Performance of UPVC Pipe Confined Concrete Columns in Compression

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DECLARATION

This thesis is the original work and has not been presented for a degree in any other university.

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DEDICATION

To the Almighty God, my family and my fiancée, Ruth Wambui.........with love.

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
BRE	British Research Establishment
BS	British Standard
CFFRP	Concrete Filled Fiber-Reinforced Polymer
CFPT	Concrete-Filled plastic Tube
CFST	Concrete-Filled Steel Tube
CFT	Concrete-Filled Tube
FM	Fineness Modulus
FRP	Fiber-Reinforced Polymer
LVDT	Linear Variable Displacement Transducer
PVC	Polyvinyl Chloride
UPVC	Unplasticized Polyvinyl Chloride
USBR	United States Bureau of Reclamation
UTM	Universal Testing Machine

LIST OF SYMBOLS

$\mathbf{A_{sp}}$	Cross-sectional area of steel spirals (mm^2)
$\mathbf{d_s}$	Diameter of the steel spirals (mm)
E	Elastic modulus of the tube in the hoop direction (N/mm^2)
f_c	Specified characteristic strength of concrete (N/mm^2)
f'_{cc}	Compressive strength of confined concrete (N/mm^2)
f'_{co}	Compressive strength of unconfined concrete (N/mm^2)
f'_{cu}	Compressive strength of standard concrete cubes (N/mm^2)
f_m	Target mean strength of concrete (N/mm^2)
f_r	Lateral confining pressure (N/mm^2)
$\mathbf{f_{sy}}$	Yield stress of the steel spirals (N/mm^2)
F_{st}	Tube stiffness (N/mm^2)
M	Margin between the target mean strength and the specified characteristic strength of concrete (N/mm^2)
P	Load (N)
R	Tube outer radius (mm)
$\mathbf{S_{sp}}$	Pitch of the steel spiral (mm)
s	Standard deviation
t	Tube thickness (mm)

ABSTRACT

Composite columns have been used in construction industry with great efficiency for a number of years. This is because composite column offers a superior column system as compared to the conventional column systems such as Reinforced concrete (RC), steel or timber columns. The reason in that composite column utilizes the combined properties of different individual materials. Steel and fiber reinforced polymer tubes have been the commonly used confining media in concrete encased column construction. However, steel is faced with the problem of corrosion especially when used in corrosive environment while manufacture of fiber reinforced polymer involves a rather expensive technology.

This research proposed a novel-type concrete-filled composite column where unplasticized polyvinylchloride (UPVC) plastic tube was used toconfine concrete.Concrete of varying class strengths namely; C30, C25, and C20 were used to fill UPVC tubes. The tubes had outer diameters of 55 mm, 83 mm and 110 mm and thicknesses of 2.5 mm, 3.0 mm and 2.5 mm respectively. The composite columns had slenderness ratios of 2, 3 and 4. The columns were then tested on a universal testing machine (UTM) to determine their behaviour under compressive load. Applied loads, deformation and strains on the specimen were monitored through in-built load cells, Linear Variable Displacement Transducers (LVDTs) and strain gauges respectively.

Results showed that UPVC pipes are effective in confining concrete, since in all cases $f'_{cc}/f'_{co}>1$. Confined strength values increased between 1.18 to 3.65 times the unconfined strength values. Columns filled with low strength concrete tended to be more ductile as since they underwent large deformations under load before failure. This great ductility implied more energy absorption capacity suggesting a potentially earthquake resistant composite column system.

There is enormous potential of UPVC tubes for use in composite systems as illustrated by this research. The resultant is a cheap, more economical type of column for light weight construction. The principal target audience for this project is individuals involved in application of building materials within the construction industry. Since the use of UPVC in confining column is a relatively new area of research, limited literature was available. Long term performance of these columns was also not studied.

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND INFORMATION

Experience gained over the years in countries such as Japan, Europe and the USA reveal that existing construction technology has not delivered the reliability needed [1]. This is evidenced by the severely deteriorated infrastructure and the inability to guarantee safety against natural hazards such as earthquakes. Here in Kenya, there have been various cases of collapse of buildings either under construction or when in use.

Also, the rapid deterioration of infrastructure, especially those constructed in severe environments such as bridge piles as shown in Plate 1.1, has increased the demand for rehabilitating and retrofitting existing concrete columns in building and bridge substructures. It is necessary to strengthen the deteriorated and damaged concrete columns to increase their carrying capacity (axial load and bending moment) and ductility for improved seismic performance [2].

a) Corroded steel piles b) Degraded concrete pile c) Deteriorated timber piles

Plate 1.1 Degradation of conventional piles [6]

Composite columns, made up of reinforced or unreinforced concrete confined with steel tubes, have been used in building construction with great efficiency for many years. Many authors [3-5] have dealt with theoretical and experimental investigations on the behavior as well as the ultimate compressive strength of concrete-filled steel columns.

Advances in the field of composite materials have resulted in the development of Fiber-reinforced polymer (FRP) sheets to confine existing concrete columns. The resulting column system is characterized by enhanced compressive strength and ductility and improved durability over conventional systems. Existing studies on the seismic behavior of FRP confined concrete columns have shown that FRP confinement can substantially improve the inelastic deformability of concrete columns [7,8]. In recent years, the compressive behavior of FRP-confined concrete has been studied extensively. Few authors [9,10] tested to-collapse concrete columns wrapped using carbon and fiberglass sheets. Saafi et al., [9], reported that the increase in axial stress over the confined specimen ranged from 51 to 131 percent for the concrete-filled glass tubes and 57 to 177 percent for the concrete-filled carbon tubes.

However, due to the high cost of advanced composite materials, the use of these materials in composite columns in light construction is not recommended. Another alternative to the advanced composite materials tubing would be the commercially available plastic unplasticized polyvinylchloride (UPVC) sewer pipes. The strength, ductility and energy absorption capacity of new concrete columns can be enhanced by providing external confinement by employing UPVC tubes [11].The tubes in composite construction will be used as formwork during construction and thereafter as an integral part of the column.

Plastics have exceptional properties, which make these materials attractive for different structural applications. Some of these properties include high resistance to severe environmental attacks, electromagnetic transparency and high strength to weight ratios. Due to these properties, there is great demand for structures such as piling, poles, highway overhead signs and bridge substructures to be made of materials that are more durable in comparison to traditional materials and systems [12]. Use of plastics in construction has been witnessed in Kenya's Nairobi-Thika highway where recycled plastic have been used to manufacture posts for road signs. UPVC is a polymer used vastly in the construction industry. UPVC tubes are characterized by having light weight which makes them easy to handle. They are impermeable to fluids and are durable (their life cycle in civil engineering construction goes beyond 50 years [12]. Very few authors [11-14] have dealt with the ultimate strength of plastic columns with concrete core.

1.2 PROBLEM STATEMENT

As stated earlier, existing construction technologies have not delivered the reliability that is required. Governments in various countries are now investing heavily to develop unique high performance construction materials and systems. Special interest is being directed towards advanced composite materials and systems. An example of advancement into these types of new composite systems is the concrete-filled steel tube (CFST) column systems. CFSTs have been used for years as piles and columns and extensive research has been established in this area of advanced composite construction materials [15,16]. However, CFSTs have the problem of corrosion of steel tubes as well as reduced confinement effectiveness at low levels of loading if the tube is also loaded in the axial direction. This is due to the fact that Poisson's ratio of concrete at low levels of loading is smaller than the value for steel [17].Mirmiran and Shahawy [18] observed that the differential radial expansion of steel tube and concrete, at low levels of loading, results in partial separation between the two materials. This separation leads to a premature buckling of the tube. Thus, effective confinement will only be achieved at higher loading when concrete begins to crack as it expands faster than the steel tube and becomes well confined [19]. An alternative to CFSTs is FRP composites which have been used as precast piles, girders, and pier columns [20,21]. As opposed to steel CFTs, Poisson's ratio of FRP tubes can be controlled through selected design of the laminate structure to provide more confinement effect [22]. The confining pressure provided by steel tubes is limited to a constant value once the tube yields, whereas FRP tubes provide a continuously increasing confining pressure, which adds to both the ultimate confined strength and ductility [23].However, with the high cost of advanced FRP composite materials, the use of concrete-filled fiber reinforced polymer (CFFRP) material in composite columns in light construction is not recommended. An alternative to the advanced composite materials tubing is the commercially available UPVC plastic pipes. The tubes are corrosion resistant and are inexpensive as compared to the steel and FRPs. Typical cost for different tube materials is as shown in Table 1.1.

Table 1.1 Typical cost data for some construction materials

Pipe serial size/ diameter (ins.)	Material cost per meter length (Ksh/m)		
	Steel (Ungalvanished) [24]	FRP [25]	UPVC [26]
2"	217	3170	125
3"	383	4380	175
4"	420	5600	250

Thus this research focused on investigating the behaviour of concrete-filled UPVC tubular columns subjected to compressive loads.

1.3 RESEARCH OBJECTIVES

1.3.1 OVERALL OBJECTIVE

To investigate the performance of concrete-filled UPVC plastic tubes when subjected to concentric axial compressive loads.

1.3.2 SPECIFIC OBJECTIVES

1) To determine the effect of concrete strength, column diameter and column height on the strength and ductility of the composite stub columns.
2) To determine the effectiveness of plastic tube confinement on the concrete columns.
3) To determine the ultimate load capacity enhancement on the composite column.
4) To determine axial stress, strain and deformations and radial strains characteristics of the composite columns.

1.4 JUSTIFICATION

By the year 2008, the cost of formwork was about 40% of the cost of concrete works, the rest being accounted for by labour and the cost of materials [27]. Eliminating or reducing this formwork in construction can significantly reduce the cost of construction. The use of plastic tubes will act as a confinement material as well as a permanent formwork and this will eliminate the need for temporary formwork.

Steel and FRP tubes have been widely researched on and used to confine concrete in CFT columns systems. However steel is prone to corrosion, weathering, and chemical attacks especially when used in severe environments such as under-sea piling. Moreover, the manufacture of FRP involves a rather expensive technology. Concrete-filled plastic tube columns thus offer such advantages as improved durability in harsh environments and cost saving during the life cycle.

A major characteristic of UPVC pipes is that they are elastic, and thus undergo large deformation under load. The strength and stiffness of thermoplastics are not high when compared with those of metals. Values of strength of unfilled thermoplastics as measured by conventional tensile tests normally lie in the range 10-100 MN/m^2, compared with at least 200 MN/m^2 for steel and the majority of aluminum alloys. Values of Young's modulus based on similar tests for thermoplastics normally lie in the range 0.3-3 GN/m^2, compared with about 70 GN/m^2 for aluminum and 200 GN/m^2 for steel [28]. Concrete on the other hand fails by developing a shear plane when loaded in compression, which is typical of brittle failure since there is little warning of impeding failure. With these opposing properties of the constituent materials, a composite section strikes a balance leading to a section with desirable characteristics for engineering application [27]. Hence, in comparison to steel CFTs, plastic CFTs produce a column system which exhibit more ductile characteristics.

UPVC pipes are characterized by a light weight as opposed to steel pipes. This implies that the resulting column system will have reduced weight. This is a good attribute for light construction and also for reducing the overall weight of the structure. Consequently, the manpower required in erecting these columns will be lower than that of steel CFT columns by the virtue of their light weight resulting in low unit labour charge.

There is great demand for new technologies in the construction industries that meet the current needs of the society. Some of the critical needs include: construction that utilizes the least materials especially for temporary work; utilization of locally available materials most of which are a waste and a nuisance to the environment and have to be recycled; structures that can be built using least cost as much as possible; construction that will involve the least of on-site work especially in urban areas that have the challenge of inadequate storage and working space [27]. This research was inspired by the above enumerated problems and geared toward providing solutions to some of these problems by providing new construction materials and technologies.

1.5 SIGNIFICANCE OF THE RESEARCH

A more flexible, highly ductile type of a column, as opposed to the conventional reinforced concrete column and steel columns incorporating UPVC pipes is introduced into the construction market. The column system will compliment and/or supplement the current systems thus easing the burden that is already imposed on these traditional construction materials, i.e., steel, timber and concrete. The resulting product is composite section exhibiting better engineering performance in terms of strength and ductility.

Use of plastic pipes in construction encourages recycling of the currently nuisance plastic. This leads to a cleaner environment [27] and more sustainable environment since plastics are highly recyclable as compared to other construction materials.

One of the most challenging aspects of the adoption of new construction techniques is lack of adequate information regarding the performance of a new product. This research provides some of the behavioral performance of the concrete-filled UPVC pipe as structural columns. The knowledge will instill confident to all players in the construction field encouraging speedy adoption of this new system into construction.

This research extends the knowledge in the area of concrete-filled PVC tubes, used as structural members, by addressing new parameters intended to simulate practical applications and loading conditions. This is necessary in order to provide a comprehensive data base for the design of this composite column. This is in regard to Marzouck and Sennah [12] who proposed that "a comprehensive experimental study is required to provide a database for experimental compressive strength of concrete filled PVC tubes. This database would include different tubes thicknesses, slenderness ratios and concrete properties."

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 CONCRETE

Concrete is an essential material. It had a worldwide estimated consumption of between 21 and 31 billion tonnes in 2006 and was the second most consumed substance on earth after water [29]. A world without concrete is almost inconceivable!

Concrete is made from mixing coarse aggregates (gravel or crushed stone), fine aggregates (sand), water, cement (or other cementitious material) and/or admixtures. These constituents are available locally and in virtually unlimited quantities. Primary materials can be replaced by aggregates made from recycled concrete. Waste materials such as fly ash, slag and silica fumes from other industries can be used to produce additions. The mixture, when placed in forms and allowed to cure becomes hard like stone. The hardening is caused by chemical action between water and the cement making concrete grows stronger with age. The strength, durability and other characteristics of concrete depend upon the properties of its ingredients, proportion of the mix, the method of compaction and other controls during placing, compaction and curing.

2.2CONCRETE MIX DESIGN

Concrete mix design is best defined as a process of selecting suitable ingredients, i.e., cement, water, coarse aggregate and fine aggregate with admixtures if any, and determining their relative proportions to give the required strength, workability and durability. Workability is specified as an important property of concrete in the fresh state. In hardened state, compressive strength and durability are of great significance.

2.2.1FACTORS CONSIDERED IN MIX DESIGN

(a) **Grade of concrete:** This gives the characteristic strength requirements of concrete. Depending upon the level of quality control available at the site, the concrete mix has to be designed for a target mean strength which is higher than the characteristic strength.

(b) **Type of cement:** The type of cement is important because of its influence on the rate of development of compressive strength of concrete as well as durability under aggressive environments. Ordinary Portland cement (OPC) and Portland Pozzolona cement (PPC) are the generally used cements in reinforced concrete construction.

(c) Type and grading of aggregate: Particle shape affects the workability of concrete while surface texture mainly affects the bond between the matrix and the aggregate particles and thus the strength of the concrete. Generally, crushed aggregates consist of angular particles having a rough surface texture resulting in concrete of lower workability but higher strengths compared with a mix made with uncrushed aggregates. It is found that the larger the size of aggregate, the smaller is the amount of cement required for a particular water cement ratio. Aggregates having a maximum nominal size of 20mm or smaller are generally considered satisfactory.

(d) Minimum water cement ratio: The minimum w/c ratio for a specified strength depends on the type of cement.

(e) Workability: The workability of concrete for satisfactory placing and compaction is related to the size and shape of the section to be concreted and is mainly influenced by the free water content available for cement hydration.

2.2.2METHODS OF CONCRETE MIX DESIGN

The mix design methods being followed in different countries are mostly based on empirical relationships, charts and graphs developed from extensive experimental investigations. Two of the most commonly used methods namely; American Concrete Institute (ACI) method and the British research establishment (BRE) method are described below.

1. ACI Mix design method

This method is based on determining the coarse aggregate content based on, dry-rodded coarse aggregate bulk density and FM of sand. Thus this method takes into account the actual voids in compacted coarse aggregates that are to be filled by fine aggregates, cement and water. The method also gives separate tables for air-entrained and non air-entrained concrete and is most suited for the design of air-entrained concrete. The method gives separate values of water and sand content for maximum size of aggregate up to 150 mm. Hence this is most suitable method for designing plum concrete. It also gives separate values for 12.5 and 25 mm down coarse aggregate.

This method suffers from following limitations: -

(a) It gives coarse aggregate contents for sand with FM range of 2.4 to 3.0. It thus ignores extremely coarse aggregates with FM more than 3.2.

(b) In this method the density of fresh concrete is not given as function of specific gravity of its ingredients. In IS (Indian Standards) and British mix design method the plastic density or yield of concrete is linked to specific gravity of ingredients.

(c) The values of density of fresh concrete given in this method range from 2285 kg/m^3 for 10 mm down aggregate to 2505 kg/m^3 for 150 mm down coarse aggregate. It is found that in many countries, the density of fresh concrete (plastic density) of 20 and 10 mm down aggregates vary from 2400 to 2600 kg/m^3. The weights calculated from the given densities often result in high cement contents.

(d) The ACI method does not take into account the effect of the surface texture and flakiness of aggregate on sand and water content, neither does it distinguish between crushed stone aggregates and natural (uncrushed) aggregates.

(e) The ACI method does not have a specific method of combining 10 mm aggregates with 20 mm aggregates.

(f) The fine aggregate content cannot be adjusted for different cement contents. Hence the richer mixes and leaner mixes may have same sand proportion, for a given set of materials.

2. British Mix design method

This design procedure is applicable to concrete for most purposes. The method is restricted to designing concrete mixes to meet workability, compressive strength and durability requirements using Portland cements complying with BS 12 [30] or BS 4027[31] and natural aggregates complying with BS 882[32] or coarse air-cooled slag complying with BS 1047[33]. It does not deal with special materials or special concretes such as lightweight aggregate concrete, or with flowing or pumped concrete. This method is based on data obtained at the Building Research Establishment, the Transport Research Laboratory and by the British Cement Association.

The British mix design method was adopted for the design of the concrete mixes in this research. The design process was guided by the BRE manual [34] and some design tables and figures have been extracted from the manual and attached as appendices at the end of this thesis report for ease of referencing by the reader. The design process is divided into five stages. Each of these stages deals with a particular aspect of the design and ends with an important parameter or final unit proportions.

Stage 1: Selection of target water/cement ratio

(i) The required characteristic strength (f_c) for each concrete mix is specified at 28 days, in this case, 20 N/mm^2, 25 N/mm^2 or 30 N/mm^2.

(ii) The margin, which is the target mean strength less specified characteristic strength as a result of variability in concrete production, is calculated as follows [34].

$M = k \times s$ .... (2.1)

Where; M is the margin

k is a value appropriate to the 'percentage defectives' permitted below the characteristic strength. (k = 1.64 for 5% defect was adopted as specified in BS 5328[35]

s is the standard deviation. (Obtained from line A in Figure 3 [34])

(iii) The target mean strength, f_m, is then calculated as follows [34].

