Republic of Iraq
Ministry of Higher Education and Scientific Research
University of Babylon
College of Engineering
Civil Engineering Department

Behavior of Strengthened Reinforced Concrete Columns Using Slurry Infiltrated Fiber Concrete (SIFCON) Shell

A Thesis

Submitted to the College of Engineering at University of Babylon in Partial Fulfillment of the Requirements for the Degree of Master in Engineering / Civil Engineering / Structure

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2023 A.D 1445 A.H

بسم الله الرحمن الرحيم

﴿فَتَعَالَى اللَّهُ الْمَلِكُ الْحَقُّ وَلَا تَعْجَلْ بِالْقُرْآنِ مِن قَبْلِ أَن يُقْضَىٰ إِلَيْكَ وَحْيُهُ وَقُل رَّبِّ زِدْنِي عِلْمًا﴾

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Supervisor Certification

We certify that this thesis entitled “**Behavior of Strengthened Reinforced Concrete Columns Using Slurry Infiltrated Fiber Concrete (SIFCON) Shell"** was presented by **"Noor Adnan Hawase"**, and made under our supervision at the Department of Civil Engineering, College of Engineering, University of Babylon, as a partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Structure).

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Dedication

I dedicate my thesis to my parents, my husband, my sisters, my brothers and my little angel my daughter Lujain for their endless love, support and encouragement throughout my pursuit for education. I hope this achievement will fulfill the dream they envisioned for me.

Noor Adnan Hawase

Acknowledgements

In The Name of Allah, the Most Gracious, the Most Merciful

I would like to express my sincere gratitude to my advisors, ***Dr. Nameer A. Alwash*** *and* ***Dr. Mohammed M. Kadhum*** *for their invaluable guidance and support throughout my master's program. Their expertise and encouragement helped me to complete this research and write this thesis. Special thanks to* ***Dr. Nameer A. Alwash*** *for serving on my thesis committee and providing helpful feedback and suggestions.*

Nobody has been more important to me in the pursuit of this project than the members of my ***family****. I would like to make special thanks to my brother* ***Haider****, my sister* ***Sarab*** *and my husband* ***Maythem****, whose love and support are with me in whatever I pursue.*

Noor Adnan Hawase

Abstract

There is little information about the behavior of the SIFCON columns, so this study will address the behavior of NSC columns coated with the SIFCON shell exposed to a concentric load to obtain valuable knowledge and a broader understanding while studying the impact of several variable parameters such as different SIFCON shell thickness, the shape of the cross-section, the type of fiber used, the volume fraction of fiber and different spaces between the ties and comparing their behavior with unstrengthen NSC columns. Slurry infiltrated fiber concrete (SIFCON) is an advanced generation of fiber-reinforced concrete (FRC) with higher fiber content reach to (4-20) % of mix volume. SIFCON offers excellent potential for use in areas that require high ductility and impact strength, particularly when designing seismic retrofits and repairing or strengthening structural reinforced concrete members. The first part of this study is the experimental work which conducted on the behavior of square and circular reinforced normal strength concrete (NSC) columns of grade (35 MPa) strengthened with SIFCON shell and compare them with unstrengthened NSC. The effect of different SIFCON shell thicknesses (20, 30) mm, fiber type (polypropylene and hooked-end steel fiber), volume fraction (4%, 6%), and ties spacing (80, 160) mm for square columns and (90, 180) mm ties spacing for circular columns were studied. Twenty-two columns were cast and tested under axial load in two groups, where the first group (control specimens) consists of four unstrengthened NSC columns (two of them have circular sections and the others with square sections) and two NSC column (square and circular) strengthened with a 20 mm SIFCON shell with a 6% steel fiber ratio. While the second group consists of sixteen NSC columns (eight of them with square sections and the other eight columns with circular section) strengthened with hybrid fiber SIFCON shell. The NSC square columns had dimensions of (80*80*800) mm, while the NSC circular columns had

dimensions of (D=90 mm * L=800 mm). It was observed that 30 mm SIFCON shell thickness gave a better load carrying capacity, and energy absorption of the strengthened columns. The maximum load achieved is about 223% and 202% for square and circular NSC column strengthened with SIFCON shell of 30 mm with 4% fiber ratio (from mix volume) respectively as a compared with unstrengthened NSC columns. The energy absorption was about 16 times and 15 times than those of NSC columns for square and circular columns respectively.

The second part of this study includes proposed equations for predicting the cube compressive strength of SIFCON and axial load carrying capacity of reinforced concrete columns strengthened by SIFCON shell. Two equations are suggested in the present study to predict the compressive strength of SIFCON with steel fiber only at 7 days and 28 days respectively with very good accuracy based on previous studies. To obtained load bearing capacity of NSC columns strengthened with SIFCON shell, modification for ACI and B.S. codes equations are suggested. The differences between load bearing capacity that obtained from experimental results and from such equations are seemed acceptable and really good in comparison with those obtained for unstrengthened columns in comparison with original ACI and BS equations.

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List of Abbreviations

SIFCON ....Slurry Infiltrated Fibrous Concrete
FRC ....Fiber Reinforced Concrete
NSC ....Normal Strength Concrete
kL/r ....Slenderness Ratio
RC ....Reinforced Concrete
Vf ....Volume Fraction of Fiber
RC..Reinforced Concrete
SF ....Silica Fume
HRWR ....High Range Water Reducing
w/c ....Water to Cement ratio
w/cm ....water to cementitious ratio
w/b ....water to binder ratio
fc' ....cylinder concrete compressive strength
fcu ....cube concrete compressive strength
fr ....Modulus of rupture
Ec ....Modulus of Elasticity
K ....Stiffness
Pu ....Maximum Applied Load
Pn ....Nominal Design Load
DUCON..Ductile Concrete
UHPC..Ultra High Performance Concrete
CFRP...Carbon Fiber Reinforced Polymer
EBR..Externally Bonded Reinforcement
PIV...Particle Image Velocimetry
GM..Grooving Method
R^2...Determination coefficient
HS...Hookes end steel fiber
PP...Polyproplene fiber
ea...,,energy absorption

CHAPTER ONE

(INTRODUCTION)

Introduction

1.1. General Overview

The one responsible for transporting the loads of structure from the slab and beam to the foundation and then to the soil is the column, therefore any damage to it can threaten the life of the building and condemn it to collapse. Thus, the weak column must be repaired or strengthened.

There are several reasons for strengthening or repairing the column such as **(Frangou et al., 1995)**:

1. Increasing the load of the column either for a design mistakes or for the owner's desire to increase the number of floors of the building.

2. Mistakes in construction, for example, steel reinforcement for the column is less than planned.

3. Compressive strength of concrete that used for column is less than the design strength.

4. The presence of sloping in the column more than allowable.

5. Foundation settlement.

6. Steel reinforcement corrosion.

7. Changing in structure function.

8. Fire exposed of building and many reasons.

This study focus on strengthening columns; researchers discovered many techniques for strengthening columns such as carbon fiber covering, reinforced concrete jacketing, steel jacketing and more **(Frangou et al., 1995)**. In this study the slurry infiltrated fiber concrete (SIFCON) will be used as a shell surrounding the columns to increase its strength.

1.2. SIFCON Definition

SIFCON is a new generation of fiber reinforced concrete (FRC), but it differs from it in terms of composition, casting technology, and the amount of fiber used. SIFCON uses (4–20)% from mix volume more fiber than FRC **(Kar, 1984)**, SIFCON contains no coarse aggregates unlike FRC. In FRC, the fiber is mixed with the other ingredients, but in SIFCON, the fibers are placed in the mold first, and the slurry is then applied in layers. Hynes first discovered SIFCON in 1968 **(Elnono et al., 2009)**. Lankard studied the properties and applications of SIFCON. In order to understand the behavior of this concrete, Naaman and Homrich studied the stress-strain characteristics of SIFCON in 1987 **(Kar, 1984; Homrich and Naaman, 1987).**

1.3. SIFCON Composition

Concrete is a brittle material with a low strength to tension, therefore steel reinforcement is added to create reinforced concrete, which has good tensile and compression behavior. Steel is a ductile material with a high tensile strength. In SIFCON, cement slurry is strengthened with fiber **(Farnam et al., 2010).** Cement, fine sand, water, and various mineral admixtures such as (silica fume, fly ash, and metakaolin) make up the SIFCON slurry. Mineral admixtures have a favorable effect on the mechanical properties of the SIFCON where part of the cement weight is replaced by a percentage of mineral admixtures which enhances compressive strength compared to normal concrete, because raising the cement percentage raises production cost, causes shrinkage problems, and affects the heat of hydration. To avoid clogging, enhance workability, achieve suitable fluidity, viscosity, and filling ability, superplasticizers are also added **(Salih et al., 2018).**

1.4. The Process for Casting SIFCON

The fiber is placed in the mold before the slurry is poured over it in layers since pouring SIFCON using the usual methods of mixing is complicated due to the overlap of a large amount of fiber together **(Farnam et al., 2010; Thomas and Mathews, 2014).** SIFCON requires vibration, which can be done mechanically or manually depending on the amount of fiber being utilized. If fiber content is small, it might be satisfied with manual operation or a light vibration. The demand for vibration grows as the fraction of fibers increases, therefore the mixture may need either moderate or intense vibration to make sure the slurry gets to all the fibers and prevent segregation **(Deepesh and Kanase, 2016; Salih et al., 2018).**

1.5. Effect of Fiber in SIFCON

The types of fibers used in the SIFCON are of wide variation, including steel fiber, polypropylene, synthetic, and others. They also vary in shape such as (straight, hooked, and other shapes), aspect ratio, density, tensile strength and volume fraction. The presence of fiber in SIFCON has a large effect on its mechanical properties because it can reduce the need for flexural steel reinforcement, increase flexural strength, enhance concrete ductility, improve tensile strength, increase (durability, energy absorption, crack resistance, compressive strength), reduce deflection and enhance elastic modulus **(Ali and Riyadh, 2018)**.

