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Experimental Study on Concrete-Filled PVC Tubes Using E-Glass Fibre Reinforced Concrete

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Abstract

Concrete-filled plastic tubes (CFPT) provide corrosion resistance compared to concrete-filled steel tubes but have low stiffness and tensile capacity, which weakens confinement. This study investigates E-glass fibre-reinforced concrete as infill to address these limitations. Compressive tests were conducted on 54 specimens in four groups: plain concrete (C), E-glass fibre reinforced concrete (EC), concrete-filled tube (CP), and E-glass fibre reinforced concrete-filled tube (ECP). Variables included specimen diameter (75–150 mm), fibre content (0–1.5% by cement weight), and confinement (with or without PVC tubes). Increasing diameter from 75 mm to 150 mm raised compressive strength by 2.1 to 4.9 times. The strength gain, however, was disproportionate to the increase in load-bearing area due to poor compaction, uneven fibre distribution, reduced confinement effectiveness, and slenderness effects. Adding E-glass fibres reduced strength by 10% to 56%, with variation likely caused by workability issues and fibre clustering. PVC confinement improved plain concrete strength proportionally to the $2t/d$ ratio but had inconsistent effects on fibre-reinforced mixes. Failure modes included bulging, shear, and tube bursting. Recommendations include improving workability, enhancing bonding, and increasing PVC tube stiffness to optimise CFPT performance.

Keywords

Concrete-filled plastic tube, E-glass fibre reinforced concrete, tube confinement, compressive strength, fibre content

INTRODUCTION

Concrete-filled tubular (CFT) columns are widely used in engineering practice due to their excellent seismic performance, which includes high axial compressive strength, stiffness, and ductility [1]. In these systems, the outer tube confines the concrete core, delaying lateral expansion, while the infill concrete supports the tube against inward buckling [2]. This confinement places the concrete in a triaxial compressive stress state [3], thereby enhancing its compressive strength [4]. CFT construction also eliminates the need for formwork, reducing both cost and construction time [5]. Owing to their superior structural performance and constructability, interest in CFTs has grown significantly, as evidenced by a sharp rise in related publications [6].

Steel-concrete composites (i.e., concrete-filled steel tubes, CFST) are among the most widely used tubular column systems but face durability issues such as corrosion, high costs, and environmental concerns, as steel manufacturing is a major source of carbon dioxide emissions [7]. This has spurred the search for alternative materials. Plastic-concrete composites (i.e., concrete-filled plastic tubes, CFPT) have emerged as promising options. PVC tubes, for example, have been found to be feasible alternatives to steel tubes under moderate load conditions [8]. Polyvinyl chloride (PVC) offers a lightweight, corrosion-resistant, and low-maintenance option. Its ease of fabrication makes it attractive for cost-effective construction. Despite being corrosion-resistant, plastics such as UPVC exhibit superb chemical resistance, remaining unaffected by most concentrations of acids, alkalis, organic chemicals, oils, and fats [9]. They also do not support combustion and are self-extinguishing [9], although their structural performance can significantly degrade under elevated temperatures. However, plastics generally have lower tensile strength and stiffness than steel, which reduces confinement effectiveness and limits compressive strength enhancement, making PVC-concrete columns more susceptible to slenderness effects [8].

One approach to overcoming these limitations is to enhance the mechanical properties of the infill concrete. Glass fibres offer advantages such as cost-effectiveness, light weight, and high tensile strength, and can curb shrinkage cracking while enhancing the flexural and tensile strength of fibre-reinforced concrete [10]. Their incorporation into concrete is relatively straightforward and can be effective for structures requiring improved compression capacity [11]. Short, discrete fibres, when well dispersed and well bonded with cement hydration products, can form a three-dimensional network that bridges cracks, restrains their growth, and enhances crack control, ductility, and post-cracking behaviour. The glass fibres produce frictional stress through bonding with the cementitious material and extrusion against the aggregate, which helps resist external loads [12]. This mechanism is beneficial in overcoming inherent limitations of concrete such as poor ductility, high brittleness, low tensile strength, low tensile strain, and poor impact toughness [12].

This study explored the application of concrete-filled plastic tubes (CFPT), using E-glass fibres to overcome the limitations of CFPT by reinforcing the infill concrete. PVC tubes served as the confinement for the E-glass fibre-reinforced concrete. The investigation examined the effects of varying specimen diameter and fibre content, as well as the presence or absence of the PVC tube, with emphasis on compressive performance and failure modes under compression. The aim was to assess the interaction between E-glass fibre concrete and the confining PVC tubes.

RESEARCH SIGNIFICANCE

While individual studies on CFPT and E-glass fibre-reinforced concrete exist, their combined use remains limited in the literature. This study addresses this gap by experimentally investigating the synergistic effects of E-glass fibre reinforcement and PVC confinement on the compressive performance and failure mechanisms of CFPT columns, with implications for advancing sustainable and durable composite structural systems, particularly for applications in aggressive or marine environments.

METHODOLOGY

Fifty-four specimens were divided into four groups: plain concrete (C), E-glass fibre reinforced concrete (EC), plain concrete-filled tube (CP), and E-glass fibre reinforced concrete-filled tube (ECP). All specimens were 300 mm in height (Figure 1). Three parameters were varied: diameter (75, 100, and 150 mm), E-glass fibre content (0%, 0.75%, and 1.5% by cement weight), and confinement condition (with or without a PVC tube) (Table 1). Three identical specimens were prepared for each configuration.

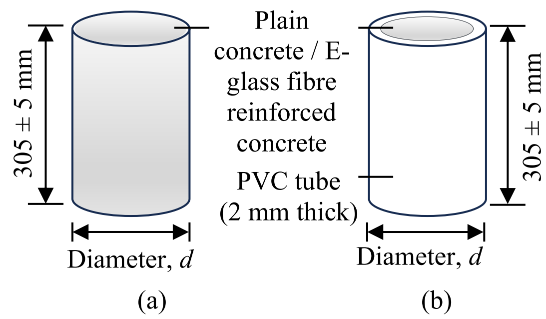


Figure 1 Specimen designs: (a) Specimens C and EC, (b) Specimens CP and ECP

The materials used were concrete, PVC tubes, and E-glass fibres. Specifications are listed in Table 2. Grade 25 concrete was prepared in six batches to account for different fibre contents and confinement conditions (Table 3). Each batch produced nine test specimens and three cubes for compressive strength testing. The mix proportions are shown in Table 4.