$f_m = f_c + M$ .... (2.2)

Where f_m is the target mean strength

f_c is the specified characteristic strength

M is the margin between the target mean strength and the specified characteristic strength of concrete

(iv) Given the cement strength class and type of aggregates used, a value of compressive strength for a mix made with a free water/cement ratio of 0.5 is read from table 2 [34]. The value of compressive strength obtained is then plotted on figure 4 [34] and a curve drawn from this point and parallel to the printed curves until it intercepts a horizontal line passing through the ordinate representing the target mean strength, f_m. The corresponding value for the free-water/cement ratio is read from the abscissa and compared with the specified maximum free-water/cement ratio and the lower value is adopted.

Stage 2: Selection of free-water content

The value of free-water content required for both fine and course aggregates are read from table 3 [34]. The value depends on the type, i.e., crushed/uncrushed and maximum size of the aggregate and this gives a concrete of the specified slump. The total free water content is then calculated as follows [34].

$$W = \frac{2}{3}W_f + \frac{1}{3}W_c \qquad (2.3)$$

Where; W_f is the free-water content appropriate to type of fine aggregates

W_c is the free-water content appropriate to type of coarse aggregates

Stage 3: Determining the Cement Content

The cement content is then calculated as follows [34].

$$\text{Cement content} = \frac{\text{free water content}}{\text{freewater/cement ratio}} \qquad (2.4)$$

The resulting value is checked against maximum and minimum value that may be specified based on the following criteria; Minimum cement content required for plain concrete to meet durability, under mild exposure, with coarse aggregates nominal size 20 mm as read from Table 2.1

Table 2.1Equivalent grades for cement content and w/c ratio for 20 mm aggregate concrete [36]

Minimum cement content (kg/m3)	Maximum free water/cement ratio	Equivalent grade
200 - 210	_	C15
220 - 230	0.80	C20
240 - 260	0.70	C25
270- 280	0.65	C30

Stage 4: Determining the Total Aggregate Content

An estimate of the density of the fully compacted concrete is obtained from Figure 5 [34].The density depends on the free-water content and the relative density of the combined aggregate in the saturated surface-dry condition (SSD). From this estimated density of the concrete the total aggregate content is calculated as follows [34].

$$TA = D - C - W \quad (2.5)$$

Where: TA is the total aggregate content (kg/m^3)

D is the wet density of concrete (kg/m^3)

C is the cement content (kg/m^3)

W is the free-water content (kg/m^3)

Stage 5: Selection of fine and coarse aggregate contents

The recommended value for the proportion of fine aggregate is obtained from figure 6 [34].The value depends on the maximum size of aggregate, workability level, the grading of the fine aggregate (defined by its percentage passing a 600 µm sieve) and the free-water/cement ratio. The proportions are then calculated as follows [34].

$$\left.\begin{aligned} FA &= TA \times \text{Proportion of Fines.} \\ CA &= TA - FA \end{aligned}\right\} \quad (2.6)$$

Where: FA is the fine aggregate content (kg/m^3)

CA is the coarse aggregate content (kg/m^3)

For the coarse aggregate, the proportioning is 1:2 for combination of 10 and 20 mm single size materials.

2.3 POLYMERS

A polymer is a long chain hydrocarbons produced by combining small molecular units (monomers) in a chemical process known as polymerization to form long chain molecules [37]. Polymers are usually formed in one of the two polymerization processes, step-reaction (or condensation) or chain-reaction (or addition) polymerization. In condensation polymerization process, the linking of molecules creates by products, usually water, and hydrogen and nitrogen gas. However no by-products are created in addition polymerization process [37]. Two main types of polymer matrices results from these two polymerization processes namely; thermosets and thermoplastic.

Thermosetting polymers contain polymers that cross-link together during the curing process to form an irreversible chemical bond [38]. The cross-linking process eliminates the possibility of the product re-melting when heat is applied, making thermosets ideal for high-heat applications such as electronics and appliances. Thermoset plastics significantly improve the material's mechanical properties, providing enhances chemical resistance, heat resistance and structural integrity. Thermoset plastics are often used for sealed products due to their resistance to deformation. Some of the advantages associated with thermosets are, more resistant to high temperatures than thermoplastics, highly flexible design, thick to thin wall capabilities, excellent aesthetic appearance, high levels of dimensional stability and cost-effectiveness. The shortcoming of using thermosets is that, they cannot be recycled, they are more difficult to surface finish and they cannot be remolded or reshaped. Examples of thermosets include polyesters, epoxies and phenolics [38].

Thermoplastic polymers soften when heated and become more fluid as additional heat is applied. The curing process is completely reversible as no chemical bonding takes place. This characteristic allows thermoplastics to be remolded and recycled without negatively affecting the material's physical properties [38]. There are multiple thermoplastic resins that offer various performance benefits, but most materials commonly offer high strength, shrink-resistance and easy bendability. Depending on the resin, thermoplastics can serve low-stress applications such as plastic bags or high-stress mechanical parts. Some of the advantages associated with thermosets are, highly recyclable; provide aesthetically-superior finishes; have high-impact resistance; remolding/reshaping capabilities; resistant to chemical attack; provide hard crystalline or rubbery surface options; and eco-friendly manufacturing. The disadvantages of thermoplastics are that they are more expensive than thermosets and can melt if heated. Examples in this category include polyvinyl chloride (PVC), polypropylene, nylon and polycarbonate [38]. Thermoplastics constitute a group of materials that are attractive to the designer for two main reasons:

(1) Their basic physical properties can be exploited in a wide range of properly designed articles that have the stiffness, robustness and resilience to resist loads and deformations imposed during the normal use and,

(2) They can readily be processed into three dimensional products of complicated shapes with repeatable dimensions, using efficient mass-production techniques that can result in low unit labour charge [28].

One of the most common thermoplastic in daily usage is polyvinyl chloride (PVC). PVC exists in unplasticized and plasticized forms, and in copolymers. Unplasticized PVC (UPVC) is hard, tough, strong, stiff and abrasion resistant, does not burn on its own and can be highly transparent. Anti-corrosion characteristics of UPVC have been proven to be outstanding. Thermal conductivity of UPVC is only 0.45% that of steel tube. This provides a stable curing condition for the concrete core to achieve high performances and high durability. The service life of UPVC tube is longer than 50 years, and with the mechanical supporting of the concrete core, it can serve longer as a protective layer of the concrete structure [11].UPVC is mainly used in the manufacture of large-diameter pipes for potable and non-potable water supply systems, waste drainage systems among other uses. Some of the physical properties of UPVC pipes are illustrated in Table 2.2.

Table 2.2 Physical properties of UPVC pipes [11].

Parameter	**Value**
Density	1300-1450 Kg/m^3
Elastic modulus	3380 Mpa
Flexure stiffness	65.5 Mpa
Poisson ratio	0.38
Ultimate tensile strength	27.5- 52 Mpa
Breaking elongation	134%
Thermal conductivity	0.14 - 0.28 kcal/m.hr^{o}c
Service life	> 50 years

Plasticized PVC is usually more flexible than UPVC. It has a wide range of use, including manufacture of industrial gloves, shoe soles, domestic electric insulation, hosepipes and tank linings

Vinyl chloride copolymer, a copolymer of vinyl chloride with vinyl acetate, has physical properties similar to those of PVC when plasticized and is easier to thermoform and mould.

PVC pipes are commonly used in civil engineering works to convey water and waste water. They are impermeable to fluids and are durable. Their life cycle in civil engineering construction goes beyond 50 years [12]. The pipes are supplied in a range of different sizes and strengths depending on the use. The light plastic materials have been used in construction mainly for aesthetics and there is very limited use structurally due to their anticipated low load carrying capacity. PVC however is non corrosive, which makes it useful in the construction of certain structures exposed to corrosive environments. PVC tubes are characterized by having light weight which makes them easy to handle.

2.3.1 POLYMER COMPOSITES

Generally, a composite structure is made by combining two or more materials without chemical interaction. This gives a unique combination of improved properties that are better than those of the individual constituents. The above definition is more general and can include plastic co-polymers, minerals and wood. FRP composites differ from general composite materials in that the constituent materials are different at the molecular level and are mechanically separable. In bulk form, the constituent materials work together but remain in their original form. The final properties of composite materials are better than constituent materials properties.

2.3.2 EVOLUTION OF POLYMER COMPOSITES IN CONSTRUCTION

Since ancient times humans used fibrous composites in different forms, e.g., straw-reinforced clay, timber and paper [39]. By the beginning of 20th century steel-reinforced concrete evolved as a different form of structural composite. The middle of the century saw the development of fiber composite plastics as a new and effective form of fibrous composites also referred to as fiber reinforced plastics (FRP). This FRP material is characterized by high strength-to-weight ratio and durability in corrosive environments [40]. This makes it to be highly preferred for aerospace and marine industry. Over the last two decades, the application of FRP has become increasingly popular in civil engineering infrastructure.

FRP provides an effective solution for the chloride induced deterioration of reinforced and pre-stressed concrete bridges making it useful for structural repair [41]. FRP has been considered to be rather expensive but recent advances in new and automated manufacturing processes have made it more affordable and competitive with other materials [42].

During the present decade intensive research has been conducted in order to investigate the properties of FRP as a new construction material. The effect of corrosive environment, i.e., salt spray, humidity, and high temperature, on concrete cylinders jacketed with S-glass and Kevlar were investigated by Bavarian et al. [43]. It was reported that there was no loss of strength or ductility. Effects of more severe environmental effects like low temperatures, freeze-thaw cycles, and sea water on FRP have also been investigated [44,45]. It was seen that degradation of strength was not substantial. Properties of carbon fibers have proven most stable in such environments. As far as long term behavior of FRP is concerned, it has been established that external carbon fiber wrap on concrete beams can significantly decrease the creep strains in concrete [46,47].

2.4 CONFINEMENT OF CONCRETE COLUMNS

2.4.1 INTRODUCTION

It is well known that confinement improves the strength and ductility of concrete [48,49]. For an axially loaded concrete element, transverse strains are induced, resulting 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 and 0.25. After reaching a certain critical stress (typically between 60% and 80% of the concrete strength), micro-cracking formation occurs in concrete and transverse strains increase quickly leading to large transverse strains for relatively small longitudinal strain. These micro-cracks evolve to macro-cracks that eventually lead to rapture of concrete.

The confinement mechanism of concrete is related to the use of materials that provide tensile strength to restrict this increase in transverse strain. At high levels of loading, confined concrete is in a tri-axial compression state of stress. In this state, the concrete depicts a superior behaviour in both strength and ductility than concrete which is uni-axially compressed.

The effect of confinement on concrete has been recognized since the early days of structural concrete. Many confinement models have been developed in order to predict the response of confined concrete. Concrete is often said to be “pressure-sensitive”, while it is perhaps better characterized as "restraint-sensitive" [50]. This clarifies why the stiffness of confining member has such a major effect on the behavior of confined concrete [51]. Also, the geometry of the cross-section and the state of loading are both factors limiting the applicability of each confinement model.

By the beginning of the 20th century some research was conducted in order to evaluate the enhanced strength of concrete due to confinement. The early tests mainly considered the 'active' state of confinement, in which the confining pressure was kept constant during the entire loading process. Considere [52] tested the tri-axial behavior of 80 mm x 300 mm mortar cylinders in which the lateral confinement was provided by constant hydraulic pressure. From the test results, the following relationship to predict the compressive strength of confined concrete was proposed:

$$f'_{cc} = k_l f'_{co} + 4.8 f_r \quad (2.7)$$

where, f'_{cc} and f'_{co} are the compressive peak stress of the confined and unconfined concrete, respectively, k_l is a constant varying between 1 and 1.5 and f_r is the lateral confining pressure.

Those findings were further investigated by Richart, Brandtzaeg, and Brown [53] for concrete cylinders. They subjected 100 mm x 200 mm normal-weight concrete cylinders to constant hydraulic pressure while applying the axial compressive load until failure. They defined the confined strength of concrete as:

$$f'_{cc} = f'_{co} + k_c f_r \quad (2.8)$$

The average value of confinement coefficient, k_c, for the tests they conducted was 4.1.

One of the deficiencies in concrete columns is lack of confinement and low energy absorption capacity [54].Concrete columns can be confined by:

1. Lateral reinforcement in the form of steel ties or spirals;
2. Encasing concrete in steel tubes;
3. External fiber composite wraps;
4. Encasing concrete in fiber composite tubes; or
5. Encasing concrete in plastic tubes (a new technology)

All these means of confinement produce the so-called 'passive' state of confinement, in which the confining effect is a function of the lateral expansion of the concrete core [40].As the axial stress increases, the corresponding lateral strain increases and the confining material develops a tensile hoop stress balanced by a uniform radial pressure, which reacts against the concrete lateral expansion [55,56]. When a confined column is subject to axial compression, the concrete expands laterally and this expansion is restrained by the confining media.

The measure of how well a certain material confines concrete is referred to as confinement effectiveness. It can be defined as f'_{cc}/f'_{co}, where f'_{cc} is the compressive strength of confined concrete and f'_{co} is the compressive strength of unconfined concrete.

2.4.2 CONFINEMENT BY LATERAL STEEL REINFORCEMENT

Richart, Brandtzaeg, and Brown [57] conducted a series of tests on 'passively' confined concrete. A series of 23 short circular concrete columns, 250 mm x 1000 mm, were tested under concentric compression. The columns were externally wrapped by mild steel spirals at 25.4 mm pitch. The diameters of the spirals varied from 3.2 mm to 9.5 mm. It was found that the confined compressive peak stress f'_{cc} could be expressed by the same equation developed for 'active' confinement (eqn. 2.8) and using the same confinement coefficient of 4.1. The confinement pressure f_r was calculated based on the maximum stress in the steel spirals using the hoop tension formula, thus

$$f_r = \frac{2 f_{sy}\, d_s}{D} \qquad (2.9)$$

Where; f_{sy} is the yield stress of the confining spirals

d_s is the diameter of the confining spirals

D is the inside diameter of the column.

However, the effect of spiral spacing was not taken into account.

Iyengar et al. [58] investigated the effect of spiral spacing. A series of spiral-reinforced normal-weight concrete cylinders were tested under concentric compression. The specimens were of two sizes: 100 mm x 200 mm with spiral pitches ranging from 30 mm to 98 mm and 150 mm x 300 mm with pitches ranging from 30 mm to 118 mm. It was concluded that the strength enhancement due to the spiral confinement could still be represented by equation 2.8 with a confinement coefficient of 4.6 instead of 4.1. A modified expression for the confining pressure f_r, was suggested as shown in equation 2.10 [58]:

$$f_r = \frac{2A_{sp} f_{sy}}{DS_{sp}} \quad (2.10)$$

Where; A_{sp} is the cross-sectional area of the spirals

f_{sy}, is the yielding stress of the spirals

S_{sp} is the pitch of the spiral of the spirals

D is the inside diameter of the column.

2.4.3 CONFINEMENT BY STEEL TUBES

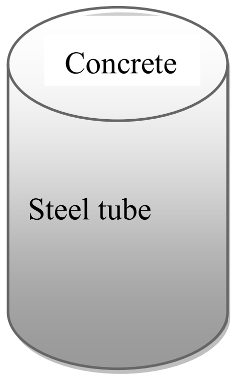

Figure 2.1 Concrete-filled steel tube

Another form of concrete confinement is by encasing concrete in a steel tube as illustrated in Figure 2.1. The steel tube acts as longitudinal, transversal, and shear reinforcement; formwork; and as a continuous confining jacket for the encased concrete. In return, concrete delays local buckling of the tube [59]. Knowles and Park [15] conducted a series of tests on concrete-filled steel tubes of different slenderness ratios, and concluded that in most cases buckling of the tube dictated the overall failure of the composite column before the activation of confinement. It was recommended that for full utilization of the tube's confinement capabilities in the circumferential direction, it should not be directly loaded in the longitudinal direction. This was later confirmed by Orito et al. [60], where it was determined that unbonded concrete-filled steel tubes had higher axial compressive strength in comparison with the bonded tubes.

Prion and Boehme [61] performed a series of tests on concrete-filled circular steel tubes. It was reported that the confinement effect is noticeable for a slenderness ratio, L/D, less than 15, where L and D are the height and diameter of the column, respectively. The failure mode for short columns (L/D < 15) was a shear failure of the concrete core. Structural steel tubes have been extensively studied for purpose of concrete confinement in past two decades and as a result numerous literature [62,63] is available.

2.4.4 CONFINEMENT BY FRP WRAPS

Since early 1980's, fiber composites have been used for confinement of concrete. Fardis and Khalili [64] wrapped bi-directional FRP fabrics on 75 mm x 150 mm and 100 mm x

200 mm concrete cylinders. Different types of FRP fabrics were used. The specimens were tested under uni-axial compression. It was concluded that confinement by FRP not only increases concrete strength, but enhances its ductility, as well. Practical use of FRP wrap is demonstrated in Plate 2.1 below

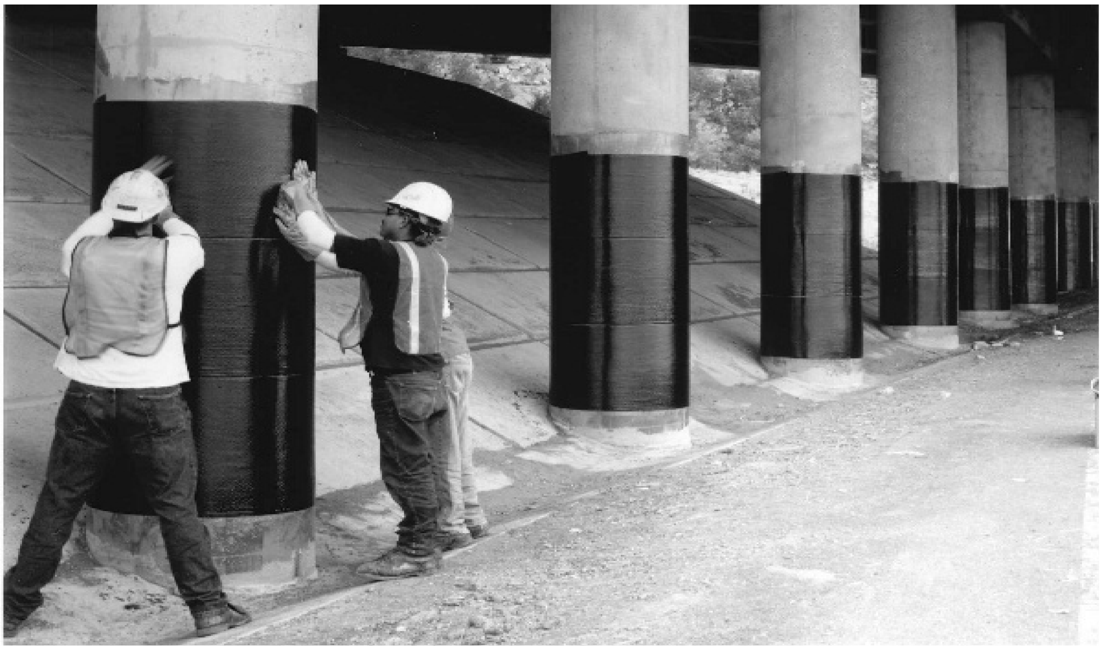

Plate2.1 FRP wrap being installed on a highway column in California, USA (Courtesy of Sika Corporation)

2.4.5 CONFINEMENT BY FRP TUBES

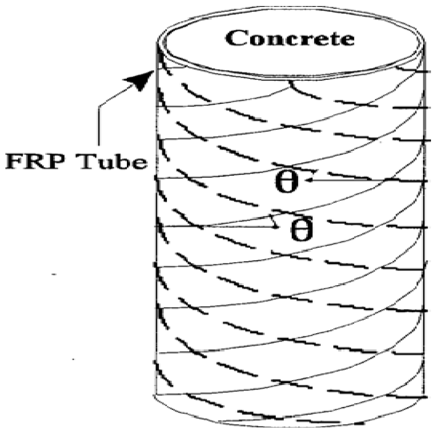

Figure 2.2 Concrete confinement using FRP tube

In early 1990's, as part of an investigation on the effect of confinement on high-strength concrete, Lahlouet al. [65] tested two 50 mm x100 mm fiber glass tubes filled with concrete. Since the fibers were axially oriented, no significant enhancement in the strength of concrete was observed.