1.6. Applications of SIFCON

There are several applications of SIFCON such as:

1. **Strengthening and repairing reinforced concrete members:** Damaged beam, column, or other structural element may need to be repaired or strengthened for a variety of reasons, such as corrosion of the steel reinforcement, cracks, and other reasons. Due to its higher strength and toughness compared to ordinary concrete, some researchers have suggested using SIFCON to strengthen some structural elements such as beam, slab and column **(Salih et al., 2018)**. Plate (1-1) and (1-2) illustrated an example of using SIFCON in beam, column and slab-column joint strengthening.

Plate (1-1): Using SIFCON layers for strengthening normal strength concrete: (a) beam **(Hameed et al., 2020)** and (b) column **(Roller et al., 2013).**

Plate (1-2): Strengthening normal strength concrete slab-column joint with SIFCON layers **(Al-Salim et al., 2021).**

2. **In pavement overlays:** Because roads have a wide surface area and are subjected to compression loads, they need a strong compressive force to be capable of withstanding these pressures **(Salih et al., 2018)**. Plate (1-3) illustrated the bridge over the Sava River in Globoko, Slovenia, serves as a sample of the use of SIFCON in pavement overlays **(Šušteršič and Zajc, 2012)**.

Plate (1-3): Using SIFCON in pavement overlays for a bridge over Sava River in Globoko, Slovenia (**Šušteršič and Zajc, 2012**).

3. **In structure designed against earthquakes:** The use of precast SIFCON flexural plastic hinges to increase the seismic resilience of reinforced concrete frames was explored by the researchers. A piece of a beam that has undergone plastic bending is said to have undergone a plastic hinge. Plastic hinges are an extension of the ductile design concept used in the construction of seismically resistant structures. Plastic hinges are a type of energy damping device that allows plastic rotation **(Robinson and Robinson, 1994)**. Specific zones near the end of a member can bend plastically to release energy without causing the

remainder of the structure to collapse. It was conclusively shown that reinforced SIFCON hinges will function better than reinforced concrete hinges. Another study demonstrated that SIFCON allows for substantially better toughness and ductility than traditional fiber concrete when used in cast-in-place connections in frame systems **(Homrich and Naaman, 1987)** see **Figure (1-1**).

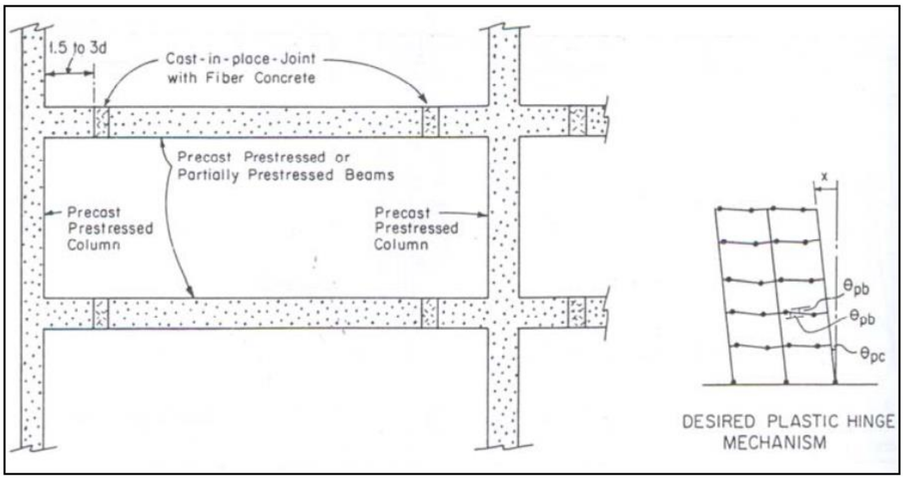


Figure (1-1): Schematic representation of SIFCON joints in the structural system **(Homrich and Naaman, 1987)**.

1.7. Problem Statement

More consideration needs to be given to the idea of employing SIFCON to strengthen columns for a variety of reasons, such as a technical problem, construction errors, an increase in the number of building floors, and other reasons. This thesis focuses on improving theoretical and practical understanding of the behavior of reinforced columns built of normal concrete (NSC) that have been strengthened with SIFCON shell. This is essential because applications of SIFCON to strengthen reinforced concrete columns are not well understood. This thesis seeks to determine whether SIFCON is appropriate for use in strengthening columns and whether it will significantly improve the concentric loaded column's strength. Researchers used SIFCON to strengthen various structural members such as beams and slabs, they noticed an increase in strength. SIFCON column behavior were also studied but the behavior of reinforced concrete columns strengthening with SIFCON shell was not yet studied experimentally from previous provided published researches. From this point, this study was suggested to provide experimental data to know the behavior of NSC columns coated with a SIFCON shell and study the effect of variable parameters on these columns.

1.8. Objective of the Present Study

The importance of this study comes in the possibility of obtaining columns capable of withstanding loads that have not been taken into account, with the least possible thickness and not to increase the cross section of the column as much as possible so that it does not affect the aesthetic and it is less expensive economically as it is known that any design must combine the economic cost, safety and aesthetic of structure .There is little information about the behavior of the SIFCON columns, so this study will address the behavior of NSC columns coated with the SIFCON shell exposed to a concentric load to obtain valuable knowledge and a broader understanding while studying the impact of several variable parameters such as different SIFCON shell thickness, the shape of the cross-section, the type of fiber used, the volume fraction of fiber and different spaces between the ties and comparing their behavior with unstrengthen NSC columns.

The objectives of this research are summarized as follows :

1. The effect of hybrid fibers (polypropylene and hooked end steel fibers) on some of the mechanical properties of SIFCON concrete such as elastic modulus, flexure strength, compression strength and split tensile strength will be studied in comparison with SIFCON including steel fiber only.

2. Experimentally the axial behavior of the square and circular solid NSC columns surrounded by the SIFCON shell will be tested and compared with unstrengthen NSC columns.
3. Study the impact of fiber type, column cross-section shape and fiber volume fraction on the energy absorption of NSC columns coated with SIFCON shell.
4. Studying the effect of using a different thickness of SIFCON layer .
5. Investigate the effect of reduce number of ties (in case of an error in construction) on the behavior of the columns.

1.9. Outline of the Thesis

This thesis consists of five chapters, which are:

Chapter one (introduction), make an overview of the causes of strengthening columns, the definition of SIFCON, its composition, the method of formation and its applications, statement of problem and the objectives of the current study .

Chapter two (Review of literature), deals with a review of scientific research and previous studies published on methods of strengthening reinforced concrete columns and the characteristics of SIFCON and ways to use it in strengthening various structural members.

Chapter three (experimental program), includes the materials used, mixing ratios, methods of preparing and pouring samples, and the tests to be carried out.

Chapter four (Results and discussion), discusses the tests carried out on SIFCON samples, reinforced concrete columns of the NSC and NSC surrounding with SIFCON columns.

While **Chapter five (numerical model)** shows proposed equations for predicting the cube compressive strength of SIFCON and axial load carrying capacity of reinforced concrete columns strengthened by SIFCON shell".

Finally **Chapter six (conclusions and recommendations)** contains the conclusions and recommendations for future research.

