Optimization of Concrete Mix Design for UPVC Tube Encased Columns: A Study

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ABSTRACT

This study focuses on assessing the load-carrying capacity of UPVC tubes filled entirely with concrete by subjecting them to axial loading until failure occurs. A total of eighteen UPVC tubes, each with a diameter of 150mm as well as a thickness of 7.11mm, as well as effective lengths ranging from 500mm to 700mm were used. M20 grade concrete sourced from two different mixes with aggregate sizes of 6.3mm as well as 10mm was placed inside the tubes to create UPVC concrete-filled tube (CFT) column samples. These column specimens were then tested for axial loading using a UTM with a capacity of 1000kN, as well as load-displacement as well as stress-strain curves were recorded. The failure mode observed in all columns was local buckling, with increased strength noted as the length of the column increased, particularly in the mix with 6.3mm coarse aggregate compared to 10mm coarse aggregate. The experimental setup also included a study on the efficacy of Polyvinyl Chloride (PVC) confinement in short plain circular concrete columns, utilizing various diameters of PVC tubes (110mm to 250mm) with two confinement methods: full confinement as well as confinement with cut ends. The results indicated a significant increase in the ultimate load capacity of the columns with external PVC tube confinement, with enhancement ratios ranging from 4.16% to 15%. Additionally, the study revealed that UPVC CFT columns exhibited an approximate 1.6% increase in compressive strength compared to theoretical values.

Keywords**--** M20, Strength, UPVC, CFTC

I. INTRODUCTION

The purpose of this work is to investigate the behaviour of reinforced columns containing polypropylene fibres that are delimited by Un-plasticized Polyvinyl Chloride (UPVC) under axial compression. In order to determine how sensitive concrete-filled UPVC pipe (CFUT) samples are to various situations, samples with a range of geometric features are evaluated [1]. The significance of columns in structural integrity is highlighted, emphasizing their crucial role in supporting overall structural stability. The paper underscores the importance of maintaining the strength as well as ductility of steel columns through appropriate strengthening, repair, as well as rehabilitation methods to ensure structural performance. Concrete-filled tubes, whether made of steel, fibre-reinforced plastic (FRP), or UPVC, are recognized as composite columns offering advantages such as low cost, resilience to environmental damage, as well as high strength-to-weight ratio [2]. UPVC pipes, commonly used in water supply systems, are classified based on their resistance to water pressure. Research findings have highlighted the benefits of employing UPVC confinement in enhancing both the mechanical strength as well as environmental durability of concrete structures, effectively shielding them from degradation [3]. By doing so, it aims to provide a comprehensive understanding of their structural behaviour. Concrete-filled tubes, serving as composite columns, comprise a tubular casing filled with concrete as well as can be fabricated from various materials such as steel, fibre-reinforced plastic (FRP), or PVC [4]. Among these options, PVC, including unplasticized PVC, stands out due to its advantageous qualities such as affordability, resilience to harsh environmental conditions, as well as a favourable strength-to-weight ratio. This study aims to shed light on the performance of such composite columns, particularly those utilizing PVC encasements, through a meticulous examination that encompasses both empirical testing as well as computational analysis [5].

Recent advancements in composite structures of UPVC (unplasticized Polyvinyl Chloride) have propelled the material to the forefront of modern engineering applications. By harnessing innovative manufacturing techniques and incorporating novel reinforcing agents, researchers have enhanced the performance and versatility of UPVC composites across various industries [6-9]. One notable advancement lies in the development of fiber-reinforced uPVC composites, where materials such as glass, carbon, or aramid fibers are strategically embedded within the polymer matrix to impart exceptional strength, stiffness, and durability [10-13]. These composites exhibit improved mechanical properties, including higher tensile and flexural strengths, as well as enhanced resistance to impact and fatigue. Moreover, advancements in nanotechnology have facilitated the integration of nano-scale fillers and modifiers into uPVC composites, further augmenting their mechanical performance and functional capabilities [15]. Additionally, the introduction of additive manufacturing technologies has enabled the fabrication of complex uPVC composite structures with intricate geometries and tailored properties, opening new avenues for lightweight and customizable components in aerospace, automotive, construction, and marine applications [16]. As research in composite materials continues to evolve, the ongoing advancements in uPVC composites promise to deliver innovative solutions for the engineering challenges of the future, driving progress towards more sustainable, efficient, and resilient infrastructure and products [17-18].