Mirmiran and Shahawy [66] proposed a CFFRP tube as shown in Figure 2.2. The tube acted as formwork for the encased concrete, hoop and longitudinal reinforcement, and corrosion resistant casing for the concrete. It basically consists of a filament-wound FRP tube filled with concrete as illustrated in Figure 2.2. This CFFRP tube is comparable to the concrete-filled steel tube

(CFST).The CFFRP tube system was proposed for bridge columns as well as for pile splicing.

The Florida Department of Transportation (FDOT) sponsored a series of projects in order to investigate the behavior of the proposed CFFT. Several parameters were considered in these studies, e.g., the type of loading, the cross-section, the bond, and the length effect. Kargahi [67] investigated the strength of CFFT under uni-axial compression. A total of 12 circular specimens were tested; nine CFFRPs tubes and three-150 mm x 300 mm plain concrete cylinders. Filament-wound E-glass/polyester tubes were used, with winding angle of ±75° with respect to the longitudinal axis of the tube. Three different tube thicknesses were included. An enhancement in the concrete strength, in the order of 2.5-3.5 times the unconfined strength, was reported. A series of split-cylinder tests were performed in order to investigate the improvement of the tensile strength of the FRP-confined concrete. It was concluded that the FRP tube improves the behavior of the concrete section in tension by containing the cracked concrete rather than confining it. A parametric study was also performed on the effect of ply thickness, winding angle, and the composite action on the confined strength of the column. The analysis was based on the confinement model of Mander et al., [49]. It was concluded that the thickness of the tube increases the pure axial strength. The presence of full composite action does not significantly improve the axial capacity of the column but rather the flexural capacity. Moreover, an increase in the fiber winding angle will decrease the pure axial strength. The pure flexural capacity is maximum at a winding angle of $\pm 45^0$.

The bond effect was investigated by Mastrapa [68]. A total of 32 150 mm x 300 mm composite cylinders were tested, half of which were wrapped in 1, 3, 5, or 7 layers of S-glass fabric, while for the other half concrete of the same batch was poured in tubes made of the same S-glass fabric and with the same number of layers. Tests were done in two series. In Series 1, multi-layer jackets were made layer-by-layer with a splice of about 17% of the perimeter of the cylinders. In Series 2, the jacket was made of a continuous wrap of the fabric with an overlap of about 32% of the perimeter of the cylinder. It was concluded that the effect of construction bond on axially loaded confined concrete is not significant.

Pico [69] tested a total of nine 150 mm x 150 mm x 300 mm square concrete-filled FRP tubes under axial compression, in order to study the effect of cross section of the CFFT. No bond was provided between the concrete core and the FRP tube. A marginal increase in strength was observed independent of the jacket thickness. The over-riding parameter in controlling the confinement was shown to be the product of the corner radius and the confining pressure.

El Echary [70] evaluated the effects of length-to-diameter (L/D) and diameter-to-thickness (D/t) ratios on the behavior of the CFFT. A total of 24 circular CFFTs (D_{inner} is 145 mm) with three different tube thicknesses (6, 10, and 14 layers) and four different lengths (300 mm, 450 mm, 600 mm, and 750 mm) were tested. No buckling was observed during the tests. The analysis of the test results indicated that the maximum eccentricity was within 10-12% of the section width. The reduction in strength was not significant. It was concluded that up to a ratio L/D of 5:1, slenderness effects are negligible.

Recently, other models have been proposed by Fam [71], Fam and Rizkalla [72], Moran and Pantelides [73], Shehata et al. [74], and Becque et al. [75]. Most of these models build upon the simple observation that the typical stress-strain curve of concrete-filled FRP composite columns has an approximately bilinear shape, as shown in figure 2.3.

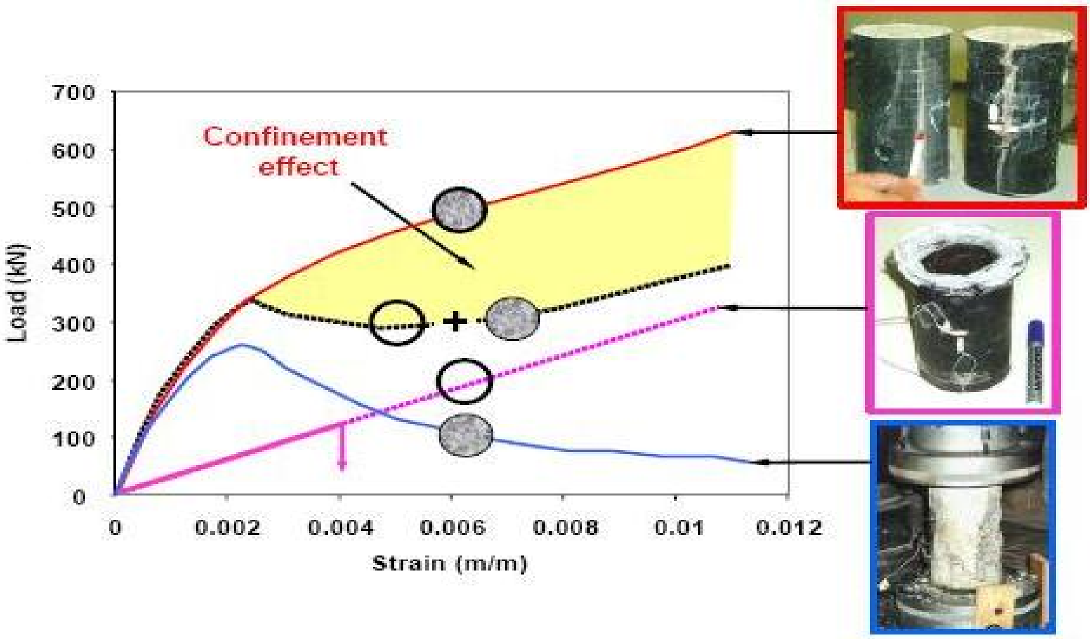

Figure 2.3 Confinement effect of FRP tube on concrete[72].

As shown in Figure 2.3, the FRP tube of a composite pile contributes structurally to the pile by resisting some of the axial load, and by providing confinement to the concrete core. The beneficial effect of confinement on the total load carrying capacity of a short, concrete-filled FRP tubular element was studied by [72]. As illustrated, the capacity of the composite stub significantly exceeds the load sharing capacity of the two individual materials. The load-strain curve starts to depart from the unconfined concrete curve in the vicinity of the unconfined concrete strength. As this stress level is approached, the concrete core starts to experience significant micro-cracking as well as increased lateral expansion. In response to the lateral expansion of the concrete, the FRP shell applies a radial confining pressure, which continuously increases due to its linear elastic properties [71]. The second slope of the load-strain curve is a function of the hoop tensile stiffness of the FRP shell, and the ultimate peak strength is governed by the hoop tensile strength of the FRP shell.

2.4.6 CONFINEMENT BY PLASTIC TUBES

Kurt C. E.[14] suggested using commercially available PVC pipes filled with a concrete core. The theoretical analysis implied an interaction between the concrete core and plastic pipe and a corresponding increase in strength of the concrete core. Under a column loading, the structural behavior of the plastic pipe was similar to the behavior of spiral reinforcement. The plastic pipe increased the strength of the concrete core approximately 3.2 times the pipe burst pressure. For a slenderness ratio of less than 20, plastic-encased concrete showed a 45° shear failure, both in the concrete core and in the plastic pipe, resulting from the combination of axial compression and hoop tension in the pipe. Since the plastic material used by Kurt was weak, the enhancement in the strength of concrete was not significant. Nevertheless his preliminary results depicted concrete-filled PVC pipes as a potentially viable column system for light weight construction.

Few researchers [11-14,27] have ventured into researching on this area and thus limited literature and data are available pertaining to the use of this type of composite column.

Preliminary tests by Marzouk et al. [12] on four PVC confined concrete column specimens and two unconfined concrete columns gave results which showed PVC tubes as a potential confinement material. The results obtained from the said research are as summarized in Table 2.3.

Table 2.3 Specimens properties and strength [12].

SPECIMEN NUMBER	PIPE THICKNESS (mm)	CONCRETE CORE DIAMETER (mm)	HEIGHT (mm)	COMPRESSIVE AXIAL RESISTANCE (kN)
1	3	100	758	287
2	3	100	562	291
3	3	100	416	311
4	N/A	100	416	265
5	3	100	270	318
6	N/A	100	270	287

From the results, the following conclusions and recommendations we made:

(1) The use of PVC tube provides considerable lateral confinement to the concrete columns and hence, increases the ultimate compressive strength of such columns.

(2) Concrete-filled PVC tubes possess a great level of ductility as observed from the axial load-displacement relationship. The tube acts as containment to the failed concrete core and exhibits large lateral deformation before failure.

(3) As the slenderness ratio increases, the compressive strength of concrete filled PVC tube decreases.

(4) Further research is required to evaluate the compressive strength of the concrete-filled PVC tubes with wide range of slenderness ratios and tube sizes, and different concrete properties.

The most recent research by Gupta [11] investigated concrete-filled UPVC pipes of varying diameters, i.e. 140 mm, 160 mm and 200 mm. Three different grades of concrete mixes: M20, M25 and M40 were used to fill the tubes. From this research work, the conclusion was as follows;

1. Confinement of concrete columns with UPVC tubes improves their compressive strength and ductility. The improvement in strength and ductility is dependent on the concrete strength and geometrical properties of the tubes.
2. Failure pattern of all the specimens were shear type failure.

3. Confinement effects of UPVC were comparable with already developed models in the literature and results were varying within ±6%.
4. Compressive strength of concrete affects the post-peak behaviour of the load-compression curve significantly. Absolute value of the slope of the curve increases with increase in concrete strength due to the increased brittleness.
5. The slope of the onset section of the curves goes down with decrease in grade of concrete.
6. The tube diameter/thickness ratio affects the post-peak behaviour of the curve; Absolute value of the slope of the curve declines by decrease in tube diameter/thickness ratio.

However, the research did not investigate on the effect of varying the slenderness (height-to-diameter) ratio since all columns had a constant height of 500 mm.

2.5 SUMMARY

It is apparent that from the review of the few researchers who have ventured into this new area of composite construction, a lot of information regarding the use of PVC pipes in composite columns construction is lacking. This is even with the fact that all these researchers have found a great potentiality in this new material for construction and have strongly stated so in their conclusions and recommendations. The current research focused on investigating various parameters that have not been tackled by previous researchers. The research focused on investigating the effects of tube diameters, heights and also the concrete strengths on the compressive strength, deformation, stress and strain characteristics of the composite columns.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 STUDY SITE

The research was conducted in the Structures and Materials laboratory ofCivil Engineering department of Jomo Kenyatta University of Agriculture and Technology, JKUAT, Kenya.

3.2 RESEARCH DESIGN

The research was conducted through laboratory experiments by firstly, determining physical properties of the various materials being used in the research and secondly, testing a number of unconfined and UPVC-confined concrete columns when subjected to monotonically increasing concentric axial compressive loads.

3.3 RAW MATERIALS

Well graded ordinary river sand and crushed stones were used as fine and coarse aggregates respectively. Both aggregates were available at the project site. Cement class 42.5 (Powerplus) was used for this research and was sourced from a local hardware based in Thika. UPVC pipes conforming to Kenyan standards, KS ISO 1452-2 [76], were procured from a plastic pipes distributing hardwares based in Nairobi and Juja, Kenya.

3.4 MATERIAL PROPERTIES

3.4.1 AGGREGATES

Both fine aggregate (sand) and coarse aggregates (Crushed stones) were air-dried until they were free of moisture, i.e., surface dry. The sand samples were tested for the following physical properties: particle size distribution, i.e., grading, fineness modulus, specific gravity and water absorption. Coarse aggregates were also tested for the following mechanical properties: specific gravity and water absorption.

3.4.1.1 FINE AGGREGATES (FA)

(a) Particle size distribution (grading) and Fineness modulus (FM)

Sand was air dried and about 1kg of representative sample from the batch was taken by riffling. It was then sieved through the following set of sieves: 10 mm, 5.00 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm and 0.15 mm in that order (i.e., from the most coarse to the finest mesh). Sieving was achieved through hand shaking for a minimum of 2 minutes or when no more particles could pass through a certain sieve. The mass retained in each of the sieve was weighed and recorded.

The FM of fine aggregates, which is the weighted average of a sieve on which the material is retained with the sieves being counted from the finest, was calculated from formula given as equation 3.1.

$$FM = \frac{\Sigma\,(\text{Cummulative \% retained})}{100} \quad \ldots\ldots (3.1)$$

(b) Specific Gravity and water absorption

(I) Apparatus

The following apparatus were used: a weighing balance of capacity not less than 3 kg, readable and accurate to 0.5 gm and of such a type as to permit the weighing of the vessel containing the aggregate and water, a well-ventilated oven to maintain a temperature of 100ºC to 110ºC, specific gravity bottle having a water tight metal conical screw top with a 6 mm hole at its apex and shallow trays.

(II) Experimental Procedure

About 500g of air-dry sand sample passing 5.0 mm sieve and retained on 0.075 mm sieve was washed thoroughly in distilled water to remove all materials finer than 0.075 mm test sieve. The washed sample was then transferred into a shallow tray and fully submerged in water for 24 hours. Water was then carefully drained from the sample by decantation. The wetted aggregates were then exposed to air currents and stirred at frequent intervals in order to evaporate surface moisture completely. Then the mass of the saturated and surface-dry (SSD) aggregates was taken (W_3). The aggregates were then placed in a specific gravity bottle and distilled water was poured into it until it was full. Entrapped air was eliminated by rotating the bottle on its side, the hole in the apex of the cone being covered with a finger. The outer surface of specific gravity bottle was wiped and weighed (W_1). The contents of the bottle were transferred into a tray. The bottle was then refilled with distilled water to the same level and its mass determined (W_2). The sample was then placed in a tray and dried in an oven at a temperature of 100ºC to 110ºC for 24±0.5 hours, cooled and weighed (W_4). The procedure was repeated two more times for the purpose of averaging the results. The values of specific gravity and water absorption were obtained from the following calculations.

Specific gravity on oven dry condition $= \frac{W_4}{W_3-(W_1-W_2)}$ .... (3.2)

Specific gravity on SSD condition $= \frac{W_3}{W_3-(W_1-W_2)}$ .... (3.3)

Apparent specific gravity on oven dry material $= \frac{W_4}{W_4-(W_1-W_2)}$ .... (3.4)

Water Absorption $= \frac{W_3-W_4}{W_4}$ .... (3.5)

3.4.1.2 COARSE AGGREGATES (CA)

Specific Gravity and water absorption

About 1 kg sample of air dried coarse aggregates passing 20 mm sieve but retained on 10 mm sieve was obtained through quartering. It was then weighed on a weighing balance and thoroughly washed to remove finer particle and dust and soaked for 24 hours. The specimen was then removed from water, shaken off and rolled in a large absorbent cloth until visible films of water were removed. Large particles were wiped individually and mass of saturated and surface-dry (SSD) aggregates was determined (W_s). The sample was then placed in a wire basket having openings of not more than 3mm and completely immersed in distilled water while ensuring no entrapped air on the surface and between the aggregates by gently tapping the immersed basket. The mass of the sample while totally immersed was measured using a double beam balance of capacity 5 kg x 0.5 g and recorded (W_w). The basket was then removed from water and allowed to drain before transferring the aggregates into a tray and oven dried at a temperature of 105-110^{0}C for 24 hours. The samples were then removed from the oven, cooled and its mass determined (W_d). The procedure was repeated two more times. The values of specific gravity and water absorption were obtained from the following calculations.

Specific gravity on SSD $= \frac{W_s}{W_s-W_w}$ .... (3.6)

Specific gravity on oven dry condition $= \frac{W_d}{W_s-W_w}$ .... (3.7)

Water Absorption $= \frac{W_s - W_d}{W_d}$ .... (3.8)

3.4.2 CONCRETE

3.4.2.1 CONCRETE MIX DESIGN

Following the procedure outlined in BRE manual [34], the design values for the three concrete mixes were computed and recorded in Table 3.1. The resultant proportions of the constituent materials were used in preparing trial concrete mixes.

Table 3.1 Design values for the different concrete mix classes

Parameter	Value		
	C20	C25	C30
Characteristic strength at 28 days, f_c, (N/mm^2)	20	25	30
Margin, M, (N/mm^2)	5	5	5
Target mean strength, $f_m = f_c +$ M, (N/mm^2)	25	30	35
Approximate compressive strength, (N/mm^2)	49	49	49
Free W/C ratio	0.70	0.60	0.55
Free water content, (Kg/m^3)	170	170	170
Cement content, (Kg/m^3)	245	285	310
Total aggregate content, (Kg/m^3)	1900	1860	1835
Fine aggregate content, (Kg/m^3)	627	615	605
Coarse aggregate content, (Kg/m^3)	1273	1245	1230
Adjusting for water absorption (Absorption of FA= 0.23% and CA = 0.91%)			
Fine aggregate content, (Kg/m^3)	625	615	605
Coarse aggregate content, (Kg/m^3)	1260	1240	1220
Total water content, (Kg/m^3)	221.5	213.5	210

3.4.2.2. PRODUCTION OF TRIAL MIX

After calculating the proportion required per cubic meter of concrete, the volume of mix, which was required to make nine cubes of size 100 mm was calculated. The volume of mix was also sufficient to carry out the concrete slump test. The batch weights of the trial mix were obtained by multiplying the volume of the mix with the proportion of the constituent materials. The mixing of concrete was done according to the BS [77] and ASTM [78] procedures given in laboratory guidelines. First, fine and course aggregates were mixed with some proportion of water added to allow for absorption. Cement was then added and mixed with the aggregates while adding the remaining water until sufficient workability was achieved.