CHAPTER TWO

(REVIEW OF LITERATURE)

Review of Literature

2.1. Introduction

Most concrete buildings consist of different structural members. The column is the most important and dangerous structural element. Therefore, any damage to it may lead to failure and possibly collapse of the building because the column is subject to load that moves vertically through it to the soil. The nature of the damage done in the reinforced concrete column can be in the form of cracks without damaging except serious cracks, steel reinforcement buckled, stirrups ruptured and concrete crushed. According to the degree of damage caused, the appropriate method of strengthening is used **(Tayeh et al., 2019)**. The structure requires development for several reasons of change in its function, different design requirements and natural disasters such as earthquakes and floods. Several methods have been used to improve reinforced concrete construction such as “fiber reinforced polymer, steel bracing, external post-tensioning, steel plate bonding, adding new structural elements, etc.". There is no ideal way each method has its own downsides, for example, when using steel plate, it does not resist fires and may be exposed to corrosion, while when using concrete jackets, dimensions and the dead load will increase. Researchers developed a type of concrete called SIFCON to be used to strengthen various members of reinforced concrete and study their behavior **(Dawood and Taher, 2021).**

2.2. SIFCON

It is an advanced generation of fiber reinforced concrete (FRC) with high strength and is characterized by a set of mechanical properties that make it suitable for some applications of special installations. It has a high fiber percentage (4-20) % from mix volume compared to FRC (1-3) %. The

SIFCON consists of cement mortar and fiber in a certain proportion, where the fibers are placed in the mold and then the mortar is poured over it. The SIFCON is characterized by distinctive mechanical properties such as high strength (compression, tensile, shearing, flexure) and high durability and ductility that make it suitable for use in earthquake-prone areas. When producing SIFCON is necessary to take into account the strength of slurry, the percentage of the fibers used, their type and the method of alignment fiber. The method of alignment fiber may be in a parallel direction or perpendicular to the direction of the load, or perhaps randomly, as the direction of fiber distribution has a great impact on the characteristics of the SIFCON such as strength and energy absorption **(Yazıcı et al., 2010)**.

2.3. Preparing the SIFCON

There are different techniques for pouring SIFCON, which are:

1. Single layer technique: in which all the fiber is placed in the mold and then the mortar is poured over it with proper vibration.
2. Three-layer technique in which the fiber is placed up to one third of the mold, then the slurry is poured and the process is repeated until the mold is fully filled.
3. Immersion technology in this technique, the slurry is placed first for one-third of the mold, then the fiber is placed and then exposed to vibration and repeats the process until the mold is fully filled.

All methods are effective for pouring SIFCON, but the immersion method and the three-layer method are better for practical application than other methods because with the increase in the fibers ratio, it becomes difficult for the slurry to reach all fibers if it is poured as single layer **(Parameswaran et al., 1993)**.

The SIFCON cannot be prepared in the usual ways of mixing because it contains a high fiber content overlapping with each other that makes the mixing process difficult, so to overcome this problem, the researchers have devised a special forming method (multi layers method) to ensure that the slurry reaches all fiber and does not segregate, this is often achieved by gravity with light vibration and sometimes it may need high vibration **(Farnam et al., 2010)**.

SIFCON is prepared in three basic steps as shown in Plate (2-1):

1. Put the fiber in the mold.
2. Weigh dry materials and mix them with water and super-plasticizer to form cement mortar.
3. Pour the mortar over the fibers which must have suitable liquidity so that it can penetrate the dense fiber network then smooth the surface **(Vijayakumar and Kumar, 2017)**.

Plate (2-1): SIFCON preparation **(Gilani, 2007).**

2.4. Materials and mixing ratios

SIFCON consists of cement mortar and fiber:

2.4.1. SIFCON mortar

Cement mortar consists of cement, sand and water, which are mostly in the ratios of (1:1, 1:1.5, and 1:2). It is possible to use some mineral admixture such as silica fume and fly ash and replace them with (10-15) % of the cement weight because increasing the cement content has a negative impact on the heat of the hydration. Because of the density of the fiber network, the penetration of the mortar through fiber is difficult, so it was noted that SIFCON do not contain coarse aggregate, and the usual sand with a size of 4.75mm cannot be used. Rather, it is necessary to use fine sand passing through a sieve measuring (1, 0.6, 0.5) mm. In addition, the percentage of water to cementitious ratio (w/cm) is variable between (0.3-0.4). Super-plasticizers are also used to reduce the water content to improve workability and obtain a slurry with appropriate liquidity so that it can reach all fiber without the need to increase the percentage of w/cm, as this super-plasticizer affects the liquidity, cohesion and penetration of cement mortar. Super-plasticizer is used (2-5) % of the cement weight, while the fiber content is (4-20)% from mix volume but the content used in practice (4-12%) **(Ali and Riyadh, 2018)**. **Table (2-1)** is shown mix design of SIFCON from previous researches.

Table (2-1): Mix design of SIFCON slurry from previous researches**.**

Cement	Sand	Silica fume %	Fly Ash	w/cm	HRWR(by wt. of cement)%	References
1	1	-	-	0.38 0.38 0.35 0.32	2 1 2 1	**(Parameswaran et al., 1993)**
1	-	-	0.3	0.3	1.9	**(Wang and Maji, 1994)**
1	1	15*	-	0.28	1.5	**(Yan et al., 1999)**
1	1	-	-	0.45	1.5	**(Rao and Ramana, 2005)**
1	1	5,10,15,20,25**	-	0.4	2	**(Elavarasi, 2016)**

*By weight of cement, silica fume was employed as a supplement rather than a replacement.

**Silica fume was employed as a replacement by cement weights.

2.4.2. Fibers

Different types of fiber are used to manufacture SIFCON. It will be mentioned the types that will be used in this study only:

1. **Steel fiber**: Because ordinary concrete is weak in tension, that is, its behavior is brittle, so adding fibers to concrete will improve some of its properties such as "energy absorption, ductility, toughness". One of the most commonly used types of fiber in SIFCON is steel fiber, which is found in several forms of "smooth surface (round, flat, or of any shape), round with end paddles, hooked end, round with end buttons" as shown in **Figure (2-1).** Fibers are available in different cross sections that may be "square, round, rectangular, diamond, flat, polygon". The most common type of steel fiber for use in SIFCON is hooked end and crimped. Fiber lengths range (6-150) mm and thickness (0.005-0.75) mm **(Naaman, 2003; Ganesan et al., 2014a; Olutoge et al., 2016)**. Short fiber is useful in resisting micro-cracks, while long fiber is useful for large cracks when high deformation occurs **(Vandewalle, 2007)**. Attention should be paid to the importance of the fiber distribution direction. If the fiber is placed along the diameter of the cylinder, it will obtain a higher compressive strength than if the fiber is placed towards the height of the cylinder because in order to resist the load, the researchers found that placing the fibers in a direction perpendicular to the direction of applied load gives twice the strength than if the fiber were placed in direction parallel to direction of applied load as shown in **Figure (2-2) (Gilani).** Alignment fibers randomly is better in that it acts

as a three dimensional reinforcement **(Ganesan et al., 2014a)**. It also controls micro cracks, as the fiber will increase its resistance to cracks and will reduce the width of cracks even after the load is applied and prevent their development from micro to major cracks **(Makun, 2017)**. "Face is subjected to friction and mechanical interference, which increases the bonding between concrete and fiber. The matrix plays an important role in transferring forces between the fibers by shearing to maintain the overlap of fiber **(Salih et al., 2018)**". Steel fiber is used in different proportions in concrete depending on aspect ratio, as its percentage increases by increasing its length or decreasing its diameter. The longer the length of steel fiber, the greater the bonding between the concrete parts, which improves the resistance of the concrete to cracks and reduces its width due to bridging action between the sides of the crack and improves the behavior of concrete from the brittle behavior to the ductile **(Ali and Riyadh, 2018).** The use of short fibers due to their small size makes it possible to use a high fiber content in a small area, which gives a SIFCON concrete with better mechanical properties **(Khamees et al., 2020).**

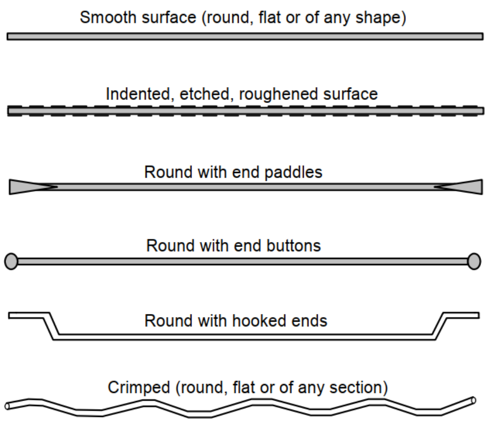


Figure (2-1): Some types of steel fiber **(Naaman, 2003).**

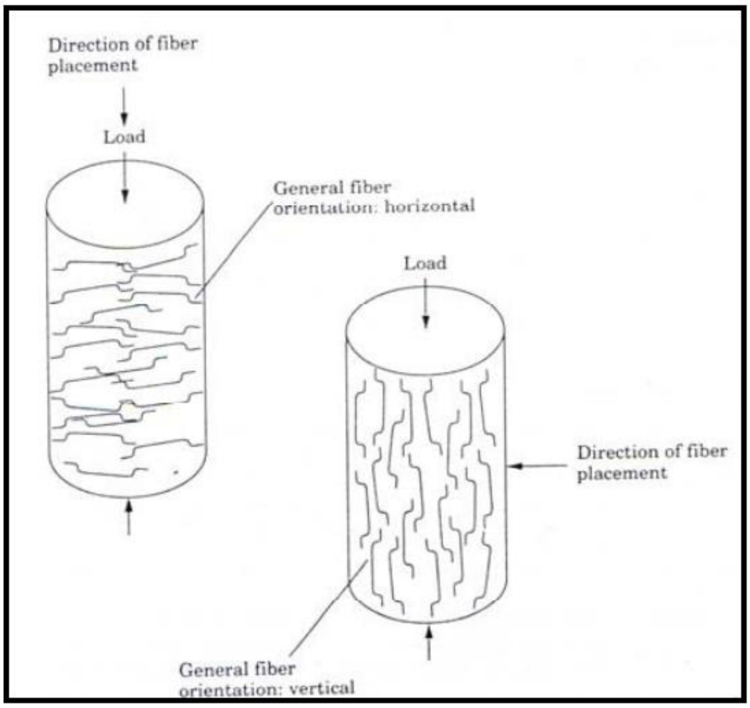


Figure (2-2): Fiber alignment **(Gilani).**

2. Polypropylene

Polypropylene is characterized by its low density compared to other types of fiber, so its use will reduce the weight of the SIFCON, whether when used alone or with another type of fiber, such as steel fiber. Polypropylene is corrosion-resistant and reduces the dead load of the building. Therefore, it is suitable for use in the manufacture of SIFCON in places exposed to corrosion. "Increasing the polypropylene fiber content reduces its effect on deflection at the small stage due to the dispersion of this type of fiber" due to low density of polypropylene, therefore it spreads in the mixture and does not be in one place **(Qian and Stroeven, 2000).**

