Experimental studies on the behavior of concrete-filled uPVC tubular columns under axial compression loads

Abraham Mengesha Woldemariam1, Walter O. Oyawa2 and Timothy Nyomboi3

Abstract: The behavior of concrete-filled uPVC tubular columns under axial compression loads were studied experimentally by testing columns prepared from five different concrete strength classes. Accordingly, the unconfined, concrete-filled uPVC tube with and without wire-mesh reinforced mortar cover and reinforced concrete columns were evaluated. The main variables considered in this study are concrete strength \( f_{c0} \), uPVC thickness to diameter ratio (2t/D) and aspect ratio (h/D). The effect of uPVC confinement on strength, ductility, energy absorption, and post-peak behavior was explored. Also, a model was developed to predict the peak strength. Results show that the uPVC confinement increased the strength, ductility, and energy absorption in between 1.28–2.35, 1.84–15.3, and 11–243 times the unconfined, respectively. The confinement performed well on increasing the strength, ductility, and energy absorption for lower concrete strength and higher 2t/D ratios. The post-peak behavior of the stress-strain curve was affected by 2t/D and h/D ratios; an abrupt drop in the stress-strain curve was observed in specimens with lower 2t/D and higher h/D ratio. For a given value of concrete strength \( f_{c0} \), tensile strength \( f_y \), thickness (t), diameter (D), and height (h), the stress-strain model

ABOUT THE AUTHORS

Abraham Mengesha Woldemariam is a recent PhD graduate in Civil Engineering (Structural) jointly from the Pan African University (PAUSTI) and Jomo Kenyatta University of Agriculture and Technology, Kenya. His research focuses on composite material and structures, uPVC tube confined concrete, structural reliability, fiber-reinforced polymer, retrofitting, and structural health monitoring.

Walter O. Oyawa (Ph.D.) is Deputy Commission Secretary of Commission for University Education, Kenya. Previously, he was a Professor in the Department of Civil Engineering, JKUAT. His research focuses on composite material, sustainable material, earthquake, structural reliability, finite element, and green building.

Timothy Nyomboi (Ph.D.) is a Manager of Design and Construction of Roads and bridges at Kenya Urban Roads Authority and a Senior Lecturer in the Department of Civil Engineering, PAUSTI. His research focuses on steel fiber reinforced concrete, sustainable material, bridges, composite materials, and highway structures.

PUBLIC INTEREST STATEMENT

Although uPVC tube is durable, ductile, low-cost, light, and resistant to the harsh environment, it is not used as concrete confining material. Very few studies have investigated the effect of uPVC tube confinement on the performance of concrete columns. To fill the gap, the effect of uPVC tube confinement on strength, ductility, energy absorption, and durability of concrete columns were evaluated. The results show that confining a concrete in a uPVC tube increased the strength, ductility, and energy absorption in between 1.28-2.35, 1.84-15.3 and 11-243 times the unconfined, respectively. Therefore, the uPVC tube can be used as a concrete confining material and stay-in-place formwork to improve the structural performance of concrete structures, reduces the duration of construction and avoid the cost incurred for timber and steel formwork.
predicted the peak strength of axially loaded concrete-filled uPVC tube column with a mean absolute error of 2.7%.

**Subjects:** Structural Mechanical Engineering; Reliability & Risk Analysis; Fracture & Damage Mechanics; Composites; Corrosion-Materials Science; Polymers & Plastics; Concrete & Cement; Structural Engineering

**Keywords:** confinement; ductility; energy absorption; strength; stress-strain; uPVC-confined concrete

1. Introduction

There is always a need to find alternative, sustainable material for building, highway structures, and bridges to overcome the drawbacks of conventional concrete and steel. Brittle failure of the concrete structure and its damage to life and property in Africa has been reported for a long period of time. At least 27 reinforced concrete buildings had collapsed in Kenya from 2006-2016 (Fernandez, 2014), 139 in Nigeria from 1978 to 2014 (Basirat et al., 2016) and 11 in Cameroon (Yaoundé & Douala) from 2010 to 2014 (Tchamba & Bikoko, 2015). Most of them are due to brittle failure of the columns causing overlapping of the floors and giving no time for people to scape. Reinforced concrete columns began to fail (collapse) from taking-off the concrete cover, leaving the reinforcement exposed. The exposed reinforcement starts buckling outward followed by concrete-reinforcement bonding fragmentation, which leads to a global collapse of the structures. Also, the waterfront peeling of the reinforced concrete structure has been a challenge to date for engineers. Countries like the U.S spends more than 1 USD billion per year for maintenance, especially for waterfront peeling (Fakharifar & Chen, 2016). Composite materials have been used extensively in the last three decades to improve the performance and avoid the brittle failure of the concrete structures. Extensive studies have been done on different types of confining materials such as steel tube, steel stirrups, FRP stirrups, FRP tubes, FRP rings, FRP shells, hybrid jackets, composite ropes, SMA warp, CFRP, and PVC for application on new structures as well as to strengthen the existing structures (Abdulla, 2017; Alves & Martins, 2009; Boersma & Breen, 2005; Fakharifar & Chen, 2016, 2017; Folkman, 2014; Gathimba et al., 2015; Gupta, 2013; Gupta & Verma, 2014; Kurt, 1978; Lam et al., 2012; Oyawa et al., 2015, 2016; Ranney & Parker, 1995; Shanmugam & Lakshmi, 2001; Woldemariam et al., 2020). Steel- concrete composite material has been one of the most widely used composite materials and has shown superior performance in increasing the load-carrying capacity, ductility, strength, and energy absorption (Lam et al., 2012; Shanmugam & Lakshmi, 2001). In concrete-filled steel tube columns, the concrete resists the vertical load and reduces potential buckling of the steel tube, and the steel tube confines the concrete and avoids sudden brittle failure of concrete (Kurt, 1978). However, the durability issues of steel, RC and steel-concrete composite structures under different environmental exposure have been a challenge. And also, the high cost of steel and the environmental issue (as manufacturing of steel emits a large percentage of carbon dioxide to the environment) has spurred to find alternative materials.

A recent development regarding the use of fiber-reinforced polymer (FRP) as a reinforcement and confinement in the concrete structure has shown a positive result. FRP confinement increased the strength of concrete and reduced the peeling of concrete cover, permeability, and protected the concrete from alkali attacks. However, the lack of material ductility delayed the use of FRP as a reinforcement. In the recent past, ductile failure of plastics (polyvinyl chloride) gained the attention of researchers to use it as a confining material in concrete. Plastics (uPVC tube) have the potential to increase strength, ductility, energy absorption and durability. However, the knowledge on the use of plastic tubes in construction is scattered and lacks information regarding how to design a concrete confined in a plastic tube (Abdulla, 2017; Alves & Martins, 2009). Un-plasticized polyvinyl chloride uPVC is the most commonly used polymer families for plumbing purposes. Unlike polyvinyl chloride (PVC), uPVC is strong, stiff, hard, and doesn’t burn by itself (Abdulla, 2017; Fakharifar & Chen, 2016; Gathimba et al., 2015; Gupta, 2013; Gupta & Verma, 2014; Oyawa et al., 2015, 2016; Woldemariam et al., 2019a). PVC/uPVC has remarkable mechanical
properties. Tests were undertaken to evaluate the durability of the uPVC tube by exposing it into acid, alkaline, and organic compounds. The material performed well under all exposure conditions and has the potential to stay for more than 50 years without deterioration (Abdulla, 2017; Alves & Martins, 2009; Fakharifar & Chen, 2017; Gupta & Verma, 2014; Ranney & Parker, 1995). Experimental investigation on damage initiation, stress deterioration, crack initiation and growth, impact tests, burst, tensile and fatigue of PVC tube has exhibited a remarkable performance that its service life may extend beyond 100 years (Abdulla, 2017; Boersma & Breen, 2005; Breen, 2006; Burn et al., 2006; Folkman, 2014). Also, plastic (uPVC) has a lower thermal conductivity of about 0.45% of a steel tube, which makes it a suitable environment to cure a core concrete compared to steel tube (J. Wang & Yang, 2012; Wang & Yang, 2010).