3.4.2.3 TESTS ON TRIAL MIX

(a) Fresh concrete

The slump test was conducted to determine the workability of fresh concrete. Concrete was placed and compacted in three layers by a tamping rod, each layer given25 strokes, in a firmly held slump cone. On the removal of the cone, the difference in height between the uppermost part of the slumped concrete and the upturned cone was recorded in mm as the slump. The design slump that was targeted was between 10 mm to 30 mm.

(b) Hardened concrete

To obtain the ultimate compressive strength of the hardened concrete, i.e., nine cubes measuring 100 mm x 100 mm x 100 mm were prepared for each concrete mix designed. The cubes were cured before testing. The procedure for making and curing the cubes was as follows; the interior surfaces of the assembled mould was thinly coated with lubricating oil to prevent adhesion of concrete onto the mould walls. Each mould was then filled with concrete and vibrated using a poker vibrator. The top surface was finished with a trowel. The cubes were then stored undisturbed for 24 hours at room temperature. After 24 hours, the mould was stripped and identification number and the date of casting marked on the surface of the concrete cubes as shown in Plate 3.1.

Plate 3.1 Sample concrete cubes before curing in water

The cubes were cured further by immersing them in water at room temperature until the testing date. Compressive strength tests were conducted on the cubes at the age of 3, 7 and 28 days. The tests after 3 and 7days were for monitoring strength development while the one on 28th day was to determine the ultimate compressive strength of the designed mix.

3.4.3UPVC PIPE

3.4.2.1 Tensile test for UPVC pipes

To determine the tensile strength of the UPVC tube material, a coupon was prepared with dimensions as shown in Figure 3.1. This sample was tested in the UTM SERVO-PLUS EVOLUTION™ machine with a loading rate of 2.0 Mpa/sec. Plate 3.2 shows the actual sample which was tested.

NB: All dimensions in mm

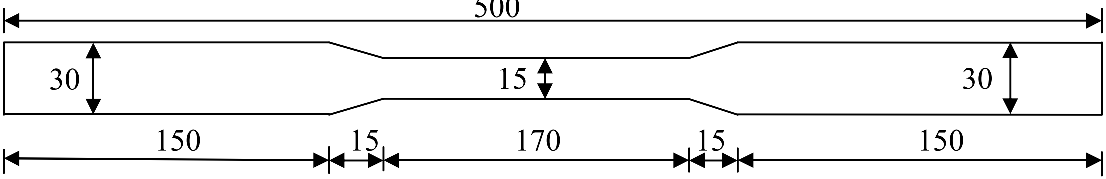

Figure 3.1Dimensions of specimen for tensile strength test

Plate 3.2 Photo of specimen for tensile strength test

3.4.2.1 Compression test for UPVC pipes

Tests on empty UPVC tubes were conducted on a compression machine in a similar manner to tests on column specimens as shown in plate 3.5. Samples of tested empty UPVC tube specimens are as shown in plate 3.3.

Plate 3.3 Samples of tested empty UPVC tubes

Typical nomenclatures for the specimen were used to designate them. For instance, P/E/110/3 represent a pipe (P) which is empty (E) having a diameter of 110 mm and a slenderness ratio of 3. The summary of the details of all tube specimens which were tested are summarized in the appendix.

3.5 SPECIMEN INSTRUMENTATION AND TESTING

3.5.1 TEST SPECIMENS

A total of 144 short columns (48 column sets replicated three times) were cast of which 72 were unconfined and 72 were UPVC-confined. 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, 3.0 mm and 2.5 mm respectively. 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 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 hours, after concrete had hardened, leaving an unconfined column specimen. The summary of all the details of the column specimens are summarized in the appendix. The specimens are organized in groups for easier referencing during analysis of results. 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. Specimens were marked for ease of identification. They were allowed to stand for 24 hours until concrete was fully hardened and then cured by covering them with sisal sacks which were wetted daily with water until the testing date as shown in Plate 3.4. The specimens were cured in water for 28 days.

Plate 3.4 Samples of stub columns after curing

3.5.2 EXPERIMENTAL SETUP AND DATA ACQUISITION

The experimental work was conducted utilizing compression machine at Structures and Materials laboratory of Civil Engineering department, JKUAT. The general setup for the experiment was as shown in Plate 3.5 below.

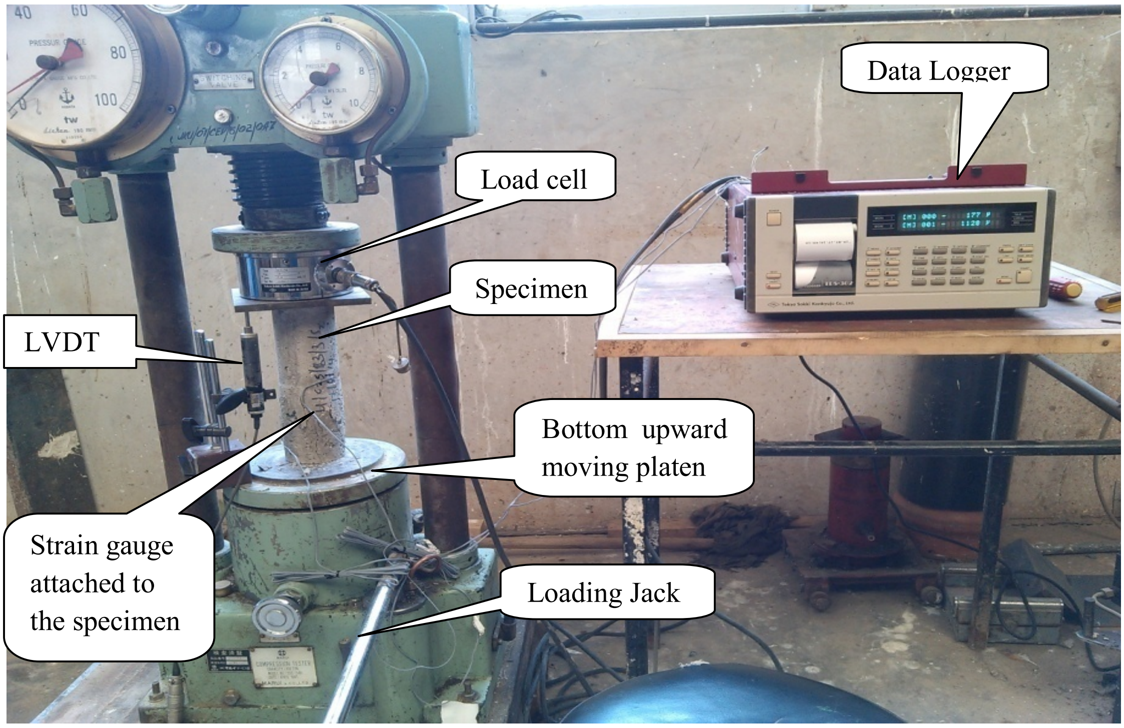

Plate 3.5 Specimen testing using compression machine

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 hydraulic jack through uniform steel end plates to achieve a constant stress distribution at the concrete cross section. The load was applied to the entire column section.

The columns were tested using an incremental loading procedure. Load cell of 500 kN-capacity was used to monitor the applied load values. For measurement of strains on the surface of the column, two types of strain gauges were used. The first type denoted as PFL-30-11-3L having a gauge length of 30 mm and gauge factor of 2.11, was used to measure strains on concrete surfaces. The second type denoted as GFLA-6-70-3L, having gauge length of 6 mm and gauge factor of 2.11, was used to measure strains on plastic surfaces. The surface gages were glued to the specimens after sanding and cleaning the contact surface of the specimens. These gauges were procured from Tokyo Sokki Kenkyujo Company limited in Japan. Axial as well as the radial strains at the outer surface of the columns were measured by means of two electrical strain gauges positioned appropriately at the column specimen mid-height. The bi-directional rosettes allowed monitoring the axial and hoop strains on the surface of the tube. In addition, a Linear Variable Displacement Transducer (LVDT) was used to measure the axial deformations on each column. The applied load was kept constant at each load stage to allow for measurements and observations. The load cell, strain gauges and LVDT were all connected to TDS 302 data logger where the results were recorded for further analysis.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 MATERIAL PROPERTIES

4.1.1AGGREGATES

(a) Gradation and Fineness Modulus

The grading curve was plotted, i.e., percentage (%) passing against sieve sizes, on a semi log graph together with the upper and lower limits of the zone II sand envelope as shown in Figure 4.1.

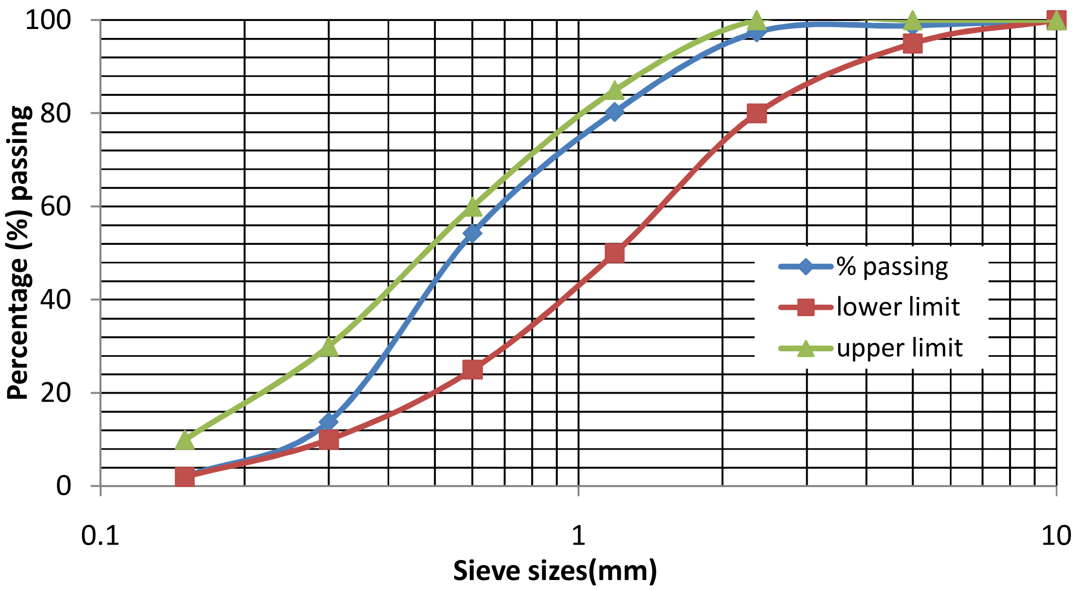

Figure.4.1 Grading curve for fine aggregates

The sand grading curve was found to be within the zone II envelope. This showed that the sand was fit for use in designing concrete mixes following the BRE method of concrete mix design. Sand falling outside this envelope should be blended with other types to ensure it is within this range for it to qualify for use in this method.

The fineness modulus (FM) of fine aggregates was calculated using equation 3.1.

Fineness Modulus = 253/100 = 2.53. The higher the FM, the coarser the fine aggregates. The value of proportion of fines was required while designing concrete mixes. It was determined by first calculating the percentage of fine aggregates passing the 600 μm sieve.

Mass passing 600μm sieve = 404.5+117.5+20.5 = 542.5 g

Therefore, percentage passing 600 μm sieve$= \frac{\text{Mass passing}}{\text{Total mass}}$x100=$\frac{542.5}{999.5}$x100=54.3% say 55%. Using the above computed value and graphs in Figure 6 [34], the proportion of fines was determined as 33%.

(b) Specific Gravity and Water Absorption

The computed values of specific gravity and water absorption for FA and CA were tabulated as shown in Table 4.1.

Table 4.1Specific gravity and water absorption of aggregates

	FA	CA
Specific gravity on oven dry basis	2.50	2.46
Specific gravity on saturated surface dry (SSD) basis	2.51	2.48
Apparent Specific gravity	2.52	2.51
Water absorption (%)	0.23	0.91

Calculations with reference to concrete mix design was based on the SSD condition of the aggregate because the water contained in all the pores in the aggregate does not take part in chemical reaction of cement. This water is therefore considered as part of the aggregate [79]. The apparent specific gravities for the aggregates averaged at 2.5. The apparent specific gravities for different rock groups ranges between 2.4 and 3.0 [79].

4.1.2CONCRETE

The results for concrete cubes compression tests were tabulated as shown in Table 4.2.

Table 4.2Summary 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) 5/10	10/20	Compressive strength at 28 days f_{cu}, (MPa)
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	310	605	410	810	30.7

** Includes free water for cement hydration and water for absorption by the aggregates to bring them to SSD*

The 28 days compressive strength exceeds the characteristic compressive strength for each class of concrete. The values are also within the specified margin. Therefore, the design mix has been achieved with the proposed calculated proportions

4.1.3UPVC PIPE

The average ultimate tensile strength (f_{py}) of the tested coupons was recorded as 39.96N/mm^2. Data for compressive tests of the tubes is summarized in the appendix. The data was used in the determination of load capacity enhancement due to UPVC tubes confinement as discussed in section 4.5.

4.2 OBSERVED BEHAVIOUR

All specimens behaved more or less in the same manner during 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. This was unique to the specimens which were tested until total collapse as shown in Plate 4.1(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 as shown in Plate 4.1(c).

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

Plate 4.1 Typical specimens' failure modes

Two failure modes were observed. The principal failure mode was a typical shear failure of the plastic tube as shown in Plate 4.1(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 [11] and Wang and Yang [80]. This type of shear failure is affected by D/t ratio. In order to avoid this type of shear failure, the ratio should be reduced by increasing the pipe thickness. 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 as shown in Plate 4.1 (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. A smooth interface between the tube and the failed concrete was observed. The conclusion was that no mechanical bond developed at the interface of concrete and the tube.

4.3 EFFECT OF VARYING DIAMETER AND SLENDERNESS RATIO ON LOAD AND COMPRESSIVE STRENGTH

Figures 4.2 to 4.4 show compressive load capacity and strength test results for confined column specimens with varying diameters, slenderness ratios and concrete mixes.

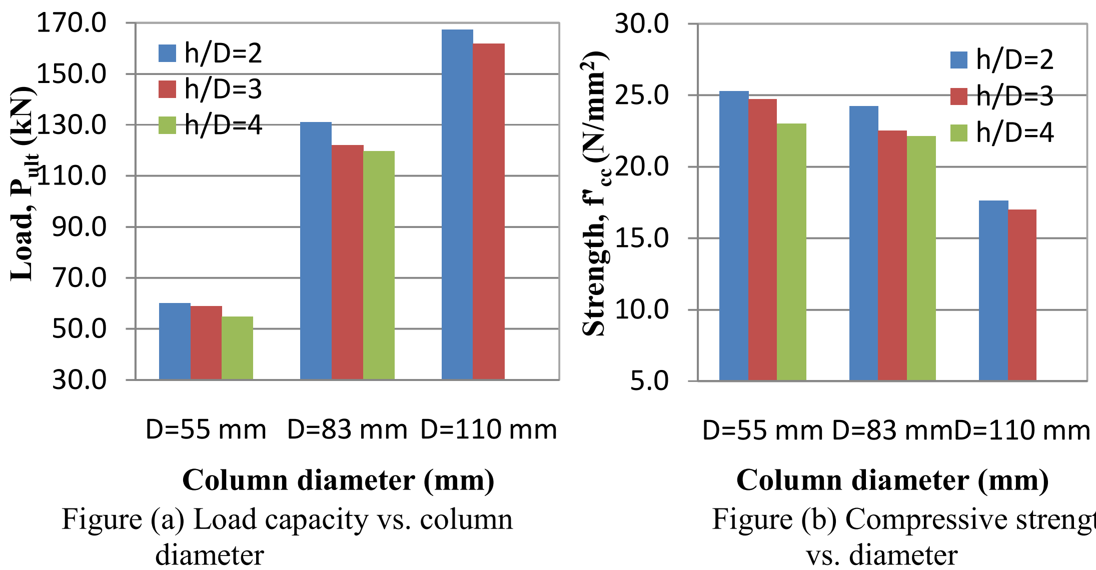

Figure (a) Load capacity vs. column diameter

Figure (b) Compressive strength vs. diameter

Figure 4.2 Load and strength variation with change in D and h/D for composite columns cast with concrete mix C20

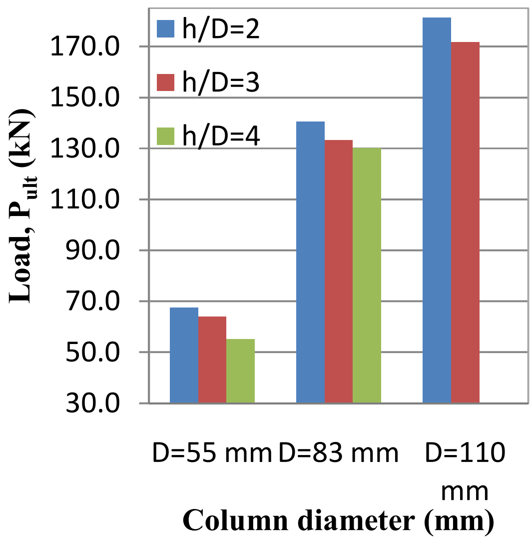

Figure (a) Load capacity vs. column diameter

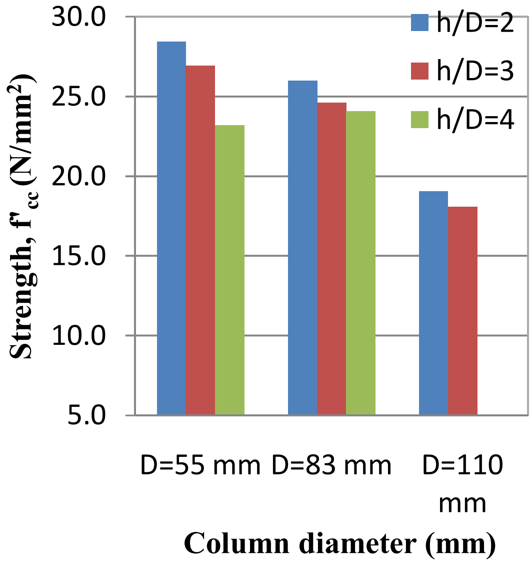

Figure (b) Compressive strength vs. diameter

Figure 4.3 Load and strength variation with change in D and h/D for composite columns cast with concrete mix C25