UPVC finds a wide range of applications across various industries due to its versatile properties as well as durability [19]. In construction, UPVC is commonly utilized for window frames, doors, as well as cladding due to its resistance to weathering, corrosion, as well as rotting. Its lightweight nature as well as ease of installation make it a preferred choice for both residential as well as commercial buildings [20]. Additionally, UPVC pipes are extensively used for water supply as well as drainage systems in buildings as well as infrastructure projects. These pipes offer excellent resistance to chemical corrosion, ensuring long-term reliability as well as minimal maintenance [21-24]. In the electrical industry, UPVC is employed for insulation purposes in cables as well as wiring, providing electrical safety as well as protection against moisture as well as chemicals. Furthermore, UPVC is also used in the manufacturing of furniture, automotive components, as well as medical devices, thanks to its rigidity, impact resistance, as well as hygienic properties [25]. Overall, UPVC's versatility, durability, as well as cost-effectiveness make it an indispensable material in a wide range of applications, contributing to sustainable as well as efficient solutions across various sectors [26].

UPVC is extensively utilized in the construction industry for a multitude of applications. One of its primary uses is in window frames as well as door profiles, where its excellent thermal insulation properties help enhance energy efficiency in buildings. Additionally, UPVC is commonly employed in roofing systems due to its weather resistance as well as longevity, providing durable protection against harsh environmental conditions. In the realm of infrastructure, UPVC pipes play a vital role in water supply networks, sewage systems, as well as underground drainage systems [27]. Their corrosion resistance as well as smooth interior surface facilitate efficient fluid flow while minimizing the risk of clogs as well as blockages. Moreover, UPVC is increasingly being adopted in interior design for decorative purposes, such as wall cladding as well as ceiling panels, thanks to its versatility, ease of maintenance, as well as wide range of available colors as well as finishes [28-29]. In the automotive sector, UPVC is utilized in various components, including door panels, dashboards, as well as interior trim, benefiting from its lightweight nature, impact resistance, as well as ability to withstand prolonged exposure to sunlight as well as temperature fluctuations. Furthermore, UPVC's non-conductive properties make it a preferred material for electrical conduits as well as cable insulation, ensuring electrical safety in residential, commercial, as well as industrial settings. Overall, UPVC's diverse range of applications underscores its significance as a reliable as well as adaptable material in modern construction, infrastructure, as well as manufacturing industries [30].

In conclusion, UPVC is a strong as well as adaptable building material that has many uses in the building industry. Because of its strength, resilience, ease of maintenance, as well as thermal efficiency, it is a well-liked option for many different building systems as well as components.

II. METHODOLOGY

In this study, short column specimens were prepared as well as subjected to three distinct confining scenarios: fully confined (Cc), confined with a 1 cm cut from both ends (CCC), as well as unconfined (Cu). These specimens were matched with four different circular PVC diameters, specifically 110 mm, 160 mm, 220 mm, as well as 250 mm. The primary objective was to evaluate how short columns, reinforced with PVC tubes, perform under axial loading conditions. To ensure that the columns exhibited behavior typical of short columns as well as to minimize the influence of slenderness effects, a height-to-diameter (H/D) ratio of 3 was maintained consistently across all specimens. This ratio helps ensure that the columns primarily experience axial loading rather than bending, which is crucial for accurate assessment of their behavior. For additional details regarding the specimens, including dimensions as well as specific configurations, readers are directed to refer to Table 3, where comprehensive information is provided.

The experimental process is conducted systematically to cast concrete specimens, with the aim of ensuring consistency and conducting a comprehensive examination of various parameters. In each experimental scenario, a total of 12 specimens are cast, with three specimens produced for each diameter being investigated. The preparation of the concrete mix is carried out meticulously, following a precise mixing ratio of 1:2:4 and a water-to-cement (W/C) ratio of 0.41, thereby ensuring uniform composition across all specimens to yield reliable results. A mechanical mixer with a volumetric capacity of 1 m^3, is employed to facilitate the mixing process, maintaining consistency and accuracy. Subsequent to casting, the specimens undergo curing for durations of 7 and 28 days in basin water at room temperature to promote hydration, as well as to enhance strength and durability.

