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Structural response of composite concrete filled plastic tubes in compression

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Abstract. Kenya has recently experienced worrying collapse of buildings during construction largely attributable to the poor quality of in-situ concrete and poor workmanship. The situation in the country is further compounded by rapid deterioration of infrastructure, hence necessitating the development of alternative structural systems such as concrete filled unplasticized poly vinyl chloride (UPVC) tubes as columns. The work herein adds on to the very limited and scanty work on use of UPVC tubes in construction. This study presents the findings of experimental and analytical work which investigated the structural response of composite concrete filled UPVC tubes under compressive load regime. UPVC pipes are cheaper than steel tubes and can be used as formwork during construction and thereafter as an integral part of column. Key variables in this study included the strength of infill concrete, the length to diameter ratio (L/D) of the plastic tube, as well as the diameter to thickness ratio (D/2t) of the plastic tube. Plastic tubes having varying diameters and heights were used to confine concrete of different strengths. Results obtained in the study clearly demonstrate the effectiveness of UPVC tubes as a confining medium for infill concrete, attributable to enhanced composite interaction between the UPVC tube and infill concrete medium. It was determined that compressive strength of the composite column specimens increased with increased concrete strength while the same decreased with increased column height, albeit by a small margin since all the columns considered were short columns. Most importantly, the experimental confined concrete strength increased significantly when compared to unconfined concrete strength; the strength increased between 1.18 to 3.65 times the unconfined strength. It was noted that lower strength infill concrete had the highest confined strength possibly due to enhanced composite interaction with the confining UPVC tube. The study further proposes an analytical model for the determination of confined strength of concrete.

Keywords: composite structures; compressive loads; concrete filled plastics; plastics; stub columns

1. Introduction

The drive towards sustainable construction practices around the world has triggered a special interest in the structural stability of old structures, especially in view of frequently occurring catastrophic natural and manmade disasters. Accordingly, there is increased demand for

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assessment and rehabilitation or retrofitting of existing structures. One of the deficiencies in reinforced concrete (RC) columns is the lack of lateral confinement and low energy absorption capacity when subjected to massive lateral forces like earthquakes, hence necessitating use of structural steel tubes to retrofit such structures (Schneider 1998, Oliveira *et al*. 2009, Oyawa *et al*. 2001). The strength, robustness, and ductility capacity of new concrete columns during construction can be enhanced by providing external confinement by employing steel tubes or wrapping with fibre reinforced plastics (Kamyar *et al*. 2015). Other areas of composite research include work by Imani *et al*. (2015) who are currently investigating the effect of post-earthquake fires on concrete-filled double-skin tube columns. A potential alternative to steel tube retrofitting technique is the plastic tube or Poly-Vinyl-Chloride (PVC) tube (Usha and Eramma 2014). The use of PVC tubes to confine RC columns is still at infancy stage, and very few studies have been done in this area (Marzouck and Sennah 2002, Gupta 2013). This study adds on to the very limited and scanty work on use of UPVC tubes in construction. UPVC pipes are cheaper than steel tubes, are readily available and can be used as formwork during construction and thereafter as an integral part of column. Generally, polymer composites are gaining acceptance in concrete structural applications due to their high ratio of strength/stiffness to self-weight and corrosion resistance (Woraphot *et al*. 2015).

Taking note of recent collapse of buildings under construction in Kenya, largely attributable to poor reinforced concrete works, this study investigated the use of un-plasticized Poly-Vinyl-Chloride (UPVC) tubes as the confining medium for composite concrete filled plastic tubes in compression. UPVC tubes are corrosive resistant and are rather inexpensive as compared to steel tubes or fibre reinforced plastic wraps. Though having lower strength compared to steel, UPVC are highly elastic undergoing large displacement under load, and provide the added advantages of being used as formwork during construction stage as well as being adverse-weather resistant when exposed to high energy regimes like marine and saline environments. It is well known that polymers are some of the most stable substances when high corrosion resistance is required. Indeed UPVC tube can be used as a protective layer against mechanical damage caused by severe environments. The thermal conductivity of UPVC is only 0.45% that of a steel tube, and UPVC tube can withstand exposure to high energy environments such as marine environments (Gupta 2013).

2. Experimental program

2.1 Material properties

2.1.1 Aggregates

Ordinary river sand and crushed rocks were used as fine (FA) and coarse aggregates (CA) respectively in the manufacture of concrete. Aggregates were washed with clean water to making sure that they are free from organic impurities such as clay, organic content, silt and other inferior materials. In order to ascertain the aggregates suitability and also to facilitate the design of concrete mixes some of essential physical properties were determined following the standard laid down laboratory procedures, results of which are summarized in Table 1.

Particle size distribution of river sand, a very significant attribute associated with fine aggregates, was also determined from the sieve analysis using British standard test sieves having sizes; 5.00 mm, 2.36 mm, 1.18 mm, 600 microns, 300 microns, 150 microns and the results presented in a graphical manner, as shown in Fig. 2 below, which is generally referred to as the

Table 1 Summary of some physical properties of aggregates

	FA	CA
Specific gravity on oven dry basis	2.59	2.46
Specific gravity on saturated surface dry (SSD) basis	2.61	2.51
Apparent specific gravity	2.65	2.60
Water absorption (%)	0.87	2.08

grading curve. The grading curve of the sand was within the Zone 2 envelope of British Standard thus suitable for use in concrete production without need for blending it. Also the fineness modulus (FM) of fine aggregates, which is the weighted average of a sieve on which the material is retained; the sieves being counted from the finest, was determined from sieve analysis and found to be 2.53. The higher the FM, the coarser the fine aggregates. FM is variable for measuring slight variations in the aggregates from the same source (i.e., a day to day check). Typical values of FM are in the range 2.0-4.0.