Table 1 Details of specimen

Dia, *d* (mm)	Without PVC Tube			With PVC Tube		
	E-glass fibre content			E-glass fibre content		
	0%	0.75%	1.5%	0%	0.75%	1.5%
75	C1	EC1	EC4	CP1	ECP1	ECP4
100	C2	EC2	EC5	CP2	ECP2	ECP5
150	C3	EC3	EC6	CP3	ECP3	ECP6

Note: Each configuration consisted of 3 identical specimens. A total of 54 specimens were tested: 27 with PVC tubes and 27 without.
C – Concrete, E – E-glass fibre, P – PVC tube

Table 2 Details of Materials

Material	Description / specification
Concrete	• Primary material for C and EC specimens, and infill for CP and ECP specimens • Designed for 25 N/mm² strength at 28 days • Aggregate size: 5 – 25 mm • Cured in water for 28 days at room temperature
PVC tube	• Used as temporary formwork for C and EC specimens, and as confinement for CP and ECP specimens • Diameters: 75, 100, and 150 mm • Height: 300 mm • Wall thickness: 2 mm
E-glass fibre	• Used as concrete reinforcement in EC and ECP specimens • Fibre diameter: 10–13 µm • Chopped length: 6 mm

Table 3 Batches of concrete

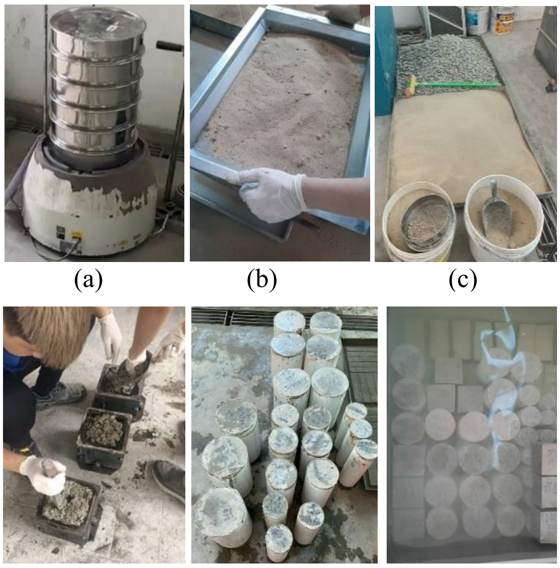
Batch no.	Specimens	Description
1	C1, C2, C3	Plain concrete (0% fibre)
2	EC1, EC2, EC3	Fibre reinforced concrete (0.75% fibre)
3	EC4, EC5, EC6	Fibre reinforced concrete (1.5% fibre)
4	CP1, CP2, CP3	Plain concrete-filled tube (0% fibre + tube)
5	ECP1, ECP2, ECP3	Fibre reinforced concrete-filled tube (0.75% fibre + tube)
6	ECP4, ECP5, ECP6	Fibre reinforced concrete-filled tube (1.5% fibre + tube)

Note: Each batch included 9 specimens with different diameters (75, 100, and 150 mm) and 3 concrete cubes (150 mm) for strength testing

Table 4 Mix design of concrete

Constituent	Weight per meter cube of concrete
Cement	328 kg/m^3
Water	190 kg/m^3
Fine aggregate	688 kg/m^3
Coarse aggregate	1224 kg/m^3

Ordinary Portland Cement (OPC) grade 42.5 was used with a water-cement ratio of 0.58. A superplasticizer (Real Power Flow RPF 630) was added at 0.5% of the cement weight to improve workability. Granite (5–25 mm) was used as coarse aggregate, and river sand passing a 600 µm sieve served as fine aggregate (Figure 2). All aggregates were oven-dried at 105°C for 24 hours to maintain consistent water content.



(a) (b) (c) (d) (e) (f)

Figure 2 Preparation of specimens in laboratory: (a) Sieving coarse aggregate, (b) Sieving find aggregate, (c) Coarse and fine aggregates, (d) Preparing cube samples, (e) Preparing specimens, (f) Curing of specimens

Short E-glass fibres (6 mm long, 10–13 µm diameter) were added at 0%, 0.75%, or 1.5% by cement weight. The cement, aggregates, and fibres were dry-mixed in a drum mixer for uniform distribution before adding water and superplasticizer.

Fresh concrete was placed into PVC tubes for casting. To prevent leakage, the tube bottoms were sealed with plastic and cellophane tape. For specimens C and EC, where the tubes would later be removed, the tubes were pre-cut lengthwise and sealed externally with tape before casting. For CP and ECP specimens, the tubes remained as part of the specimens, so no pre-cutting was done.

Concrete was poured in three roughly equal layers; each compacted with a tamping rod. After 24 hours, the PVC tubes of C and EC specimens were removed. All specimens (C, EC, CP, and ECP) were then cured in water at room temperature for 28 days before testing.

The testing program consisted of two parts: (a) material tests and (b) specimen tests. Material tests included slump, cube compression, and PVC tensile tests to verify the consistency and quality of materials (Table 5 and Figure 3). Specimen tests evaluated the compressive behaviour of C, EC, CP, and ECP specimens. A Universal Testing Machine (MTS Model 64.206) applied compressive load at a constant rate of 0.10 mm/s until failure. Load, displacement, and failure modes were recorded.

(a) (b) (c) (d)

Figure 3 Test conducted: (a) Slump test, (b) Cube compression test, (c) PVC tensile test, (d) Specimen compression test

Table 5 Test program

Sample	Test Conducted	Purpose	Standard Referred	Testing Equipment
Concrete	Slump test	To assess the workability of fresh concrete in each batch	ASTM C143	Standard slump test set
	Cube compression test (150 mm)	To determine the compressive strength of each concrete batch	BS EN 12390-3	ELE International Compression Machine, ADR Auto V2.0, 2000 kN capacity
PVC tube	Tensile test	To measure the tensile strength of the PVC tube	ASTM D638	Universal Testing Machine, Inspekt 300-1, 300 kN capacity
Specimens	Compression test	To determine the compressive strength and failure mode of specimens C, EC, CP, and ECP	-	Universal Testing Machine, MTS 64.206, 2000 kN capacity

RESULTS AND DISCUSSIONS

A. SLUMP TEST RESULTS

Based on the slump test results in Table 6, all concrete mixes were relatively dry and showed low workability, with slump values between 7 and 33.5 mm. This indicates the mixes were unsuitable for heavily reinforced sections and required mechanical vibration rather than manual compaction [13]. In this study, although the specimens were unreinforced, they were manually compacted into tubes as small as 75 mm in diameter. This likely led to poor compaction, honeycombing, and voids in the hardened concrete, which could compromise structural performance.