Polypropylene has high ductility, fineness, and dispersion, so it can resist plastic cracks. It is available in various types, such as staple fiber, coarse synthetic monofilament and micro polypropylene as shown in Plate (2-2) **(Hsie et al., 2008)**.

(Thomas and Mathews, 2014) investigated the behavior and strength of SIFCON using various fibers, including polypropylene and hooked-end steel fiber. Various fiber volumes (4, 5, and 6)% from mix volume were taken through this study. Flexural, compression, and split tensile tests were all performed. Results demonstrated that 5% of the steel and polypropylene fibers showed the best value in compression, tension, and flexural strength among 4, 5, and 6 percentages. Compared to 5% volume of fiber, both fiber outcomes for 6% indicated a reduction in strength. Polypropylene fibers can also be added to reduce the specimen's density and crack width.

(Al-Salim et al., 2021) studied how using hybrid fiber (steel fiber and polypropylene) SIFCON concrete in flat slab-column connections could increase energy absorption. Eight specimens of reinforced concrete slab-column connections were evaluated; six of them were cast as hybrid slab-column connections (normal strength concrete (NSC) and SIFCON) with 6% steel fiber alone and hybrid fiber (3% steel fiber and 3% polypropylene), while the other two slab-column connections were cast as NSC as control specimens. According to the results, using SIFCON increased energy absorption by (36.04% to 77.37%) when compared to control specimens.

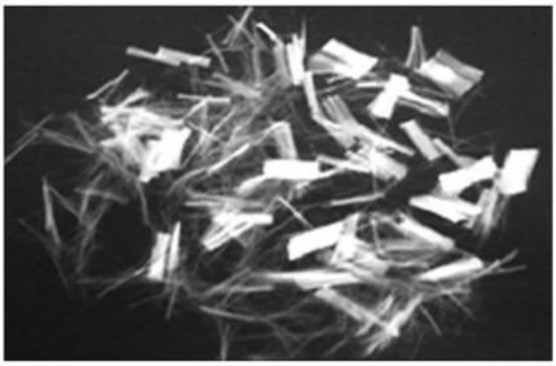


Plate (2-2): Some types of polypropylene fiber **(Ganesan et al., 2014b; Al-Salim et al., 2021).**

3. Hybrid Fiber Concrete

In hybrid concrete, it is possible to use two or three types of fiber, such as different types of steel fiber, types of polypropylene fiber, or carbon with steel fiber. Thin fiber is generally used for micro cracks and thick fiber for macro crack **(Markovic et al., 2004; Stähli and Van Mier, 2004)**. Concrete is a weak tensile strength material, so fibers are added to overcome this problem. Fibers increase tensile strength, give concrete a ductile behavior, increase the durability of the concrete and improve its durability. Fiber is present in various shapes, measurements and materials such as (steel, carbon, glass, etc.). Steel fiber is the most common use and also synthetic fiber which are used to control cracks. Recently, there has been an evolution of reinforced concrete with fiber, where more than one type of fiber has been used together in concrete, this is called hybrid concrete. Sometimes in which fibers of the same type are used, but in different sizes, or fibers made of different materials **(Vandewalle, 2007). (Ganesan et al., 2014b)** studied the effect of polypropylene fiber and steel on bond strength and bond stress-slip response on deformed reinforcement bars immersed in high-performance concrete. The number of samples were used are 96. The main variables were volume fraction and diameter of bar. Crimped steel fiber was used at (0.5%, 1%) and polypropylene at (0.1, 0.15, 0.2)% from mix volume, while the diameters used for reinforcement bars are (10, 12, 16, 20) mm. For hybrid concrete, use 1% crimped steel fiber and 0.2% polypropylene. The results showed that hybrid concrete gave better results compared to high-performance concrete (HPC). It was found that the use of 1% steel fiber and 0.15% polypropylene, give the best results compared to other types.

(Kanagavel and Kalidass, 2017) used a set of fiber to obtain hybrid concrete. These fibers are polypropylene, steel fiber and carbon fiber, and studied some mechanical properties such as compressive strength, splitting tensile strength and impact resistance. The results showed that using this combination of fiber together improves the studied mechanical properties of hybrid concrete.

From this point the current study will focus on using hybrid fiber SIFCON concrete where the hooked end steel fiber and polypropylene will be used.

2.5. Properties of SIFCON and Mix Design

The bonding properties between fiber and mortar depend on the mechanical properties of the slurry, curing conditions, mineral admixture and durability problems. Researches have shown that SIFCON has a unique role in controlling the development of cracks as a result of the high content of fiber and its appropriate distribution method **(Farnam et al., 2010)**. The SIFCON mortar should be designed so that it can reach all the fiber in the mold and the content of this fiber depends on the shape of the fiber and the type of application. SIFCON mortar is also made of fine sand but does not contain coarse aggregates and it also consists super-plasticizers. SIFCON are concrete with a ductile behavior when exposed to pressure **(Dagar, 2012)**. One of the components of cement mortar for the SIFCON is cement, which can be replaced by some mineral admixture such as "silica fume, metakaoline, ground granulated blast-furnace slag" which will reduce "cost, hydration heat, shrinkage problems and increase the density of fiber matrix" **(Yalçınkaya and Beglarigale, 2014)**. The creation of any structure requires materials with advanced and improved properties such as "strength, stiffness, toughness, durability and ductility." The most common material for use in construction is concrete. But concrete has its downsides, as it has "low energy absorption and low ductility", so to solve this problem, the researchers added fiber to concrete and followed different ways to increase the fiber content in concrete until they discovered a new type of ordinary fiber reinforced concrete called SIFCON concrete **(Geetha, 2016)**. It is an important factor in the design of SIFCON to obtain a suitable liquid slurry to penetrate the fiber network **(Vijayakumar and Kumar, 2017).** The strength of SIFCON to non-fiber compression for one day (25-35) MPa and (50-70) MPa in 28 days, but with the addition of fibers, its compressive strength may range from (40-80) MPa for one day and (90-169) MPa for 28 day depending on the percentage of fibers used. The highest strength to SIFCON recorded was 210 MPa **(Gilani)**. **Table (2-2)** is shown an example of slurry mix proportions from pervious study.

Table (2-2): An example of Compressive strength values and slurry mix design from previous research **(Homrich and Naaman, 1987).**

Mix No.	Mix Materials	Relative Weight of Materials	w/cm (1)	Strength Range in 28 days (MPa)
1	Type I Cement	1	0.3	52-117
	Fly Ash	0.2		
	SP	0.03		
	Water	0.36		
2	Type I Cement	1	0.35	41-93
	Fly Ash	0.2		
	SP	0.02		
	Water	0.36		
	Silica Slurry (2)	0.2		
3	Type I Cement	1	0.3	41-86
	Fly Ash	0.2		
	SP	0.04		
	Water	0.26		
	Silica Slurry (2)	0.3		
4	Type I Cement	1	0.26	69-121
	Fly Ash	0.25		
	SP	0.04		
	Water	0.325		

(1) w/cm is water/cementitious materials ratio including mineral admixture

(2) A slurry of about 50% (water and silica) by weight.

2.6. Previous Studies on Strengthening Various Reinforced Concrete Members with SIFCON

(Balaji and Thirugnanam, 2014) studied cyclic behavior for exterior beam-column joints made of RC and FRC strengthened with SIFCON layers of 20 mm thick, where crimpled steel fiber was used at 9%. The researcher poured 12 samples and examined them under the cyclic load effect to study the behavior of "load-deformation, ductility, ultimate load carrying capacity, failure characteristics". The results showed that beam-column joints made of RC and FRC strengthening with SIFCON increased by 23% in maximum load carrying capacity compared to non-strengthened, while the ductility factor was 61% more for RC and 72% for FRC compared to non-strengthened beam-column joints. Energy absorption increased 40% and 38% for RC and FRC beam-column SIFCON-coated joints respectively.