2.1.2 Cement

Cement is widely used as the binder material in the concrete matrix in many applications. The common uses of cement are as a component in the production of mortar in masonry, and of concrete, for concrete constructions. The cement commonly used in Kenya is categorized as class 32.5 and is mostly Portland pozzolana cement. Cement class 42.5 may also be produced on special order to the manufacturer and has the key attribute of high early strength as well as higher strength at later age. Cement Class 42.5 (Ordinary Portland cement) was used in this research.

2.1.3 Concrete

Three series of concrete grades C20, C25 and C30 were designed for use in this research work. While the grades were based on the standard cube test, the unconfined strength of the concrete specimens (σ_{co}) was determined on specimens of the same height and inner diameter as the encasing plastic tube for composite stub columns. The method of concrete mixing design applied here was in accordance to the Department of Environment of British Research Establishment (BRE), United Kingdom (1988) and the determination of various parameters necessary for the design of the mixes was based on the design tables and figures drawn from the BRE manual. The mixing of concrete was done according to the BS, ASTM and JIS procedures given in laboratory guidelines. The BRE mix design procedure from the DOE, UK was adopted for this research. A summary of the calculated mix proportions and the concrete's compressive strength, f_{ck}, at 28 days is as given in Table 2.

Table 2 Summary of concrete mix proportions

Class of mix	Water*/ cement ratio	Water* (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)		Compressive strength at 28 days f_{ck} (MPa)
					5/10	10/20	
C20	0.84	221.5	265	625	420	840	20.7
C25	0.75	213.5	285	615	415	825	27.2
C30	0.70	210.0	310	605	410	810	30.7

* Includes free water for cement hydration and water for absorption of aggregates to make them SSD.

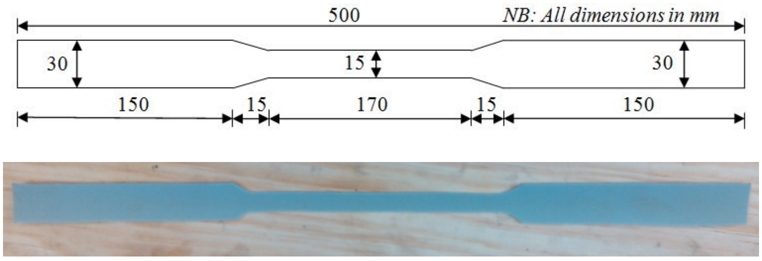


Fig. 1 Dimensions of UPVC specimen for tensile strength test

Table 3 Nominal physical properties of UPVC pipes

Parameter	Density	Elastic modulus	Flexure strength	Tensile strength	Compressive strength	Poisson ratio	Elongation
Value	14-14.6 KN/m^3	3000 MPa	65.5 MPa	40 MPa	59 MPa	0.38	80-150%

2.1.4 Plastic tubes

Unplasticized polyvinyl chloride (UPVC) tubes were used to confine plain concrete stub columns. UPVC pipes conforming to Kenyan standards KS ISO 3633 and KS 2079-1-2007 were procured from Masterpipe Kenya (LTD) and Agroflow irrigation systems Limited, plastic pipes manufacturing companies based in Nairobi, Kenya.

To determine the tensile strength of the UPVC tube material, a coupon was prepared with dimensions as shown in Fig. 1. This sample was tested in the UTM SERVO-PLUS EVOLUTION™ machine with a loading rate of 2.0 Mpa/sec. Nominal properties of UPVC tube are given in Table 3.

2.2 Instrumentation and testing

A total of 144 short columns (i.e., 48 column sets replicated three times, for statistics) were cast i.e., 72 unconfined concrete columns and 72 UPVC-confined concrete columns. UPVC tubes with three different outer diameters: 55 mm, 83 mm and 110 mm were used to confine concrete. The thicknesses of the tubes were 2.5 mm for 55 mm diameter, 3.0 mm for 83 mm diameter and 2.5 mm for 110 mm diameter. The height of specimens ranged from 110 mm to 332 mm, from which a slenderness factor for each column was derived as height of column/diameter of tube. The three predesigned concrete mixes namely C20, C25, and C30 were used to fill the UPVC tubes. For each class of concrete and for each diameter and height selected, three unconfined and three UPVC-confined columns having the same length were cast. To obtain unconfined conditions for a concrete column of a similar diameter and height as a confined column, empty UPVC tube was split on one side along the length and tied with binding wires which was then used as a mould for casting of columns. The outer plastic casing was then removed after 24 hrs, leaving an unconfined column specimen. Typical nomenclatures for the specimen are used to designate them. For instance, C/C25/110/3 represent a confined (C) concrete column cast with concrete grade C25, having a diameter of 110 mm and a slenderness ratio of 3. Freshly cast specimens were allowed to stand for 24 hrs until concrete was fully hardened. They were then marked for ease of identification then cured by covering them with sisal sacks which were wetted daily with water until the testing date. The specimens were cured for 28 days prior to testing (Fig. 2).