Workability remained low despite using a superplasticizer and a relatively high water-cement ratio of 0.58. A high water-cement ratio provides more free water to lubricate the mix, and superplasticizer helps by dispersing cement particles. However, these effects were not evident. This may be due to the oven-dried aggregates absorbing a large amount of water during mixing. Some of the superplasticizer may also have been absorbed along with the water, reducing its effectiveness. As a result, less free water and active admixture were available to improve flow, leading to poor workability. [14] reported that oven-dried natural aggregates absorbed water quickly, reducing free water and causing rapid slump loss, especially within the first hour. Similarly, [15] found that aggregates with high water absorption can lower the effective water-cement ratio and reduce consistency.

Table 6 Slump test results

Batch no.	Specimen	Slump (mm)
1	C1, C2, C3	30
2	EC1, EC2, EC3	10
3	EC4, EC5, EC6	15
4	CP1, CP2, CP3	33.5
5	ECP1, ECP2, ECP3	25
6	ECP4, ECP5, ECP6	7

Surface-dried aggregates would have been more suitable than oven-dried aggregates, as they minimise moisture imbalance, reduce excessive water absorption, and help maintain the intended water-cement ratio. Although useful in controlled conditions, oven-dried aggregates can disrupt mix proportions if not properly accounted for. [14] reported that oven-dried aggregates give a higher initial slump but lose it rapidly, while saturated surface-dried and air-dried aggregates show normal slump values and loss rates. Trial mixes, which help assess workability and adjust mix proportions or admixture dosage, were not conducted in this study. While reduced workability from fibre inclusion was expected, its severity was underestimated, likely affecting compaction and causing voids in the hardened concrete, potentially compromising performance.

The inclusion of E-glass fibres reduced concrete workability. Plain concrete had slumps of 30 mm (batch 1) and 33.5 mm (batch 4). With E-glass fibres, the slump dropped sharply, reaching 7 mm in batch 6 with 1.5% fibre content (Table 6). Similar trends were reported by [16] for self-compacting concrete and by [11], both noting reduced workability with higher fibre content.

This reduction is attributed to the high specific surface area of the fibres, which increases the surface that needs wetting and reduces the amount of free water available to lubricate cement particles [10]. Glass fibres, however, do not absorb water into their structure, although their surfaces can still be wetted. [17] reported the general physical properties of glass fibres, but water absorption was not provided. Additionally, friction between the fibres and the cementitious matrix further impedes workability [18]. To achieve the desired workability, higher superplasticizer dosages are required. For instance, [16] reported that in self-compacting concrete, increasing the glass fibre content from 0.1% to 0.8% raised the required superplasticizer from 5 to 6.25 kg/m^3. Although this approach improves flow, relying on excessively high dosages to compensate for a difficult mix is not ideal.

B. CUBE COMPRESSIVE STRENGTH TEST

Table 7 presents the mass and compressive strength of concrete cube samples for each batch. The cube masses were generally consistent, around 8 kg, with COV values not exceeding 2%, indicating uniform sample preparation and minimal variation in material composition. No significant difference in mass was observed between fibre-free batches (1 and 4) and fibre-reinforced batches (2, 3, 5, and 6), likely because the specific gravity of E-glass fibre is similar to that of the aggregate. According to [17], the specific gravity of E-glass fibre ranges from 2.6 to 2.7. Their density is also comparable to concrete, avoiding excessive weight addition to structures [19].

Table 7 Cube compressive strength results

Batch no.	Cube mass (kg)						Cube compressive strength (N/mm^2)					
	S1	S2	S3	Average	SD	COV (%)	S1	S2	S3	Average	SD	COV (%)
1	8.04	8.05	8.07	8.05	0.02	0.2	39.0	35.0	35.3	36.4	0.21	0.6
2	7.89	8.17	8.15	8.07	0.16	2.0	30.4	34.4	30.5	31.8	2.76	8.7
3	7.96	8.01	8.04	8.00	0.04	0.5	35.4	33.1	34.3	34.3	0.85	2.5
4	8.04	8.05	8.03	8.04	0.01	0.1	36.3	34.3	30.5	33.7	2.69	8.0
5	8.13	8.12	8.16	8.14	0.02	0.2	31.4	29.1	29.0	29.8	0.07	0.2
6	8.00	7.96	7.86	7.94	0.07	0.9	28.9	30.7	27.5	29.0	2.26	7.8

Slightly lower masses were observed in some fibre-reinforced batches (3 and 6), which may suggest minor challenges in compaction when fibre is incorporated, particularly at 1.5% fibre content.

The compressive strength of the concrete ranged from 29 to 36.4 N/mm^2, with all batches exceeding the target strength of 25 N/mm^2. This was attributed to the standard mix design, which was based on a higher target mean strength of 38.12 N/mm^2 to ensure a 95% probability of achieving the required strength.

Batches containing 0% fibre (1 and 4) recorded the highest strengths (36.4 and 33.7 N/mm^2), while fibre-reinforced batches (2, 3, 5, and 6) showed slightly lower strengths. This reduction may be associated with the addition of E-glass fibres, which can hinder proper compaction or create localized weak zones within the matrix. The COV values for compressive strength in some fibre-reinforced and concrete-filled tube batches (batches 2, 4, and 6) were relatively high (7.8–8.7%), exceeding the preferable COV of 5% often considered indicative of good uniformity for lab-cast cubes. This reflects variability from fibre distribution, casting in tubes, and the small sample size (n = 3). Despite this, the variability remains within acceptable limits, and no clear trend between fibre content and strength can be conclusively established.