(Geetha, 2016) studied the strengthening of reinforced concrete beam using layers of SIFCON as shown in Plate (2-3). The researcher studied the behavior of reinforced concrete beam in flexure and shear strengthened with precast SIFCON laminates, where plain concrete was the grade of 20 MPa. Hooked end steel fiber was used by 7%. The results indicated that the use of SIFCON contributed to an increase in beam resistance compared to that of RC beam made of plain concrete.

Plate (2-3): NSC beam strengthened with SIFCON layers **(Geetha, 2016).**

(Sisupalan and Paul, 2019) studied the strengthening of beam of ordinary reinforced concrete and another from FRC using precast layers of SIFCON. These layers were glued with epoxy to the bottom of the beam as well as on its sides under the influence of two points load test. It was used plain concrete of grade of M30 and used hooked end steel fibers by (5%, 7%, 9%, and 11%). The ratio of 5% gave the highest results. The results showed that strengthening FRC and RC beams with SIFCON gave a noticeable increase in improving the load capacity.

(Hameed et al., 2020) studied the bending strength, toughness and ductility of prisms made of ordinary concrete strengthened with layers of SIFCON. Prisms were coated only from the bottom, from above only and from all sides with different thicknesses (3.5, 2.5, and 1.5) cm and used steel fiber by (6%, 7.5%, and 9%). The results showed that increasing the thickness of the SIFCON layer and its proportion of steel fiber leads to an improvement in "load bearing capacity, toughness and ductility" where the highest results were obtained when the prism was fully strengthened with SIFCON, where it was 23 times higher than control prism.

2.7. SIFCON Column Energy Absorption

Energy absorption capacity described as the area enclosed by the load-displacement curve until the maximum load was reached, which represents the energy absorption of a concrete column which could sustain before indicating a substantial decrease in load carrying capacity **(Barros et al., 2007; Abdulraheem and Kadhum, 2017)**.

2.8. Concrete Columns

2.8.1. Slenderness Ratio

Columns are classified according to their slenderness ratio into short columns and long columns. The ratio of slenderness is given in the following relation: (KL/r) where (KL) is the effective length of the column and (r) is the radius of gyration. If the column length is more than 12 times the smallest dimensions of the cross-section of the column, it is classified as a long column, and if it is smaller or equal to 12 times the smallest dimensions, it is considered a short column. Long columns are characterized by high slenderness, which makes them fail by buckling, unlike short columns that fail by crushing **(Plain, 2000)**.

2.8.2. Stiffness of RC Column

"It is a term used to describe the force required to achieve a certain deformation of origin". In general, stiffness is the amount of load dividing deformation relative to an elastic body and given in relation K=F/d". Stiffness is not a fixed amount, but variable depending on the type of load, its location, and the type of deformation, so there is more than one concept of stiffness" **(Baumgart, 2000)**. The initial stiffness depends on the intensity and distribution of stress on columns cross-section, in addition to the amount of flexural and shear cracks. Flexural cracking causes reduction in the net cross sectional area and moment of inertia, hence a reduction in initial flexural rigidity of the column section. This leads to the increasing difficulty in making accurate predictions of the initial stiffness of RC members **(Li, 2012).**

2.9. Types of Failure in Concrete Columns

Depending on the ratio of slenderness, there are three types of failure for columns:

1. Column failure due to pure compression: The reinforcement steel and concrete in reinforced concrete columns are stressed when they are axially loaded. Steel and concrete attain their yield stress at high loads relative to the column's cross-sectional area, and the column fails without lateral deflection. The collapse of the concrete column is caused by material failure, which has crushed the column. To get around this, the concrete column needs to have enough cross-sectional area so the stress stays below the set limit. This kind of failure

typically occurs in pedestals that do not bend under axial loads and have a height to least lateral dimension of less than 12.

2. Column failure due to combined compression and bending: Axial loads, lateral loads and moments are frequently applied to short columns. Short columns bend and deflect to the side when subjected to lateral loads and moments. Under these conditions, material failure occurs and a reinforced concrete column fails when the stresses in steel and concrete exceed its yield stress. Combination compression and bending failure is the name given to this kind of failure.
3. Column failure due to elastic instability: The ratio of a long column's effective length to its smallest lateral dimension is greater than 12. For a certain cross-sectional area and percentage of reinforcing steel, under such conditions, the load carrying capability of reinforced concrete columns is significantly reduced. Such concrete columns have a tendency to become unstable and buckle to any side when they are subjected to even minor loads. Therefore, in such circumstances, the steel reinforcement reaches its yield stress even for small loads and fails as a result of lateral elastic buckling. It is unacceptable in real concrete construction for this kind of failure **(Mishra, 2014).**

2.10. Previous Studies on the Strengthening of Columns

The degree to which the majority of the current buildings are subjected to structural damage depends significantly on the quality of the design, details, and construction. A building structure's lifespan can frequently be extended by an engineer utilizing simple repair and strengthening techniques. The choice of the repair/strengthening technique becomes crucial since high costs would prevent many building owners from performing critical repairs. There are presently numerous strengthening and repair techniques used for reinforced concrete (RC) columns. Unfortunately, most of them are highly costly, time-consuming, and require stopping building use while repair is done. Therefore, the degree to which the majority of the current buildings stock are subjected to structural damage depends significantly on the quality of the design details and construction.

(Frangou et al., 1995) used post-tensioning metal strips around the column and then securing them in place with metal clips is the technique being investigated for the repair or strengthening of columns as shown in **Figure (2-3)**. The initial results demonstrate that this strengthening can improve member ductility and strength to levels higher than those made achievable by normal reinforcement.

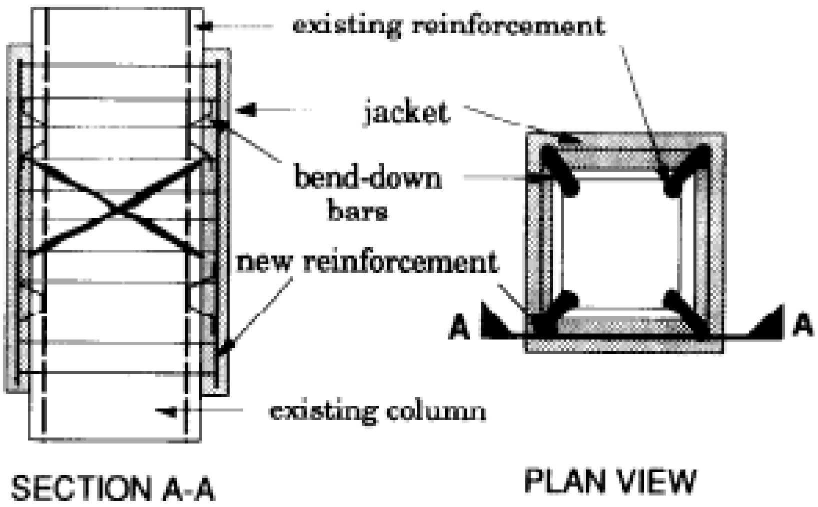


Figure (2-3): Strengthening column using post-tensioning metal strips **(Frangou et al., 1995).**

(Vandoros and Dritsos, 2008) experimentally investigated the effectiveness of strengthening concrete columns by adding jackets to mid, full-size columns as shown in Plate (2-4) to compare outcomes to those of monolithic specimens and unreinforced original specimens. This technique included welding the jacket stirrup ends together, welding steel dowels into the jacket and original column interface, and welding the longitudinal reinforcement bars of the jacket to the longitudinal reinforcement bars of the original column. Even when the jacket was constructed without any treatment at the interface, a significant increase in strength and stiffness was observed. It was also found that the apparent crack patterns and the failure mechanism are affected by the strengthening method. In addition, it was found that welding the stirrup ends of the jacket together prevented the longitudinal bars of the jacket from buckling.

Plate (2-4): Strengthening concrete columns by adding jackets through welding steel dowels into the jacket **(Vandoros and Dritsos, 2008)**.

(Tarabia and Albakry, 2014) investigated the performance and behavior of RC square columns strengthened with steel cage as shown in Plate (2-5). Ten specimens of axially loaded columns were subjected to an experimental program till failure. The primary analyzed parameters were the size of the steel angles, strip spacing, grout material between column sides and angles, and the connection between the steel cage and the specimen head. The ultimate loads of the strengthened columns, in addition to the impact of the confining stress caused by the steel cage and axial forces in the vertical angles, were also determined analytically using a simple stress technical aspects and strain compatibility, taking into account both directly and indirectly connected cases. It was determined that this form of strengthening is quite effective because it increased the axial load capacity of the strengthened columns. The ability of the steel angle to sustain a significant portion of the applied axial force and the confinement effect of the external steel cage were both responsible for this gain. The buckling of the steel angle followed by the crushing of the original columns caused the failure in the majority of the strengthened specimens.