The experimental work was conducted utilizing compression machines at Structures and Materials laboratory of Civil Engineering Department of Jomo Kenyatta University of Agriculture and Technology in Kenya. The specimens were allowed to dry prior to testing. All specimens were tested up to failure under monotonic loads. The specimens were subjected to concentric axial compressive load applied at the specimens' center by means of a compression testing hydraulic machine through uniform steel end plates to achieve a constant stress distribution at the concrete cross section (Fig. 3). The load was applied to the entire column section. Soliman (2011) in his study on behaviour of long concrete columns confined by means of plastic tubes noted that when the load was applied to the entire section, the contribution by the concrete core and tube to the total axial force was constant along the height of the column, and was not affected by the bond strength. Furthermore, Gardner and Jacobson (1967) in their study on structural behaviour of concrete filled steel tube observed that the bond strength had no influence on the structural behaviour of the column.

The columns were tested using an incremental loading procedure. Load cell of 500 kN capacity was used to monitor the applied load values. Due to the extensiveness and the magnitude of sample specimens being handled in this research work, only compressive strength data is presented in this paper. The applied load was kept constant at each load stage to allow for measurements and observations. The load cell was connected to TDS 303 data logger where the results were recorded for further analysis.

Fig. 2 Samples of stub columns ready for testing

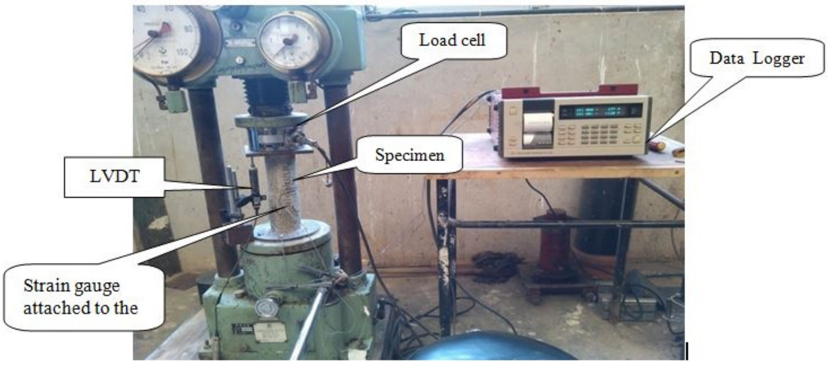


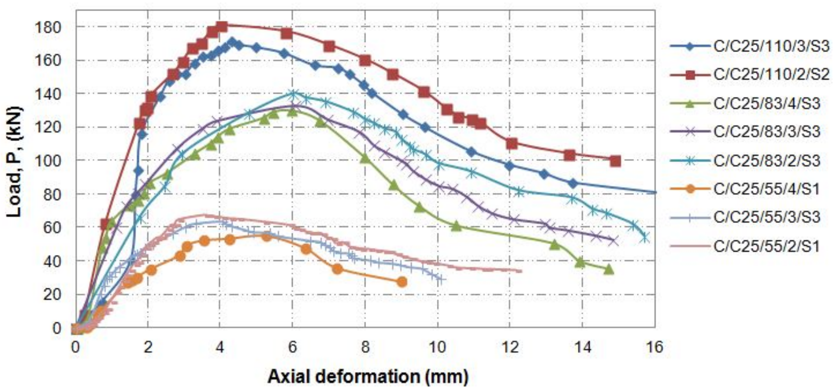
Fig. 3 Specimen testing using compression machine

3. Results and discussions

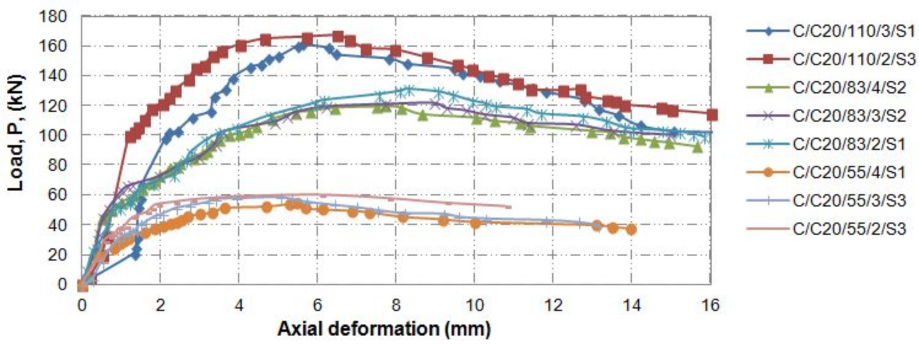
3.1 Load-deformation response, and failure modes

Figs. 4(a) and (b) give typical load versus axial deformation of the tested composite stub columns for concrete grades C25 and C20. It is observed that the composite columns demonstrate enhanced ductility attributable to composite interaction. Ductility is a solid material's ability to deform under stress, and in particular to undergo permanent deformation through elongation (reduction in cross-sectional area) or bending at room temperature without fracturing. Ductility of the stub columns is observed to increase with reduced slenderness ratio and vice versa. It is to be said that a slender column reduces composite interaction between the infill material and encasing tube. Slenderness ratio is a key parameter in the design of columns. For each type of column system, there is always a critical slenderness ratio below which failure occurs by crushing and above which failure occurs by buckling, buckling. Indeed Figs. 4(a) and (b) reveal that the ultimate strength of the composite stub columns reduces as the slenderness ratio increases. On the other hand, the strength of the composite columns increases with increased tube diameter as would be expected.