III. REINFORCEMENT RATIO'S IMPACT, RING BEAM WIDTH'S IMPACT, RING BEAM HEIGHT'S IMPACT, ECCENTRICITY'S IMPACT

Previous research studies [1–5] have shown interest in the effect of the reinforcement ratio on the maximum bearing capacity of concrete-filled UPVC tubes. Research has typically shown that concrete-filled UPVC tubes have a maximum bearing capacity that increases with an increase in the reinforcement ratio [6–10]. This is so that the concrete core is better contained, increasing the material's strength as well as ability to support loads. Other characteristics, such as tube diameter, thickness, as well as length, may also have an effect on how much the reinforcement ratio can support at maximum bearing capacity [16–20]. In order to identify the best reinforcement tactics for reaching targeted levels of structural performance, studies have looked into the combined effects of these variables.

In order to verify the theoretical predictions as well as numerical simulations about how the reinforcement ratio affects bearing capacity, experimental testing has been carried out [21–25]. In order to study the behaviour of the concrete-filled UPVC tube specimens under axial compression as well as determine their ultimate bearing capacity, these studies load the specimens with varied reinforcement ratios. To sum up, the maximum bearing capacity of UPVC tubes filled with concrete is mostly determined by the reinforcing ratio. Higher bearing capabilities are often the result of raising the reinforcement ratio; however, there may be practical limitations as well as declining returns to exceedingly high reinforcement ratios. To improve the design of reinforcement as well as create useful guidelines for improving the structural performance of UPVC tube columns, more study is required.

IV. SIMULATING AS WELL AS MODELLING FEM

Finite Element Method (FEM) modeling as well as simulation have become essential tools in civil engineering for analyzing as well as predicting the behavior of various structures as well as systems. Engineers rely on FEM to understand how structures respond to different loads, such as gravity, wind, seismic, as well as thermal forces. By simulating stresses, strains, deformations, as well as failure modes, FEM aids in optimizing designs for safety, efficiency, as well as cost-effectiveness. In foundation analysis, FEM assesses factors like settlement, bearing capacity, as well as slope stability, which are critical for designing stable foundations. Geotechnical applications involve modeling complex soil behavior as well as soil-structure interaction to analyze processes like consolidation as well as slope stability. Optimization techniques based on FEM allow engineers to explore different design alternatives as well as find the most efficient as well as cost-effective solutions. Probabilistic analysis using FEM evaluates the risk as well as reliability of structures under uncertain conditions, considering factors like material variability, loading variability, as well as modeling uncertainties. This helps engineers make informed decisions about safety measures as well as design modifications to mitigate risks as well as ensure the long-term performance of structures. Overall, FEM has become an indispensable tool in civil engineering, enabling engineers to design innovative, efficient, as well as resilient structures that meet the demands of modern infrastructure projects. Its versatility as well as accuracy make it a cornerstone of structural analysis as well as design in the field. Moreover, probabilistic analysis using FEM evaluates the risk as well as reliability of structures under uncertain conditions, considering factors such as material variability, loading variability, as well as modeling uncertainties. This helps engineers make informed decisions to enhance safety as well as ensure the long-term performance of structures.

V. RESULT AND DISCUSSION

The examination of compressive strength testing results, as presented in Table 1, offers insights into the performance of various scenarios as well as diameters after seven days. Notably, columns confined with CCC tubes, particularly those with diameters of 110, 160, as well as 220 mm, exhibit superior compressive strength compared to their counterparts, Cu as well as Cc columns. This strength advantage can be attributed to the lateral confinement provided by CCC columns, enhancing their load-bearing capacity. Additionally, the strategic cutting of tube ends aids in confining the concrete effectively. However, for 250 mm diameter columns, the enhancement in compressive strength for CCC columns is less pronounced than for Cc columns, resulting in the latter displaying higher strength. Conversely, Cc columns consistently outperform Cu columns across all diameters due to their comprehensive confinement, distributing the applied load between the concrete as well as PVC tube. Nonetheless, this distribution somewhat compromises the keeping functionality of Cc columns, impacting their load-bearing capacity. Table 2 further quantifies the improvement attributed to PVC tube confinement for both Cc as well as CCC types. The most substantial enhancement, reaching 15% for CCC as well as 8.3% for Cc columns, is observed once the column diameter is 110 mm, with diminishing gains as the diameter increases. This comprehensive analysis sheds light on the nuanced effects of PVC tube confinement on column strength across varying scenarios as well as diameters.

