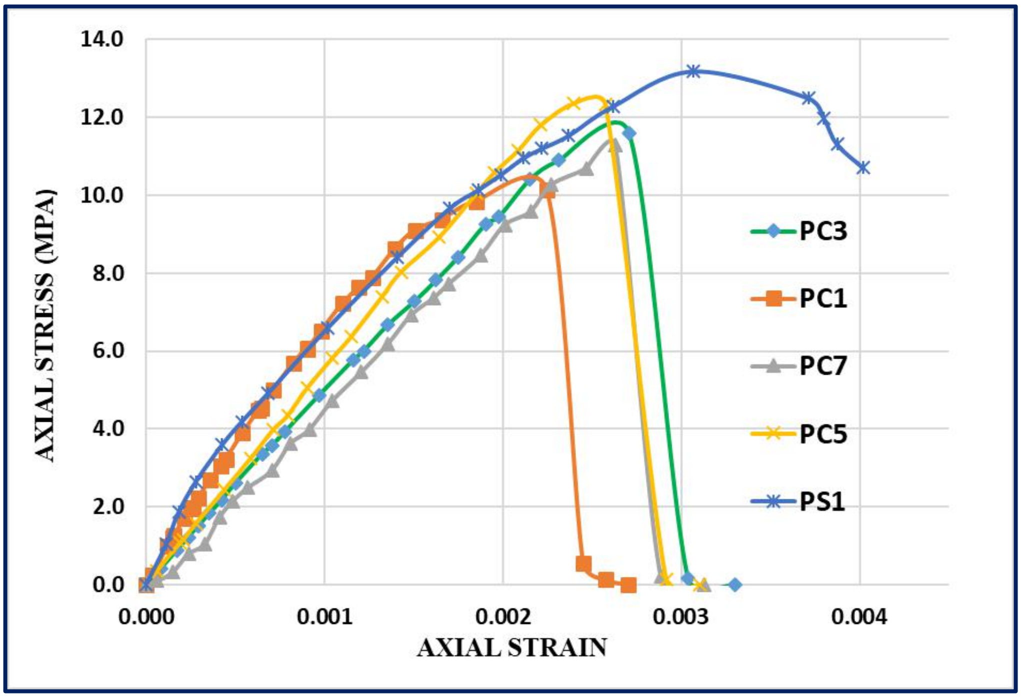

Fig.5: The stress-strain relationships for PC piles compared with PS1 pile.

The trend of specimens given in figure (5) clearly demonstrates that the increase in the carbon fibre bristles ratio had an effect on the capacity of PC piles. But the overall capacity was low compared to the reference pile, as well as the strain, which means less ductility, and that led to unexpected failure, which is not preferred. That's clearly shown when PC piles reach failure stress. The failure was like an explosion. The failure of carbon fibre concrete pillars is depicted in figure (6). Though it was obvious that the increase in the carbon fibre bristles ratio from 0.75% to 1.5% of cement weight led to an increase in the maximum stresses of the pile and slightly improved the ductility of the pile.

Fig.6: The failure of piles reinforced with carbon fibre bristles.

3.2. Piles with geogrid confinement (PCG).

The maximum axial stress, strain at the maximum axial stress, and maximum strain of the reference pile and PCG piles, table (4). Upon comparison with the reference pile, it became evident that the PCG piles exhibited a maximum capacity ranging from 101.59% to 124.64%. Additionally, the strain at the maximum axial stress ranged from 93.85% to 103.19%, while the maximum strain ranged from 80.30% to 91.89%. The results of the study indicate that the implementation of geogrid confinement led to a notable enhancement in the maximum capacity of PCG piles, with an increase ranging from 1.59% to 24.64%. Additionally, it was observed that the strain at maximum stress experienced an increase of 3.19% in the PCG5 pile.

Table 4: Results summary of Reference pile and PCG piles.

Group	Pile Code	Max. Axial Stress (MPa)	Strain at Max. stress $*10^{-6}$ (mm/mm)	Max. Strain $* 10^{-6}$ (mm/mm)
First Group (Reference)	PS 1	13.19	3069	4022
Third Group	PCG 1	13.4	2880	3260
	PCG 3	15.1	3010	3395
	PCG 5	16.44	3167	3696
	PCG 7	14.41	2960	3230

The behaviour clearly shows that the initial stiffness of PCG piles with geogrid confinement was better compared with the reference pile, figure (7). The geogrid confinement of piles led to increasing strain which improve ductility. Also, the confinement of geogrid improved the load capacity of the piles. The failure was more ductile and predicted, first cracks started to show then failure occur when the geogrid confinement failed, figure (8).