With regard to failure modes, all specimens behaved more or less in the same manner during



(a)



(b)

Fig. 4 (a) Typical load-deformation curves for composite columns (constant concrete strength of C25); (b) Typical load-deformation curves for composite columns (constant concrete strength of C20)

(a) Shearing (b) Mid-height bulging (c) Top bulging (d) Bursting (e) Local buckling of empty tubes

Fig. 5 Typical composite and empty UPVC tube specimens after test - failure modes

the loading process. Sounds were heard during the early or middle stages of loading, which may be attributed to the micro cracking of the concrete. Bursting of the plastic tube was also witnessed toward the end of the loading process, for those specimens which were tested until total collapse (Fig. 5(d)). It was also observed that the failure of the plastic tube was preceded by flow of resin which manifested itself by white patches at highly stressed sections (Fig. 5(c)).

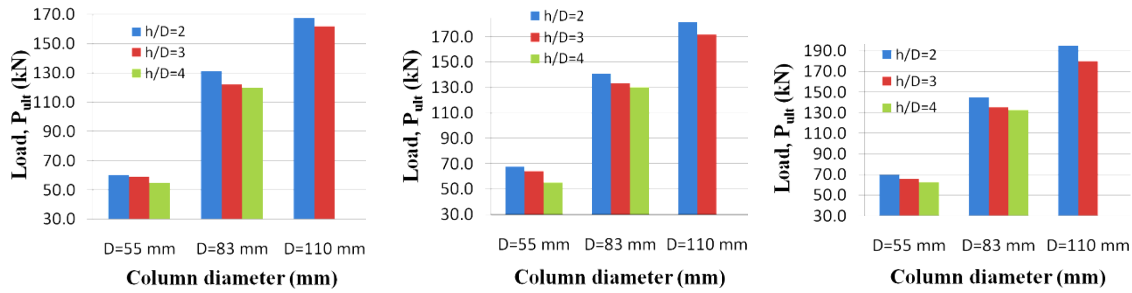
Generally, two failure modes were observed. The principal failure mode was a typical shear failure of the plastic tube (Fig. 5(a)). A typical characteristic of shear failure is that the core concrete is damaged by shear stress in one direction due to weak confinement effect of the tube. The shear crack direction can be judged by the appearance of the specimen.

The same type of mode of failure was also observed by Gupta (2013) and Wang and Yang (2011) in their experimental program. This type of shear failure is affected by D/t ratio, and in order to avoid this type of shear failure, the ratio should be reduced, i.e., the wall thickness of the pipe should be increased. The second type of failure mode observed was bulging which lead to column specimen crushing under compression. This bulging was observed to occur either near the bottom, top or mid-height of the specimen (Figs. 5(b) and (c)). This is a typical failure mode of short columns under pure concentric axial compressive load. At the end of the loading process, the encased concrete is totally crushed and almost pulverized. It was also observed that no concrete was attached to the remainder of the tube, and a smooth interface was discovered. This led to the conclusion that no bond is developed between concrete and UPVC tube.

For empty tubes, failure was by local buckling at the ends (Fig. 5(e)). It is hence clear that the presence of infill concrete prevents or delays local buckling of the plastic tubes, thus converting the plastic tube to a restraining medium against lateral expansion of the infill material. This is the essence of composite interaction where each material enhances the other e.g., the plastic tube confines and restrains the infill concrete from bursting while the infill concrete delays the buckling of the plastic tube. Future studies may focus on the fire resistance of the composite section, and possible improvements made to the composite systems.

3.2 Effect of varying diameter and height effects on load and compressive strength of specimen

Fig. 6 illustrates compressive load test results on composite concrete filled UPVC tubular stub columns. The Figure presents the variation of Load capacity, P_{ult} of concrete filled UPVC tubular



(a) Group I specimen (concrete C20) (b) Group II specimens-C25 (c) Group III specimens-C30

Fig. 6 Variation of load capacity, P_{ult} of concrete filled UPVC tubular columns with change in infill concrete strength, encasing tube diameter and height

columns with change in infill concrete strength, encasing tube diameter and height for confined specimens. As expected, the load carrying capacity of the composite columns increases with increase in the grade of concrete, as is evidenced by the results in group I through III. It is further recorded that as the specimen diameter increases so does the load capacity, while as the height to diameter ratio increases the load capacity of the composite column also decreases. The height to Diameter ratio (h/D) correlates to slenderness ratio of a column, and hence affects the ultimate strength of the composite column. At any particular diameter, it is observed that the ultimate strength of a composite column decreases with increase in h/D ratio. Euler postulated that elastic buckling of a column occurs at a load Pcr given as $Pcr = \pi^2 EI/(KL)^2$, where E is the modulus of elasticity, I is the moment of Inertia of the section, L is the length of the column, and K is a factor to adjust for column end conditions. It is now well documented that concrete filled steel tubular columns have excellent structural properties, such as high compressive strength, large ductility and large energy absorption capacity. As a result, composite tubular columns have been gradually used widely in the world. The trend is likely to increase rapdidly as more innovative materials are evolved for composite structures.