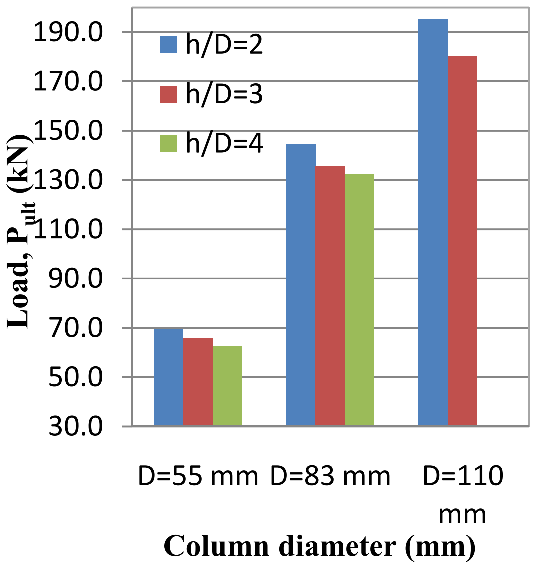

Figure (a) Load capacity vs. diameter

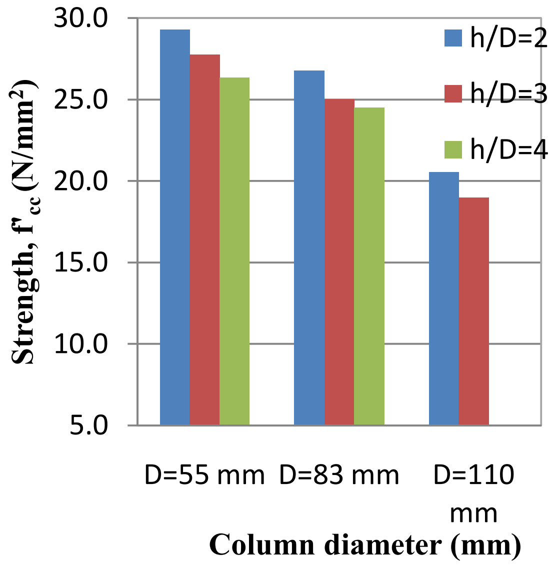

Figure (b) Compressive strength vs. diameter

Figure 4.4 Load and strength variation with change in D and h/D for composite columns cast with concrete mix C30

As expected, the load carrying capacity and the compressive strength increase with increase in the grade of concrete due to the increased elastic modulus of concrete. The results further show that for columns cast with the same concrete mix, load capacity increases with increase in column diameter. This is attributable to the increased load-carrying area.It was observed that the load capacity values were in the range 54.7 kN-195.3 kN, while the values of compressive stress were in the range of 17 MPa-29.3 MPa. The load capacity and the compressive strength both decrease with increase in slenderness ratio. That is due to the stiffness of column specimens which reduces as slenderness ratio increases. Slender columns tend to fail by buckling more easily as opposed to short columns.In this research, however the variation is small since all the columns considered are short with a maximum slenderness ratioof 4

Provided the slenderness ratio is kept constant, the height increases as the diameter is increased.Thus bigger diameter columns are taller compared to smaller diameter columns of the same slenderness ratio. However, the longer the column the more susceptible it is to failure by local buckling. This explains why the column compressive strength decreases when the diameter of the column is increased from 55 mm to 110 mm.

4.4 CONFINEMENT EFFECTIVENESS

Figure 4.5 shows the effect of concrete strength, tube thickness and slenderness ratio on confinement of columns.

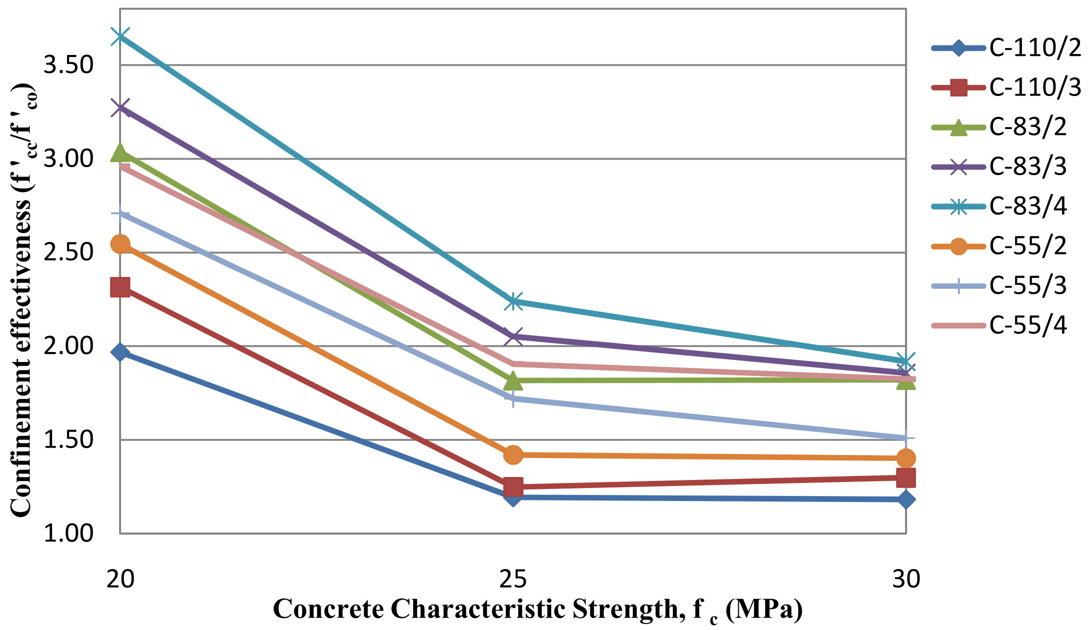

Figure 4.5 Confinement effectiveness vs. concrete strength

The confinement effectiveness, f'_{cc}/f'_{co}, has been defined earlier as the ratio between the maximum strength of the confined to the strength of the unconfined concrete. It is clear from Figure 4.5 that plastic pipes are effective in confining concrete, since in all cases $f'_{cc}/f'_{co}>1$. The enhancement in strength due to confinement of circular columns is substantial. Depending on the level of confinement, strength is increased between 1.18 to 3.65 times the unconfined strength.

Figure 4.5 shows a general trend where confinement effectiveness curve goes down with increase in the grade of concrete. This is typical for all column specimens tested regardless of their diameter, height or tube thickness. This can be attributed to the brittleness of a higher grade concrete as a result of high elastic modulus. It is worth noting that elastic modulus is directly related to the compressive strength of concrete. It follows that low strength concrete is less stiff and is therefore able to 'flow' thus interacting with concrete tube more effectively. This explains why there is increased composite action, and hence the f'_{cc}/f'_{co} ratio for columns cast with low strength concrete.

Another observation from figure 4.5 is that the confinement effectiveness increases with increase in slenderness ratio. This is depicted by the upward shift of the curves when the slenderness ratio is increased with diameter kept constant. As slenderness ratio increases, the load carrying capacity and consequently the column compressive strength reduces. However the rate of reduction in axial load capacity and strength is more pronounced in unconfined columns than in confined columns. Therefore the ratio of the stresses will be higher for longer columns due to the greater difference in stress than for short columns.

A notable observation is how the confinement effect for the 83 mm diameter columns set was higher than the other columns. This is due to the fact that the tube thickness was higher (3.0 mm) as compared to the other columns (2.5 mm). This higher tube thickness increased the tubes stiffness as can be predicted from the simplified equation of bending for a tube section (see equation 4.1)

$$F_{st}= \frac{Et}{R} \qquad (4.1)$$

Where F_{st} is the tube stiffness

E is the elastic modulus of the tube in the hoop direction

t is the tube thickness

R is the tube outer radius

4.5 LOAD CAPACITY ENHANCEMENT

When a composite structural element is used in construction it is expected to exhibit improved properties than those of the individual constituent materials. A comparative study was made in order to determine the benefits accrued in using this new type of composite columns. In this study, capacity enhancement ratio, P_{cc}/P_{sum}, was used for comparison purposes. P_{cc} was defined as the load carrying capacity of confined column. P_{sum} is the summation of load carrying capacity of empty plastic tube and unconfined concrete columns, as expressed in equation 4.2,

$$P_{sum} = P_{co} + P_{empty} \quad (4.2)$$

Where; P_{co} is the load carrying capacity of unconfined concrete column

P_{empty} is the load carrying empty plastic tube

The computations are included in the appendix. The computed results were then presented graphically as shown in Figure 4.6.

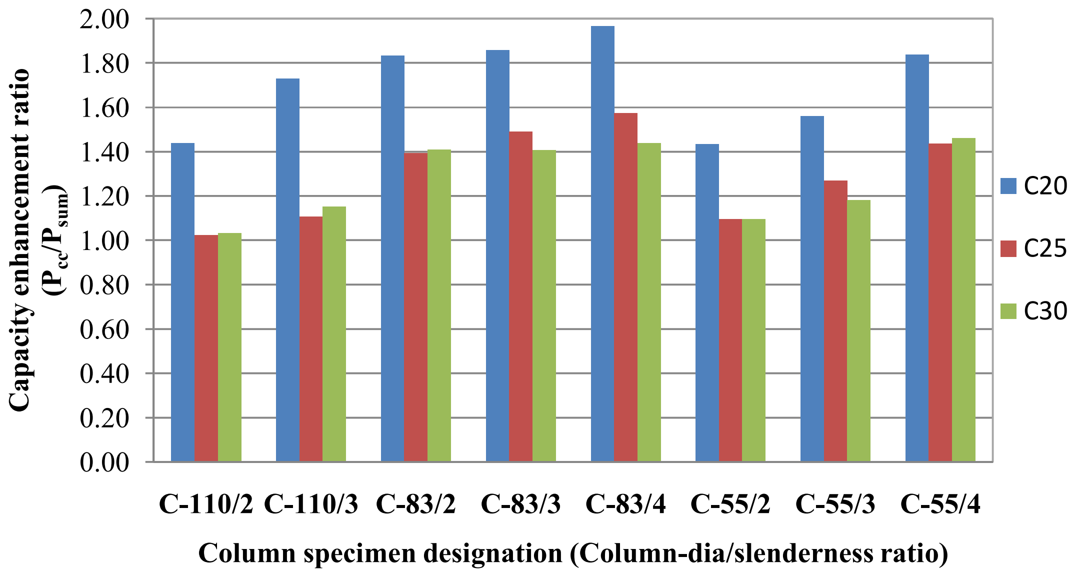

Figure 4.6 Capacityenhancement for composite column sections

$P_{cc}/P_{sum} > 1$ for all columns indicating that the ultimate load of the components acting in a composite manner is higher than total load for the sums of the individual components. This is because, in a composite section, the best properties of the components are utilized. The plastic tube provides a confining effect for the concrete, hence setting tensile stresses in the tube. The tube is able to take these stresses as opposed to concrete which is weak in tension. The confining of concrete on the other hand, sets the concrete in tri-axial state of stress. Since concrete is strong in compression, the performance of concrete in this state is highly optimized. The general trend noted in Figure 4.6 is that capacity enhancement for a composite column is more pronounced in concrete of low strength than in concrete having high compressive strength, attributable to the 'flow ability' of low strength concrete. Also capacity enhancement increases with increased columns' slenderness ratio. With increasing column height, the rate of reduction in axial load capacity is more pronounced in unconfined columns than in confined columns. Therefore the ratio will be higher for longer columns due to the greater difference in load capacities than for short columns. These two phenomenons were also observed earlier on confinement effectiveness and similar explanation follows.

4.6 LOAD-DEFORMATION CHARACTERISTICS

Figures 4.7 to 4.12 show the load-deformation curves of the composite column specimens. From Figures 4.7 to 4.9 the column specimens vary in tube diameters and slenderness ratios but have been cast with the same concrete mix.

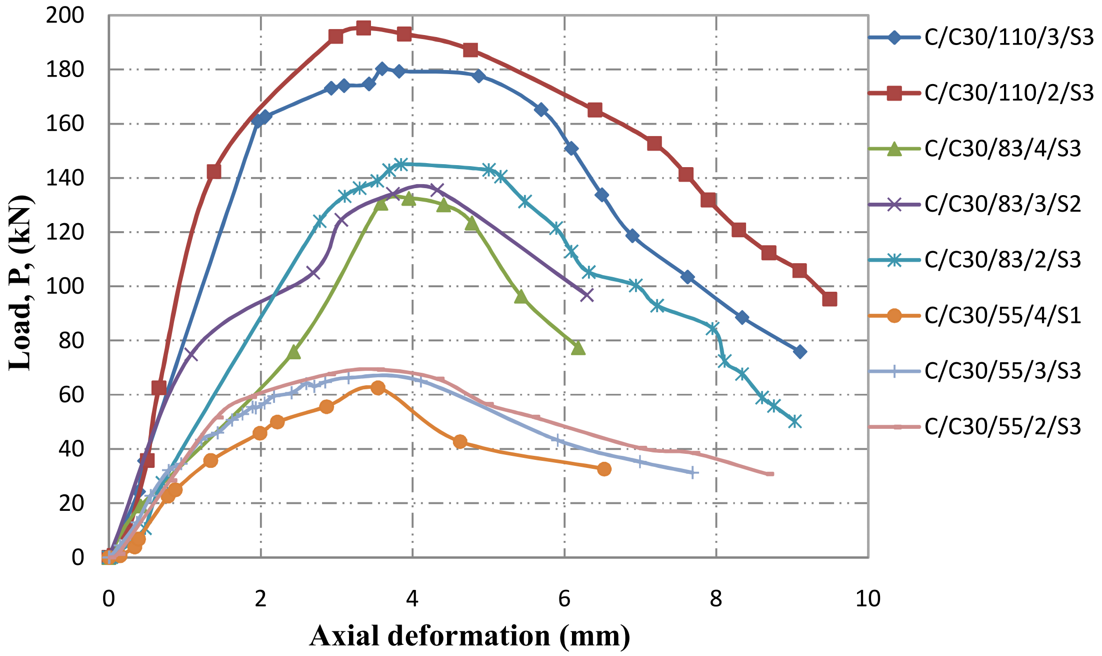

Figure 4.7 Load-deformation curves for concrete class C30 composite columns

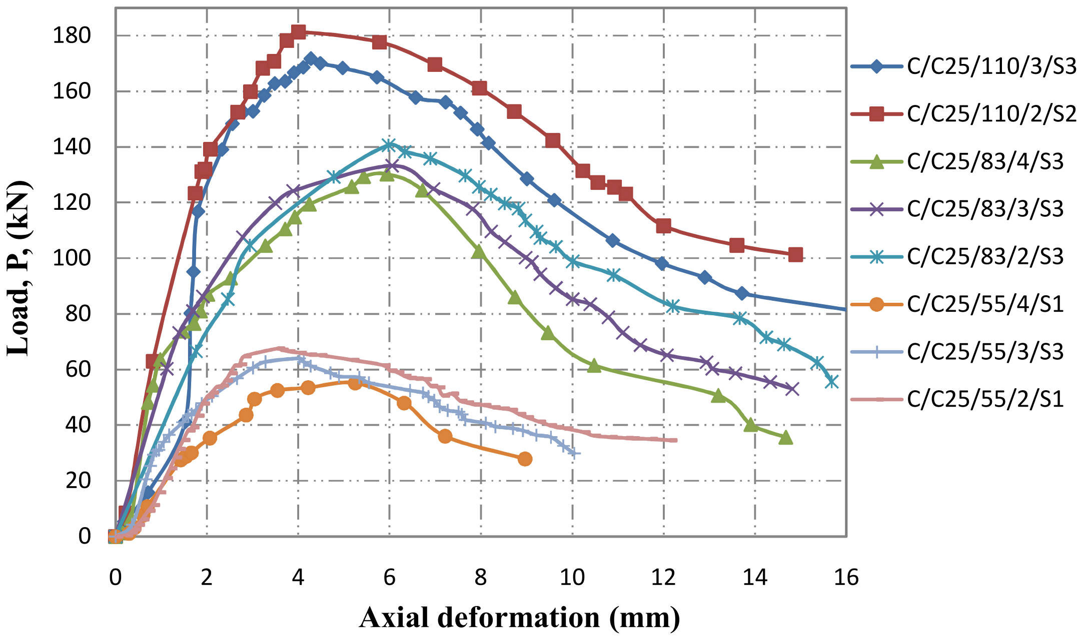

Figure 4.8 Load-deformation curves for concrete class C25 composite columns

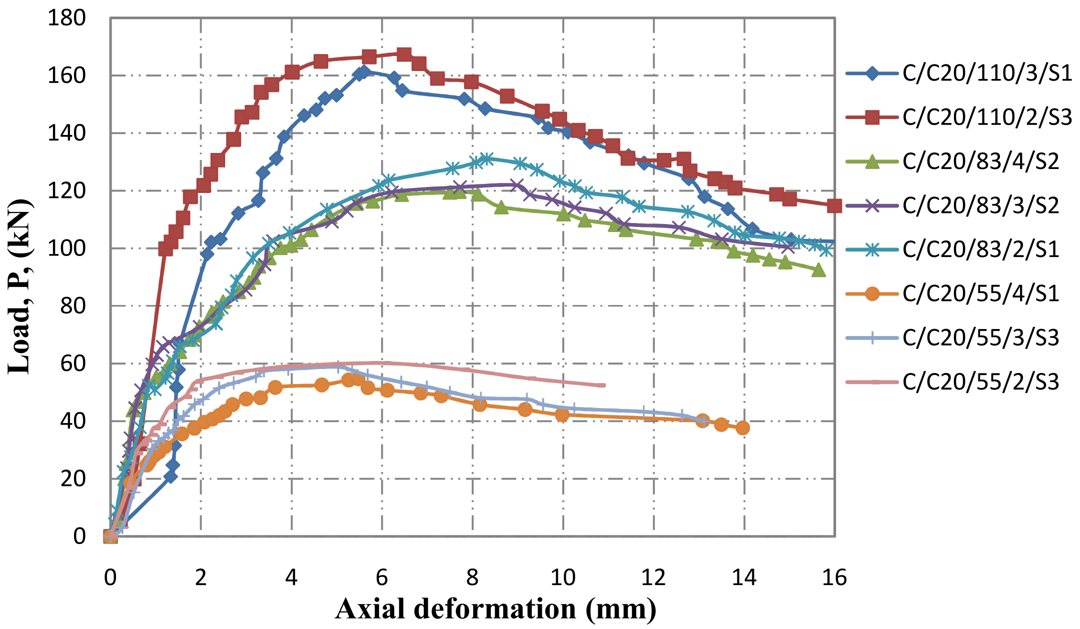

Figure 4.9 Load-deformation curves for concrete class C20 composite columns

As the diameter of tube increases the peak load capacity increase, but the same decreases with increased slenderness ratio as seen from Figures 4.7 to 4.9.

Figures 4.10 to 4.12 represents curves for column specimens of different slenderness and cast with different concrete mixes but having the same tube diameters.