Previous researches on concrete columns confined by plastic tube have shown a positive result, but the results on strength and ductility were very scattered from one research to another. Confining a concrete in plastic tube increased the strength and ductility of concrete (Fakharifar & Chen, 2016, 2017; Gathimba et al., 2015; Jamaluddin et al., 2017; Oyawa et al., 2016; K. Wang & Young, 2013; Woldemariam et al., 2019b; Xue et al., 2016). Marzoucka and Sennah (2002) evaluated the effect of uPVC confinement on the axial strength of concrete columns by testing concrete-filled uPVC tubular columns under axial compression loads, and the result showed that the strength increased by 11–17% (Marzoucka & Sennah, 2002). In a similar study, the strength and strain of concrete confined by plastic tube increased in between 1.324 to 2.345 and 2.094 to 5.540 times the unconfined, respectively (J. Wang & Yang, 2012). Oyawa et al. (2016) reported a similar finding on the strength of axially loaded uPVC confined concrete stub columns with different uPVC tube diameter, concrete grade, and height to diameter ratio. The strength increased by 1.18 to 3.65 times the unconfined strength. In another study, the axial strength and strain of the PVC tube confined concrete column increased by 168.8 and 147.3% times the unconfined strength, respectively (Saadoon, 2010). Similarly, an increase of over 40% was reported for axial strength and strain of confined concrete columns compared to the unconfined (Jamaluddin et al., 2017). In another study, confining a concrete stub column using a PVC tube has increased the strength by 71.8% (Kurt, 1978). Gupta (2013) evaluated the effect of uPVC diameter and core concrete strength on the strength, ductility, and energy absorption of uPVC tube confined concrete columns. The result showed that the strength, ductility, and energy absorption increased by 1.352 to 2.100, 1.30 to 2.65 and 1.55 to 3.52 times the unconfined, respectively (Gupta, 2013). Also, Gupta and Verma (2014) evaluated the durability of PVC confined RC columns by dipping the specimens into a salt solution, which was 20 times natural seawater. The result showed that the PVC had protected the column from salt-induced deterioration (Gupta & Verma, 2014).

The literature shows that the uPVC confinement improved the structural performance of concrete; however, the findings on strength and ductility are very scattered from one research to another and limited in the scope of the study. The effect of uPVC confinement on energy absorption, failure mode, stress-strain (elastic & inelastic), and post-peak behavior of uPVC confined concrete, and how the uPVC confined concrete undergoes straining for the applied load beyond the elastic state was not fully understood. Therefore, it is necessary to carry out an extensive experimental investigation on strength, ductility, energy absorption, stress-strain relation, and mode of failure. This research work is to investigate the performance of concrete-filled uPVC tubular columns under axial compression loads. It will give a full understanding of tensile properties of uPVC material, load-carrying capacity, strength, ductility, energy absorption, failure mode, stress-strain behavior, and post-peak behavior of uPVC confined concrete.
2. Experiment program

2.1. Materials

Ordinary Portland cement (OPC) power plus 42.5 N conforming to European Norm EN 197–1:2011 (European Standard, 2011), locally available natural sand and crushed stone were used throughout the experiment to prepare five different concrete mixes. The fine and coarse aggregate material characterization were done according to BS standard, and the results are presented in Table 1. The sampling was done according to BS EN 932–1, 1997 (British Standard Institution, 1997). Both the fine and coarse aggregates were graded through sieving and curve plotting according to BS EN 12620: 2013; BS EN 933–1:2012 (British Standard Institution, 2012b) and BS EN 933–2, 1996 (British Standard Institution, 1996).

Un-plasticized polyvinyl chloride (uPVC) pipes produced by Elson plastics ltd. (a company based in Nairobi, Kenya) was used for this research. The tensile and compressive properties of uPVC are also the most important parameters and obtained through testing the specimens according to their respective standards. The tensile strength will be used to calculate the confining pressure and to relate the yield stress of material under multiaxial loading in von Mises stress equation (failure criterion). The specimens were prepared from two different uPVC pipes having a thickness of 3 and 2.5 mm, and designated as uPVC1 and uPVC2, respectively. The tensile property of uPVC material was obtained through a tensile test of dogbone coupon specimens as shown in Figure 1. The test was performed by applying a constant rate of 5 mm/min according to ASTM D638 (ASTM International, 2014); and an average ultimate tensile strength, Young’s modulus of elasticity, poisons ratio, and the stress-strain graph are presented in Table 2 and Figure 2. The compressive strength of the empty uPVC tube was obtained by testing a hollow uPVC specimen under axial compression load. The load-carrying capacity or strength of uPVC pipe is required later to compare the sum of individual load-carrying capacity (concrete + uPVC) with that of uPVC confined concrete. The equivalent cylinder size specimen was prepared by cutting the uPVC into the required size as shown in Figure 3 and tested using a UTM machine at a rate of 0.2MPa/s.

2.2. Concrete mixture proportions

Five different types of concrete mixtures were used to prepare the concrete core in the uPVC confined concrete and were C12/15, C16/20, C20/25, C25/30, & C28/35 (cylinder/cube). The mix designs were prepared based on BS EN 206: 20,134(British Standard Institution, 2013) and BS EN 8500–1/2:2012(British Standard Institution, 2012a). The design values of the constituent material are summarized in Table 3.

2.3. Specimens preparation

The specimens were prepared according to the parameters considered under the study (see Figure 4 and Table 4). First, a total of 60 unconfined and 60 equivalent concrete-filled uPVC tube cylinders with five different concrete strength classes (cylinder/cube: C12/15, C16/20, C20/25, C25/30, & C28/35), five different thickness to diameter ratios (2t/D = 0, 0.043, 0.055, 0.067, & 0.079), and height to diameter ratio of two(h/D = 2) were prepared to investigate the effect of concrete strength and 2t/D ratio of uPVC on the behavior of concrete-filled uPVC tubular cylinders under axial compression.

### Table 1. Fine and coarse aggregate properties

| Test type             | Fine Aggregate | Coarse Aggregate | Standard                  |
|-----------------------|----------------|-----------------|--------------------------|
| Specific gravity      | 2.62           | 2.70            | BS EN 1097–6: 2013       |
| Bulk density          | 1479.96 kg/m3  | 1420 kg/m3      | BS EN 1097–6: 2013       |
| Water absorption      | 2.42%          | 1.34%           | BS EN 1097–6: 2013       |
| Moisture content      | 0.28%          | 1.42%           | BS EN 1097–5 2008        |
| Fineness modulus      | 3.65           |                 |                          |
loads. Second, a total of 24 uPVC confined concrete columns with four different values of aspect ratio (h/D = 2, 4, 6 & 8), thickness to diameter ratio (2t/D = 0.055 & 0.067), and a concrete compressive strength of 25MPa were prepared to investigate the effect of aspect ratio’s (h/D) on

| Parameter                      | Parallel to the Extrusion (1) | Perpendicular to the Extrusion (2) | Variation (%) | Average (1) & (2) |
|-------------------------------|-------------------------------|-----------------------------------|---------------|-------------------|
| Ultimate tensile strength (MPa) | 49.74                        | 50.10                             | 0.72          | 49.92             |
| Young’s Modulus (GPa)         | 3.58                          | 3.61                              | 0.84          | 3.595             |
| Poisson ratio                 | 0.342                         | 0.339                             | 0.88          | 0.3405            |
the behavior of concrete-filled uPVC tubular columns under axial compression loads. Third, a wire-mesh reinforced mortar cover M3 (1:3) was used to cover the uPVC tube from direct exposure to fire. For that, a total of 6 concrete-filled uPVC tube columns having C25 concrete strength, uPVC diameter (D = 110), aspect ratio (h/D = 2 & 4), and outer wire-mesh reinforced mortar cover was prepared.

Fourth, a total of 9 columns (3 plain concrete, 3 reinforced concrete, and 3 concrete-filled uPVC tubes) having C25 concrete strength and aspect ratio (h/D = 4) were prepared to study the effect of uPVC confinement and to compare with reinforced concrete.

The uPVC tubes were prepared by cutting a uPVC through varying the high to diameter ratio (h/D = 2, 4, 6 & 8). The wet concrete mixes were prepared; and accordingly, concrete cubes (BS EN 12,390–2:2009), concrete cylinders (ASTM C39-12 & C496-11), uPVC confined and unconfined concrete columns were cast by filling the wet concrete mix in three layers and compacting till no bubbles were seen on the surface (BS EN 12,390–2:2009). After 24 hours, the specimens were de-molded, labeled, and cured in water for 28 days.

2.4. Specimen labeling
The specimens were labeled based on concrete strength class (C1 = C12/15, C2 = C16/20, C3 = C20/25, C4 = C25/30, & C5 = C28/35), uPVC diameter (P1 = 63 mm, P2 = 90 mm, P3 = 110 mm, & P4 = 140 mm) and height to diameter ratio (H1 = (h/D = 2), H2 = (h/D = 4), H3 = (h/D = 6), and H4 = (h/D = 8); wire-mesh reinforced mortar cover (M); Reinforced concrete (RC). Hence:

- C1H1 means plain concrete column having a concrete strength of C12/15 and aspect ratio of two (h/D=2).
- C1P1H1 means a confined concrete column having a concrete strength of C12/15, the uPVC diameter of 63mm, and an aspect ratio of two (h/D=2).
- MC3P3H1 means a confined concrete column having a concrete strength of C20/25, the uPVC diameter of 100mm, the aspect ratio of two (h/D=2), and wire-mesh reinforced mortar cover.