3.3 Experimental confinement effectiveness

Table 4 and Fig. 7 report finding on how confinement of infill concrete is affected by varying concrete strength, tube thickness and slenderness ratio. The measure of how well a certain material confines concrete is referred to as confinement effectiveness which is defined as $\sigma_{cc}/\sigma_{co,}$ where σ_{cc} = compressive strength of confined concrete; σ_{co} = compressive strength of unconfined concrete. From the results as presented in Table 4 and Fig. 7, it is clear that plastic pipes are effective in confining concrete, as evidenced by the increased compressive stress. The enhancement in strength due to confinement of circular columns is substantial (Fig. 7). Depending on the level of confinement, strength is increased anywhere from 1.18 to 3.65 times the unconfined strength. It also observed from Fig. 7 confinement effectiveness curve goes down with increase in the unconfined strength of concrete. This is typical for all column specimens tested regardless of their diameter, height or tube thickness, and is attributable to the fact that the higher the strength of the concrete, the more brittle and less expansive it is. It is postulated that lower strength concrete is less stiff (as indicated by its low elastic modulus which is usually related to the compressive strength of concrete), and is therefore able to 'flow' thus interacting with concrete tube more effectively, with consequent increase in composite action. Another observation from Fig. 7 is that the confinement effectiveness decreases with increase in slenderness ratio. This is depicted by the downward shift of the curves when the slenderness ratio is increased with diameter kept constant. This can be explained in the context that as slenderness ratio increases, the load carrying capacity of the column reduces, especially that of the encasing plastic tube hence reducing composite interaction. A notable observation is how the confinement effect for the 83mm-diameter columns set was higher than the other column. This is attributed to the fact that the tube thickness was higher (3.0 mm) as compared to the other columns (2.5 mm). Generally, cconfinement action is dependent on the tendency of the concrete infill to dilate when loaded, as well as the radial stiffness of the confining member to restrain the dilation.

For an axially loaded unconfined concrete element, transversal strains are induced resulting

Table 4 Summary of experimental results in terms of Column load capacity, column strength and confinement effectiveness

Column label (Dia./slen.)	Tube thickness, t, (mm)	Concrete designation	Column load capacity (kN) Confined P_{cc}	Column load capacity (kN) Unconfined, P_{co}	Column strength (Mpa) Confined σ_{cc}	Column strength (Mpa) Unconfined, σ_{co}	Confinement effectiveness (σ_{cc}/σ_{co})
C-110/2	2.5	C20	167.3	77.4	17.6	8.9	1.97
		C25	181.3	138.2	19.1	16.0	1.20
		C30	195.3	150.3	20.5	17.4	1.18
C-110/3	2.5	C20	161.8	63.7	17.0	7.4	2.32
		C25	171.8	125.2	18.1	14.5	1.25
		C30	180.2	126.4	19.0	14.6	1.30
C-83/2	3.0	C20	131.1	37.2	24.2	8.0	3.04
		C25	140.6	66.6	26.0	14.3	1.82
		C30	144.8	68.4	26.8	14.7	1.82
C-83/3	3.0	C20	121.9	32.1	22.5	6.9	3.27
		C25	133.2	55.9	24.6	12.0	2.05
		C30	135.5	62.8	25.0	13.5	1.86
C-83/4	3.0	C20	119.7	28.2	22.1	6.1	3.65
		C25	130.2	50.0	24.1	10.7	2.24
		C30	132.5	59.4	24.5	12.8	1.92
C-55/2	2.5	C20	60.1	19.5	25.3	9.9	2.55
		C25	67.5	39.3	28.4	20.0	1.42
		C30	69.6	41.0	29.3	20.9	1.40
C-55/3	2.5	C20	58.8	17.9	24.7	9.1	2.71
		C25	64.0	30.7	26.9	15.7	1.72
		C30	66.0	36.1	27.8	18.4	1.51
C-55/4	2.5	C20	54.7	15.3	23.0	7.8	2.96
		C25	55.1	23.9	23.2	12.2	1.91
		C30	62.6	28.3	26.3	14.4	1.83

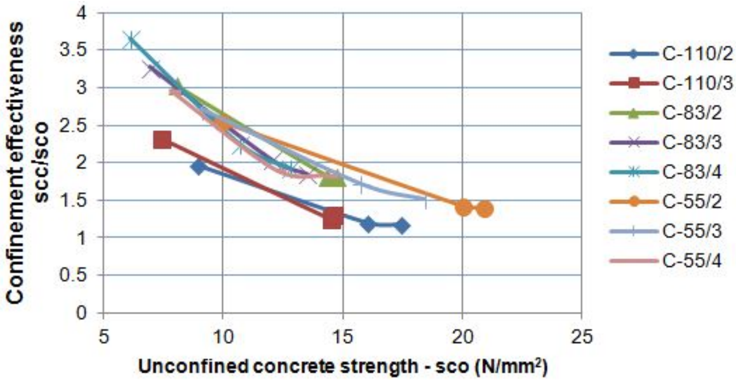


Fig. 7 The relationship between confinement effectiveness and unconfined concrete strength

into radial concrete expansion (*Poisson's effect*). Under low loading conditions, the transverse strains are proportional to longitudinal strain, and associated by the *Poisson's* coefficient which for concrete usually varies between 0.15 to 0.25. After reaching a certain critical stress (typically between 60% and 80% of the concrete strength), micro-cracking formation occurs in concrete, transversal strains increases quickly leading to large transversal strains for relatively small longitudinal strain. These micro-cracks evolve to macro-cracks that eventually lead to concrete rapture with cracks parallel to the loading. The rupture of unconfined concrete can be delayed by confining the concrete appropriately. The confinement mechanism of concrete is related to the use of materials that provides tensile strength to restrict this increase in transversal strain. The effect of confinement of concrete at high levels of loading leads to a triaxial compression stress state in concrete, which provides a superior behaviour in both strength and ductility than concrete which is uniaxially compressed. Concrete columns can be confined by: lateral reinforcement in the form of steel ties or spirals; encasing concrete in steel tubes; external fiber composite wraps; encasing concrete in fiber composite tubes; or encasing concrete in plastic tubes (a new technology). All these means of confinement produce a so-called 'passive' state of confinement, in which the confining effect is a function of the lateral expansion of the concrete core.