Plate (2-5): RC square columns strengthened with steel cage **(Tarabia and Albakry, 2014)**.

According to the knowledge of author based on previous researches, only **(Roller et al., 2013)**, investigate the residual axial load carrying capacity of the circular column under contact and close-in detonations, the researcher conducted a number of tests on the exposed hardened concrete surface. The scale ratio of the tested column model is 1:3, and it has spiral transverse reinforcement with a 2.5 mm diameter and eight longitudinal reinforcement bars of 7.5 mm diameter. At the base of the column was a spherical PETN explosive charge. The performance of the strengthened column using 15 mm thick layers of advanced material, such as polymer concrete, SIFCON, ductile concrete (DUCON), and ultra-high-performance concrete(UHPC), was compared to that of the column built with regular strength concrete. It was a localized strengthening of the cross-section in the area of the potential damage for the SIFCON with more than 5% steel fiber ratio. Plate (2-6) shown failure mode of columns with different materials for strengthening. Through a uniaxial compressive test, the load-carrying capacity of the blast-damaged column was determined. It was discovered that employing polymer concrete and SIFCON under contact blast and retrofitting approaches under close-in blast, respectively, may improve the column's residual axial load carrying capacity by around 70% and 100%, respectively. While the column with DUCON coating provided the highest performance under contact blast, the performance of the column enhanced with a 15 mm thick coating of SIFCON was shown to be superior under close-in blast loading.

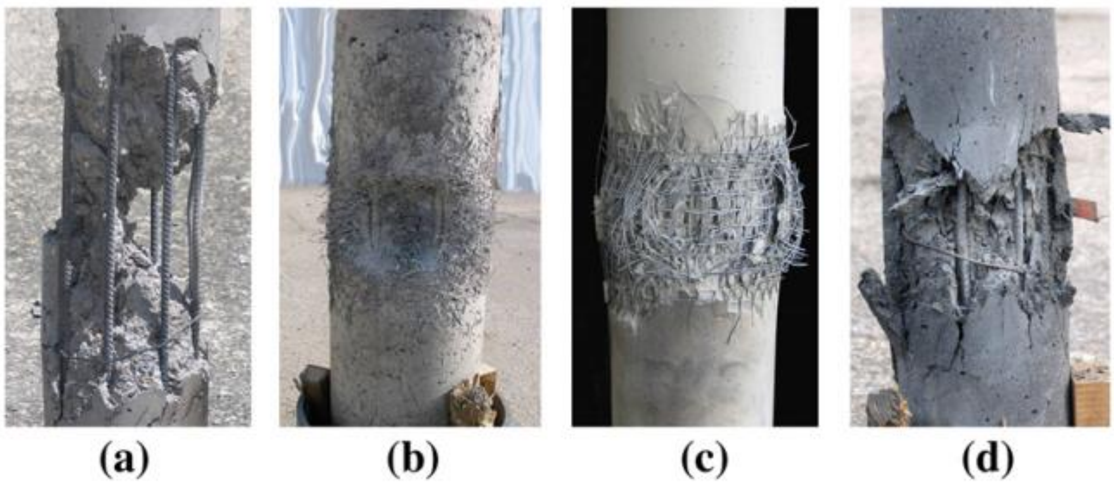


Plate (2-6): Failure mode of columns under explosion loads, with cross-sections made of (a) RC, (b) SIFCON, (c) DUCON, and (d) UHPC **(Roller et al., 2013).**

(Moshiri et al., 2015) investigated how strengthened RC columns behaved when longitudinal carbon fiber reinforced polymer (CFRP) was used as external compression reinforcement as shown in Plate (2-7). Ten RC columns, including 5 circular columns with a 150 mm diameter and 5 square columns with a dimension of 133 mm, were cast. The specimens in compression with CFRP were strengthened using four different techniques: conventional externally bonded reinforcement (EBR), near surface mounted (NSM), recently introduced grooving method (GM), in the forms of externally bonded reinforcement on grooves, and externally bonded reinforcement in grooves. The specimens were taken through monotonic uniaxial compression testing, and a thorough discussion of the various consequences of the strengthening approaches was conducted. The stress transfer between a longitudinal CFRP sheet and a concrete substrate was also further investigated using particle image velocimetry (PIV), an image-based deformation measurement technique. Following the CFRP's buckling being delayed by using the grooving method (GM) to connect it to the concrete surface, experimental results showed that compression CFRP sheets that strengthened RC columns are better.

Plate (2-7): Failure modes of strengthened RC columns using carbon fiber reinforced polymer (CFRP) and (GM) method **(Moshiri et al., 2015).**

2.11. Concluding Remarks

1.The studied literature shows that there are only a few studies in the field of reinforced concrete columns strengthened by SIFCON using hybrid fiber. A summary of the results of the literature review is as follows.

2. SIFCON has exceptional qualities over plain concrete, including durability, energy absorption capacity, ductility and stiffness

3. The strength properties of SIFCON are significantly influenced by the matrix strength, composition, and fiber alignment .

4. Compared to composites that only contain one type of fiber, hybrid composites have excellent engineering properties.

5. Steel fiber is the most popular type of fibers that used in preparing SIFCON, but the current study focusses on adding polypropylene to steel fiber as a hybrid SIFCON to reduce cost, dead weight and to prevent corrosion.

6. There is no ideal ratio for mixing steel fiber with polypropylene, because the researches using these fibers together is few. According to these studies, it was found that with decreasing polypropylene fiber ratio relative to steel fiber, the strength is increased. Therefore, it was suggested to fixed polypropylene ratio and use the following fiber ratios 4% (2% hooked end steel fiber + 2% polypropylene) and 6% (4% hooked end steel fiber + 2% polypropylene).

7. According to previous studies, it was found that the most popular mixing ratios of cement to sand in SIFCON preparing are (1:1), (1:1.5) and (1:2). The mixing ratio of (1:1) is the best, because with increasing sand, the strength is decreased. Therefore, the ratio of (1:1) will be used in this study.

Therefore, the objective of the current investigation is the need to study the behavior of NSC columns strengthened with SIFCON shells and subjected to concentric loading to provide valuable information and a better understanding of their behavior. In addition, study the effect of various parameters such as SIFCON shell thickness, fiber type and volume fraction, cross-section shape, and spaces between ties of columns (in case of construction errors), and compares their its behavior with unstrengthened NSC columns.

CHAPTER THREE

(EXPERIMENTAL PROGRAM)

Experimental Program

3.1. Introduction

The details of the experimental program are laid out in this chapter. Details of the materials used (cement, sand, fibers, mineral admixtures, and chemical admixtures), mix proportions, preparation, mixing, casting procedures, curing, and testing program of column specimens are presented, along with an explanation of the research methodology used to achieve the goals outlined in chapter one. The goal of the experimental research was to analyze the behavior of NSC columns strengthened with SIFCON shell and compare it to unstrengthen normal concrete reinforced column specimens due to the lack of previous experimental work to study NSC columns strengthened with SIFCON shell.The experimental variables investigated for the column specimens were:

1. The shape of section (square and circular).

2. Type of fiber (hooked end steel fiber and polypropylene).

3. Spaces between ties (80, 160) mm for square columns and (90, 180) mm for circular columns.

4. Thickness of SIFCON shell (20, 30) mm.

5. Fiber volume fraction (4%, 6%).

Details of the tests on samples and column specimens used throughout this study:**Tests of SIFCON for Samples**

1. Tests of fresh SIFCON (mini slump flow and V-funnel test);
2. Compressive strength;
3. Splitting tensile strength;
4. flexural strength;
5. Modulus of elasticity;

- **Tests of SIFCON Shell Column Specimens**

1. Axial displacement;

2. Load mid-height lateral displacement relationship; and
3. Ultimate load carrying capacity of the column specimens.

- **Tests of NSC Samples**

1. Test of fresh NSC (slump test);
2. compressive strength;

- **Tests of NSC Column Specimens**

1. Axial displacement;
2. Load mid-height lateral displacement relationship; and
3. Ultimate load carrying capacity of the column specimens.

SIFCON is a composite material made of a variety of components, including cement, sand, super-plasticizers, mineral admixtures, water, and fiber. These materials have a variety of qualities, including (specific of gravity, unit weight, gradation and water content). It is necessary to determine the type of constituent materials and mixing ratios. The materials utilized, their source, chemical composition, and physical characteristics of materials will all be discussed in detail in this chapter. The required tests were carried out in the labs of the Department of Civil Engineering at the University of Babylon/ Faculty of Engineering.

3.2. Research Methodology

The experimental strategy for this study was divided into two parts. The initial stage involved the selection, preparation, and assessment of the raw materials' physical and chemical characteristics. The next step in this phase involves creating trail mixes to determine the best weight ratios for mixing, the type of concrete to use, and the quantity of chemical and mineral additions to add. The chosen ingredients were then combined using the best mixing ratio. Finally, the cast samples and column specimens are cured for the necessary ages (7, 28 and 56) days. The flowchart shown in **Figure (3-1)** illustrates the overall experimental program.