C. PROPERTIES OF PVC TUBE

Three PVC samples were tested under tensile load, giving an average yield strength of 26.29 N/mm^2 (Table 8). This is less than 1/10 the yield strength of steel tubes reported by [20] (278.9–331.3 N/mm^2), [21] (312.7–335.2 N/mm^2), and [22] (345–415 N/mm^2). PVC also has much lower stiffness, being over 50 times lower than steel and about 5 times lower than concrete [8].

Although PVC is cheaper, with a cost ratio of 0.5 compared to 1 for steel [8], its low tensile strength is a major limitation. Unlike steel tubes, PVC offers minimal axial resistance and limited confinement to concrete [23]. Therefore, any strength enhancement from using PVC tubes was expected to be modest.

Table 8 Tensile test result of PVC tube

Sample	Area, *a* (mm^2)	Yield strength, f_y (N/mm^2)
S1	27.02	25.53
S2	26.11	26.73
S3	29.11	26.6
Average	27.41	26.29
SD	1.54	0.66
COV (%)	5.6	2.5

D. COMPRESSIVE STRENGTH OF SPECIMEN

Table 9 presents the compressive strength results for specimens C, EC, CP, and ECP. The consistency of the results varied considerably, with COV values ranging from 1.8% to 35.1%. The higher variability in some specimens is likely due to a combination of factors: (a) low workability from using oven-dried aggregates, (b) inclusion of E-glass fibres, and (c) challenges in achieving proper compaction within the narrow space of the PVC tube.

Table 9 Compressive strength of specimen

Specimen	Sample 1 (kN)	Sample 2 (kN)	Sample 3 (kN)	Average (kN)	SD (kN)	COV (%)
C1	92.14	95.39	115.41	101.0	12.6	12.5
C2	143.73	261.05	238.76	214.5	62.3	29.0
C3	475.23	514.62	495.82	495.2	19.7	4.0
EC 1	96.57	121.67	129.34	115.9	17.1	14.8
EC 2	212.38	187.21	182.73	194.1	16.0	8.2
EC 3	253.19	177.64	292.03	241.0	58.2	24.1
EC 4	90.54	107.17	75.03	90.9	16.1	17.7
EC 5	195.99	163.44	149.31	169.6	23.9	14.1
EC 6	188.25	273.50	285.09	248.9	52.9	21.3
CP 1	142.00	137.81	153.31	144.4	8.0	5.5
CP 2	274.41	284.03	276.42	278.3	5.1	1.8
CP 3	518.55	503.94	495.00	505.8	11.9	2.4
ECP 1	79.76	96.55	89.00	88.4	8.4	9.5
ECP 2	131.13	119.78	115.54	122.2	8.1	6.6
ECP 3	305.22	301.72	534.61	380.5	133.5	35.1
ECP 4	87.85	94.39	93.18	91.8	3.5	3.8
ECP 5	221.35	243.60	226.10	230.4	11.7	5.1
ECP 6	295.32	331.17	341.14	322.5	24.1	7.5

Table 10 Average compressive strength by specimen diameter, steel fibre content, and confinement state

Diameter, *d* (mm)	Without PVC Tube			With PVC Tube		
	E-glass fibre content			E-glass fibre content		
	0%	0.75%	1.5%	0%	0.75%	1.5%
75	101.0	115.9	90.9	144.4	88.4	91.8
100	214.5	194.1	169.6	278.3	122.2	230.4
150	495.2	241.0	248.9	505.8	380.5	322.5

The average values were reorganized in Table 10 based on specimen diameter, E-glass fibre content, and the presence of a PVC tube. This helps to clearly show how these parameters affect compressive strength.

EFFECTS OF SPECIMEN DIAMETER

Compressive strength generally increased as the specimen diameter grew from 75 to 150 mm, with strength rising by 2.1 to 4.9 times (Table 11). This improvement is likely due to the larger load-bearing area, which reduces internal stress for a given load. Lower stress concentration decreases the risk of localized failure, allowing the specimen to sustain a higher total load before failure. However, the strength increase was not directly proportional to the cross-sectional area. For example, although the area became 4 times larger, strength at 0.75% fibre content increased by only 2.1 times without a PVC tube and 4.3 times with one. This indicates that other factors also influenced the compressive strength.

Table 11 Rate of strength increment as the specimen diameter increased from 75 mm to 150 mm

Category	Specimen Property / Fibre Content	75 mm	150 mm	Increment Ratio
Geometry of Specimens	Cross-sectional area (mm²)	4418	17671	4 times
Compressive Strength (without PVC tube) (N/mm^2)	0% fibre	101.0	495.2	4.9 times
	0.75% fibre	115.9	241.0	2.1 times
	1.5% fibre	90.9	248.9	2.7 times
Compressive Strength (with PVC tube) (N/mm^2)	0% fibre	144.4	505.8	3.5 times
	0.75% fibre	88.4	380.5	4.3 times
	1.5% fibre	91.8	322.5	3.5 times

Table 12 Factors influencing strength improvement

	Specimens C	Specimens EC	Specimens CP	Specimens ECP
Larger load-bearing area[1]	√	√	√	√
Poor compaction [2]	√ or X	√ or X	√ or X	√ or X
Uneven fibre distribution [2]	X	√	X	√
Lower slenderness ratio (*h/d*) [1]	X	X	√	√
Lower confinement ratio (2*t/d*) [2]	X	X	√	√

Note: [1]favourable, [2]non favourable; √ - presence, X – not presence

Low concrete workability increased the risk of poor compaction, which may have led to voids or honeycombing. The inclusion of E-glass fibres further reduced workability, increasing the chances of uneven fibre distribution or clumping. These issues can form weak zones that limit strength, regardless of specimen diameter or fibre content.

Larger diameters also altered the geometry and confinement conditions. A lower slenderness ratio (*h/d*) reduced the risk of buckling under axial load, which benefited compressive strength. However, a lower confinement ratio (2*t/d*) reduced the effectiveness of the PVC tube in resisting lateral expansion. [24] and [7] reported that higher 2*t/d* ratios improve confinement. As diameter increased, the reduced 2*t/d* ratio allowed more lateral expansion of the concrete, weakening confinement and limiting further strength gains [25].