3.4 Analytical estimation of confined strength of concrete

3.4.1 Mechanics of confinement

Mechanics of confinement in concrete filled tubular members has been studied by several researchers in an attempt to develop models to quantify the effects of confinement on strength and ductility of concrete. Concrete infill surrounded by an enclosing restraining medium and subjected to axial load will develop passive lateral pressure as it expands under the influence of axial compression (Chen and Zhang 2012, Gupta and Singh 2014, Tao *et al*. 2013). The expansion of the infill concrete creates a multiaxial state of stress which is dependent on several factors including size and strength of the confining and restraining mediums, Poisson ratio of the concrete fill and restraining medium, amongst others. More recently, work by Tiziano *et al*. (2014), Vinay *et al*. (2015) and Patel *et al*. (2014) have sought to determine the effects of seismic loads on slender concrete filled tubes so as to evaluate the validity of current specifications to estimate the strength of slender composite beam columns. Even more innovative is the experimental work by Mohammadreza and Sanjay (2014) that sought to improve the buckling response of square steel tubes by using steel foam. They concluded that steel foam improves the maximum strength and the ability of energy absorption of the steel tubes significantly.

For the case of concrete filled steel tubular members, Gardner (Gardner and Jacobson 1967) proposed that as the steel tube restrains the dilating concrete core, and internal pressure develops between the steel tube and concrete, creating hoop stresses as given in Fig. 8.

Confinement action thus requires mutual simultaneous interaction and is dependent on the tendency of the concrete infill to dilate when loaded, as well as the radial stiffness of the confining member to restrain the dilation. When this interaction is active, it is rational to assume that there will be geometric (strain) compatibility between the core and the shell, and also the equilibrium of forces in the free-body diagram for any sector of the confined section.

As illustrated in Fig. 8, equilibrium of forces acting on the steel tube is obtained as summation of forces on the small element subtended by angle $\partial\theta$ from the centre i.e.

$$\sum F_y = \sigma_{sh}(2t) = \int_0^{\pi} \sigma_l r_i \sin\theta d\theta \qquad \Leftrightarrow \sigma_l = \frac{t}{r_i}\sigma_{sh} = \frac{2t}{D_i}\sigma_{sh} \tag{1}$$

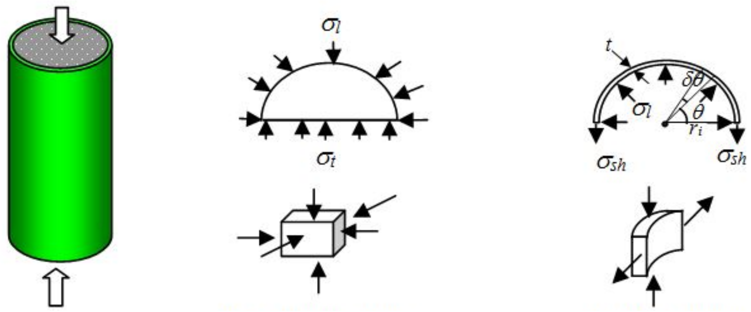
3.4.2 Analytical confined strength of concrete

The strength of infill material with nonlinear and non-homogeneous characteristics under a multi-axial state of stress may be difficult to establish theoretically, necessitating the use of test data to develop empirical or semi empirical approaches. Early investigators showed that the strength of confined concrete (σ_{cc}) and the corresponding longitudinal strain (ε_{cc}) at the strength of concrete confined by an active hydrostatic fluid pressure can be represented by the following simple relationships (Gupta 2013)

$$\sigma_{cc} = \sigma_{co} + k_1\sigma_1 \tag{2}$$

$$\varepsilon_{cc} = \varepsilon_{co}(1 + k_2\sigma_1 / \sigma_{co}) \tag{3}$$

Where σ_1 is the lateral confining pressure on fill material, σ_{co} and ε_{co} are the unconfined fill material strength and strain at ultimate strength, respectively, while k_1 and k_2 are constants. Richart *et al*. (1928), one of the earliest researchers in this field, found k_1 = 4.1 and k_2 = $5k_1$. Since then a number investigators have basically modified this simple linear model, to suit the various



(a) Concrete stress (b) Steel stress

Fig. 8 Interaction of concrete and steel in CFT column under compression conditions of their tests (Mander *et al*. 1988). These include Newman and Newman (1969), Sastcioglu and Razvi (1992), the Architectural Institute of Japan-AIJ (1997) and Cusson and Paultre (1995) as is shown in Table 5. Based on current work, a proposed model is also presented.