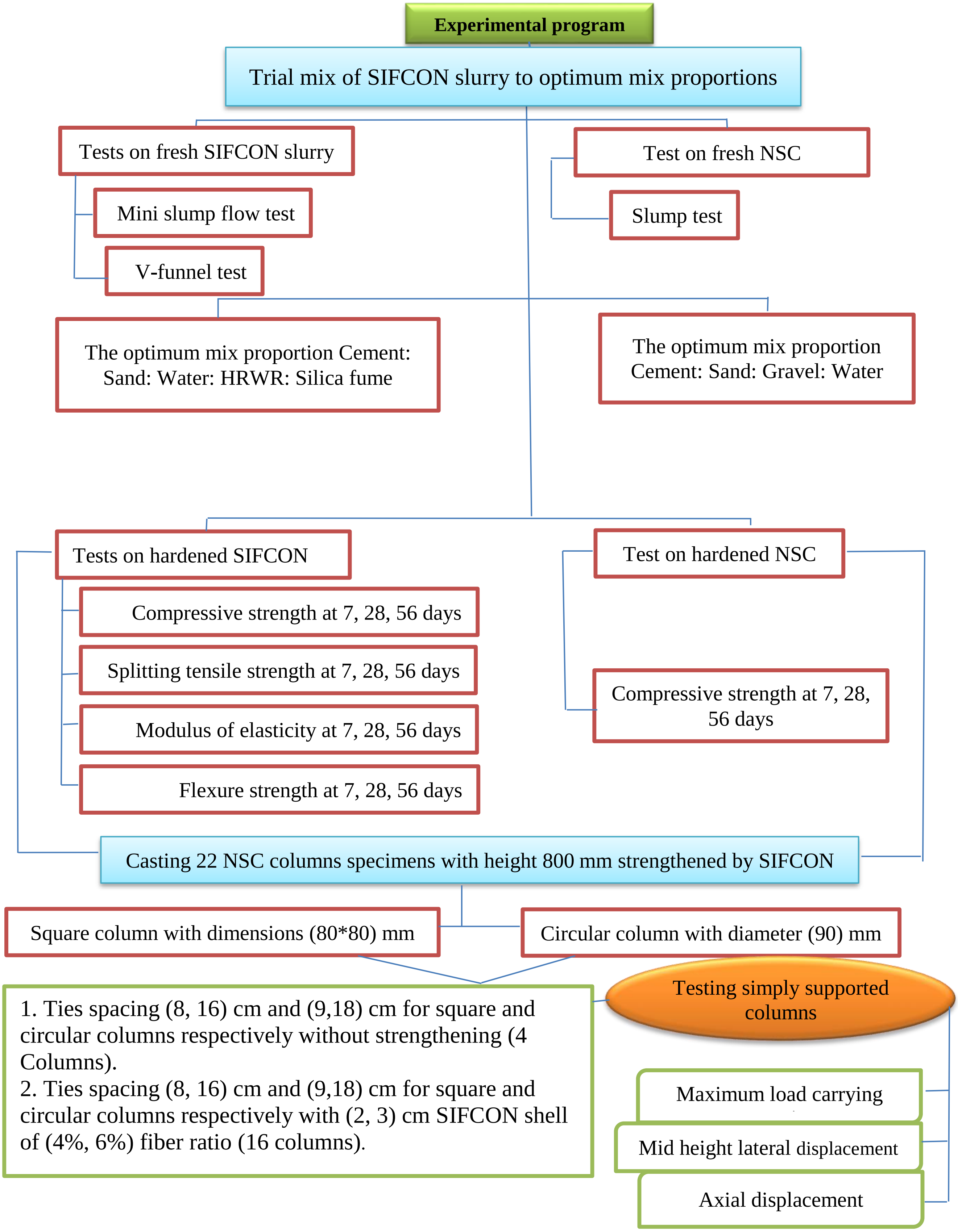


Figure (3-1): Experimental program flowchart

3.3. Materials for SIFCON

3.3.1. Portland Cement

Ordinary Portland cement (type I), produced in Iraq and obtained from local markets, was the type of cement employed in this study. To protect it from exposure to various atmospheric conditions, it was stored in a dry location. **Tables (3-1)** and **(3-2)** show the results of the employed cement's chemical analysis and physical test, respectively. The Iraqi Standard Specification **(IQS No. 5/1984)** was met with this cement.

Tables (3-1): Chemical analysis of cement.

Chemical compositio	Percentage by weight	Limit of IQSNo.5/1984
Lime	62.41	..………..…………
Silica	20.88	..………..…………
Alumina	6.04	..………..…………
Iron Oxide	5.40	..………..…………
Magnesia	1.60	≤ 5
Sulfate	1.19	$\leq$ 2.5 if C_3A> 5%
Free lime	0.84	..………..…………
Loss on ignition (L.O.I)	2.68	$\leq$ 4
Insoluble residue, I.R	0.56	$\leq$ 1.5
Lime Saturation factor	0.91	1.02 – 0.66

Table (3-1): Continued.

Main Compounds	Percentage by weight	Limit of IQSNo.5/1984
Tricalcium silicate, C3S	53.57	…………….
Dicalcium silicate, C_2S	19.45	…………….
Tricalcium aluminate, C_3A	1.62	≤ 3.5
Tetracalcium Aluminoferrite, C_4AF	16.43	…………….

Table (3-2): Physical properties of cement.

Physical properties	Test result	Limit of *IQS No.5/1984*
Initial setting time (hour: min.)	02:23	≥00:45 (hour: min.)
Final setting time (hour: min.)	03:25	≤10:00 (hour: min.)
Specific surface area (Blain Method) m^2/kg	326	≥ 250
Compressive Strength (MPa)		
3 days	20.33	≥ 15
7 days	27.45	≥ 23

3.3.2. Fine Aggregate

As a substitute for natural sand, natural fine aggregate from the AL-Ukhaider region was employed. This natural sand was too coarse to be utilized in mortar production (in SIFCON). To prepare mortar, only fine sand that has been sieved through a 600 μm sieve to remove larger particles is used, and employing this size of sand proved successful for all mortar mixes during the experimental work. The grading and sieve analysis of fine aggregate are displayed in **Tables (3-3)**. It is compliant with the **(IQS No. 45/1984)** restriction zone (4). **Table (3-4)** lists the physical and chemical properties of natural sand.

Table (3-3): Grading and sieve analysis of fine aggregate for (SIFCON).

Sieve Size (mm)	Cumulative passing (%)	Limits of IQS (No.45/1984) zone (4)
10	100	100
4.75	100	95 – 100
2.36	100	95 – 100
1.18	100	90 – 100
0.60	100	80 – 100
0.30	45	15 – 50
0.15	10	0 – 15

Table (3-4): Physical and chemical properties of fine aggregate (for SIFCON).

Main properties	Test results	Limits of IQS (No.45/1984)
Specific gravity	2.60	–
Finines Modules	1.45	–
Sulfate content %	0.387	≤ 0.5%
Absorption %	2	–

3.3.3 Silica fume (SF)

A by-product of the manufacturing of elemental silicon or alloys, silica fume (SF) is an extremely fine non-crystalline silica that is created in electric arc furnaces. The silica fume, which condenses from the gases exiting from the furnaces, contains a very high concentration of amorphous silicon dioxide and is made up of extremely small, spherical particles with a typical diameter of (0.1 to 0.2) μm. This reduces it to a size that is around 100 times smaller than the typical cement particle. The cement paste's microstructure is enhanced by silica fume which increase its resistance to all types of external impact. In this study, silica fume, which known as Mega Add MS (D) in the industry and made by the (CONMIX) company, was utilized as a partial replacement (10% by weight) for cement. The physical requirements and the chemical analysis of the SF used are shown in **Tables (3-5)** and **(3-6)**. The outcomes demonstrate that the (SF) utilized in the current investigation complies with the **(ASTM C1240-05, 2015)**. Plate (3-1) shows the silica fume used in this research.

Plate (3-1): Silica fume.

Table (3-5): The chemical analysis of the silica fume*.

Oxide composition	**Oxide content %**	**ASTM C1240–05**
Silicon dioxide (SiO_2)	89.41	Minimum 85%
Aluminum oxide (Al_2O_3)	0.63	—
Ferric Oxide (Fe_2O_3)	0.45	—
Calcium oxide (CaO)	0.82	< 1
Sulfur trioxide (SO_3)	0.87	< 2
Potassium Oxide and Sodium oxide (K_2O+Na_2O)	1.35	–
Loss on ignition (L.O.I)	4.10	Maximum 5%
Chloride content (CL)	0.18	–
Free calcium Oxide (CaO)	2.15	–

*Manufacture properties.

Table (3-6): The physical analysis of the silica fume*.

Main property	Results	ASTM C1240 – 05 Limits
Strength activity index	130	≥ 105
Percent retained on 45 µm (No. 325) sieve %	1.70	≤ 10
Specific surface, min, m^2/g	23	≥ 15

*Manufacture properties.