| Constituent Materials | Cement | Fine aggregate | Coarse aggregate | Total water | W/C ratio |
|-----------------------|--------|----------------|-----------------|-------------|-----------|
| Units                 | Kg/m³  | Kg/m³          | Kg/m³           | Kg/m³      | -         |
| C15                   | 290    | 667            | 1253            | 223        | 0.70      |
| C20                   | 325    | 632            | 1253            | 223        | 0.65      |
| C25                   | 360    | 602            | 1247            | 222        | 0.58      |
| C30                   | 380    | 582            | 1247            | 221        | 0.55      |
| C35                   | 410    | 552            | 1247            | 221        | 0.51      |
| Label   | Concrete Class | Diameter, D (mm) | Thickness of uPVC tube (mm) | Height of the specimens, h (mm) | 2t/D | h/D | Number of specimens |
|---------|----------------|-----------------|-----------------------------|---------------------------------|------|-----|---------------------|
| C1H1    | C15            | 63, 90, 110 and 140 | -                           | 126, 180, 220 and 280           | -    | 2   | 12                  |
| C1P1H1  | C15            | 63              | 2.5                         | 126                             | 0.079| 2   | 3                   |
| C1P2H1  | C15            | 90              | 3                           | 180                             | 0.067| 2   | 3                   |
| C1P3H1  | C15            | 110             | 3                           | 220                             | 0.055| 2   | 3                   |
| C1P4H1  | C15            | 140             | 3                           | 280                             | 0.043| 2   | 3                   |
| C2H1    | C20            | 63, 90, 110 and 140 | 126, 180, 220 and 280       | -                               | 2    | 12  |         |
| C2P1H1  | C20            | 63              | 2.5                         | 126                             | 0.079| 2   | 3                   |
| C2P2H1  | C20            | 90              | 3                           | 180                             | 0.067| 2   | 3                   |
| C2P3H1  | C20            | 110             | 3                           | 220                             | 0.055| 2   | 3                   |
| C2P4H1  | C20            | 140             | 3                           | 280                             | 0.043| 2   | 3                   |
| C3H1    | C25            | 63, 90, 110 and 140 | 126, 180, 220 and 280       | -                               | 2    | 12  |         |
| C3P1H1  | C25            | 63              | 2.5                         | 126                             | 0.079| 2   | 3                   |
| C3P2H1  | C25            | 90              | 3                           | 180                             | 0.067| 2   | 3                   |
| C3P3H1  | C25            | 110             | 3                           | 220                             | 0.055| 2   | 3                   |
| C3P4H1  | C25            | 140             | 3                           | 280                             | 0.043| 2   | 3                   |
| C4H1    | C30            | 63, 90, 110 and 140 | 126, 180, 220 and 280       | -                               | 2    | 12  |         |
| C4P1H1  | C30            | 63              | 2.5                         | 126                             | 0.079| 2   | 3                   |

(Continued)
| Label  | Concrete Class | Diameter, D (mm) | Thickness of uPVC tube (mm) | Height of the specimens, h (mm) | 2t/D | h/D | Number of specimens |
|--------|----------------|-----------------|-----------------------------|---------------------------------|------|-----|-------------------|
| C4P2H1 | C30            | 90              | 3                           | 180                             | 0.067| 2   | 3                 |
| C4P3H1 | C30            | 110             | 3                           | 220                             | 0.055| 2   | 3                 |
| C4P4H1 | C30            | 140             | 3                           | 280                             | 0.043| 2   | 3                 |
| C5H1   | C35            | 63, 90, 110 and 140 | -                          | 126, 180, 220 and 280           | -    | 2   | 12                |
| C5P1H1 | C35            | 63              | 2.5                         | 126                             | 0.079| 2   | 3                 |
| C5P2H1 | C35            | 90              | 3                           | 180                             | 0.067| 2   | 3                 |
| C5P3H1 | C35            | 110             | 3                           | 220                             | 0.055| 2   | 3                 |
| C5P4H1 | C35            | 140             | 3                           | 280                             | 0.043| 2   | 3                 |
| C3P2H2 | C25            | 90              | 3                           | 360                             | 0.067| 4   | 3                 |
| C3P2H3 | C25            | 90              | 3                           | 540                             | 0.067| 6   | 3                 |
| C3P2H4 | C25            | 90              | 3                           | 720                             | 0.067| 8   | 3                 |
| C3P3H2 | C25            | 110             | 3                           | 440                             | 0.055| 4   | 3                 |
| C3P3H3 | C25            | 110             | 3                           | 660                             | 0.055| 6   | 3                 |
| C3P3H4 | C25            | 110             | 3                           | 880                             | 0.055| 8   | 3                 |
| MC3P3H1| C25            | 110             | 3                           | 220                             | 0.055| 2   | 3                 |
| MC3P3H2| C25            | 110             | 3                           | 440                             | 0.055| 4   | 3                 |
| C2H2   | C20            | 140             | -                           | 560                             | -    | 4   | 3                 |
| C2P4H2 | C20            | 140             | 3                           | 560                             | 0.043| 4   | 3                 |
| RC2H2  | C20            | 140             | -                           | 560                             | 0.043| 4   | 3                 |
- RC3H2 means RC columns having a concrete strength of C20/25, reinforcing steel, and an aspect ratio of two (h/D=4).

2.5. Instrumentation, test setup, and loading program
On day 28, the specimens were brought out from the water, and the two sides of the confined columns were smoothened using a concrete cutting machine to avoid a local buckling of the uPVC tube at the edge, and allowed to dry prior to testing. All the specimens (concrete cubes, concrete cylinders, uPVC confined concrete columns) were tested on the same day. The test was performed using a compression Machine (Servo-Plus Evolution Control Unit), which has a capacity of 2000kN with a load rate control system and a testing frame with hydraulic loading jack (a load-controlled mechanism) (see Figure 5). Also, a load cell, transducers and strain gages connected to TDS-630 Datalogger were used to capture the measurements as shown in Figure 5. The instrumentation was done by placing two strain gauges on the specimens to measure axial and lateral strains. The specimen was placed in between the two flattens of the compression testing machine, and also in between the upper and lower beam of the testing frame. Two LVDTs (Linear variable differential transducers) were placed vertically pointing to the moving plate of the machine to measure the axial deformation. Then, the strain gauges, load cells, and LVDTs were connected to TDS-630 data logger. The load was applied to the specimen at the rate of 0.2MPa/s till failure. The data were recorded both from the compression machine (Load-time data, Max. Load & Max. Strength) and TDS-630 Datalogger (time, Load, axial strain, radial strain, & displacement).

3. Results and discussions
3.1. Load-deformation
For unconfined concrete, the axial deformation was very small, accompanied by a brittle failure after reaching a peak load. The load-carrying capacity increased from a minimum of 12% to a maximum of 65% for uPVC confined equivalent cylinder having an aspect ratio of two (h/D = 2) and four different confinements to concrete ratio (2t/D). The confinement performed well for lower concrete strength, increasing the load-carrying capacity up to 65% as shown in Figure 6. The deformation for the tested specimens of uPVC confined concrete columns increased substantially compared to the unconfined columns. At a failure loading, the deformation increased from less than 1 mm for unconfined to a maximum of 28 mm for uPVC confined. Figure 7 shows a sample load-deformation curve of concrete-filled uPVC tube equivalent cylinder. For lower aspect ratios (h/D = 2 & 4), the concrete-filled uPVC tube column undergone only axial deformation, whereas specimens with an aspect ratio (h/D = 6 & 8) undergone single and double curvature at a peak load.
as shown in Figure 9. The specimen with uPVC confinement had undergone high deformation after reaching the peak (maximum) load resulting in a ductile failure. The minimum deformation at a failure load registered was 4.7 mm which is by far more than the unconfined concrete (<1 mm). The deformations of all confined concrete cylinders from the peak to failure load were more than 53% of the total deformation, and whereas less than 19% for the unconfined concrete cylinder. When the unconfined concrete columns were loaded beyond the elastic limit, the crack propagated very fast, allowing the columns to undergo sudden and brittle failure. For confined concrete columns, the uPVC tube confinement restrained the crack propagation and the concrete from dilating laterally, allowing the concrete to carry additional loads and undergo ductile failure.

3.2. Failure modes and patterns
The failure modes observed for uPVC confined concrete columns under axial compression loads were a drum-type, shear-type (rarely observed), and buckling type failure, as shown in Figures 8 and 9. The hollow uPVC tube failed through local buckling inward and outward under axial compression loads. At a confined state, the uPVC was restrained by concrete from local buckling. Unlike steel, no local buckling of the uPVC tube was seen at an early stage of loading because of the lower Young’s modulus elasticity of uPVC. For a uPVC confined concrete specimens, at about
90% to 100% of the peak load, the uPVC starts changing the color from grey to whitish-grey in the middle of the specimen and further developing bumps and strips on the surface. The color change was due to the yielding and elongation of the uPVC pipe. The change in color was dependent on the thickness of the uPVC pipe. The more the thick, the later the change in color or no change in color depending on the strength of the concrete. Failure modes observed were drum, shear and buckling type failure, which were dependent on the failure mode of the concrete core. The drum type failure occurred due to the expanding of the concrete core at the middle resulting from cone type failure, and the shear-type failure occurred due to shear failure of the concrete core. For specimen with a higher aspect ratio (h/D = 6 & 8) in Figure 9(a), a buckling failure with single and double curvature was observed. The uPVC along and around the crack of core concrete has undergone color change, which shows much elongation and plastic deformation of the uPVC tube around the cracked region. In addition to the color change, the specimen developed a pump along the direction of the crack. For a specimen with wire-mesh reinforced mortar Figure 9(b), the delamination of the cover started at about 70% of the peak load.