In this study, the existing models and a proposed model given in Table 5 are evaluated for suitability vis-à-vis experimental results. Confinement effectiveness is defined as σ_{cc}/σ_{co};

where σ_{cc} = compressive strength of confined concrete, and

σ_{co} = compressive strength of unconfined concrete.

The confining pressure σ_l is related to the internal diameter of the encasing tube ($D_{int} = D - 2t$), tensile strength of encasing tube (σ_{sy}) and encasing tube wall thickness (t) by Eq. (4) below as given by various authors

$$\sigma_l = \frac{2t\sigma_{sy}}{(D_{\text{int}})} = \frac{2t\sigma_{sy}}{(D-2t)} \tag{4}$$

Table 5 Existing and proposed confined strength and strain models

Researcher	Confined strength	Strain at confined strength
Richart *et al*. 1928	$\sigma_{cc} = \sigma_{co} + k_1\sigma_1$ where $k_1 = 4.1$ and $\sigma_l = \frac{2t}{D_i}\sigma_{sh}$	$\varepsilon_{cc} = \varepsilon_{co}(1 + k_2\sigma_l/\sigma_{co})$ where $k_2 = 5k_1$
Newman and Newman 1971	$\sigma_{cc} = \sigma_{co} + k_1\sigma_1$ where $k_1 = 3.7\{\sigma_1\ \sigma_{co})^{(-0.14)}$ and $\sigma_l = \frac{2t}{D_i}\sigma_{sh}$	
Saatcioglu and Razvi 1992	$\sigma_{cc} = \sigma_{co} + 6.7(\sigma_l)^{-0.17}\sigma_l$ where $\sigma_l = \frac{2t}{D_i}\sigma_{sh}$	$\varepsilon_{cc} = \varepsilon_{co}\left[1 + \frac{5\sigma_l}{\sigma_{co}}\right]$
Architectural Institute of Japan (AIJ) 1997	$\sigma_{cc} = \sigma_{co} + \frac{(4.1)(0.19)2t\sigma_{sy}}{(D-2t)}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = \begin{cases} 1 + 4.7\left(\frac{\sigma_{cc}}{\sigma_{co}} - 1\right), & \text{when } \frac{\sigma_{cc}}{\sigma_{co}} \le 1.5 \\ 3.35 + 20\left(\frac{\sigma_{cc}}{\sigma_{co}} - 1.5\right), & \text{when } \frac{\sigma_{cc}}{\sigma_{co}} > 1.5 \end{cases}$
Cusson and Paultre 1995	$\sigma_{cc} = \sigma_{co} + 2.1\sigma_{co}\left(\frac{\sigma_l}{\sigma_{co}}\right)^{0.7}$ where $\sigma_l = \frac{2t}{D_i}\sigma_{sh}$	$\varepsilon_{cc} = \varepsilon_{co} + 0.21\left(\frac{\sigma_l}{\sigma_{co}}\right)^{1.7}$
Proposed Oyawa (2015)	$\sigma_{cc} = \sigma_{co} + 4.1\sigma_1$ where $\sigma_l = \left(\frac{\alpha}{\sqrt{\sigma_{co}}}\right)\frac{2t\sigma_{sy}}{(D-2t)}$	

Nomenclature

σ_{cc} Confined strength of fill material

σ_{co} Unconfined strength of fill material

σ_1 Lateral confining pressure on fill material

σ_{sy} steel yield strain

ε_{cc} Strain at confined strength of fill material

ε_{co} Strain at unconfined strength of fill material

However, it is herein argued that the above equation for the confining lateral pressure fails to capture the effect of the properties of concrete such as Poisson's ratio on the lateral pressure. It is therefore proposed that the equation below be adopted for the lateral confining pressure

$$\sigma_l = \left(\frac{\alpha}{\sqrt{\sigma_{co}}}\right)\frac{2t\sigma_{sy}}{(D_{\mathrm{int}})} = \left(\frac{\alpha}{\sqrt{\sigma_{co}}}\right)\frac{2t\sigma_{sy}}{(D-2t)} \tag{5}$$

In Eq. (5), α is a dimensionless factor that depends on Poisson's ratio, bulk modulus and strains at ultimate strength for the infill concrete material (Oyawa *et al*. 2001). Experimental work by Yiyan *et al*. (2014) on the behavior of concrete-filled steel tube columns confined by fiber-

Table 6 Comparison of experimental confined strength and analytical confined strength of concrete