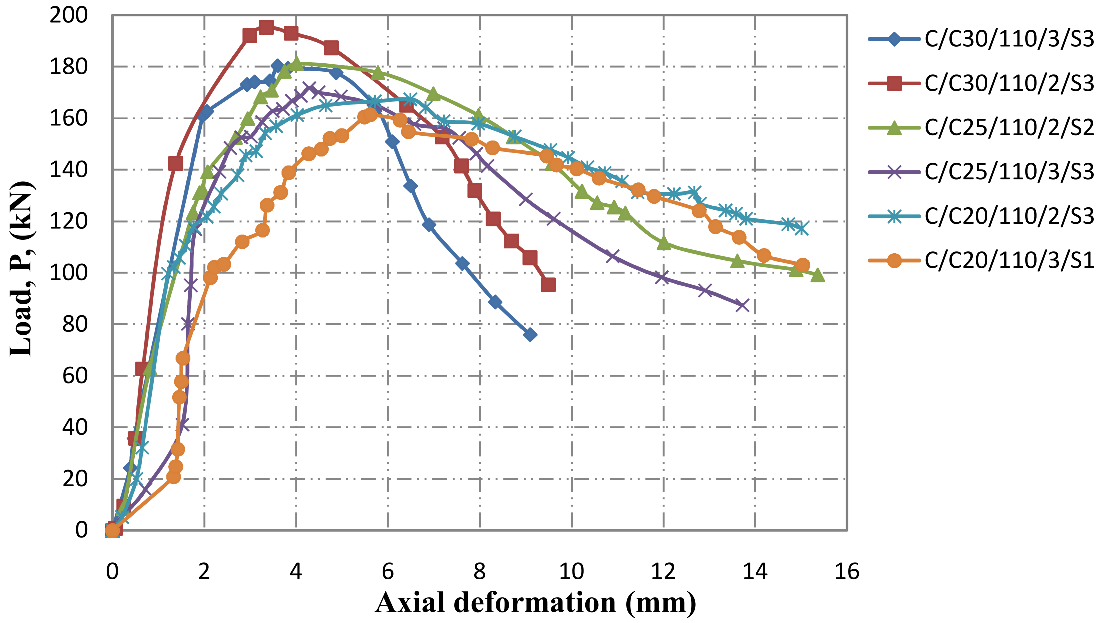

Figure 4.10 Load-deformation curves for D=110mm composite columns

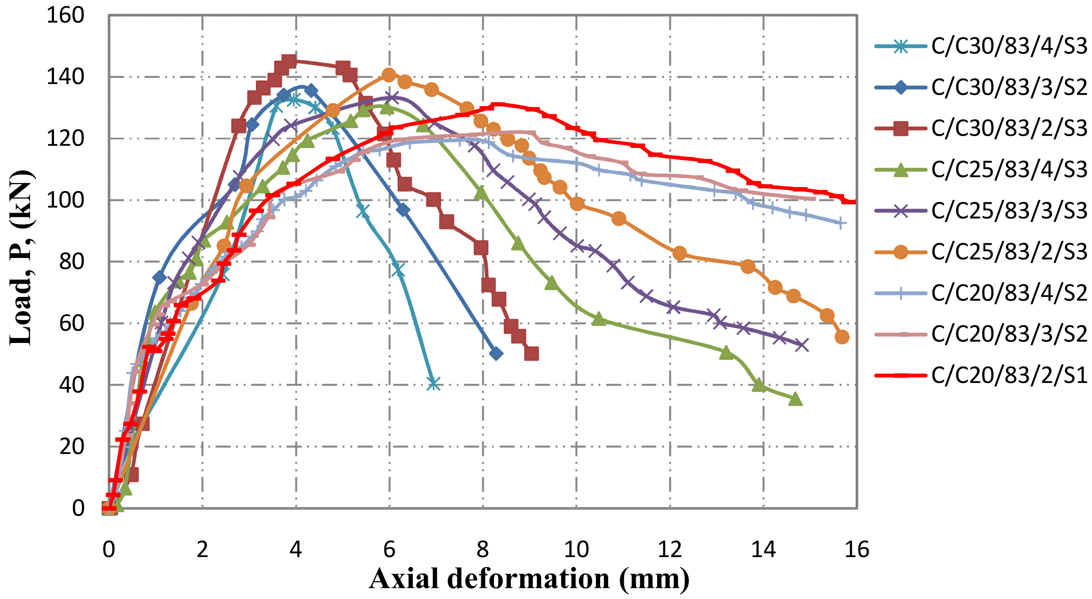

Figure 4.11 Load-deformation curves for D=83 mm composite columns

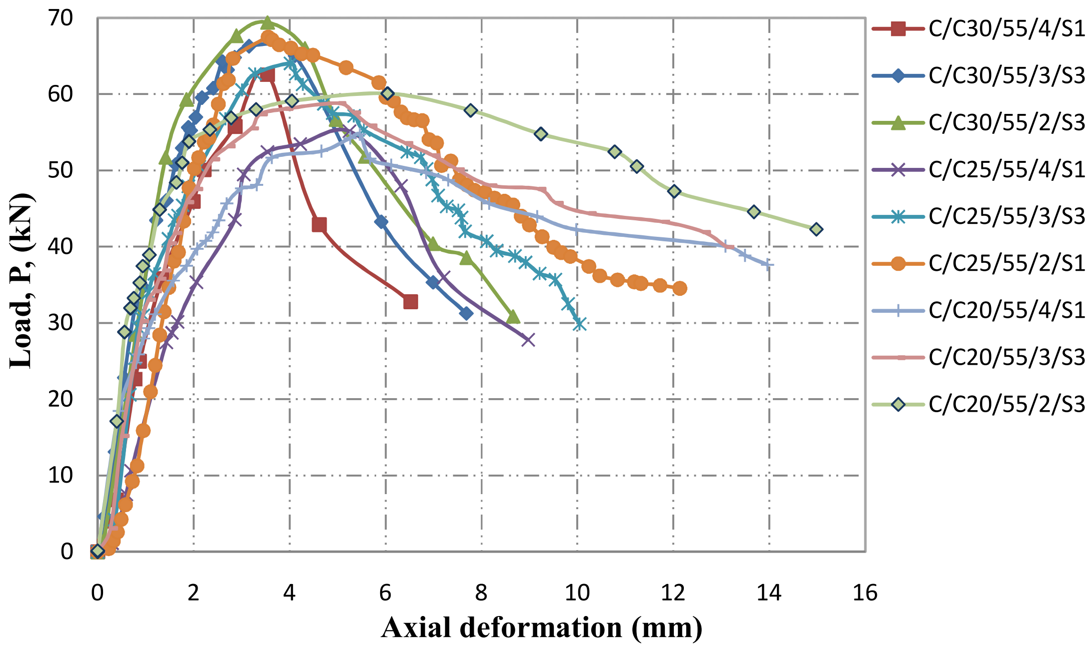

Figure 4.12 Load-deformation curves for D=55 mm composite columns

Observations made from Figures 4.10 to 4.12 shows that low strength composite column undergoes large deformation before reaching the ultimate load capacity. Concrete filled with high strength concrete attain peak load fast. For a low strength concrete, the elastic modulus is also low and consequently stiffness is low. Low strength concrete is more flexible and is able to 'flow' thus interacting with the tube more effectively, with consequent increase in composite action. In unconfined state, concrete of low strength will generally disintegrate at very low loads but when confined will tend to resist much higher loads due to confining effect of the encasing tube. Looking at Figures 4.10 to 4.12, it is seen that concrete strength affects the post-peak behaviour of the curve significantly. For composite columns filled with different concrete strengths but having the same diameter, the sloping curve becomes steep with increase in the grade of concrete. Absolute values of the slope of the curve increase with increase in concrete strength because the core concrete becomes more brittle. The residual strength of specimen decreases with increase in concrete strength. This further substantiates the ' higher ductility' claim of lower strength concrete.

The area under the Load-deformation curves represents energy absorption capacity of the composite columns. It follows that the lower the strength of concrete and consequently the higher the ductility of the column specimen, the higher the energy absorption capacity of that column. The energy absorption capacity increases with increase in diameter of the column. Increase in tube thickness increases ductility and hence the energy absorption capacity

4.7 STRESS - STRAIN RESPONSE

Figures 4.13 to 4.15 show stress-strain curves of composite columns. The curves have been grouped according to the strength of the infilling concrete.

The response consists of three distinct regions. In the first region, behaviour is similar to plain concrete. The lateral expansion of the concrete core in this region is insignificant and thus the plastic tube plays no role in confining concrete at this region. With the increase in micro cracks, a transition zone is entered in which the tube exerts a lateral pressure on the core to counteract the core's tendency for stiffness degradation. Finally, a third region is noted in which the tube is fully activated, and the stiffness is generally stabilized around a constant rate. The response in the third region is mainly dependent on the stiffness of the tube.

In the third region, response in the lateral direction is closer to a straight line than the response in the axial direction. This is due to excessive cracking of the concrete core which is no longer a homogeneous material. Therefore, lateral expansion of the specimen is directly dependent on the response of the tube, which is assumed to be linearly-elastic. On the other hand, as the lateral cracks in the core expand, slight shifting and settling of the aggregates occur. This makes the specimen to experiences mild softening in the axial direction. Ultimate failure is realized when the tube can no longer carry any load. This occurs when the tube fails in shear fracture mode. It is also worth noting that plastic tube applies a continuously increasing pressure on the concrete core until the tube reaches its failure.

In compression, the stress-strain curve for concrete is linearly elastic up to about 30 percent of the maximum compressive strength. Above this point, the stress increases gradually up to the maximum compressive strength. Upon attaining maximum compressive strength, the curve descends into a softening region and eventually crushing failure occurs at an ultimate strain in tension. The stress-strain curve for concrete is approximately linearly elastic up to the maximum tensile strength, after this point, the concrete cracks and the strength decreases gradually to zero.

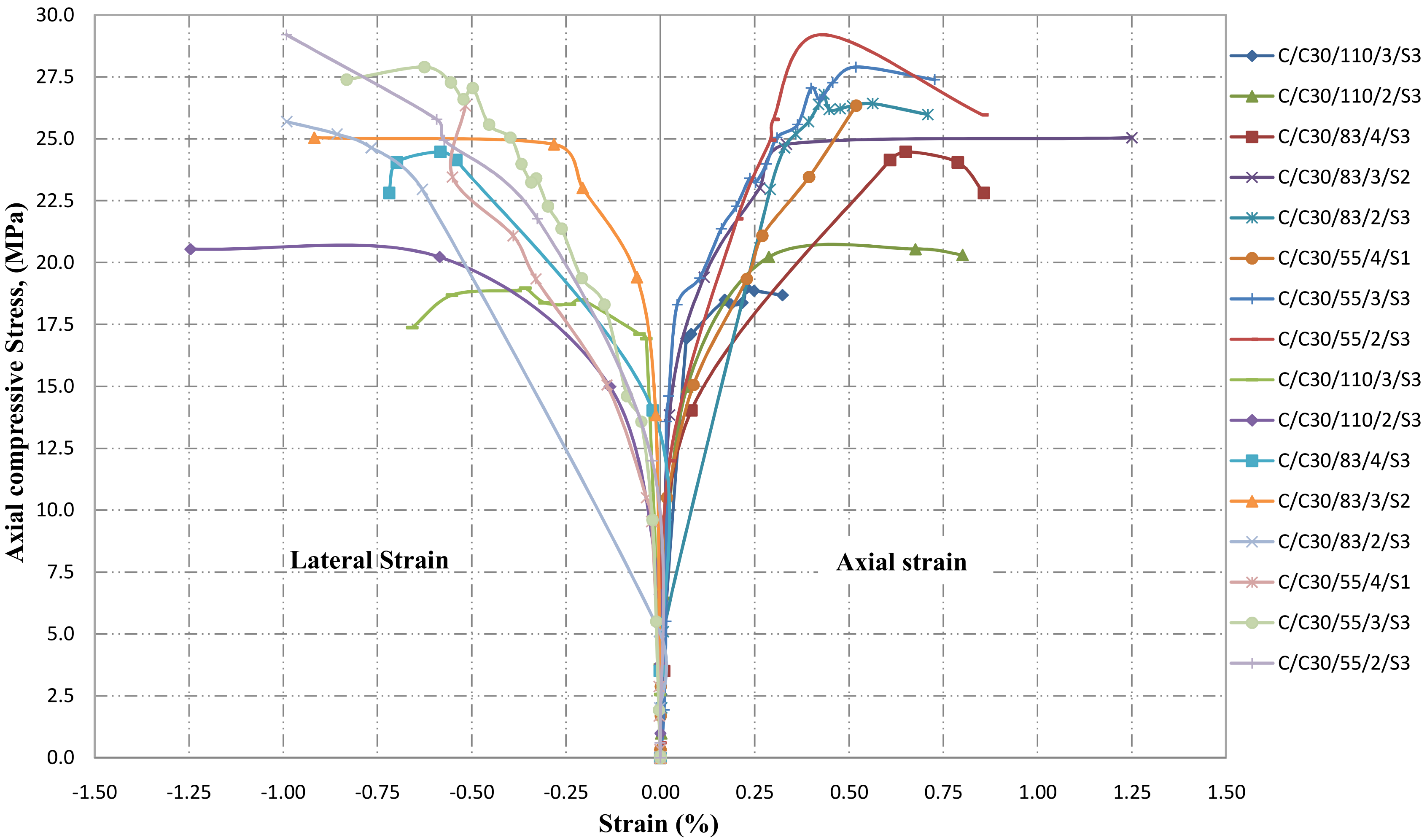

Figure 4.13 Stress-strain curves for concrete class C30 composite columns

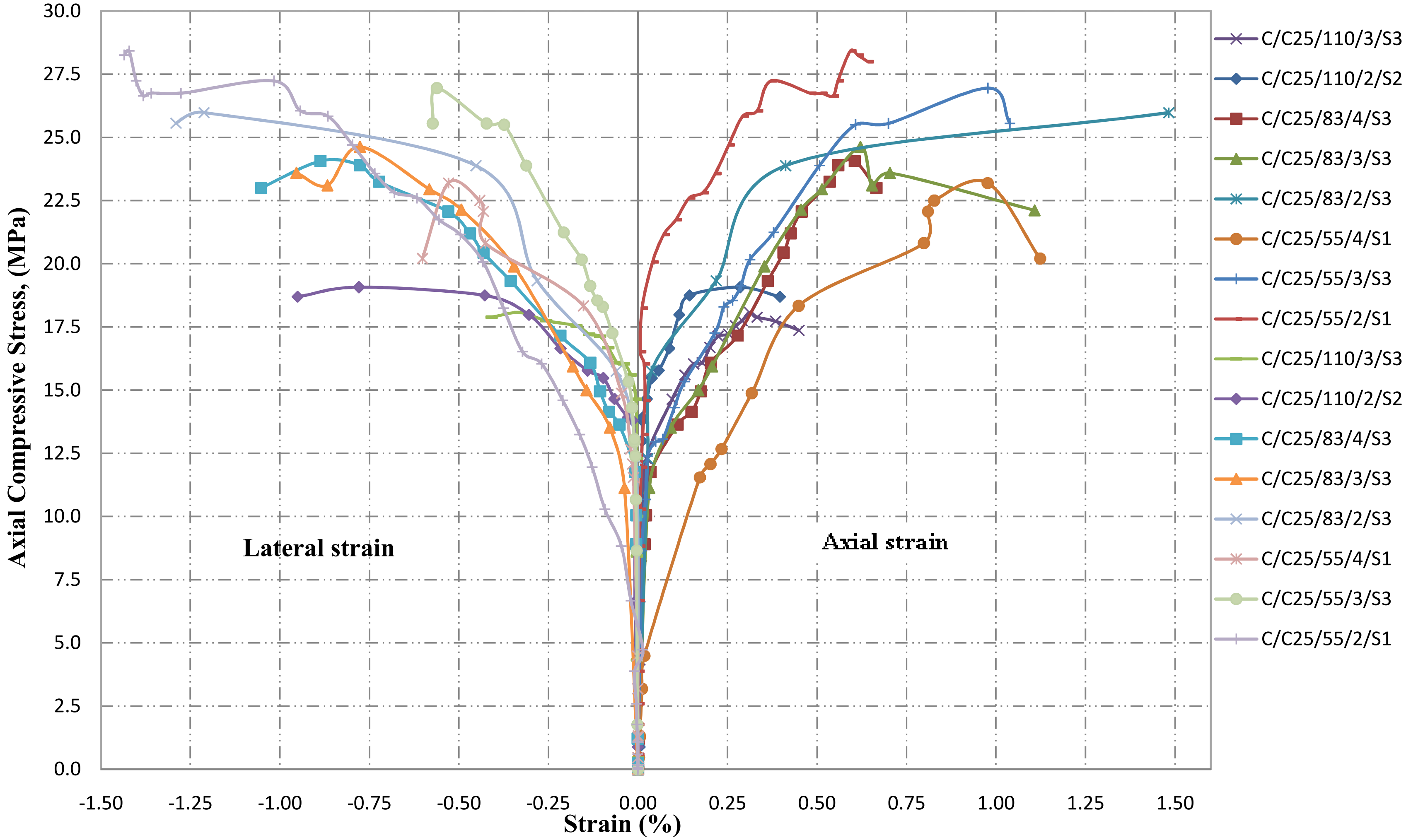

Figure 4.14 Stress-strain curves for concrete class C25 composite columns

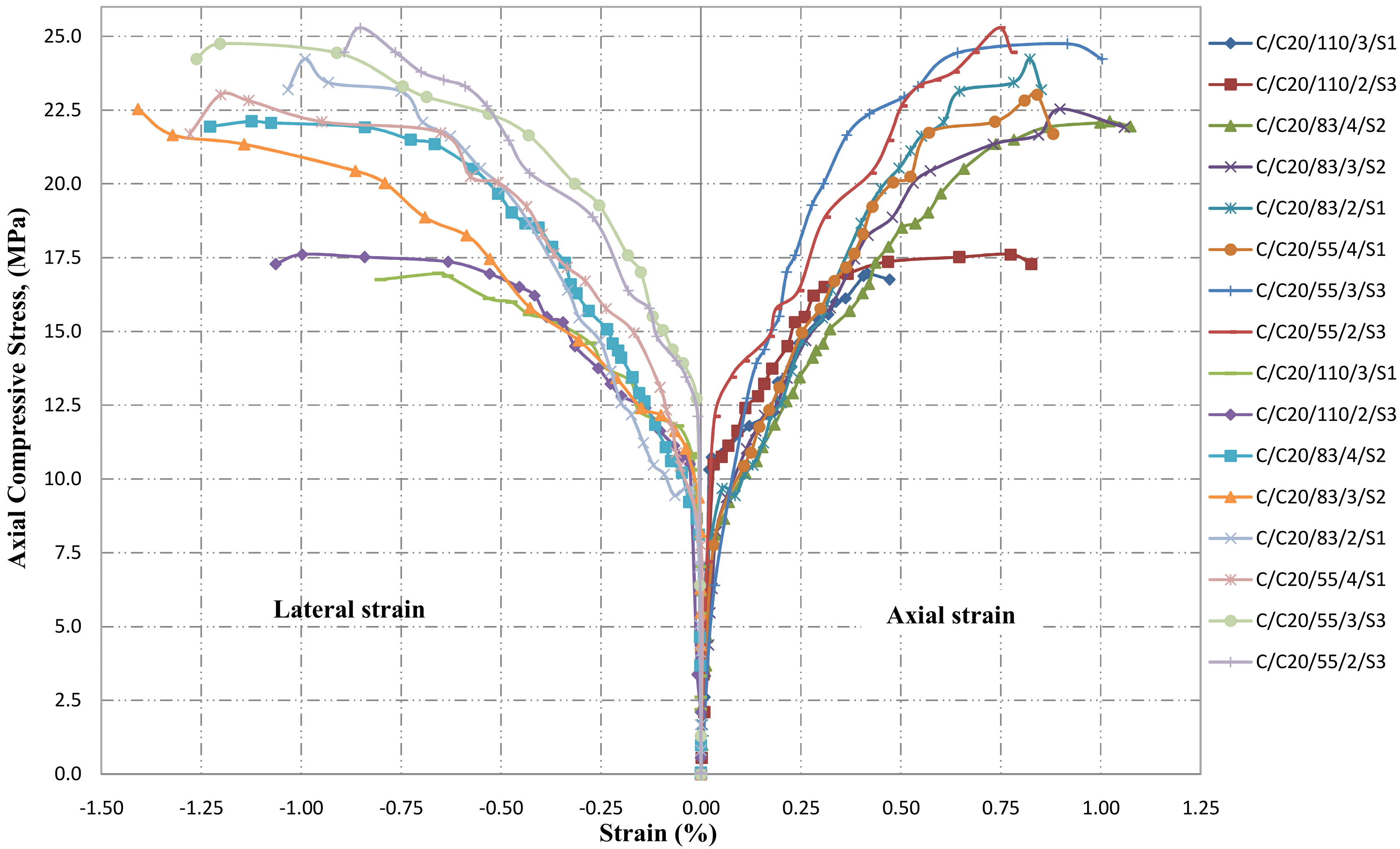

Figure 4.15 Stress-strain curves for concrete class C20 composite columns

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

The present study focused on the structural feasibility of concrete-filled plastic tube (CFPT) column by studying their behaviour under compressive loading. The following were the conclusions and recommendations from the research.