Table 1: Compressive strength after seven days of life

Sample's Radius (mm)	Strength of Cu (MPa)	Strength of Ccc (MPa)
110	10.8	12.41
160	11.1	12.5
220	12.09	13.56
250	13.44	14

Table 2: The compression capacity is increased using PVC tubes after seven days

Sample's Radius (mm)	Improvement Using Cc %	Improvement Using Ccc%
110	8.3	15
160	8.1	12.61
220	6	12.16
250	5	4.16

The assessment of compressive strength results after 28 days, detailed in Table 3 as well as visualized in Figure 1, provides further insight into the performance of different column configurations. Notably, CCC columns consistently exhibit the highest compressive strength across all diameters, outperforming both Cc as well as Cu columns, except for the 250 mm diameter, where Cc columns yield marginally higher strength than CCC columns. Additionally, Table 10 presents the percentage enhancement achieved by using PVC tubes. The highest enhancement, observed at a diameter of 110 mm, reaches 15% for CCC columns as well as 8.3% for Cc columns, with diminishing returns as the diameter increases. Notably, both Tables 8 as well as 10 highlight a consistent enhancement in compressive strength across both seven as well as 28-day curing periods, underscoring the efficacy of PVC tube reinforcement in enhancing the strength of short columns. This comprehensive analysis underscores the role of PVC tube confinement in bolstering the compressive strength of short columns, providing valuable insights into their performance across different scenarios as well as curing periods.

Table 3: Compressive strength after 28 days of age

Sample's Radius (mm)	Strength of Cu (MPa)	Strength of Ccc (MPa)
110	16.62	19.09
160	17.08	19.23
220	18.60	20.86
250	20.68	21.54

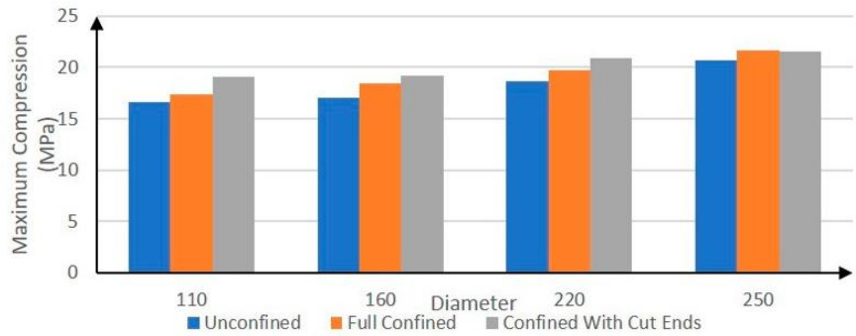

Figure 1: Comparing the compressive strengths of each scenario at 28 days

Table 4: Using PVC tubes to increase compressive strength over a 28-day period

Sample's Radius (mm)	Improvement Using Cc %	Improvement Using Ccc
110	8.3	14.9
160	8.1	12.6
220	6.0	12.2
250	5.0	4.2

The failure modes observed in the specimens, as illustrated in Figure 1, offer valuable insights into the behavior of the tested columns. Of particular significance is the increased confining action observed in cut samples, where the PVC pipe acts solely as a confining element without bearing any compression load. This comprehensive understanding of failure modes provides insight into the mechanisms involved during structural testing as well as highlights the efficiency of PVC tube confinement in improving the performance of short columns.

VI. NUMERICAL ANALYSIS

To ensure accurate simulation, specific parameters as well as mechanisms were established, as depicted in Figure 2a-c. To simulate the compression load on the columns, a load control mechanism utilizing pressure load was implemented. Additionally, Figures 13 as well as 14 illustrated the compression as well as tension damage of concrete, contributing to a comprehensive understanding of its behavior under various loading conditions. This Finite Element (FE) analysis provides valuable insights into the structural response of the columns, complementing experimental observations with detailed numerical simulations.

$$\varepsilon_c = (0.71\ f'c + 168) * 10^{-5}$$

For $0 < \varepsilon < \varepsilon'_0$,

$$\frac{\sigma}{\sigma_u} = 2\frac{\varepsilon}{\varepsilon'_0}\left(1 - \frac{\varepsilon}{2\varepsilon'_0}\right)$$

For $\varepsilon'_0 < \varepsilon < \varepsilon_{cu}$,

$$\frac{\sigma}{\sigma_u} = 1 - 0.15\left(\frac{\varepsilon - \varepsilon'_0}{\varepsilon_u - \varepsilon'_0}\right)$$