3.3. Confinement effectiveness
The confinement effectiveness is the measure of how the uPVC pipe confines the concrete. It is the ratio of uPVC confined concrete strength to the unconfined concrete strength \( \left( f_{cc}/f_{co} \right) \). The effectiveness increased as the 2t/D ratio increases and decreased as the concrete strength increases, as shown in Table 5 and Figure 10. For different 2t/D ratio of the equivalent cylinder (h/D = 2), the confinement effectiveness decreased from a maximum of 2.35 to a minimum of 1.28 as the core concrete strength increased from C15 to C35. Similar researches made by Oyawa et al. (2016) showed that the confinement effectiveness ranged between 1.18 & 3.65 for different concrete strength and pipe sizes.
| Label | D (mm) | t (mm) | $f_a$ (MPa) | $f_c$ (MPa) | $\epsilon_{co}$ (mm/mm) | $\epsilon_{cc}$ (mm/mm) | $\epsilon_{1}$ (mm/mm) | $\epsilon_{cr}$ (mm/mm) | $f_{cc}$ (MPa) | $\mu_{cr}$ | $E$ (MJ/m$^3$) | $W_a$ | $\frac{W_a}{f_{cc}}$ |
|-------|--------|--------|-------------|-------------|-------------------------|-------------------------|-------------------------|-------------------------|-----------------|-----------|----------------|-------|-----------------|
| C1    | 63     | 2.5    | 24.38       | 0.0183      | 0.014                    | 0.014                    | 2.356                   | 8.946                    | 4.397           | 3.192     | 13.350         | 6.500 | 1.000           |
| C1P1H1| 63     | 2.5    | 27.47       | 0.0133      | 0.0085                  | 0.0065                   | 1.992                   | 5.217                    | 4.397           | 3.111     | 7.647           | 1.221 | 10.461          |
| C1P2H1| 90     | 3      | 26.80       | 0.0181      | 0.008                   | 0.014                    | 1.943                   | 7.115                    | 3.643           | 3.570     | 18.250         | 3.134 | 29.235          |
| C1P3H1| 110    | 3      | 24.93       | 0.0184      | 0.0095                  | 0.13                     | 1.808                   | 7.216                    | 2.942           | 3.786     | 13.684         | 1.779 | 15.023          |
| C1P4H1| 140    | 3      | 23.76       | 0.0147      | 0.0090                  | 0.04                     | 1.722                   | 5.778                    | 2.284           | 4.363     | 4.444           | 0.636 | 5.951           |
| C2    | 66.89  | 0.0029 | 1.992       | 5.217       | 4.397                   | 3.111                    | 7.647                   | 1.221                    | 10.461          | 44.113    | 64.266          | 5.951 | 22.980          |
| C2P1H1| 63     | 2.5    | 28.72       | 0.0138      | 0.0055                  | 0.056                    | 1.700                   | 4.826                    | 4.397           | 2.691     | 10.182          | 1.230 | 15.570          |
| C2P2H1| 90     | 3      | 28.48       | 0.0161      | 0.00525                 | 0.0745                   | 1.686                   | 5.635                    | 3.643           | 3.181     | 14.190          | 1.744 | 23.334          |
| C2P3H1| 110    | 3      | 26.99       | 0.0098      | 0.00325                 | 0.0515                   | 1.598                   | 3.433                    | 2.942           | 3.432     | 15.846          | 1.138 | 25.949          |
| C2P4H1| 140    | 3      | 24.57       | 0.0094      | 0.005                   | 0.065                    | 1.454                   | 3.316                    | 2.284           | 3.361     | 13.000          | 1.110 | 18.066          |
| C3    | 16.89  | 0.0029 | 1.896       | 0.038       | 0.0017                  | 0.033                    | 1.896                   | 0.038                    | 0.0017          | 0.033    | 1.896           | 0.038 | 0.0017          |
| C3P1H1| 63     | 2.5    | 28.72       | 0.0138      | 0.0055                  | 0.056                    | 1.700                   | 4.826                    | 4.397           | 2.691     | 10.182          | 1.230 | 15.570          |
| C4    | 20.13  | 0.0031 | 1.885       | 0.054       | 0.0019                  | 0.035                    | 1.885                   | 0.054                    | 0.0019          | 0.035    | 1.885           | 0.054 | 0.0019          |
| C4P1H1| 63     | 2.5    | 32.13       | 0.0159      | 0.004                   | 0.1155                   | 1.596                   | 5.227                    | 4.397           | 2.727     | 28.875          | 3.122 | 48.599          |
| C4P2H1| 90     | 3      | 30.68       | 0.0221      | 0.0065                  | 0.104                    | 1.524                   | 7.239                    | 3.643           | 2.895     | 16.000          | 2.465 | 24.720          |
| C4P3H1| 110    | 3      | 29.66       | 0.0129      | 0.006                   | 0.065                    | 1.473                   | 4.225                    | 2.942           | 3.238     | 10.833          | 1.477 | 16.602          |
| C4P4H1| 140    | 3      | 28.01       | 0.0072      | 0.0035                  | 0.031                    | 1.391                   | 2.373                    | 2.284           | 3.449     | 8.857           | 0.634 | 12.933          |

(Continued)
Table 5. (Continued)

| Label | D (mm) | t (mm) | $f_a$ (MPa) | $f_s$ (MPa) | $\varepsilon_a$ (mm/mm) | $\varepsilon_s$ (mm/mm) | $\varepsilon_1$ (mm/mm) | $\varepsilon_c$ (mm/mm) | $\varepsilon_{cr}$ (mm/mm) | $k_1$ | $\mu_0$ | $E$ (MJ/m$^3$) | $W_o$ | $\frac{E}{\mu_0}$ |
|-------|--------|--------|-------------|-------------|-------------------------|-------------------------|------------------------|------------------------|------------------------|------|--------|----------------|------|-------------|
| C5    |        |        | 24.12       | 0.0033      | 0.0020                  | 0.0037                  |                        |                        |                        |      |        |                |      |             |
| C5P1H1| 63     | 2.5    | 34.73       | 0.0097      | 0.0035                  | 0.0645                  | 1.440                  | 2.983                  | 4.397                  | 2.412 | 18.429   | 1.556         | 25.613| 24.497      |
| C5P2H1| 90     | 3      | 34.31       | 0.0154      | 0.007                   | 0.058                   | 1.423                  | 4.726                  | 3.643                  | 2.798 | 8.286    | 1.460         | 12.161| 22.987      |
| C5P3H1| 110    | 3      | 32.77       | 0.0186      | 0.0045                  | 0.05475                 | 1.358                  | 3.640                  | 2.942                  | 2.939 | 12.167   | 1.419         | 27.834| 32.297      |
| C5P4H1| 140    | 3      | 30.87       | 0.0080      | 0.00325                 | 0.037                   | 1.280                  | 2.451                  | 2.284                  | 2.955 | 11.385   | 0.697         | 13.894| 10.968      |

Note: C1 = C15, C2 = C20, C3 = C25, C4 = C30, C5 = C35, P1 = D = 63 mm, P2 = D = 90 mm, P3 = D = 110 mm, P4 = D = 140 mm, & H1 = h/D = 2, where “D” is diameter and “h” is height.
3.4. Effect of Core concrete strength, 2t/D and h/D
As shown in Figures 11 and 13, the strength of uPVC confined concrete increased as 2t/D ratio increased and decreased linearly as the aspect ratio (h/D) increased. The uPVC confinement increased the strength for all five classes of concrete used in this research; however, it showed a decreasing rate as the core concrete strength increased, as shown in Figure 12. For concrete confined in a 63 mm diameter uPVC tube prepared from C15, C20, C25, C30, & C35, the strength increased by 135, 99, 70, 59, & 43% respectively. Similarly, the strength increased by 123, 94, 68, 52, & 42%, 113, 80, 60, 47, & 37% and 103, 72, 45.5, 40, & 28% for 90, 100 & 140 mm uPVC tube confinement respectively.

3.5. Concrete-filled uPVC tubular columns with wire-mesh reinforced mortar cover
The wire-mesh reinforced mortar cover was provided to avoid the uPVC from direct exposure to fire. In Figure 14, the result on peak strength of unconfined and uPVC tube confined with and
without wire-mesh reinforced mortar were presented. The wire-mesh reinforced mortar does not contribute to strength; the strength remains dependent on $2t/D$ and $h/D$. For the specimen with wire-mesh reinforced mortar, at about 70 to 85% of the peak load, the delamination or peeling of the cover started and continued till failure (see Figure 15). After the load reaches the peak, the specimens with aspect ratio less than or equal to four ($h/D \leq 4$) have started undergoing drum and shear-type failure and whereas the specimens with aspect ratio above four ($h/D > 4$) have started undergoing buckling and shear-type failure. The drum and buckling type failure were the most prevalent mode of failure, and whereas shear type failure was a rarely seen failure mode.