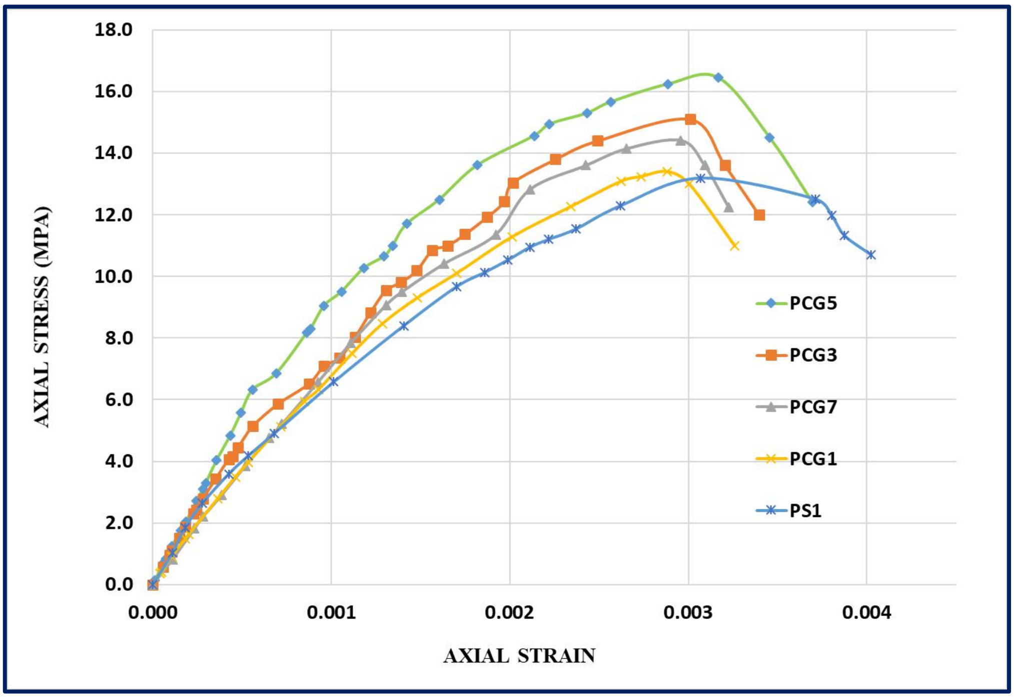

Fig.7: The stress-strain relationships for PCG piles compared with ps1 pile.

Fig.8: Failure of Carbon fibre concrete piles with geogrid confinement

3.3. piles with carbon fibre bars Rft (PCC).

From the results the maximum axial stress, strain at maximum axial stress, and maximum strain of the reference pile and PCC piles, table (5). After comparing the test results of PCC piles with the reference pile, it becomes evident that the PCC piles exhibited a maximum capacity ranging from 123.58% to 139.50%. Additionally, the strain at the maximum axial stress for the PCC piles ranged from 109.80% to 123.167%, while the maximum strain observed ranged from 109.89% to 124.31%. The utilisation of carbon fibre bars was observed to enhance the maximum carrying capacity of PCC piles by a range of 23.58% to 39.50%. Additionally, a noticeable improvement in the strain at maximum stress was observed, ranging from 9.80% to 23.167%, along with an enhancement in the maximum strain, ranging from 9.89% to 24.31%.

Table 5: Results summary of Reference pile and PCC piles.

Group	Pile Code	Max. Axial Stress (MPa)	Strain at Max. stress *10^{-6} (mm/mm)	Max. Strain * 10^{-6} (mm/mm)
First Group (Reference)	PS 1	13.19	3069	4022
Fourth Group	PCC 1	16.3	3780	4420
	PCC 3	17.5	3370	4600
	PCC 5	18.4	3390	5000
	PCC 7	16.81	3645	4829