5.1 CONCLUSIONS

(1) It was concluded that the failure of CFPT columns can occur in either of the two ways. These are shear failure or by crushing.

(2) It was concluded that mechanical bond does not develop at the interface of concrete and the tube. The conclusion was drawn from the observed smooth interface between the tube and the failed concrete.

(3) It was also concluded that the column load capacity and the compressive strength decrease with increase in slenderness ratio.

(4) From the research, conclusion was made that load capacity increases with increase in column diameter. This was attributed to the increased load-carrying area.

(5) It was concluded that UPVC pipes are effective in confining concrete, since in all cases $f'_{cc}/f'_{co}>1$. Confined strength values increased between 1.18 to 3.65 times the unconfined strength values.

(6) It was observed that confinement effectiveness is dependent on the strength of concrete where effectiveness reduces with the increase of the concrete strength. It was thus concluded that the lower the strength of infilling concrete the more the ductile the column. This suggested a potentially earthquake resistant composite column system.

(7) It was also concluded that the lower the strength of concrete and consequently the higher the ductility of the column specimen, the higher the energy absorption capacity of that column. This was determined from the area under the Load-deformation curves which represented energy absorption capacity of the composite columns.

(8) It was concluded that the response consists of three distinct regions for all composite columns. In the first region, behaviour is similar to plain concrete. The second

region, transition zone occurs due to increased micro cracks. The tube exerts a lateral pressure on the core to counteract the core's tendency for stiffness degradation. Finally, a third region is noted in which the tube is fully activated, and the stiffness is generally stabilized around a constant rate. The response in the third region is mainly dependent on the stiffness of the tube.

5.1 RECOMMENDATIONS

The enormous potential of plastic tubes for use in composite systems is well illustrated by findings of this study. Nevertheless, there is need for more research in the use of this kind of polymer material in composite construction. Therefore a list of other related issues are recommended for further research.

(1) Further research is required in order to ascertain the performance in other aspects of engineering of this type of composite column. These would include aspects such as creep, expansion and contraction in relation to concrete and resistance to deterioration.

(2) There is also need for innovative techniques for dealing with fire resistance and the exposure of polymer material to damaging rays such as ultra-violet radiations.

(3) The tube thickness also affects the confinement effect of the plastic tubes. This research recommends extensive research to be conducted with different tube diameter and thickness ratio (D/2t). This will help in establishing the actual contribution that the tube thickness makes in column confinement.

(4) It is recommended that future researchers on this area should venture into modelling so as to provide design guide for this type of column.

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APPENDICES

A 1 Extracts from BRE manual [31]

Table 2 Approximate compressive strength of concrete mixes made with a free water/cement ratio of 0.5

Cement strength class	Type of coarse aggregates	Compressive strengths (N/mm2)			
		Age (days)			
		3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Table 3 Approximate free-water contents required to give various levels of workability

Slump (mm) Vebe time (s)		0-10 >12	10-30 6-12	30-60 3-6	60-180 0-3
Maximum aggregates size (mm)	Aggregates Type				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

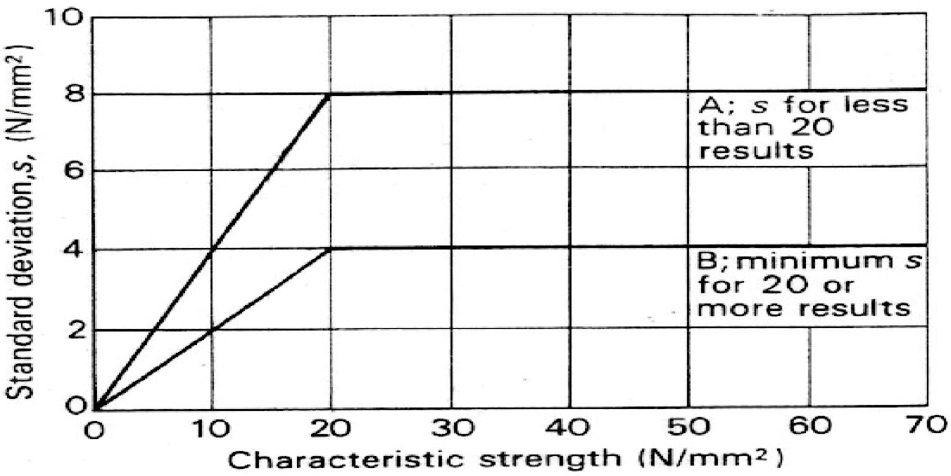

Figure 3 Relationship between standard deviation and characteristic strength

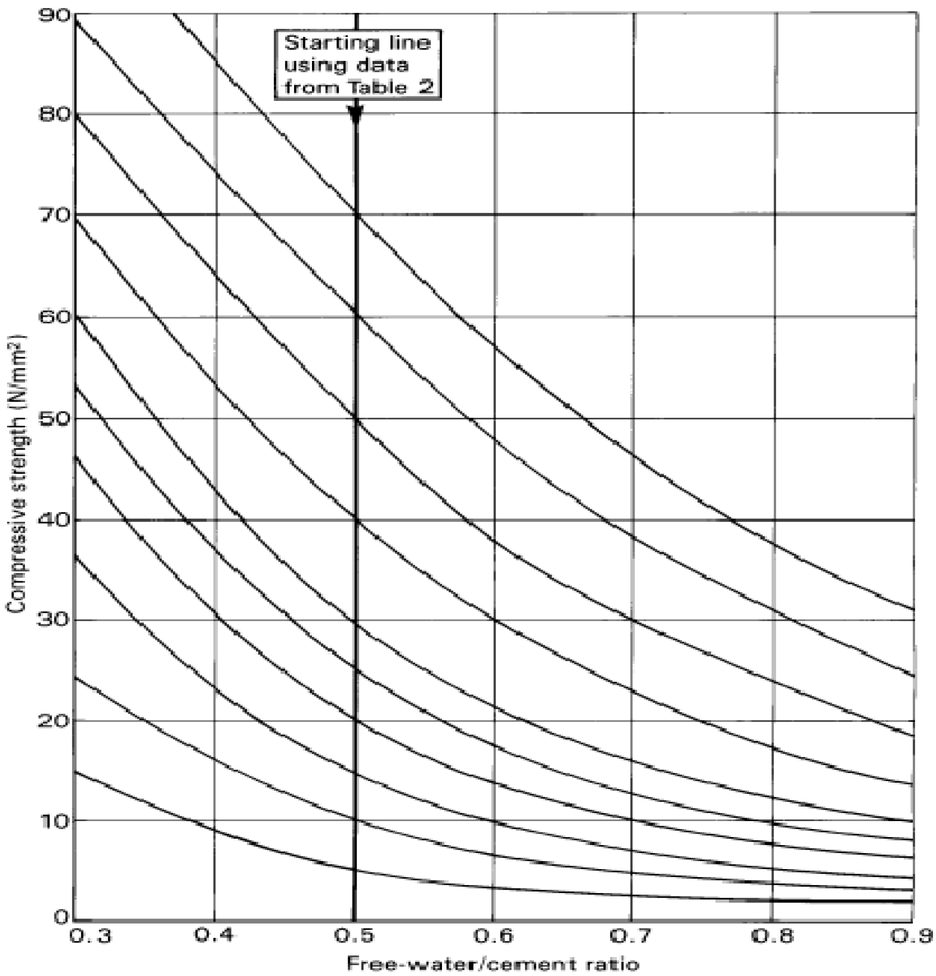

Figure 4 Relationship between compressive strength and free-water/ cement ratio

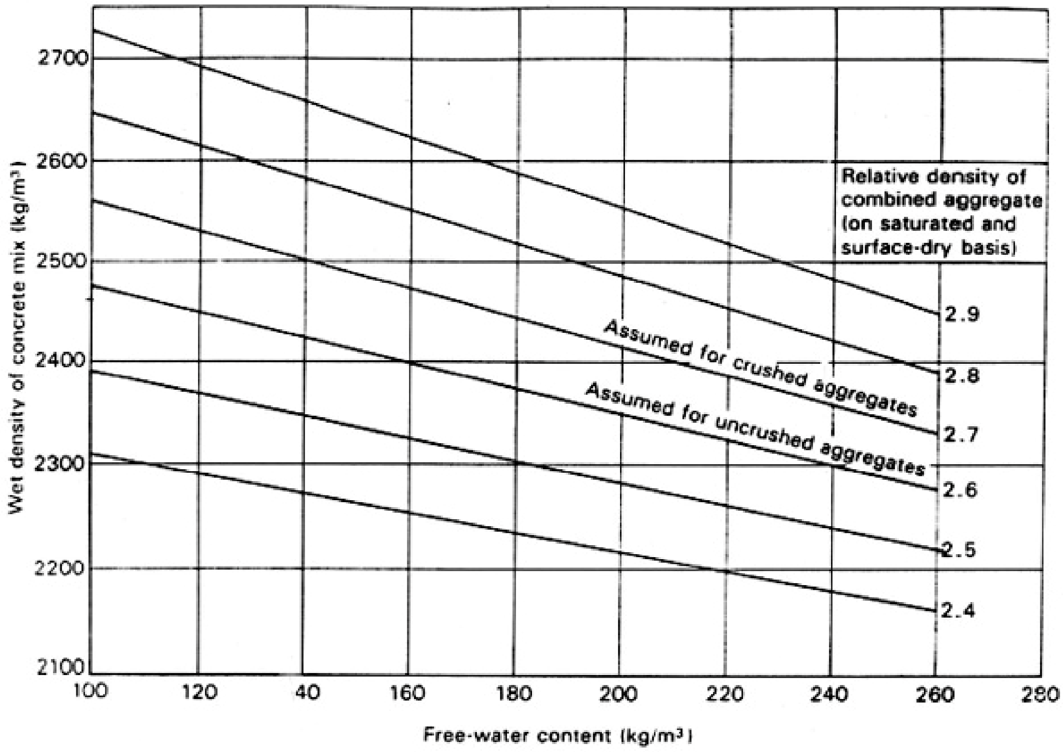

Figure 5 Estimated wet density of fully compacted concrete

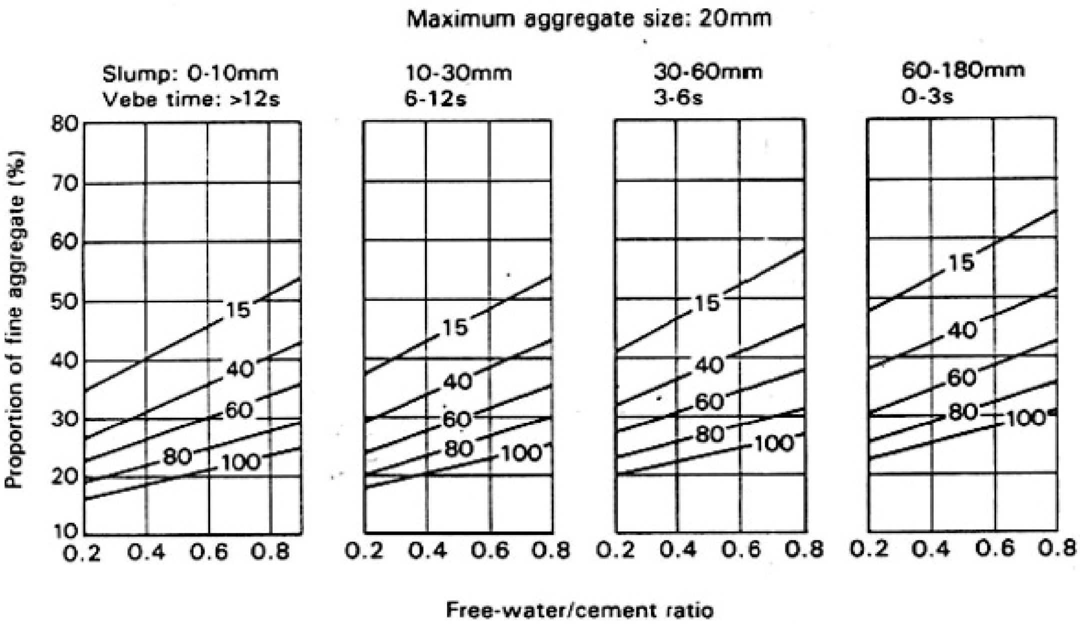

Figure 6: Recommended proportions of fine aggregate for various levels of free-w/c ratio according to percentage passing a 600 μm sieve

A 2 Details of test specimens

Table A2.1 Details of Group I column specimens

Concrete grade	Sample. No	Column Designation	Column specimen dimensions			Slenderness (h/D) ratio
			Outer diameter, D (mm)	Height, h (mm)	Tube thickness, t (mm)	
C20	1	C/C20/110/2/S1	110	220	2.5	2
	2	C/C20/110/2/S2	110	220	2.5	2
	3	C/C20/110/2/S3	110	220	2.5	2
	4	C/C20/110/3/S1	110	330	2.5	3
	5	C/C20/110/3/S2	110	330	2.5	3
	6	C/C20/110/3/S3	110	330	2.5	3
	7	C/C20/83/2/S1	83	166	3.0	2
	8	C/C20/83/2/S2	83	166	3.0	2
	9	C/C20/83/2/S3	83	166	3.0	2
	10	C/C20/83/3/S1	83	249	3.0	3
	11	C/C20/83/3/S2	83	249	3.0	3
	12	C/C20/83/3/S3	83	249	3.0	3
	13	C/C20/83/4/S1	83	332	3.0	4
	14	C/C20/83/4/S2	83	332	3.0	4
	15	C/C20/83/4/S3	83	332	3.0	4
	16	C/C20/55/2/S1	55	110	2.5	2
	17	C/C20/55/2/S2	55	110	2.5	2
	18	C/C20/55/2/S3	55	110	2.5	2
	19	C/C20/55/3/S1	55	165	2.5	3
	20	C/C20/55/3/S2	55	165	2.5	3
	21	C/C20/55/3/S3	55	165	2.5	3
	22	C/C20/55/4/S1	55	220	2.5	4
	23	C/C20/55/4/S2	55	220	2.5	4
	24	C/C20/55/4/S3	55	220	2.5	4

Table A2.2 Details of Group II column specimens

Concrete grade	Sample. No	Column Designation	Column specimen dimensions			Slenderness (h/D) ratio
			Outer diameter,D (mm)	Height, h (mm)	Tube thickness, t (mm)	
C25	1	C/C25/110/2/S1	110	220	2.5	2
	2	C/C25/110/2/S2	110	220	2.5	2
	3	C/C25/110/2/S3	110	220	2.5	2
	4	C/C25/110/3/S1	110	330	2.5	3
	5	C/C25/110/3/S2	110	330	2.5	3
	6	C/C25/110/3/S3	110	330	2.5	3
	7	C/C25/83/2/S1	83	166	3.0	2
	8	C/C25/83/2/S2	83	166	3.0	2
	9	C/C25/83/2/S3	83	166	3.0	2
	10	C/C25/83/3/S1	83	249	3.0	3
	11	C/C25/83/3/S2	83	249	3.0	3
	12	C/C25/83/3/S3	83	249	3.0	3
	13	C/C25/83/4/S1	83	332	3.0	4
	14	C/C25/83/4/S2	83	332	3.0	4
	15	C/C25/83/4/S3	83	332	3.0	4
	16	C/C25/55/2/S1	55	110	2.5	2
	17	C/C25/55/2/S2	55	110	2.5	2
	18	C/C25/55/2/S3	55	110	2.5	2
	19	C/C25/55/3/S1	55	165	2.5	3
	20	C/C25/55/3/S2	55	165	2.5	3
	21	C/C25/55/3/S3	55	165	2.5	3
	22	C/C25/55/4/S1	55	220	2.5	4
	23	C/C25/55/4/S2	55	220	2.5	4
	24	C/C25/55/4/S3	55	220	2.5	4