3.6. Comparison of plain concrete, RC and confined strength

Plain concrete, concrete-filled uPVC tube, and Reinforced concrete circular column were prepared and tested to compare the strength. The concrete strength and reinforcement used to prepare the specimens were C20 concrete, $5\phi10$ mm longitudinal steel, and stirrup of $\phi6$ mm @ 130 mm spacing, as shown in Figure 4. The results in Figure 16 shows, RC and concrete-filled uPVC columns have similar strength, but high ductility was observed on concrete-filled uPVC tube columns.
3.7. Stress-strain behavior

The stress-strain behavior of unconfined and confined concrete columns are presented in Figures 17, 18, 19, 20 and 21. For unconfined specimen, a brittle failure was observed; the maximum strain recorded at failure load is 0.00376. The strain measured from the peak to the failure load was less than 19% of the total strain. The concrete crack propagated very fast when the unconfined concrete columns were loaded beyond the elastic limit, which caused the columns to undergo sudden and brittle failure. For specimens confined in a uPVC tube, no brittle failure was observed; the specimens underwent high deformation compared to the unconfined. The uPVC tube confinement restrained the crack propagation and the concrete from dilating laterally, allowing the concrete to carry additional loads and undergo ductile failure. Also, the peak strength decreased as the aspect ratio \((h/D)\) increased, which was due to the slenderness effect. For lower aspect ratio \(h/d = 2\) of concrete-filled uPVC tubular columns, high deformation was observed; the strain measured from the peak to failure load was more than 53%. The aspect ratio significantly affected the post-peak behavior; a gradual drop in the stress-strain curve was observed for lower aspect ratio (see Figure 18). For higher aspect ratios \((h/D \geq 4)\), an abrupt drop in the stress-strain curve was observed (see Figures 19, 20 and 21).
3.7.1. Ductility

Ductility is the ability of the material to undergo inelastic deformation before failure. It is determined by the ratio of the strain at fracture (or strain at the inelastic yield strength demand) to strain at maximum elastic strength (Cui & Sheikh, 2010; Najdanović & Milosavljević, 2014; Wu, 2004; Zhong et al., 2012). Both the unconfined and confined ductility factors were calculated using the expression given in Equation (1) and stress-strain response parameters in Figure 22. The ductility factor was used to study the deformation of the tested specimens, and the results were presented in Tables 5 and 6. The unconfined concrete column suddenly ruptured after reaching the peak load, but the brittle failure was compensated by uPVC confinement. The ductility index was much affected by 2t/D and h/D ratio’s; the specimens with higher 2t/D and lower h/D had higher ductility factor. For a confined specimen with h/D = 2, the ductility factor increased by 1.84–15.3 times the unconfined. Apart from the ductility factor, an increase of peak strain from uPVC confinement was observed due to the delay of core concrete cracking and lateral expansion. For

![Figure 16. Axial comp. strength of plain, concrete-filled uPVC tube and RC column.](image1)

![Figure 17. Stress-Strain graph of the unconfined concrete cylinder for C25.](image2)
uPVC confined concrete, a brittle failure was not observed; the confinement helped the specimen to undergo ductile deformation and stay for a prolonged period of time.

$$\mu_{cf} = \frac{\varepsilon_{cr}}{\varepsilon_1}$$  \hspace{1cm} (1)

3.7.2. Energy absorption capacity

Energy absorption is the toughness of the material measured from the stress-strain data. It is the area under a stress-strain curve and measured using the expression given in Equation (2). Energy absorption was reported in different ways depending on the strain value chosen to end the
integration (Cui & Sheikh, 2010; Karabinis & Rousakis, 2002; Wang, 2014; Wu, 2004; Zhang et al., 2012). In this study, the energy absorption per volume at 100% strain (ultimate toughness) was calculated for both confined and unconfined specimens, as shown in Tables 5 and 6. OriginPro data analysis software was used to calculate the area under the stress-strain graph, as shown in Figure 23. The uPVC confinement increased energy absorption capacity. For an aspect ratio of $h/D = 2$, the ratio of confined to unconfined energy absorption per volume ($E_C / E_U$) increased from 10.968 to 243.145 times the unconfined.

$$E = \int d\sigma d\varepsilon$$  \hspace{1cm} (2)
3.7.3. Work index
The work index is the material capability to undergo straining for the applied load beyond the elastic state. The work index is evaluated by the ratio of the total area under the stress-strain curve until failure to the area of the stress-strain curve under the elastic region, Equation (3). For confined specimens of aspect ratio two (h/D = 2), the calculated work index value ranged from 10.97 to 48.599 and whereas 2.65 to 2.884 for unconfined specimens as shown in Tables 5 and 6. The confinement effect of delaying the core concrete cracking and lateral expansion of the post-elastic region improved the inelastic resistance of concrete-filled uPVC tube column.

\[ W_{cr} = \frac{E}{E_1} = \frac{E}{2(f_{cc} + \varepsilon_1)} = \frac{2E}{(f_{cc} + \varepsilon_1)} \]  

(3)

3.8. Analytical equations on peak strength and strain
The analytical expression for confined concrete that relates the tensile strength and thickness of the confining material, core concrete strength, and the diameter in Equation (4) was developed for the first time in 1928 (Richart et al., 1928). This expression was later modified by many researchers for different types of confining material. The peak strength of concrete-filled uPVC tube columns were dependent on the uPVC thickness to diameter ratio (see Figure 26), core concrete strength (see Figure 26), and aspect ratio (h/D) (see Figure 25). For a circular cross-section, the lateral confining pressure is uniformly distributed on the perimeter.

\[ f_{cc} = f_{co} + k_1 f_l \]  

(4)

Where \( f_l = \frac{2\pi f_t}{\pi^2 D^2} \); \( f_t \) is lateral confining pressure; \( f_c \) is tensile strength of uPVC tube; \( k_1 \) is the confinement coefficient; \( D \) is the diameter of a confined cylinder; \( t \) is the thickness of the uPVC tube as shown in Figure 24.