Column label (Dia./slen.)	External diameter (mm)	Tube thickness, t, (mm)	Experimental strength, Mpa	Analytical strength, Mpa					
				Confined concrete strengths by researchers					
			Confined concrete strength, σ_{cc}	Proposed	Richart	Newman	Saatcioglu	AIJ	Cusson
C-110/2	110	2.5	19.3	19.4	16.8	17.7	20.4	10.4	9.2
	110	2.5	20.9	23.8	23.8	25.5	27.4	17.5	16.3
	110	2.5	22.6	24.9	25.2	27.0	28.8	18.9	17.7
C-110/3	110	2.5	18.7	18.9	15.2	15.9	18.8	8.8	7.6
	110	2.5	19.9	22.7	22.3	23.8	25.9	16.0	14.8
	110	2.5	20.8	22.8	22.4	24.0	26.0	16.1	14.9
C-83/2	83	3	28.2	26.1	20.8	21.2	25.2	10.4	8.4
	83	3	30.2	27.8	27.1	28.6	31.5	16.7	14.8
	83	3	31.1	28.0	27.5	29.0	31.9	17.1	15.2
C-83/3	83	3	26.2	26.4	19.7	19.8	24.1	9.3	7.3
	83	3	28.6	26.8	24.8	25.9	29.2	14.4	12.5
	83	3	29.1	27.4	26.3	27.7	30.7	15.9	14.0
C-83/4	83	3	25.7	26.8	18.8	18.7	23.3	8.5	6.4
	83	3	28.0	26.3	23.5	24.5	28.0	13.2	11.2
	83	3	28.5	27.1	25.5	26.8	30.0	15.2	13.2
C-55/2	55	2.5	30.6	30.7	26.3	26.7	31.1	13.1	10.4
	55	2.5	34.4	34.7	36.4	38.6	41.2	23.1	20.7
	55	2.5	35.5	35.2	37.3	39.5	42.1	24.0	21.5
C-55/3	55	2.5	30.0	30.8	25.5	25.7	30.3	12.2	9.6
	55	2.5	32.6	32.2	32.0	33.6	36.8	18.8	16.2
	55	2.5	33.6	33.7	34.8	36.7	39.6	21.5	19.0
C-55/4	55	2.5	27.9	31.3	24.2	24.0	29.0	10.9	8.3
	55	2.5	28.1	31.0	28.6	29.5	33.4	15.3	12.7
	55	2.5	31.9	31.7	30.8	32.1	35.6	17.5	15.0

Table 7 Average percentage and standard deviation of **Analytical/Experimental** confined strength

	Proposed	Richart	Newman and Newman	Saatcioglu and Razvi	AIJ	Cusson
Average (%): $\frac{\text{Analy.}}{\text{Exper.}}$	101	93	97	109	56	49
Standard deviation: $\frac{\text{Analy.}}{\text{Exper.}}$	7	12	15	12	15	16

reinforced polymer (FRP), determined that the axial compressive capacity of such composite columns is dependent on the strength of unconfined concrete and a confinement index. They also presented that the confining pressure provided by the FRP wrap is dependent on the elastic modulus of the FRP wrap.

In this current study, α is a semi-empirical factor derived in consideration of past and current experimental work, especially from the works of Richart *et al.* (1928), Newman and Newman (1969), Sastcioglu and Razvi (1992), the Architectural Institute of Japan-AIJ (1997) and current work by the authors. By fitting experimental results to analytical work, α is currently determined to be equal to 4. Tables 6 and 7 give a comparison of experimental confined strength of the infill concrete versus analytical confined strength of the infill concrete. The Tables reveal that the proposed equation with $\alpha = 4$ gives the best estimation of the analytical strength. That is to say, the determined **Analytical/Experimental** confined strength of concrete is 101% for the proposed model, while the others are 93%, 97%, 109%, 56% and 49% respectively. It also observed from Table 7 that the proposed model gives the lowest standard deviation as compared to the other existing analytical models. Unlike the other equations proposed by Richart, Newman and Newman, Sastcioglu and Razvi, Architectural Institute of Japwan (AIJ) and Cusson, the proposed equation takes into consideration the properties of the infill material in the calculation of the lateral pressure on the infill material. The Tables also show that analytical equations by AIJ and Cusson are very conservative and probably useful for confined strength of high strength concrete or for slender composite stub columns.

4. Conclusions

This paper presents the results of an experimental programme which investigated the structural performance of concrete filled UPVC tubular columns under compressive load. The study determined that UPVC are effective in confining concrete, as evidenced by the increased compressive strength of confined concrete when compared to unconfined concrete. The enhancement in strength due to confinement of circular columns is substantial and depending on the level of confinement, strength is increased anywhere from 1.18 to 3.65 times the unconfined strength values. It was evident that confinement effectiveness is dependent on the strength of concrete where higher strength concrete results in reduced confinement effectiveness attributable to reduced lateral expansion hence reduced interaction with the confining UPVC tube. Low strength concrete, on the other hand, tends to be more ductile than high strength concrete, hence enabling enhanced composite interaction with the confining medium.

The study also discusses existing analytical models for the determination of confined concrete strength by UPVC tube, and proposes an improved analytical model that, unlike existing models, incorporates the effect of concrete properties on the confining lateral pressure. The proposed analytical model is determined to give the best estimation of confined compressive strength of concrete when compared to existing analytical models. The proposed model introduces a factor which is determined to be equal to 4 from experimental data. By considering several other equations from past works by researchers, α is postulated to correlate to or depend on the combined effects of Poisson's ratio, bulk modulus and strains at ultimate strength for the infill concrete material. The study has determined that **Analytical/Experimental** confined strength of concrete is 101% for the proposed model, while the others are 93%, 97%, 109%, 56% and 49% respectively. It also determined that the proposed model gives the lowest standard deviation as compared to the other existing analytical models.

It is generally demonstrated that UPVC tubes have a great potential for use as the encasing medium in concrete filled tubular columns. The tubes will further serve as permanent formwork during construction. With regard to fire, available literature confirms the UPVC pipes do not support combustion and are self-extinguishing. They are, therefore, ideally suited for use in buildings and other constructions. It is also documented that UPVC is of superb chemical resistance since it is unaffected by most concentrations of acids, alkalis, organic chemicals, oils and fats. This resistance to corrosion by most chemicals makes uPVC pipes indispensable for use in marine structures or in corrosive environments.

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