In general, as the specimen diameter increased from 75 to 150 mm, five factors could influence the strength enhancement: (a) larger load-bearing area, (b) poor compaction, (c) uneven fibre distribution, (d) lower slenderness ratio (*h/d*), and (e) lower confinement ratio (2*t/d*) (Table 12). The actual rate of strength increase depended on the presence of these factors and whether each contributed positively or negatively to the strength. For example, the increased load-bearing area applied to all specimens, while the reduced *h/d* and 2*t/d* ratios were relevant only to specimens with PVC tubes (CP and ECP). Poor compaction and uneven fibre distribution depended on the quality of fabrication, with the latter affecting only specimens containing E-glass fibres. These varying combinations may explain the inconsistent trend in strength improvement observed in Table 11.

EFFECTS OF E-GLASS FIBRE

E-glass fibres generally reduced the compressive strength of concrete. This is evident from the strength ratios in Table 13, which compare the compressive strength of fibre-reinforced specimens (EC and ECP) to their non-fibre counterparts (C and CP). Most specimens showed a reduction in strength, with ratios ranging from 0.44 to 0.90, indicating a decrease of 10% to 56%. An exception was EC1 (0.75% fibre, 75 mm diameter), which recorded a 15% increase in strength. However, no consistent trend was observed with varying fibre content or specimen diameter, suggesting the effects of E-glass fibre on compressive strength were inconsistent. This may be attributed to uneven fibre distribution or reduced workability, both of which can compromise the concrete's integrity. [12] further noted that with increasing glass fibre content, the relative cement content decreases and may be insufficient to fully package the fibres, thereby weakening the bond between fibres and the cement matrix. This raises a concern about the reliability and effectiveness of E-glass fibre as a compressive strength enhancer in concrete, especially when proper dispersion, adequate cement paste, and workability are not ensured.

Table 13 Strength ratio of specimens with respect to specimens with 0% fibre

Dia., *d* (mm)	Without PVC tube		With PVC tube	
	E-glass fibre content		E-glass fibre content	
	0.75%	1.50%	0.75%	1.50%
75	1.15	0.90	0.61	0.64
100	0.90	0.79	0.44	0.83
150	0.49	0.50	0.75	0.64

Note: Strength ratio = compressive strength of specimens with fibres / compressive strength of specimens without fibres (0% fibre).

To address the inconsistent effects of E-glass fibres on compressive strength, several measures can be taken. First, improving concrete workability is essential. This can be achieved by using superplasticizers and avoiding oven-dried aggregates, which absorb mix water and reduce flow. Second, fibre content should be kept within an optimal range to prevent clumping. [11] reported an 18.04% increase in compressive strength when glass fibre content was raised to 0.1%, beyond which strength decreased due to weaker bonding. Third, the total water in the mix should account for water that adheres to the fibre surfaces, reducing the free water available to lubricate the matrix. These measures can improve the uniformity and performance of E-glass fibre-reinforced concrete in structural applications.

The effect of fibres on concrete compressive strength is debatable [17]. Some studies have reported strength gains, others noted reductions, and some found no significant change. For example, [26] observed that E-glass fibre content up to 1.5% increased compressive strength by 10–20% compared with the control mix, but higher volumes reduced it. Similarly, [19] reported a 22.97% increase when using a combination of manufactured sand and glass fibres. In contrast, [27] found that 0.12% fibre volume reduced strength by 1% at 28 days, while 0.22% and 0.43% caused 15% reductions. [28] and [16] reported no significant effect on compressive strength in self-compacting concrete, although split tensile and flexural strengths improved. Likewise, [29] found that glass fibre addition had minimal influence, with glass fibre reinforced concrete showing compressive strength almost equal to that of the control concrete.

The strengthening effect of glass fibres is due to the strong bond between the fibre surface and cement hydration products [12]. When evenly distributed, the fibres form a three-dimensional network that helps control cracking. This network can restrain crack formation and growth, bridge existing cracks, reduce stress concentration at crack tips, redistribute stress, alter crack paths, prevent further crack expansion, and slow down crack development [12].

However, these benefits are more pronounced under tensile and flexural loads than in compression. According to [18], the addition of glass fibres enhanced compressive strength by 1.45%, increased split tensile strength by 10.3%, and improved flexural strength by 10.04%. In compression, fibres may still interact with the matrix by (a) providing confinement through resistance to lateral expansion, (b) limiting microcrack growth, and (c) reducing brittleness and explosive failure. Nevertheless, the gain in compressive strength is limited because failure is primarily governed by crushing and microcrack coalescence, which are mechanisms that fibres are less effective at controlling. Additionally, the minimal lateral expansion caused by concrete's low Poisson's ratio may not be sufficient to fully engage the tensile resistance of the fibres. Consequently, the positive effects of glass fibres are more consistent and significant in tension and flexure than in compression.

EFFECTS OF PVC TUBE

Table 14 presents the strength ratio, comparing the compressive strength of confined specimens (CP and ECP) to their unconfined counterparts (C and EC). The comparison showed mixed results. Seven specimens exhibited strength gains (strength ratio > 1.0), while two showed reduced strength (strength ratio < 1.0). The strength ratio varied widely, ranging from 0.63 to 1.58, indicating a 37% reduction to a 58% increase in strength. This implies that the effectiveness of PVC confinement is not consistent and may depend on other factors such as specimen geometry, concrete quality, fibre content, or confinement integrity.

Table 14 Strength ratio of specimens with PVC tubes with respect to specimens without PVC tubes

Diameter, *d* (mm)	E-glass fibre content		
	0%	0.75%	1.5%
75	1.43	0.76	1.01
100	1.30	0.63	1.36
150	1.02	1.58	1.30

Note: Strength ratio = compressive strength of specimens with PVC tube / compressive strength of specimens without PVC tube.

PVC tubes enhanced the compressive strength of plain concrete. All specimens without fibres (0% fibre) showed increased strength when confined with PVC tubes, as indicated by strength ratios greater than 1.0. The strength ratios for specimens with 75 mm, 100 mm, and 150 mm diameters were 1.43, 1.30, and 1.02, respectively, showing that strength gain decreased with increasing diameter. This trend is attributed to the reduced $2t/d$ ratio, which lowered the confinement effectiveness of the PVC tubes and limited their ability to resist lateral expansion and control microcracks. These findings align with [24], who showed that uPVC tubes can increase the axial load capacity of confined concrete cylinders to 1.12–1.65 times the sum of the individual unconfined capacities.