Table A2.3 Details of Group III column specimens

Concrete grade	Sample. No	Column Designation	Column specimen dimensions			Slenderness (h/D) ratio
			Outer diameter, D (mm)	Height, h (mm)	Tube thickness, t (mm)	
C30	1	C/C30/110/2/S1	110	220	2.5	2
	2	C/C30/110/2/S2	110	220	2.5	2
	3	C/C30/110/2/S3	110	220	2.5	2
	4	C/C30/110/3/S1	110	330	2.5	3
	5	C/C30/110/3/S2	110	330	2.5	3
	6	C/C30/110/3/S3	110	330	2.5	3
	7	C/C30/83/2/S1	83	166	3.0	2
	8	C/C30/83/2/S2	83	166	3.0	2
	9	C/C30/83/2/S3	83	166	3.0	2
	10	C/C30/83/3/S1	83	249	3.0	3
	11	C/C30/83/3/S2	83	249	3.0	3
	12	C/C30/83/3/S3	83	249	3.0	3
	13	C/C30/83/4/S1	83	332	3.0	4
	14	C/C30/83/4/S2	83	332	3.0	4
	15	C/C30/83/4/S3	83	332	3.0	4
	16	C/C30/55/2/S1	55	110	2.5	2
	17	C/C30/55/2/S2	55	110	2.5	2
	18	C/C30/55/2/S3	55	110	2.5	2
	19	C/C30/55/3/S1	55	165	2.5	3
	20	C/C30/55/3/S2	55	165	2.5	3
	21	C/C30/55/3/S3	55	165	2.5	3
	22	C/C30/55/4/S1	55	220	2.5	4
	23	C/C30/55/4/S2	55	220	2.5	4
	24	C/C30/55/4/S3	55	220	2.5	4

Table A2.4 Details of Group IV column specimens

Concrete grade	Sample. No	Column Designation	Column specimen dimensions: Outer diameter, D (mm)	Height h (mm)	Tube thickness, t (mm)	Slenderness (h/D) ratio
	1	U/C20/110/2/S1	110	220	2.5	2
	2	U/C20/110/2/S2	110	220	2.5	2
	3	U/C20/110/2/S3	110	220	2.5	2
	4	U/C20/110/3/S1	110	330	2.5	3
	5	U/C20/110/3/S2	110	330	2.5	3
	6	U/C20/110/3/S3	110	330	2.5	3
	7	U/C20/83/2/S1	83	166	3.0	2
	8	U/C20/83/2/S2	83	166	3.0	2
	9	U/C20/83/2/S3	83	166	3.0	2
	10	U/C20/83/3/S1	83	249	3.0	3
	11	U/C20/83/3/S2	83	249	3.0	3
	12	U/C20/83/3/S3	83	249	3.0	3
C20	13	U/C20/83/4/S1	83	332	3.0	4
	14	U/C20/83/4/S2	83	332	3.0	4
	15	U/C20/83/4/S3	83	332	3.0	4
	16	U/C20/55/2/S1	55	110	2.5	2
	17	U/C20/55/2/S2	55	110	2.5	2
	18	U/C20/55/2/S3	55	110	2.5	2
	19	U/C20/55/3/S1	55	165	2.5	3
	20	U/C20/55/3/S2	55	165	2.5	3
	21	U/C20/55/3/S3	55	165	2.5	3
	22	U/C20/55/4/S1	55	220	2.5	4
	23	U/C20/55/4/S2	55	220	2.5	4
	24	U/C20/55/4/S3	55	220	2.5	4

Table A2.5 Details of Group V column specimens

Concrete grade	Sample. No	Column Designation	Column specimen dimensions			Slenderness (h/D) ratio
			Outer diameter D (mm)	Height h (mm)	Tube thickness t (mm)	
C25	1	U/C25/110/2/S1	110	220	2.5	2
	2	U/C25/110/2/S2	110	220	2.5	2
	3	U/C25/110/2/S3	110	220	2.5	2
	4	U/C25/110/3/S1	110	330	2.5	3
	5	U/C25/110/3/S2	110	330	2.5	3
	6	U/C25/110/3/S3	110	330	2.5	3
	7	U/C25/83/2/S1	83	166	3.0	2
	8	U/C25/83/2/S2	83	166	3.0	2
	9	U/C25/83/2/S3	83	166	3.0	2
	10	U/C25/83/3/S1	83	249	3.0	3
	11	U/C25/83/3/S2	83	249	3.0	3
	12	U/C25/83/3/S3	83	249	3.0	3
	13	U/C25/83/4/S1	83	332	3.0	4
	14	U/C25/83/4/S2	83	332	3.0	4
	15	U/C25/83/4/S3	83	332	3.0	4
	16	U/C25/55/2/S1	55	110	2.5	2
	17	U/C25/55/2/S2	55	110	2.5	2
	18	U/C25/55/2/S3	55	110	2.5	2
	19	U/C25/55/3/S1	55	165	2.5	3
	20	U/C25/55/3/S2	55	165	2.5	3
	21	U/C25/55/3/S3	55	165	2.5	3
	22	U/C25/55/4/S1	55	220	2.5	4
	23	U/C25/55/4/S2	55	220	2.5	4
	24	U/C25/55/4/S3	55	220	2.5	4

Table A2.6 Details of Group VI column specimens

Concrete grade	Sample. No	Column Designation	Column specimen dimensions			Slenderness (h/D) ratio
			Outer diameter, D (mm)	Height, h (mm)	Tube thickness, t (mm)	
C30	1	U/C30/110/2/S1	110	220	2.5	2
	2	U/C30/110/2/S2	110	220	2.5	2
	3	U/C30/110/2/S3	110	220	2.5	2
	4	U/C30/110/3/S3	110	330	2.5	3
	5	U/C30/110/3/S2	110	330	2.5	3
	6	U/C30/110/3/S3	110	330	2.5	3
	7	U/C30/83/2/S1	83	166	3.0	2
	8	U/C30/83/2/S2	83	166	3.0	2
	9	U/C30/83/2/S3	83	166	3.0	2
	10	U/C30/83/3/S1	83	249	3.0	3
	11	U/C30/83/3/S2	83	249	3.0	3
	12	U/C30/83/3/S3	83	249	3.0	3
	13	U/C30/83/4/S1	83	332	3.0	4
	14	U/C30/83/4/S2	83	332	3.0	4
	15	U/C30/83/4/S3	83	332	3.0	4
	16	U/C30/55/2/S1	55	110	2.5	2
	17	U/C30/55/2/S2	55	110	2.5	2
	18	U/C30/55/2/S3	55	110	2.5	2
	19	U/C30/55/3/S1	55	165	2.5	3
	20	U/C30/55/3/S2	55	165	2.5	3
	21	U/C30/55/3/S3	55	165	2.5	3
	22	U/C30/55/4/S1	55	220	2.5	4
	23	U/C30/55/4/S2	55	220	2.5	4
	24	U/C30/55/4/S3	55	220	2.5	4

Table A2.7 Details of Empty UPVC tube specimens

Sample. No	Column Designation	Column specimens dimensions (mm)			Slenderness (L/D) ratio
		Outer diameter, D (mm)	Height, h (mm)	Tube thickness, t (mm)	
1	$P/E/110/2/S_1$	110	220	2.5	2
2	$P/E/110/2/S_2$	110	220	2.5	2
3	$P/E/110/2/S_3$	110	220	2.5	2
4	$P/E/110/3/S_1$	110	330	2.5	3
5	$P/E/110/3/S_2$	110	330	2.5	3
6	$P/E/110/3/S_3$	110	330	2.5	3
7	$P/E/83/2/S_1$	83	166	3.0	2
8	$P/E/83/2/S_2$	83	166	3.0	2
9	$P/E/83/2/S_3$	83	166	3.0	2
10	$P/E/83/3/S_1$	83	249	3.0	3
11	$P/E/83/3/S_2$	83	249	3.0	3
12	$P/E/83/3/S_3$	83	249	3.0	3
13	$P/E/83/4/S_1$	83	332	3.0	4
14	$P/E/83/4/S_2$	83	332	3.0	4
15	$P/E/83/4/S_3$	83	332	3.0	4
16	$P/E/55/2/S_1$	55	110	2.5	2
17	$P/E/55/2/S_2$	55	110	2.5	2
18	$P/E/55/2/S_3$	55	110	2.5	2
19	$P/E/55/3/S_1$	55	165	2.5	3
20	$P/E/55/3/S_2$	55	165	2.5	3
21	$P/E/55/3/S_3$	55	165	2.5	3
22	$P/E/55/4/S_1$	55	220	2.5	4
23	$P/E/55/4/S_2$	55	220	2.5	4
24	$P/E/55/4/S_3$	55	220	2.5	4

A 3 **Properties of aggregates**

Table A3.1 Grading and FM of fine aggregates

sieve size (mm)	mass retained (g)	% retained	% passing	% cumulative retained	lower limits	upper limits
10	0	0	100	0	100	100
5	12	1	99	1	95	100
2.36	14	1	97	3	80	100
1.19	170.5	17	80	20	50	85
0.6	260.5	26	54	46	25	60
0.3	404.5	40	14	86	10	30
0.15	117.5	12	2	98	2	10
< 0.15	20.5	2	-	-	-	-
Total	999.5			253		

Table A3.2 specific gravity and water absorption of fine aggregates

Sample No.	S1	S2	S3
Mass of bottle +water+ sample (W1)	1664.5	1666.5	1666
Mass of bottle +water (W2)	1361.5	1361.5	1361.5
Mass of SSD sample (W3)	505	507.5	504.5
Mass of Oven Dry sample (W4)	504	506	503.5
Sp. gravity on oven Dry Basis $\{W_4/(W_3-(W_1-W_2)\}$	2.50	2.50	2.52
Sp. gravity on SSD Basis $\{W_3/(W_3-(W_1-W_2)\}$	2.50	2.51	2.52
Apparent sp. gravity $\{W_4/(W_4-(W_1-W_2)\}$	2.51	2.52	2.53
Water absorption $\{(W_3-W_4)/W_4)x100\}$	0.20	0.30	0.20
Mean values:	Sp. gravity on oven Dry Basis =		2.50
	Sp. gravity on SSD Basis =		2.51
	Apparent Sp. gravity =		2.52
	Water absorption % =		0.23

Table A3.3 Specific gravity and water absorption of coarse aggregates

Sample No.	SA	SB	SC
Mass of SSD sample (W_s)	1016.5	1012	1014
Mass of submerged sample (W_w)	593	613.5	607.5
Mass of Oven Dry sample (W_d)	1004.5	1004.5	1006
Sp. gravity on SSD Basis $\{W_s/(W_s-W_w)\}$	2.40	2.54	2.49
Sp. gravity on oven Dry Basis $\{W_d/(W_s-W_w)\}$	2.37	2.52	2.47
Apparent sp. Gravity $\{W_d/(W_d-W_w)\}$	2.44	2.57	2.52
Water absorption $\{(W_s-W_d)/W_d)x100\}$	1.19	0.75	0.80
Mean values		Sp. gravity on oven Dry Basis =	2.46
		Sp. gravity on SSD Basis =	2.48
		Apparent Sp. gravity =	2.51
		Water absorption % =	0.91

A 4 **Test results of column specimens**

Table A4.1 Test results of Group I column specimens

S. No	Column Series Designation	Column specimens dimensions (mm)			Slenderness (h/D) ratio	Average load (kN)	Average strength (N/mm^2)
		Outer diameter D	Height h	Tube thickness t			
1	C/C20/110/2	110	220	2.5	2	167.3	17.6
2	C/C20/110/3	110	330	2.5	3	161.8	17.0
3	C/C20/83/2	83	166	3.0	2	131.1	24.2
4	C/C20/83/3	83	249	3.0	3	121.9	22.5
5	C/C20/83/4	83	332	3.0	4	119.7	22.1
6	C/C20/55/2	55	110	2.5	2	60.1	25.3
7	C/C20/55/3	55	165	2.5	3	58.8	24.7
8	C/C20/55/4	55	220	2.5	4	54.7	23.0

Table A4.2 Test results of Group II column specimens

S. No	Column Series Designation	Column specimens dimensions (mm)			Slenderness (h/D) ratio	Average load (kN)	Average strength (N/mm^2)
		Outer diameter D	Height h	Tube thickness t			
1	C/C25/110/2	110	220	2.5	2	181.3	19.1
2	C/C25/110/3	110	330	2.5	3	171.8	18.1
3	C/C25/83/2	83	166	3.0	2	140.6	26.0
4	C/C25/83/3	83	249	3.0	3	133.2	24.6
5	C/C25/83/4	83	332	3.0	4	130.2	24.1
6	C/C25/55/2	55	110	2.5	2	67.5	28.4
7	C/C25/55/3	55	165	2.5	3	64.0	26.9
8	C/C25/55/4	55	220	2.5	4	55.1	23.2

Table A4.3 Test results of Group IIIcolumn specimens

S. No	Column Series Designation	Column specimens dimensions (mm)			Slenderness (h/D) ratio	Average load (kN)	Average strength (N/mm^2)
		Outer diameter D	Height, h	Tube thickness t			
1	C/C30/110/2	110	220	2.5	2	195.3	20.5
2	C/C30/110/3	110	330	2.5	3	180.2	19.0
3	C/C30/83/2	83	166	3.0	2	144.8	26.8
4	C/C30/83/3	83	249	3.0	3	135.5	25.0
5	C/C30/83/4	83	332	3.0	4	132.5	24.5
6	C/C30/55/2	55	110	2.5	2	69.6	29.3
7	C/C30/55/3	55	165	2.5	3	66.0	27.8
8	C/C30/55/4	55	220	2.5	4	62.6	26.3

Table A4.4 Test results of Group IV column specimens

S. No	Column Series Designation	Column specimens dimensions (mm) Outer diameter, D	Height, h	Tube thickness, t	Slenderness (h/D) ratio	Average load (kN)	Average strength (N/mm^2)
1	U/C20/110/2	110	220	2.5	2	77.4	8.9
2	U/C20/110/3	110	330	2.5	3	63.7	7.4
3	U/C20/83/2	83	166	3.0	2	37.2	8.0
4	U/C20/83/3	83	249	3.0	3	32.1	6.9
5	U/C20/83/4	83	332	3.0	4	28.2	6.1
6	U/C20/55/2	55	110	2.5	2	19.5	9.9
7	U/C20/55/3	55	165	2.5	3	17.9	9.1
8	U/C20/55/4	55	220	2.5	4	15.3	7.8

Table A4.5 Test results of Group V column specimens

S. No	Column Series Designation	Column specimens dimensions (mm) Outer diameter, D	Height, h	Tube thickness, t	Slenderness (h/D) ratio	Average load (kN)	Average strength (N/mm^2)
1	U/C25/110/2	110	220	2.5	2	138.2	16.0
2	U/C25/110/3	110	330	2.5	3	125.2	14.5
3	U/C25/83/2	83	166	3.0	2	66.6	14.3
4	U/C25/83/3	83	249	3.0	3	55.9	12.0
5	U/C25/83/4	83	332	3.0	4	50.0	10.7
6	U/C25/55/2	55	110	2.5	2	39.3	20.0
7	U/C25/55/3	55	165	2.5	3	30.7	15.7
8	U/C25/55/4	55	220	2.5	4	23.9	12.2

Table A4.6 Test results of Group VI column specimens

S. No	Column Series Designation	Column specimens dimensions (mm)			Slenderness (h/D) ratio	Average load(kN)	Average strength (N/mm^2)
		Outer diameter, D	Height, h	Tube thickness, t			
1	U/C30/110/2	110	220	2.5	2	150.3	17.4
2	U/C30/110/3	110	330	2.5	3	126.4	14.6
3	U/C30/83/2	83	166	3.0	2	68.4	14.7
4	U/C30/83/3	83	249	3.0	3	62.8	13.5
5	U/C30/83/4	83	332	3.0	4	59.4	12.8
6	U/C30/55/2	55	110	2.5	2	41.0	20.9
7	U/C30/55/3	55	165	2.5	3	36.1	18.4
8	U/C30/55/4	55	220	2.5	4	28.3	14.4

Table A4.7 Test results of Empty UPVC tube specimens

S. No	Column Series Designation	Column specimens dimensions (mm)			Slenderness (L/D) ratio	Average load (kN)	Average Strength (N/mm^2)
		Outer diameter, D	Height, h	Tube thickness, t			
1	P/E/110/2	110	220	2.5	2	39	4.1
2	P/E/110/3	110	330	2.5	3	30	3.2
3	P/E/83/2	83	166	3.0	2	34.3	6.3
4	P/E/83/3	83	249	3.0	3	33.6	6.2
5	P/E/83/4	83	332	3.0	4	32.7	6.0
6	P/E/55/2	55	110	2.5	2	22.5	9.5
7	P/E/55/3	55	165	2.5	3	19.7	8.3
8	P/E/55/4	55	220	2.5	4	14.5	6.1

A 5 Summary of experimental results of composite columns

Table A5.1Summary of experimental results of composite columns

Column's - Dia/slenderness ratio	Tube thickness, t, (mm)	Concrete strength, $f'_{cu,}$ MPa	Load carrying capacity (kN) (confined), P_{cc}	(Unconfined) P_{co}	(Empty tubes) P_{epty}	Components sum (P_{sum}= (P_{co}+P_{epty}))	Capacity enhancement (P_{cc}/P_{sum})	Column strength, Mpa (confined) f'_{cc}	(Unconfined) f'_{co}	Confinement effectiveness (f'_{cc}/f'_{co})
C-110/2	2.5	20	167.3	77.4	39	116.4	1.44	17.6	8.9	1.97
		25	181.3	138.2	39	177.2	1.02	19.1	16.0	1.20
		30	195.3	150.3	39	189.3	1.03	20.5	17.4	1.18
C-110/3	2.5	20	161.8	63.7	30	93.7	1.73	17.0	7.4	2.32
		25	171.8	125.2	30	155.2	1.11	18.1	14.5	1.25
		30	180.2	126.4	30	156.4	1.15	19.0	14.6	1.30
C-83/2	3.0	20	131.1	37.2	34.3	71.5	1.83	24.2	8.0	3.04
		25	140.6	66.6	34.3	100.9	1.39	26.0	14.3	1.82
		30	144.8	68.4	34.3	102.7	1.41	26.8	14.7	1.82
C-83/3	3.0	20	121.9	32.1	33.6	65.6	1.86	22.5	6.9	3.27
		25	133.2	55.9	33.6	89.4	1.49	24.6	12.0	2.05
		30	135.5	62.8	33.6	96.3	1.41	25.0	13.5	1.86
C-83/4	3.0	20	119.7	28.2	32.7	60.9	1.96	22.1	6.1	3.65
		25	130.2	50.0	32.7	82.7	1.57	24.1	10.7	2.24
		30	132.5	59.4	32.7	92.1	1.44	24.5	12.8	1.92
C-55/2	2.5	20	60.1	19.5	22.5	42.0	1.43	25.3	9.9	2.55
		25	67.5	39.3	22.5	61.7	1.09	28.4	20.0	1.42
		30	69.6	41.0	22.5	63.5	1.10	29.3	20.9	1.40
C-55/3	2.5	20	58.8	17.9	19.7	37.7	1.56	24.7	9.1	2.71
		25	64.0	30.7	19.7	50.5	1.27	26.9	15.7	1.72
		30	66.0	36.1	19.7	55.8	1.18	27.8	18.4	1.51
C-55/4	2.5	20	54.7	15.3	14.5	29.8	1.84	23.0	7.8	2.96
		25	55.1	23.9	14.5	38.4	1.43	23.2	12.2	1.91
		30	62.6	28.3	14.5	42.8	1.46	26.3	14.4	1.83