For concrete confined by steel, Richart et al. (1928) assumed a constant value of 4.1 for \( k_1 \) in Equation (4). This value was later modified by many researchers for different types of confining material. Balmer (1949) found \( k_1 \) value varied between 4.5 and 7 and suggested to use the average value of 5.6 (Balmer, 1949). Although many researchers came up with their own \( k_1 \) values and models, it is found that the models are unable to predict the ultimate strength of concrete confined by different materials (Toutanji & Saafi, 2002). In this research, the value of \( k_1 \) for each specimen was calculated by using Equation (4) for \( f_{co} \) and \( f_{cc} \) values obtained from the experiment.
| Label   | D(mm) | t (mm) | h/D | 2t/D | $f_{co}$ (MPa) | $f_{cc}$ (MPa) | $\varepsilon_{co}$ (mm/mm) | $\varepsilon_{cc}$ (mm/mm) | $\varepsilon_{1}$ (mm/mm) | $\varepsilon_{cr}$ (mm/mm) | $f_{cr}$ (MPa) | $k_{1}$ | $\mu_{cr}$ | $E$ (MJ/m$^3$) | $W_{cr}$ |
|---------|-------|--------|-----|------|----------------|----------------|--------------------------|--------------------------|----------------|----------------|-------------|--------|-------------|----------------|-------|
| C3P2H1-1 | 90    | 3      | 2   | 0.067 | 16.89 | 28.48 | 0.003                        | 0.003                     | 0.067                       | 0.067                  | 5.754 | 3.643       | 3.181          | 22.333 | 1.603       | 37.534        |       |
| C3P2H1-2 | 90    | 3      | 2   | 0.067 | 16.89 | 29.01 | 0.003                        | 0.003                     | 0.082                       | 0.082                  | 4.945 | 3.643       | 3.327          | 27.333 | 1.885       | 43.326        |       |
| C3P2H1-3 | 90    | 3      | 2   | 0.067 | 16.89 | 27.95 | 0.003                        | 0.010                     | 0.075                       | 0.075                  | 4.923 | 3.643       | 3.036          | 7.692  | 1.750       | 12.843        |       |
| C3P2H2-1 | 90    | 3      | 4   | 0.067 | 16.89 | 26.25 | 0.003                        | 0.010                     | 0.025                       | 0.025                  | 3.203 | 3.643       | 2.569          | 8.929  | 0.400       | 10.884        |       |
| C3P2H2-2 | 90    | 3      | 4   | 0.067 | 16.89 | 24.99 | 0.003                        | 0.013                     | 0.025                       | 0.025                  | 4.009 | 3.643       | 2.223          | 6.533  | 0.552       | 11.786        |       |
| C3P2H2-3 | 90    | 3      | 4   | 0.067 | 16.89 | 25.94 | 0.003                        | 0.013                     | 0.030                       | 0.030                  | 3.846 | 3.643       | 2.484          | 9.375  | 0.610       | 14.697        |       |
| C3P2H3-1 | 90    | 3      | 6   | 0.067 | 16.89 | 22.79 | 0.003                        | 0.014                     | 0.014                       | 0.014                  | 4.154 | 3.643       | 1.619          | 13.900 | 0.233       | 20.460        |       |
| C3P2H3-2 | 90    | 3      | 6   | 0.067 | 16.89 | 24.13 | 0.003                        | 0.016                     | 0.025                       | 0.025                  | 4.849 | 3.643       | 1.987          | 16.733 | 0.502       | 27.754        |       |
| C3P2H3-3 | 90    | 3      | 6   | 0.067 | 16.89 | 23.26 | 0.003                        | 0.015                     | 0.029                       | 0.029                  | 4.462 | 3.643       | 1.748          | 18.063 | 0.632       | 33.969        |       |
| C3P2H4-1 | 90    | 3      | 8   | 0.067 | 16.89 | 20.75 | 0.003                        | 0.035                     | 0.050                       | 0.050                  | 10.769 | 3.643       | 1.059          | 2.000  | 0.602       | 2.320         |       |
| C3P2H4-2 | 90    | 3      | 8   | 0.067 | 16.89 | 21.85 | 0.003                        | 0.010                     | 0.010                       | 0.010                  | 3.077 | 3.643       | 1.361          | 1.282  | 1.175       | 13.794        |       |
| C3P2H4-3 | 90    | 3      | 8   | 0.067 | 16.89 | 20.81 | 0.003                        | 0.031                     | 0.050                       | 0.050                  | 9.538 | 3.643       | 1.076          | 61.111 | 0.652       | 6.966         |       |
| C3P3H1-1 | 110   | 3      | 2   | 0.055 | 16.89 | 26.30 | 0.003                        | 0.010                     | 0.039                       | 0.039                  | 3.077 | 2.942       | 3.198          | 9.750  | 0.897       | 17.048        |       |
| C3P3H1-2 | 110   | 3      | 2   | 0.055 | 16.89 | 27.16 | 0.003                        | 0.010                     | 0.064                       | 0.064                  | 2.923 | 2.942       | 3.490          | 25.600 | 1.379       | 40.631        |       |
| C3P3H1-3 | 110   | 3      | 2   | 0.055 | 16.89 | 27.50 | 0.003                        | 0.010                     | 0.052                       | 0.052                  | 3.046 | 2.942       | 3.606          | 15.846 | 1.381       | 30.908        |       |
| C3P3H2-1 | 110   | 3      | 4   | 0.055 | 16.89 | 23.63 | 0.003                        | 0.033                     | 0.100                       | 0.100                  | 10.178 | 2.942       | 2.290          | 16.667 | 1.991       | 28.080        |       |
| C3P3H2-2 | 110   | 3      | 4   | 0.055 | 16.89 | 24.59 | 0.003                        | 0.013                     | 0.018                       | 0.018                  | 4.000 | 2.942       | 2.617          | 7.200  | 0.370       | 12.043        |       |
| C3P3H2-3 | 110   | 3      | 4   | 0.055 | 16.89 | 24.23 | 0.003                        | 0.014                     | 0.020                       | 0.020                  | 4.246 | 2.942       | 2.494          | 4.878  | 0.412       | 8.284         |       |
| C3P3H3-1 | 110   | 3      | 6   | 0.055 | 16.89 | 23.15 | 0.003                        | 0.018                     | 0.066                       | 0.066                  | 5.397 | 2.942       | 2.127          | 10.967 | 0.248       | 3.575         |       |
| C3P3H3-2 | 110   | 3      | 6   | 0.055 | 16.89 | 22.46 | 0.003                        | 0.015                     | 0.061                       | 0.061                  | 4.622 | 2.942       | 1.893          | 30.535 | 1.175       | 52.335        |       |

(Continued)
Table 6. (Continued)

| Label       | D (mm) | t (mm) | h/D | 2t/D | f<sub>co</sub> (MPa) | f<sub>cr</sub> (MPa) | ε<sub>co</sub> (mm/mm) | ε<sub>cc</sub> (mm/mm) | ε<sub>1</sub> (mm/mm) | ε<sub>cr</sub> (mm/mm) | k<sub>r</sub> | E (MJ/m<sup>3</sup>) | W<sub>cr</sub> |
|-------------|--------|--------|-----|------|-------------------|-------------------|------------------|------------------|------------------|------------------|--------|----------------|----------|
| C3P3H3-3   | 110    | 3      | 6   | 0.055| 21.99            | 0.003             | 0.014            | 0.004            | 0.035            | 4.215            | 1.733  | 10.000        | 0.326    | 8.471          |
| C3P3H4-1   | 110    | 3      | 8   | 0.055| 20.98            | 0.003             | 0.015            | 0.005            | 0.020            | 4.714            | 1.390  | 3.922         | 0.316    | 5.909          |
| C3P3H4-2   | 110    | 3      | 8   | 0.055| 20.27            | 0.003             | 0.019            | 0.006            | 0.077            | 5.763            | 1.148  | 14.000        | 1.268    | 22.744         |
| C3P3H4-3   | 110    | 3      | 8   | 0.055| 18.62            | 0.003             | 0.017            | 0.005            | 0.086            | 5.292            | 2.942  | 16.226        | 1.293    | 26.206         |
| MC3P3H1-1  | 110    | 3      | 2   | 0.055| 24.44            | 0.003             | 0.017            | 0.006            | 0.097            | 5.329            | 2.942  | 16.195        | 1.862    | 25.390         |
| MC3P3H1-2  | 110    | 3      | 2   | 0.055| 24.75            | 0.003             | 0.012            | 0.006            | 0.072            | 3.794            | 2.942  | 13.005        | 1.246    | 18.300         |
| MC3P3H1-3  | 110    | 3      | 2   | 0.055| 24.59            | 0.003             | 0.014            | 0.008            | 0.054            | 4.218            | 2.942  | 7.197         | 0.989    | 10.739         |
| MC3P3H2-1  | 110    | 3      | 4   | 0.055| 24.08            | 0.003             | 0.018            | 0.008            | 0.058            | 5.483            | 2.942  | 7.250         | 0.960    | 9.966          |
| MC3P3H2-2  | 110    | 3      | 4   | 0.055| 23.50            | 0.003             | 0.011            | 0.004            | 0.046            | 3.277            | 2.942  | 13.031        | 0.701    | 17.050         |
| MC3P3H2-3  | 110    | 3      | 4   | 0.055| 22.57            | 0.003             | 0.015            | 0.005            | 0.054            | 4.471            | 2.942  | 10.712        | 0.899    | 15.927         |
and the lateral confining pressure ($f_l$) calculated for each specimen using the equilibrium conditions. As it is shown in Table 5, Figures 27 and 28, it is found that the value of $k_1$ decreased as the core concrete strength increased; and increased as the $2t/D$ ratio decreased. $k_1$ is dependent on both the concrete strength ($f_{co}$) and $2t/D$ ratio. Thus, a regression analysis was done by fitting $f_{co}$ vs $k_1$ and $2t/D$ vs $k_1$ where $k_1$ was defined as a function of $f_{co}$ and $2t/D$. The expressions from the regression analysis were combined to give an expression for $k_1$ in Equation (5).

$$k_1 = \frac{2.7}{(f_{co})^{0.394}(2t/D)^{0.453}}$$  \hspace{1cm} (5)

Substituting Equation (5) to Equation (4), the strength of uPVC tube confined concrete with an aspect ratio of two ($h/D = 2$) can be expressed in Equation (6).

$$f_{cc} = f_{co} + \frac{2.7f_l}{(f_{co})^{0.394}(2t/D)^{0.453}}$$ \hspace{1cm} (6)

As the aspect ratio ($h/D$) increases from 2 to 8, the peak strength decreased (see Figure 25 and Table 6). The results on two different $2t/D$ and four $h/D$ ratios used to define the relation of uPVC confined concrete. The strength for specimens with an aspect ratio of two ($h/D = 2$) can be calculated by Equation (6), for concrete class (C25) confined by 90 and 110 mm uPVC pipe, and the strength calculated by Equation (6) were equivalent to 28.5 and 27 MPa, respectively. A regression analysis was done by fitting ($h/D - 2$) vs $f_{cc}$ data where an expression for $f_{cc}$ in
Equation (7) and Equation (8) as a function of h/D were obtained for concrete confined by two different sizes of pipe.

\[ f_{cc(P2)} = -1.2481 \left( \frac{h}{D} - 2 \right) + 28.5 \]  \hspace{1cm} (7)

\[ f_{cc(P3)} = -1.1755 \left( \frac{h}{D} - 2 \right) + 27 \]  \hspace{1cm} (8)
From the above equation, the two constants were equal to the peak strength of (p = 90 & 110 mm) uPVC confined concrete with h/D = 2. The coefficients (coef1 = −1.2481 & coef2 = −1.1755) are only dependent on 2t/D or f_l values. Hence, \( \text{coef} = -0.869(f_l)^{0.28} \).