The marginal strength gain of CP3 (0% fibre, 150 mm diameter, strength ratio = 1.02) suggests that the confinement effect was nearing its limit. For specimens with diameters exceeding 150 mm, or with a $2t/d$ ratio lower than 0.027 (tube thickness t = 2 mm; diameter d = 150 mm), strength improvement is likely negligible. In such cases, the PVC tube would primarily serve as permanent formwork and a barrier against environmental exposure rather than as an effective confinement mechanism. PVC tubes provide low confinement on concrete columns but can undergo significant plastic deformation to accommodate concrete dilation [30].

A similar trend of decreasing confinement effectiveness with increasing diameter was not observed in specimens containing E-glass fibres. At 0.75% fibre content, the highest strength gain occurred in specimen ECP3 (150 mm diameter) with a 58% increase, while specimen ECP2 (100 mm diameter) showed the greatest loss at 37%. In contrast, at 1.5% fibre content, the highest gain was observed in specimen ECP5 (100 mm diameter) at 36%, while ECP4 (75 mm diameter) recorded only a 1% increase.

In specimens without fibres, confinement effectiveness consistently decreased with increasing diameter. This trend was absent in fibre-reinforced specimens, suggesting that E-glass fibres influenced the compressive strength response. The inconsistent trend within the fibre-reinforced group further implies that the interaction between E-glass fibres and PVC confinement may be governed by additional factors beyond specimen diameter.

One possible reason is the inclusion of E-glass fibres, which reduced the concrete's workability. This likely caused poor compaction and more entrapped air, leading to voids that act as stress points and weaken strength. The slump values in Table 6 dropped to 7–25 mm with fibre addition, confirming the reduced flow. Low workability may also have led to uneven fibre distribution, a weaker bond between fibres and the matrix, and reduced stress transfer efficiency.

These workability-related issues may have masked the expected effect of specimen diameter on confinement, leading to the lack of a clear trend in fibre-reinforced specimens. The severity of these problems likely varied between batches due to differences in mixing time, free water content, and workmanship. These variations could have affected fibre dispersion and compaction quality, adding to the inconsistent compressive strength results.

Another factor may be the incompatible interaction between E-glass fibres and PVC tubes in providing confinement. Although both offer passive confinement, they work through different mechanisms. E-glass fibres improve internal resistance by bridging cracks and reducing tensile strains, while PVC tubes provide external confinement by limiting lateral expansion of the concrete. Under axial load, both concrete and PVC expand laterally due to Poisson's effect. However, the PVC tube only activates its confinement once the concrete's lateral expansion exceeds that of the tube.

Since E-glass fibres can suppress microcrack growth and limit lateral strain during early loading, their presence may have reduced or delayed the activation of PVC confinement. PVC also has a lower modulus of elasticity than concrete, especially when fibres are present, creating a stiffness mismatch that further weakens early confining action. Together, these deformation differences likely limited the combined confinement effect of the fibre-tube system. A similar effect was reported by [1] for concrete-filled steel tubes, where no composite action was observed at the initial elastic stage because the steel expanded faster in the radial direction due to its higher Poisson's ratio. Consistent with this, [8] noted that the low stiffness of plastic tubes compared to concrete makes current design approaches for PVC-concrete composites inadequate.

FAILURE MODE

Figure 4 shows the typical failure modes of unconfined specimens (C and EC). These modes illustrate how specimens without tube confinement failed under excessive load, highlighting their load-resisting behaviour and underlying weaknesses. Under compression, the specimens experienced elastic shortening and lateral expansion. Microcracks formed in the concrete, especially at the cement matrix-aggregate interface, once the material's deformation capacity was exceeded. With further loading, these microcracks grew and merged into larger cracks. At the ultimate state, the specimens lost integrity due to severe damage, including localized crushing, spalling, and vertical splitting cracks. A similar load response is likely under PVC tube confinement (specimens CP and ECP), as the low strength of PVC would probably not alter the failure mechanism in a significant way. However, the tube's presence could slow the progression of damage to some extent.

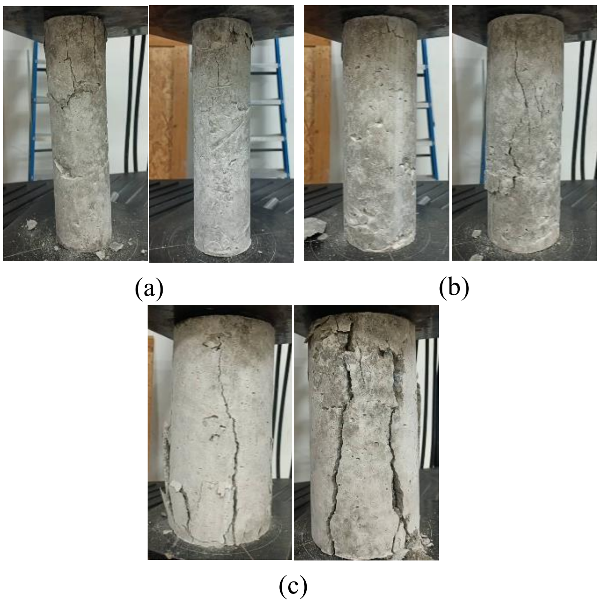
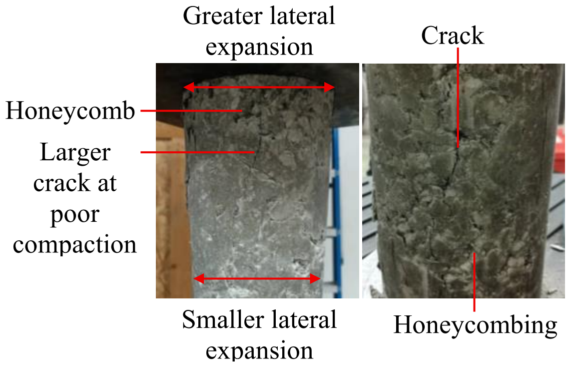


Figure 4 Typical failure mode of unconfined specimens: (a) 75 mm diameter, (b) 100 mm diameter, (c) 150 mm diameter

In this study, poor concrete workability led to inadequate compaction in some specimens, where defects such as voids and honeycombing were observed (Figure 5). While these defects may appear minor on the surface, their internal severity is uncertain, and the risk remains. Such defects create weak zones that concentrate stress, intensifying crack development and accelerating failure. As shown in Figure 5(a), the honeycombed region exhibits greater lateral expansion and larger cracks than well-compacted areas. In Figure 5(b), a major crack passes through regions with voids and poor consolidation, confirming these as points of weakness. A similar response is likely in specimens with tube confinement (CP and ECP). Although the tube may provide some restraint to crack growth, the weakness caused by compaction defects would likely outweigh this benefit, causing failure to occur sooner than in well-compacted specimens.