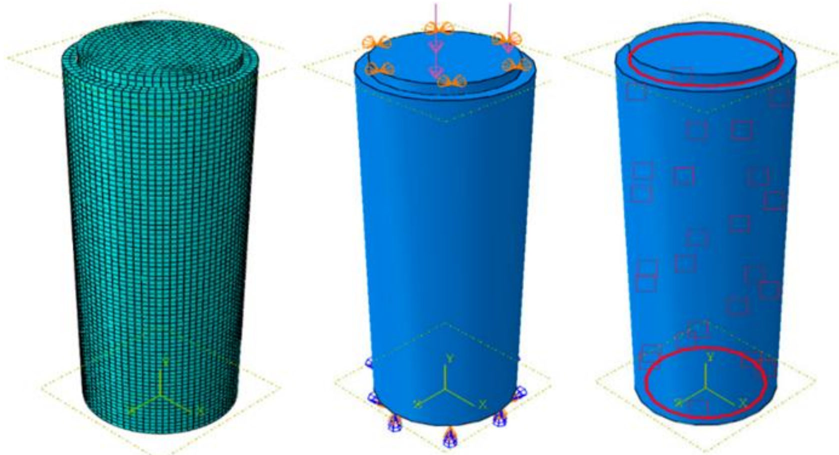

Figure 2: (a) Mesh model of the restricted column with a PVC cut end; (b) boundary conditions and loading; (c) interaction between the concrete's side surfaces and its PVC inner surface

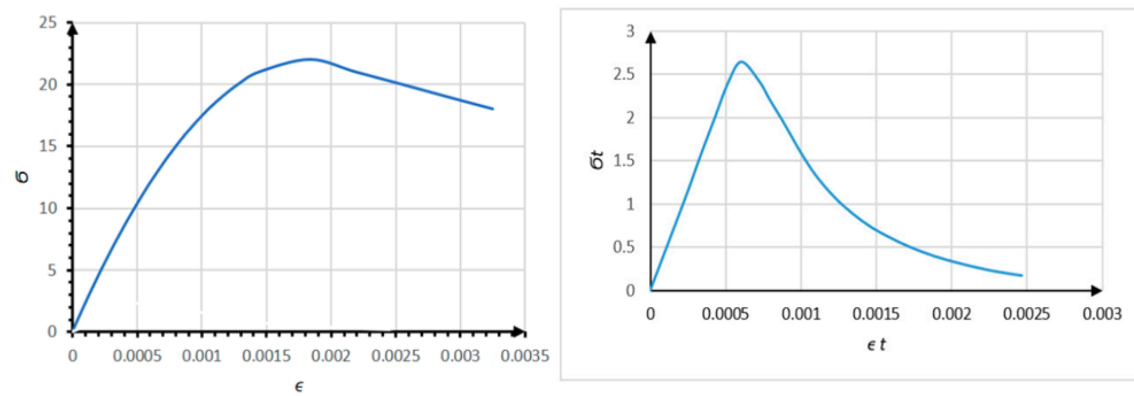

Figure 3: (a) Concrete's compression stress stress-strain curve; (b) Tension stress in concrete: stress-strain relationship

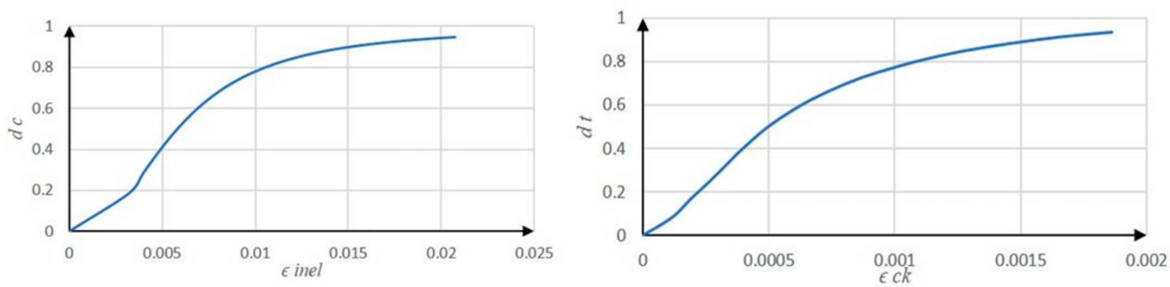

Figure 4: (a) Concrete damage caused by compression; (b) Concrete damage while under tension

The consequences of the numerical examines are summarized in Table, revealing a significant similarity between the numerical as well as experimental results across all diameters. This consistency highlights the reliability as well as accuracy of the finite element (FE) approach in capturing the behavior of the tested columns. The use of such statistical analyses provides valuable insights into the agreement between numerical simulations as well as experimental observations, bolstering confidence in the FE approach as a dependable tool for analyzing the behavior of structural elements.

$$R^2 = 1 - \frac{\sum_{r=1}^{n} (\gamma - \breve{\gamma})^2}{\sum_{r=1}^{n} (\gamma - \bar{\gamma})^2}$$

In Equation (4), γ represents the despicable of the actual compressive strength values, while γ˘ denotes the predicted compressive strength values. Figure displays the distribution of relative errors (RE) for the FE approach across all diameters as well as scenarios, considering all 12 samples combined. The RE ranges from 0.16% to 6%, with only one value falling below 10%. This indicates the FE approach's efficiency in simulating compressive strength, with minimal discrepancies between predicted as well as actual values.