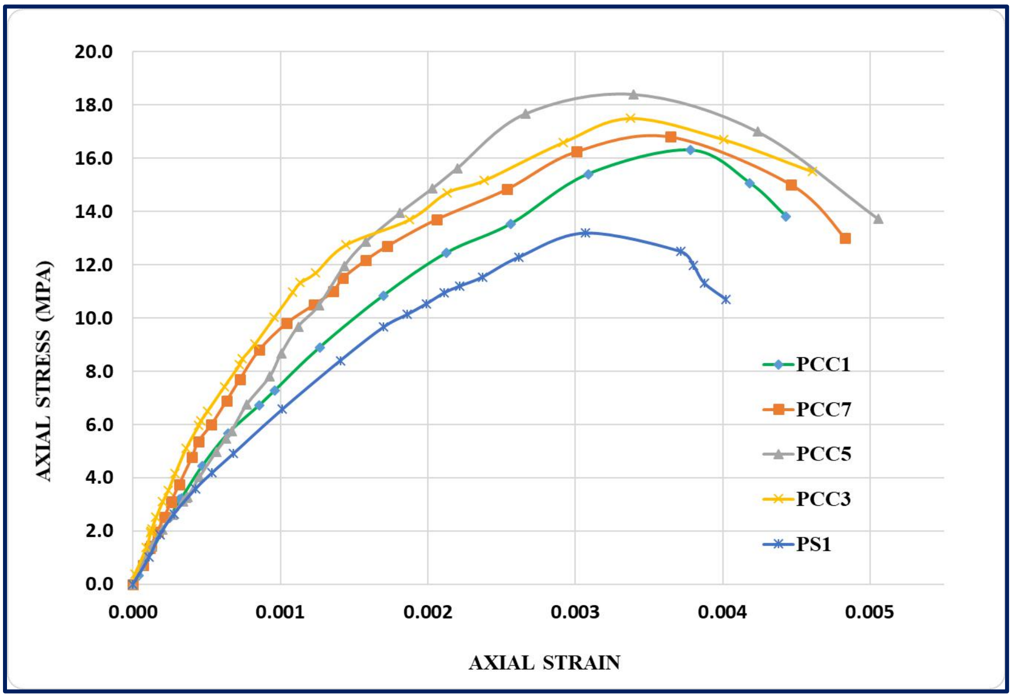

Fig.9: The stress-strain relationships for PCC piles compared with PS1 pile.

From figure (9) the behaviour shows that the stiffness of PCC piles increased compared with the reference pile. Also, the load capacity of piles was increased. The carbon fibre bars reinforcement of piles led to an increase in a strain which improved ductility. The failure was more ductile and predicted, first cracks started to show then failure occur when the carbon fiber bars Rft failed, figure (10).

Fig.10: The failure of the failure of PCC piles.

3.4. The highest load-carrying capacity pile of all three groups.

Maximum axial stress, strain at maximum axial stress, and maximum strain of the reference pile and highest load-carrying capacity pile from all three previous groups as indicated in table (6). Based on the findings, it is evident that the PC5 pile exhibited a maximum capacity of 93.60% in comparison to the reference pile. Furthermore, the PCG5 pile demonstrated a notable improvement in maximum capacity, with a percentage increase of 24.64%. Similarly, the PCC5 pile displayed a substantial enhancement in maximum capacity, with a percentage increase of 39.50% when compared to the reference pile. The strain observed at the point of maximum axial stress for the PC5 pile was found to be 78.00% of the strain observed in the reference pile. In contrast, the PCG5 pile exhibited an improvement of 103.193% in the strain at the maximum axial stress, while the PCC5 pile showed an even greater improvement of 110.45% when compared to the reference pile. The PC5 pile exhibited a maximum strain of 77.17% in relation to the reference pile, while the PCG5 pile displayed a maximum strain of 91.89% in comparison to the reference pile. The PCC5 pile exhibited a significant enhancement in maximum strain, with a 124.316% increase compared to the reference pile.

Table 6: Results summary of PS1 pile and maximum load-carrying capacity piles from all three previous groups.

Pile Code	Max. Axial Stress (MPa)	Strain at Max. stress $*10^{-6}$ (mm/mm)	Max. Strain $* 10^{-6}$ (mm/mm)
PS 1	13.19	3069	4022
PC 5	12.35	2394	3104
PCG 5	16.44	3167	3696
PCC 5	18.4	3390	5000