(a) (b)

Figure 5 Implications of poor compaction on failure behaviour: (a) greater lateral expansion with a larger crack at the honeycombed region, (b) major cracking concentrated at the honeycombed region.

Three main failure modes were observed in the confined specimens (CP and ECP): bulging, shear, and tube bursting (Figure 6). Bulging was more common in smaller specimens with lower fibre content, such as 75 mm and 100 mm diameters with ≤0.75% fibre. Shear failure occurred in larger specimens with higher fibre content (150 mm, 1.5% fibre). Tube bursting was observed in only one specimen, 75 mm in diameter with 1.5% E-glass fibre content. These findings align with [24], who reported drum and shear failures as the most common modes, depending on the failure mode of the core concrete.

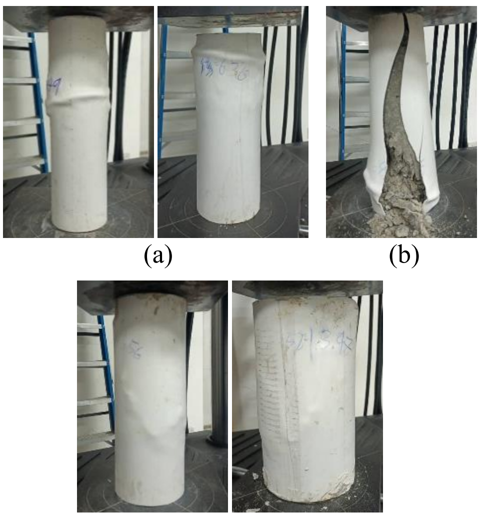

(a) (b) (c)

Figure 6 Typical failure mode of confined specimens CP and ECP: (a) Bulging, (b) Tube bursting, (c) Shear

Bulging failure resulted from the combined effects of significant axial shortening and excessive lateral dilation of the concrete core. These deformations caused relative movement between the cement matrix and aggregates, leading to internal crushing and localised spalling. Under axial load, the PVC tube shortened and experienced outward local buckling, while concrete dilation generated radial pressure that further deformed the tube outward. A similar failure mechanism was reported by [1] for concrete-filled steel tubes, where the tube entered inelastic outward buckling after microcracks in the concrete had propagated.

Shear failure was indicated by surface deformation of the tube, suggesting abrupt sliding of the concrete along an inclined plane. Internal crushing and spalling may have occurred but were not predominant. Under axial loading, elastic shortening and lateral expansion initiated microcracks once the strain limit was exceeded. With increasing load, these microcracks propagated, merged into larger cracks, and formed a shear plane due to the combined effects of axial shortening and lateral expansion. Failure occurred along the inclined plane when internal shear stresses exceeded the concrete's shear resistance.

Tube bursting involved rupture or tearing of the PVC tube, exposing the damaged concrete core. The concrete expanded laterally under compression, intensified by internal crushing, spalling, or splitting. This dilation generated tensile stresses in the hoop direction of the PVC tube. Once these stresses exceeded the tube's tensile capacity, rupture occurred.

Another possible failure mode is buckling, which was not observed in this study due to the low slenderness (*h/d* ratio) ranging from 2 to 4, based on diameters, *d*, of 75 to 150 mm and a height, *h*, of approximately 300 mm. This aligns with [7], who found that specimens with low aspect ratios of 2 and 4 exhibited drum (bulging) and shear failures, while higher aspect ratios of 6 and 8 led to buckling and shear failures. Increased slenderness raises the risk of global instability through buckling, which can significantly reduce compressive strength.

The three failure modes observed in this study provide valuable insight into strategies for strengthening CFPT columns. Bulging-related failure highlights the need to improve confinement effectiveness and to mitigate local outward buckling of the tube. Shear-related failure suggests that the tube may not be providing adequate confinement throughout the loading process, allowing diagonal shear planes to develop in the core. Tube bursting emphasises the importance of ensuring sufficient hoop tensile capacity in the confining tube. [30] found that PVC tubes contribute little to the axial strength of concrete columns, while fibre-reinforced polymer (FRP) wraps with fibres oriented in the hoop direction can significantly strengthen the columns.

Based on these observations, strengthening strategies for PVC tubes should focus on: (a) measures to limit local outward buckling, (b) methods to enhance overall confinement effectiveness, and (c) improvements to the tube's hoop tensile capacity.

Potential solutions include: (a) increasing tube wall thickness to better resist local buckling under axial load, (b) enhancing tube stiffness to oppose lateral expansion and thereby improve confinement effectiveness, and (c) increasing tensile strength to prevent bursting.

Bursting failure, in particular, should be avoided, as an intact tube can act as a safety mechanism by containing debris at the fracture stage, reducing the risk of falling fragments. However, increasing tensile strength alone may be insufficient; if tube stiffness remains low, the benefit will mainly be in post-peak ductility, with little to no improvement in compressive strength.

LIMITATIONS AND FUTURE WORK

In this study, the compressive failure of specimens appears to be associated with excessive relative deformation between the cement matrix and aggregates, arising from elastic shortening and lateral expansion. Conceptually, minimising this relative deformation could delay failure and enhance compressive strength. This may be achieved by (a) reinforcing the concrete with fibres, (b) confining it with a tube, (c) having the tube contribute to axial load resistance together with the concrete, and (d) improving the matrix-aggregate bond.