The general equation in Equation (9) was developed by combining Equation (6), Equation (7), and Equation (8).

\[
f_{cc} = f_{co} + \frac{2.7f_l}{(f_{co})^{0.3941}(f_l)^{0.453} - 0.869(f_l)^{0.28}(h/D)^2}
\]

\[
(9)
\]
The strain at a peak strength of the concrete-filled uPVC tube column is dependent on confining pressure and core concrete strength. The expression in Equation 10 was developed based on the relation in Figures 30 and 31:

$$\varepsilon_{cc} = \varepsilon_{co} + 0.043 \left( \frac{f_l}{f_{co}} \right)^{0.89}$$  \hspace{1cm} (10)

The peak strength model was used to predict the peak strength and the values were compared with the experimental test results (see Figure 29). The predicted values were in good agreement with the experimental results.
with the experimental test results. The model is capable of predicting the peak strength at a mean absolute error (MAE) of 2.7%, Equation (11).

\[
\text{MAE} = \frac{\sum_{i=1}^{N} \left| \frac{(f_{\text{c}}(\text{Exp}) - f_{\text{c}}(\text{Model}))}{f_{\text{c}}(\text{Exp})} \right|}{N} \times 100
\]

(11)

4. Conclusion
Based on the experiments carried out and the results on strength, ductility, energy absorption, failure mode, and post-peak behavior, the following conclusions are drawn:

- The uPVC tube in a concrete-filled uPVC tube column added a substantial contribution to the axial load carrying capacity for specimens prepared from lower concrete strength. For column, with an aspect ratio of two (h/D=2), the load-carrying capacity at a confined state was 1.12-1.65 times the sum of individual capacity at an unconfined state. The confinement coped the concrete dilation; serving the concrete to undergo ductile failure.

- The main failure modes observed were drum, shear and buckling type failure. For lower aspect ratios of the specimens (h/D =2 & 4), drum and shear-type failure modes were observed. The failure modes of uPVC confined columns were much influenced by the type of core concrete failure. The drum type failure occurred due to the expanding of core concrete at the middle from cone type failure whereas the shear-type failure occurred due to shear failure of the core concrete. For higher aspect ratios of the tested specimen (h/D=6 & 8), buckling (single and double curvature) and shear failure occurred. The wire-mesh reinforced mortar cover did not contribute to the strength; the delamination of wire-mesh reinforced mortar cover started around 70-100% of the peak load.

- For an aspect ratio of two, the uPVC tube in a uPVC confined concrete column increased the strength by 1.28 -2.35 times the unconfined column. The effectiveness of the confinement was dependent on the core concrete strength and 2t/D ratio. The effectiveness increased as the core concrete strength decreased, and the 2t/D ratio increased. Also, the confinement performed well for higher aspect ratios as the unconfined column resistance to load reduces abruptly with the increase in aspect ratio (h/D).
The post-peak stress-strain behavior of uPVC confined concrete proved to be affected by 2t/D ratio and h/D. The absolute value of the slope decreased as the 2t/D ratio increased. The aspect ratio significantly affected the post-peak behavior; a gradual drop in the stress-strain curve was observed for lower aspect ratio whereas an abrupt drop in the stress-strain curve was observed for a higher aspect ratio (h/D ≥ 4).

The uPVC confinement increased the ductility and energy absorption of the columns. For h/D ratio of two, the ductility and energy absorption increased by 1.84-15.3 and 11-243 times the unconfined concrete column respectively. The confinement effect of delaying the core concrete cracking and lateral expansion improved the ductility; serving the concrete column to undergo straining beyond the elastic state without failure for a prolonged period of time compared to the unconfined column.

The stress-strain model predicted the peak strength of the axially loaded concrete-filled uPVC tube column with a mean absolute error of 2.7%.

A ductile failure and high elongation capacity of the uPVC tube is a prominent behavior that attracted the attention to use as a confining material. However, more work is required on the performance of a uPVC confined concrete column. To further understand, additional tests should be done on uPVC confined concrete columns under eccentric, lateral, and pure bending load.

Nomenclature

| Symbol | Description |
|--------|-------------|
| E      | Energy Absorption Capacity |
| uPVC   | Unplasticized polyvinyl chloride |
| t      | Thickness |
| RC     | Reinforced concrete |
| PVC    | Polyvinyl chloride |
| h      | Height |
| FRP    | Fiber-reinforced polymer |
| D      | Diameter |
| μcr    | Ductility factor |
| k1     | Confinement Coefficient |
| fy     | Yield stress of uPVC |
| fl     | Lateral confining pressure |
| fco    | Unconfined compressive strength |
| fcc    | Confined compressive strength |
| WC     | Work index |
| Pu     | uPVC tube Load-carrying Capacity |
| Pco    | Unconfined Load carrying capacity |
| Pcc    | Confined load-carrying Capacity |
| EU     | Unconfined concrete energy absorption capacity |
| EC     | Confined concrete energy absorption capacity |
| εco    | Strain at max strength of Unconfined concrete |
| εcc    | Strain at max strength of Confined concrete |
| ε1     | Elastic strain at max strength |
| εf     | Strain at failure load |

Acknowledgements

The authors sincerely thank the African Union Commission (AUC) and Africa-ai-Japan Project for funding this research.

Funding

This work was supported by the African Union Commission (AUC) and Africa-ai-Japan project. (We have received material support to conduct the experiment)

Author details

Abraham Mengesha Woldemariam
E-mail: abrish27@yahoo.com
ORCID ID: http://orcid.org/0000-0003-2709-2147

Walter O. Oyawa
E-mail: oyawaw@yahoo.com

Timothy Nyombo
E-mail: tryombo@hotmail.com

1 Civil Engineering Department, Pan African University Institute for Basic Sciences, Technology and Innovation (PAUSTI), JKUAT, Nairobi 62000-00200, Kenya.

2 Civil, Const. & Env. Engineering Department, Jomo Kenyatta University of Agriculture and Technology (JKUAT), PAUSTI & CUE, Nairobi 62000-00200, Kenya.

3 Department of Civil and Structural Engineering, PAUSTI and Kenya Urban Roads Authority, Nairobi, Kenya.
Citation information
Cite this article as: Experimental studies on the behavior of concrete-filled uPVC tubular columns under axial compression loads, Abraham Mengesha Woldemariam, Walter O. Oyawa & Timothy Nyambai, Cogent Engineering (2020), 7: 1768649.