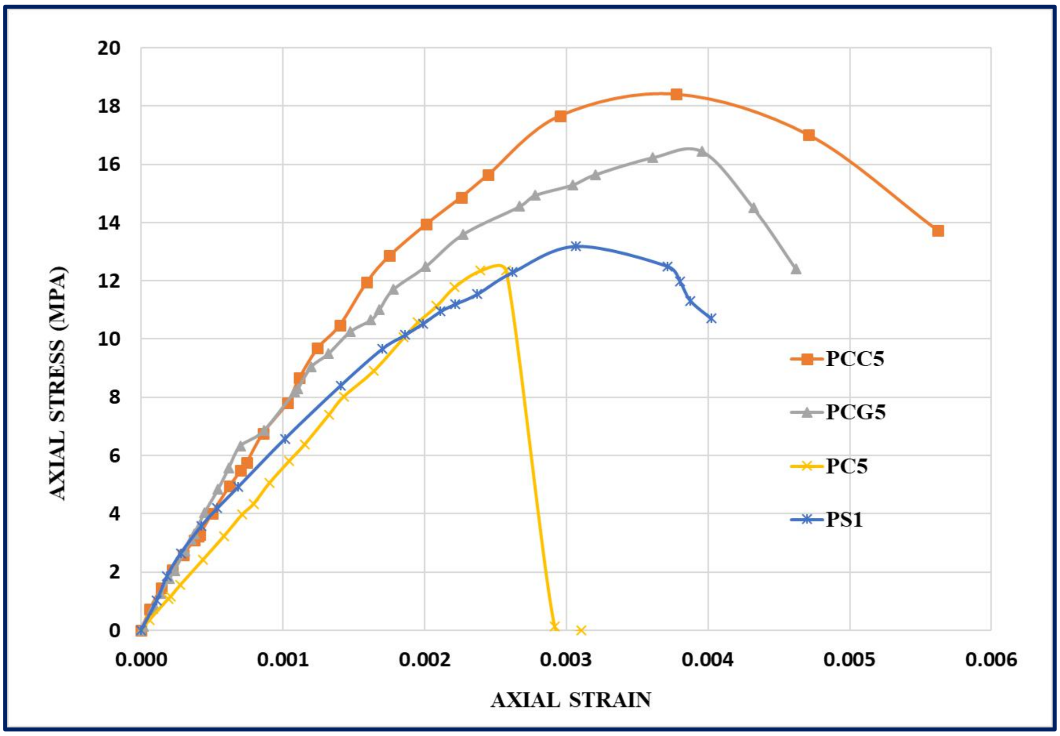

Fig.11: Stress-strain relationships for the highest load-carrying capacity pile from all three previous groups compared with PS1 pile.

The results showed that the 1.25% carbon fibre bristles ratio of cement weight was the best ratio, figure (11). When comparing the load-carrying capacity of the highest capacity piles from each of the three aforementioned types to the reference pile, it was observed that the utilisation of partial reinforcing using carbon fibre bristles generally enhanced the pile's capacity. The reinforcing of piles with steel bars, CFRP bars, or geogrid is mostly recommended to enhance the ductility of the pile. Among these options, the utilisation of CFRP bars as reinforcement yielded the most desirable results. The utilisation of geogrid confinement resulted in an acceptable load-carrying capacity accompanied by desirable ductile-carrying characteristics.

3.5. Cost analysis and Feasibility Study.

The utilization of carbon fiber concrete piles reinforced with geosynthetics enhances the load-carrying capacity of piles in comparison to the reference pile, as evidenced by the data stated in table (7). However, it is important to note that the cost associated with applying these reinforcement techniques remains relatively high when compared with conventional methods. Nevertheless, it is essential to consider the benefits offered by such reinforcements, including increased durability against detrimental environmental factors and reduced costs associated with pile rehabilitation. Furthermore, as the use of these reinforcements becomes more common and mass production becomes possible, it is expected that the overall cost will go down.

Table 7: Axial load-carrying capacity and cost ratio of all piles to reference pile.

Specimen	Maximum axial capacity at failure (MPa)	Capacity ratio	Cost (L.E)	Cost ratio
PS1 (Reference)	13.19	1	28	1
PC1	10.12	0.77	99	3.54
PC3	11.59	0.88	132	4.71
PC5	12.35	0.94	165	5.89
PC7	11.29	0.86	197	7.04
PCG1	13.4	1.02	106	3.79
PCG3	15.1	1.14	139	4.96
PCG5	16.44	1.25	172	6.14
PCG7	14.41	1.09	204	7.29
PCC1	16.3	1.24	352	12.57
PCC3	17.5	1.33	380	13.57
PCC5	18.4	1.39	408	14.57
PCC7	16.81	1.27	435	15.54

IV. CONCLUSION

The outcomes of the previous study could be summarised as follows:

1. The use of carbon fibres bristles in concrete mixture leads to improving the strength capacity of concrete piles.
2. The percentage of 1.25% carbon fibres bristles of cement weight gave the best results.
3. Despite the use of carbon fibres concrete piles gave good compressive stresses capacity but we recommend using confinement reinforcement to improve the ductility of piles.
4. The use of carbon fibre concrete piles with geogrid confinement gave a better load-carrying capacity with more ductile behaviour.
5. The use of carbon fibre concrete piles with carbon fibre bars reinforcement gave the best vertical load resistance and the highest compressive stiffness.
6. The use of geogrid confinement or carbon fibre bars reinforcement to resist vertical loads could be a better alternative compared to traditional reinforcement of piles.
7. Even though the cost of using carbon fibre concrete piles reinforced with geosynthetics is high right now, taking into consideration the benefits of using such reinforcements will help to make the piles more resistant to harmful environmental factors and lower the cost of pile rehabilitation. With the expansion of the use of these types and mass production, it will definitely lead to a reduction in cost.

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