Evaluating these factors in the context of using E-glass fibre reinforced concrete in PVC tubes as a concrete-filled plastic tube (CFPT) system suggests that the current design may not be optimal. While E-glass fibres can reinforce the concrete, the associated reduction in workability must be addressed. Fibre addition may also disrupt the bond between the cement matrix and aggregates, particularly if fibre clumping occurs. PVC tubes can be used to confine the concrete and share axial load, but their low mechanical properties are likely to limit these benefits.

Future studies could explore ways to improve workability, with self-compacting concrete being a preferred option for CFPT columns. These columns involve vertical casting, where high workability is essential for proper compaction. This need is greater because the concrete is inside a non-transparent tube, making it difficult to detect or correct compaction issues without special equipment.

The use of fibres to enhance tensile strength, flexural resistance, and ductility can benefit CFPT columns, especially under bending or eccentric loads. [31] found that adding glass fibre to high-performance cementitious materials without coarse aggregate in square steel tubular columns improved confinement, axial strength, stiffness, and toughness for both centrically and eccentrically loaded specimens. Future research could focus on improving fibre-matrix and matrix-aggregate bonds to ensure effective stress transfer. Poor bonding weakens composite action, reducing strength and toughness. Possible solutions include fibre surface treatments or supplementary cementitious materials to refine the microstructure and strengthen the interfacial transition zone.

The concrete-tube interaction in CFPT columns can be improved by (a) increasing confinement effectiveness, (b) preventing local buckling of the tube, and (c) enhancing the tube-concrete bond.

Confinement effectiveness can be increased by using non-shrinking or expansive concrete, which maintains or slightly increases pressure against the tube. This offsets shrinkage and improves the tube's ability to restrain lateral expansion. The interaction of such mixes with fibre reinforcement should be examined, as fibres may limit volume change or introduce internal stresses.

Local buckling of the tube is another concern. Without infill concrete, a PVC tube under axial load is prone to local buckling. In CFPT columns, the concrete core restrains inward buckling but offers little resistance to outward buckling [32]. Due to the low hoop strength of PVC, external confinement measures such as steel rings, ties, spirals, jackets, or FRP wraps may be considered [1]. Such confinement can substantially enhance axial load capacity; for example, plain sockets in CFPT with PVC tubes increased ultimate load by 21.3% to 55.2% compared with columns without sockets [33]. FRP wraps, in particular, can effectively inhibit local buckling of the PVC tube and restrain the lateral dilation of the encased concrete [30]. Future studies could investigate strategies to delay or prevent outward buckling.

The tube-concrete bond could also be improved to enhance axial load sharing and overall column performance. Future studies could investigate methods to achieve a stronger bond and better composite action between the tube and the infilled concrete.

The findings of this study are limited by the specific materials and testing setup used. Most research on plastic tube-confined concrete has been restricted to short, small-diameter specimens tested under uniaxial compression [8], and this study followed a similar scale. The PVC tubes had low tensile resistance, a wall thickness of 2 mm, and diameters of 75 to 150 mm. The E-glass fibres were of a single type, 10–13 μm in diameter, and chopped to 6 mm. Fibre content ranged from 0% to 1.5% by cement weight. Concrete workability was low, with slump barely exceeding 33.5 mm. These results cannot be generalised to other cases involving the same fibre at different dosages, other fibre types, hybrid fibre mixes, or CFPT systems with the same or other plastics of different dimensions or properties. The controlled laboratory conditions (sheltered curing, full water submersion) and small-scale casting (300 mm height) may not reflect real structural applications. In practice, environmental factors such as temperature changes, moisture ingress, UV exposure, and chemical attack, absent in this study, could affect long-term performance. While the mechanisms observed may still apply, field conditions could diminish the expected gains or exacerbate strength degradation. Future work should address material variability, scaling effects, and environmental durability, with full-scale load tests and long-term monitoring to confirm CFPT column performance in service.

CONCLUSIONS

This study examined plain and E-glass fibre-reinforced concrete specimens, with and without PVC tube confinement, to assess the effects of diameter, fibre content, and confinement on compressive strength.

Increasing specimen diameter from 75 to 150 mm raised compressive strength by 2.1–4.9 times. This gain was mostly below the level expected from the fourfold increase in load-bearing area, due to poor compaction, uneven fibre distribution, and reduced confinement effectiveness (2*t/d*), partly offset by the positive effect of reduced slenderness (*h/d*).

The inclusion of E-glass fibres appeared to be associated with a 10–56% reduction in compressive strength, with only one case showing a 15% gain. However, this association cannot be definitively confirmed, as no consistent trend was observed with varying fibre content or specimen diameter. The reduction may also be linked to poor workability and/or fibre clumping.

PVC confinement had an inconsistent effect on the compressive strength of fibre-reinforced concrete, with variations ranging from a 37% reduction to a 58% increase, suggesting that other factors such as specimen geometry, concrete quality, fibre content, or confinement integrity played a more dominant role. In contrast, specimens without fibres showed a clear trend: strength gain decreased as the 2*t/d* ratio decreased, indicating lower confinement effectiveness of the PVC tube, which became notably diminished when the ratio fell below 0.027.

Three failure modes were observed in confined specimens: bulging, shear, and tube bursting. Bulging occurred mainly in smaller specimens (≤100 mm, ≤0.75% fibre), shear in larger specimens (150 mm, 1.5% fibre), and bursting in one case (75 mm, 1.5% fibre). These patterns suggest that stronger CFPT columns require improved tube stiffness, confinement effectiveness, and hoop tensile capacity.

E-glass fibre-reinforced CFPT column performance is limited by low workability, weak matrix-aggregate and tube-concrete bonds, and the low mechanical strength of PVC. Future studies should explore methods to enhance workability, improve interfacial bonding (fibre-matrix and matrix-aggregate), and strengthen tube confinement (through higher stiffness, buckling resistance, and hoop strength) to achieve better compressive performance and durability.

The findings of this study are limited to the specific PVC tube properties, E-glass fibre type, mix proportions, and laboratory-scale specimens tested. Variations in material properties, specimen scale, or environmental exposure may influence the observed trends. Further research is needed to validate these results under full-scale loading and long-term service conditions.

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