References
Abdulla, N. A. (2017). Concrete filled PVC tube: A review. Construction and Building Materials, 156 (2017), 321–329. https://doi.org/10.1016/j.conbuildmat.2017.08.156
Alves, L. M., & Martins, P. A. F. (2009). Cold expansion and reduction of thin-walled PVC tubes using a die. Journal of Materials Processing Technology, 209(9), 4229–4236. https://doi.org/10.1016/j.jmatprotec.2008.11.015
ASTM International. (2016). ASTM D638 Standard test method for tensile properties of plastics. https://doi.org/10.1520/D0638-14A1
Balmer, G. G. (1943). Shearing strength of concrete under high triaxial stress-computation of Mohr’s envelope as a curve: Report No. SP-23. . Denver, Co., 1949: Bureau of Reclamation.
Bosirat, A. F., Samuel, A. D., Timothy, A. O., & Oluwatayo in, A. O. (2016). Causes, effects and remedies to the incessant building collapse in Lagos State, Nigeria. International Journal of Basic & Applied Sciences, 16 (4), 15–30. http://ijens.org/Vol_16_I_04/167703-1604-1818-1BAS-IJENS.pdf
Boersma, A., & Breen, J. (2005). Long term performance prediction of existing water distribution systems. In 9th International Conference PVC. England (2005).
Breen, J. (2006). Expected lifetime of existing water distribution systems-management summary (TNO Report MT-RAP-06-18692/MSO). TNO Science and Industry.
British Standard Institution. (1998). BS EN 933-2 Tests for geometrical properties of aggregates. Determination of particle size distribution. Test sieves, nominal size of apertures. BSI Standards Ltd.
British Standard Institution. (1997). BS EN 933-1 Tests for General Properties of Aggregates: Part 1. Methods for Sampling.
British Standard Institution. (2012a). BS 8500-1:2006 +A1:2012 Concrete. Complementary British Standard to BS EN 206-1. Method of specifying and guidance for the specifier.
British Standard Institution. (2012b). BS EN 933-1:Tests for geometrical properties of aggregates Part 1: determination of particle size distribution— sieving method.
British Standard Institution. (2013). BS EN 206:2013 Concrete. Specification, production and conformity.
Burn, S., Davis, P., & Schiller, T. (2006). Long-term performance prediction for PVC pipes (Report 91092F). American Water Works Association Research Foundation (AWWARF).
Cui, C., & Sheik, S. A. (2010). Experimental study of normal- and high-strength concrete confined with fiber-reinforced polymers. Journal of Composites for Construction, 14(5), 553–561. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000116
European Standard. (2011). EN 197-130 Cement. Composition, specifications and conformity criteria for common cements.
Fakharifar, M., & Chen, G. (2016). Compressive behavior of FRP-confined concrete-filled PVC tubular columns. Composite Structures, 141(May), 91–109. https://doi.org/10.1016/j.compstruct.2016.01.004
Fakharifar, M., & Chen, G. (2017). FRP-confined concrete filled PVC tubes: A new design concept for ductile column construction in seismic regions. Construction and Building Materials, 130(2017), 1–10. https://doi.org/10.1016/j.conbuildmat.2016.11.056
Fernandez, R. H. F. (2014). Strategies to reduce the risk of building collapse in developing countries strategies. Carnegie Mellon University.
Folkman, S. (2014). Validation of the long life of pvc pipes. In 17th Plastic Pipes Conference (pp. 1–9). September 22–24, 2014, Chicago, Illinois, USA: The Plastic Pipes Conference Association (PPCA)
Gathimba, N. K., Oyawa, W. O., & Mang’uria, G. N. (2015). Performance of UPVC pipe confined concrete columns in compression [MSc. Thesis]. Jomo Kenyatta University of Agriculture and Technology.
Gupta, P. K. (2013). Confinement of concrete columns with unplasticized Poly-vinyl chloride tubes. International Journal of Advanced Structural Engineering, 5(1), 1–8. https://doi.org/10.1186/2008-6695-5-19
Gupto, P. K., & Verma, V. K. (2014). Study of concrete-filled unplasticized poly-vinyl chloride tubes in marine environment. Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment, 230(2), 229–240. https://doi.org/10.10117/1475090214560448
Jamaludin, N., Azeez, A. A., Rahman, A. N., Attyiah, A. N., Ibrahim, H. W. M., Mohamad, N., & Adnan, S. H. (2017). Experimental investigation of concrete filled PVC tube columns confined by plain PVC socket. MATEC Web of Conferences, 103, (2017), 1–8. https://doi.org/10.1051/matecconf/201710302006
Karabinis, A. I., & Roussakis, T. C. (2002). Concrete confined by FRP material: A plasticity approach. Engineering Structures, 24(7), 923–932. https://doi.org/10.1016/S0141-0296(02)00011-1
Kurt, C. E. (1978). Concrete Filled Structural Plastic Columns. Journal of the Structural Division, 104(1), 55–63.
Lam, D., Dai, X. H., Han, L. H., Ren, Q. X., & Li, W. (2012). Behaviour of inclined, tapered and STS square CFST stub columns subjected to axial load. Thin-Walled Structures, 54(May), 94–105. Contents. https://doi.org/10.1016/j.tws.2012.02.010
Marzoucka, M., & Sennah, K. (2002). Concrete filled PVC tubes as compression members. In International seminar, Composite material in concrete construction (pp. 31–38). September 5–6, 2002, Scotland, UK: ICE Publishing.
Najdanović, D., & Milosavlević, B. (2014). Strength and ductility of concrete confined circular columns. Journal of the Croatian Association of Civil Engineers, 66(5), 417–423. https://doi.org/10.14256/JCE.986.2013
Oyawa, W. O., Gathimba, N. K., & Geoffrey, N. M. (2015). Innovative composite concrete filled plastic tubes in compression. In 2015 World Congress on Advances in Structural Engineering and Mechanics (ASEM15) (pp. 1–15). August 25–29, 2015, Incheon, Korea: ASEM15 Congress.
Oyawa, W. O., Gathimba, N. K., & Mang’uria, G. N. (2016). Structural response of composite concrete filled plastic tubes in compression. Steel and Composite Structures, 21(3), 589–604. https://doi.org/10.12989/sacs.2016.21.3.589
Raney, T., & Parker, L. (1995). Susceptibility of ABS, FEP, F4, FRP, PTFE, and PVC Well Casing to Degradation by Chemicals. US Army Corps of Engineers (Report No.
A study of the failure of concrete under combined compressive stresses (Vol. 26). University of Illinois Bulletin. https://doi.org/10.1067/mno.2001.114875

Shanmugam, N. E., & Lokshmi, B. (2001). State of the art report on steel – Concrete composite columns. Journal of Constructional Steel Research, 57 (10), 1041–1080. https://doi.org/10.1016/S0143-974X(01)00021-9

Tchamba, J. C., & Bikoko, T. G. L. J. (2015). Failure and collapse of building structures in the cities of Yaoundé and Douala, Cameroon from 2010 to 2014. Modern Applied Science, 10(1), 23. https://doi.org/10.5539/mas.v10n1p23

Wang, J. (2014). Investigation on compressive behaviors of thermoplastic pipe confined concrete. Construction and Building Materials, 35(October2012), 578–585. https://doi.org/10.1016/j.conbuildmat.2012.04.017

Wang, J., & Yang, Q.-B. (2012). Investigation on compressive behaviors of thermoplastic pipe confined concrete. Construction and Building Materials, 35 (October2012), 578–585. https://doi.org/10.1016/j.conbuildmat.2012.04.017

Wang, K., & Young, B. (2013). Fire resistance of concrete-filled high strength steel tubular columns. Thin-Walled Structures, 71 (2013), 46–56. https://doi.org/10.1016/j.tws.2013.05.005

Wang, & Yang, Q. (2010). Experimental study on mechanical properties of concrete confined with plastic pipe experimental study on mechanical properties of concrete. ACI Materials Journal, 107(2), 132–137. https://doi.org/10.14359/51663576

Richart, F., Brandtzæg, A., & Brown, R. L. (1928). A study of the failure of concrete under combined compressive stresses (Vol. 26). University of Illinois Bulletin. https://doi.org/10.1067/mno.2001.114875

Saadoon, A. S. (2010). Experimental and theoretical investigation of PVC-Concrete composite columns. University of Basrah.

Shanmugam, N. E., & Lokshmi, B. (2001). State of the art report on steel – Concrete composite columns. Journal of Constructional Steel Research, 57 (10), 1041–1080. https://doi.org/10.1016/S0143-974X(01)00021-9

Tchamba, J. C., & Bikoko, T. G. L. J. (2015). Failure and collapse of building structures in the cities of Yaoundé and Douala, Cameroon from 2010 to 2014. Modern Applied Science, 10(1), 23. https://doi.org/10.5539/mas.v10n1p23

Wang, J. (2014). Investigation on compressive behaviors of thermoplastic pipe confined concrete. Construction and Building Materials, 35(October2012), 578–585. https://doi.org/10.1016/j.conbuildmat.2012.04.017

Wang, J., & Yang, Q.-B. (2012). Investigation on compressive behaviors of thermoplastic pipe confined concrete. Construction and Building Materials, 35 (October2012), 578–585. https://doi.org/10.1016/j.conbuildmat.2012.04.017

Wang, K., & Young, B. (2013). Fire resistance of concrete-filled high strength steel tubular columns. Thin-Walled Structures, 71 (2013), 46–56. https://doi.org/10.1016/j.tws.2013.05.005

Wang, & Yang, Q. (2010). Experimental study on mechanical properties of concrete confined with plastic pipe experimental study on mechanical properties of concrete. ACI Materials Journal, 107(2), 132–137. https://doi.org/10.14359/51663576

Woldemariam, A. M., Oyawa, W. O., & Nyomboi, T. (2019a). Behavior of concrete-filled single and double-skin uPVC tubular columns under axial compression loads. Open Construction and Building Technology Journal, 13(2019), 164–177. https://doi.org/10.2174/1874836801913010164

Woldemariam, A. M., Oyawa, W. O., & Nyomboi, T. (2019b). Structural performance of uPVC confined concrete equivalent cylinders under axial compression loads. Buildings, 9(4), 83. https://doi.org/10.3390/buildings9040082

Woldemariam, A. M., Oyawa, W. O., & Nyomboi, T. (2020). Reliability assessment of axially loaded uPVC tube confined reinforced concrete columns. Structures, 23 (November 2019), 529–538. https://doi.org/10.1016/j.istruc.2019.11.009

Wu, Y. F. (2004). The effect of longitudinal reinforcement on the cyclic shear behavior of glass fiber reinforced gypsum wall panels: Tests. Engineering Structures, 26 (11), 1633–1646. https://doi.org/10.1016/j.engstruct.2004.06.009

Xue, J., Li, H., Zhai, L., Ke, X., Zheng, W., & Men, B. (2016). Analysis of mechanical behavior and influencing factors of high strength concrete columns with PVC pipe under repeated loading. Xi’An Jianzhu Keji Daxue Xuebao/Journal of Xi’An University of Architecture and Technology, 48, 26–28. https://doi.org/10.15986/j.istruc.2016.01.004

Zhang, X.-H., Lu, X.-B., Zhang, L.-M., Wang, S.-Y., & Li, Q.-P. (2012). Experimental study on mechanical properties of methane-hydrate-bearing sediments. Acta Mechanica Sinica, 28(5), 1356–1366. https://doi.org/10.1007/s10409-012-0162-3