Table 5: The results of the numerical analysis

Sample's Radius (mm)	Strength of Cu (MPa)	Strength of Cc (MPa)	Strength of Ccc (MPa)
110	15.66	16.27	18.42
160	16.77	17.61	18.58
220	18.57	19.56	20.14
250	20.33	21.47	21.42

Moreover, the FE analysis reveals notable findings regarding specimens with a diameter of 250 mm. specifically, it indicates that specimens confined with cut ends exhibit lower load-bearing capacity compared to fully confined specimens. This observation aligns with the experimental results. Furthermore, the failure modes observed in the FE analysis mirror those observed in the experimental testing. Figures 5 illustrate the occurrence of buckling in fully confined samples with a diameter of 110 mm due to their small diameter relative to their length. Similarly, the failure mode observed in unconfined samples begins at the ends before longitudinal cracks develop, consistent with experimental findings. These insights validate the accuracy as well as reliability of the FE approach in predicting the behavior of the tested columns, providing valuable information for structural analysis as well as design.

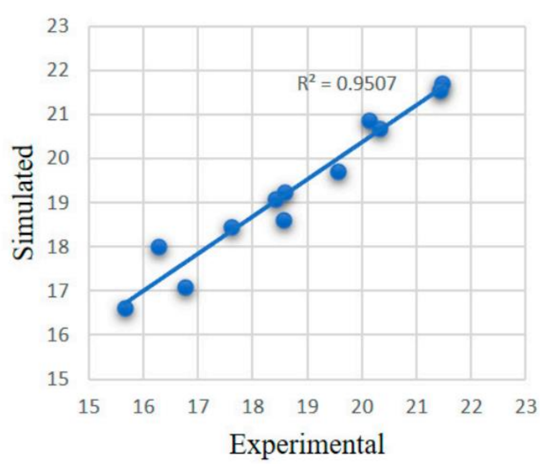

Figure 5: Comparison of the simulated and real data for each scenario's compressive strength

VII. CONCLUSION

This study examines the performance evaluation of PVC tubes for short circular columns using both investigational as well as numerical approaches, while exploring the effects of different confinement strategies on compressive strength. Experimental results across various diameters, confinement methods, as well as testing ages reveal distinct compressive strength values for fully confined, unconfined, as well as cut-ended columns. Confining columns with PVC tubes enhances compressive strength, with fully confined samples showing enhancements of 5% to 8.3%, as well as samples with cut ends exhibiting enhancements between 4.16% as well as 15% relative to column diameter. Notably, columns confined with cut ends display superior compressive strength compared to fully confined ones, except for those with a 250 mm diameter. The enhancement in compressive strength remains consistent at both seven as well as 28-day ages across different diameters as well as confinement methods. Failure modes primarily involve buckling of PVC tubes or shear failure in the concrete core. Moreover, numerical analysis using the Finite Element (FE) approach validates experimental results for compressive strength as well as failure mode. The FE model closely aligns with experimental findings, with a coefficient of determination (R2) of 0.95 as well as a relative error (RE) ranging from 0.16% to 6%. The predicted failure mode by the FE model closely resembles that observed in experiments. To enhance future research, the use of UPVC as a replacement for PVC as well as exploring oval-shaped columns are recommended to further improve performance as well as broaden the study's scope. This survey highlights the significance of PVC tube confinement in enhancing compressive strength as well as offers insights for future research directions. Additionally, a novel stress-strain model within a UPVC tube is proposed, altering traditional models of concrete confined with materials such as steel. The strain at break for short specimens evaluated ranged from 1.25% to 1.70%, with both the 2t/D ratio as well as the h/D ratio impacting the post-peak stress-strain behavior of UPVC-confined concrete. Increasing the 2t/D ratio reduced the slope's absolute value. UPVC confinement significantly improved the columns' ductility as well as energy absorption capabilities, highlighting its potential to improve structural resilience as well as performance.

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