3.3.4. Fibers

1. **Hooked end steel fiber:** It was discovered that to penetrate the fiber bed without clogging or honeycombing, SIFCON fibers must be loose (single or discrete). Therefore, it was necessary to dissolve and remove bonded fibers before using them in the molds. Steel fibers with a hooked end that measure 30 mm in length and 0.5 mm in diameter were provided by the Chinese HEBEL YUSEN METAL WIRE MESH company followed the standard **(ASTM A820-96)**. In 20 Kg bags, the steel fiber was imported. According to the producer company, the technical characteristics of hooked end fiber are shown in Table (3-7).

2. **Polypropylene Fiber:** The second type of fiber was Polypropylene fiber, which had a diameter of 0.85 mm and a length of 60 mm followed **(EN 14889-2:2006)**. The Sika firm in Zurich, Switzerland, provided this fiber. Plate (3-2) displays polypropylene fiber. **Table (3-7)** describes the technical and physical characteristics of the employed fibers.

Table (3-7): Characteristics of steel fiber and polypropylene*.

Property	**Steel fiber**	**Polypropylene**
Description	Deformed shape Hooked end	Deformed shape
Appearance	Bright and clean wire	White straight fibers
Length, L (mm)	35	60
Diameter, D (mm)	0.5	0.85
Aspect ratio	60	71.42
Density (kg/m^3)	7800	910
Tensile strength (MPa)	1100	430

*Manufacture properties.

Plate (3-2): Samples of (**a**) hooked end steel fiber and (**b**) polypropylene fiber.

3.3.5. High Range Water Reducing Admixture (HRWR)

The high-range water-reducing admixture utilized in this study was imported from the Master Builders Solutions Dubai, UAE company and is known commercially as Gelnium 54. Glenium 54 was created for uses primarily in the ready-mixed and precast concrete industries, where the greatest levels of durability and performance are required. Used Master-Glenium 54 is based on an original carboxylic polymer with long lateral chains. The cement is dispersed much better as a result. The same electrostatic dispersion takes place at the beginning of the mixing process, but the presence of the lateral chains, connected to the polymer backbone, produces a steric barrier that stabilizes the cement particles. The water need for flowable concrete is considerably decreased thanks to this technique, which also improves early strength. It complied with the specification **(ASTM C-494 Type F and G BS EN 934-2)**. All varieties of Portland cement and cementious materials, including micro silica, fly ash, and ground granulated blast furnace slag (GGBS), can be used in these mixes. Glenium 54 has better carbonation resistance, lower permeability, better resistance to abrasive atmospheric conditions, reduced shrinkage and creep, and increased durability. It also has increased flexural strength and increased early and ultimate compressive strengths. The technical description of (Gelnium 54) is presented in **Table (3-8)**.

Table (3-8): Technical description of (Gelnium 54)*.

Form	**Viscous liquid**
Commercial name	Gelinim 54
Chemical composition	Sulphonated melamine and naphthaline
Appearance	Whitish to straw colored liquid
Relative density	1.07gm/cm ^{3} at 20 C°
Chloride content	Nil.
PH	4 – 7

Table (3-8): Continued.

Form	**Viscous liquid**
Storage	Should be stored above 5C°
Transport	Not classified as dangerous
Classification	Not hazard
Alkali content (as Na_2O)	0.26%

*Manufacture properties.

3.3.6. Water

SIFCON concrete mixing and curing of specimens both used tap water from the college site. The temperature of the mixing water was held constant at (25±2 ° C) and PH= 7.

3.4. Materials for Normal Strength Concrete

3.4.1. Portland cement

The same type of cement used to make SIFCON was used.

3.4.2. Fine Aggregate

Natural sand from the (Al-Ekhaider) region was used as the fine aggregate for the entire project. The obtained findings showed that the grading of the sand and sulfate content, as stated in **Tables (3-9)** and **(3-10),** and the grading of fine aggregate within zone 2 were in compliance with the limits of the Iraqi Specification **(IQS 45/1984)**.

Tables (3-9): Grading of fine aggregate for (NSC).

Size of sieve (mm)	Passing Presentage	
	Fine aggregate	Limitation for zone No2. (IQS 45/1984)
10	100	100
4.75	97	90 – 100
2.36	81	75 – 100
1.18	70	55 -90
0.60	54	35 – 59
0.30	21	8 – 30
0.15	7	0- 10

Table (3-10): Physical and chemical properties of fine aggregate for (NSC).

Physical properties		
Properties	Test result	Iraqi specification No.45/1984
Specific gravity	2.65	-------------
% Absorption	0.94	-------------
Fine material Passing from Sieve (75 μm) %	4.2	5% (max.)
Fineness modulus	%2.6	-------------
Chemical properties		
Sulfate content	0.15	≤ 0.5% (max.)

3.4.3. Coarse Aggregate (Gravel)

Natural rounded gravel with a maximum size of 10 mm was used as the coarse aggregate for NSC columns. This material was also sourced locally in Iraq from the (AL-Nibaai) region. The findings showed that the coarse aggregate utilized in this study complied with the requirements of **(ASTM C33, 2006)**. Before usage, the gravel is cleaned, dried by storing it outside in the air, and then stored in containers with a wet, dry surface to not absorb the water from mixture. **Tables (3-11)** and **(3-12)** provides information on the grading and physical characteristics of coarse aggregate.

Table (3-11): Grading of coarse aggregate.

Sieve Size (mm)	Cumulative passing precentage	Limits of ASTM C33,2006
12.5	100	100
10	93	85 – 100
4.75	14	10 – 30
2.36	4	0 – 10
1.18	1	0 – 5

Table (3-12): Physical and chemical characteristics of coarse aggregate.

Physical properties	Test result	Limits of Iraqi specification No. 45/1984
Specific gravity	2.60	—
Sulfate content %	0.08	0.1 (max)
Absorption %	0.70	—

Table (3-12): Continued**.**

Chemical properties	
Compound	**Oxides content %**
Silicon dioxide	65.03
Aluminum oxide	0.87
Ferric oxide	0.6
Calcium oxide	12.31
Sodium oxide	0.09
Phosphorus oxide P_2	0.01
Loss on Ignition	14.33

3.4.4. Water

Tap water was used in the mixing and curing of the concrete and PH= 7.

3.4.5. Steel Reinforcements

Deformed steel bars of (Ø 4 mm) diameter were employed as lateral reinforcement (ties) and (Ø 6 mm) bars were utilized as longitudinal reinforcement in typical reinforced concrete columns. A digital computer that was used in conjunction with the testing device to determine the reinforcing bars' mechanical properties is shown in **Table (3-13).** Plate (3-3) is shown steel reinforcement used in reinforced NSC columns.

Table (3-13): Mechanical properties of steel reinforcement*.

Nominal bar diameter (mm)	Actual bar diameter (mm)	Yield stress Fy (MPa)	Ultimate strength Fu (MPa)	Elongation (%)
4	3.82	555	620	7.5
6	5.90	560	607	11

*Testing of steel bars was carried out in Strength of Materials laboratory at the College of Materials Engineering / University of Babylon

Plate (3-3): Steel reinforcement used in NSC columns.

3.5. Tests for Fresh SIFCON Slurry

Testing SIFCON mortar when it is still fresh is crucial for the production of SIFCON. To pass through the dense fiber bed, the matrix must be sufficiently liquid and fine. Mini slump flow and V-funnel tests are the only two tests that EFNARC has recommended for use with SIFCON mortar **(EFNARC, 2002)**. SIFCON mortar flowability, filling capacity, resistance to segregation, and viscosity were all evaluated using these tests. The mini-flow test measures the slurry's flowability, homogeneity, and resistance to segregation, whereas the viscosity of the slurry was determined using the V-funnel test (flow rate measurement). The two SIFCON mortar tests that were conducted are briefly summarized here.

3.5.1. Mini Slump Flow Test

It is the simplest and quickest test method available for evaluating the horizontal flow and filling capacity of SIFCON mortar. Visual observation during the test can also expose the uniformity and segregation resistance of the slurry **(Ali, 2018).** A cone-shaped mold with internal dimensions of 100 mm at the base, 70 mm at the top, and 60 mm at the height was utilized for the mini slump flow test **(EFNARC, 2002),** as illustrated in Plate (3-4). Scoop, trowel, and a base plate made of a hard, non-absorbent material were also needed for this test. This test required about 0.5 liter of slurry to complete. It is necessary to moisten the device's base and the sides of the slump cone before placing it in the center of the plate, filling it with mortar using a scoop, and leveling its surface with a trowel while removing extra mortar from the area surrounding the cone. The cone is progressively raised up to disseminate the slurry across the table after the device's base receives 25 automated blows in 15 seconds to vibrate the slurry. The mini slump flow value in millimeters is represented by the average of two diameters of the slurry propagation measured in two perpendicular directions. The ability of the slump flow to fill formwork under its own weight increases with the slump flow value. For SIFCON mortar, a value of (240-260) mm spread diameters is necessary **(EFNARC, 2002)**. The test value was 245mm.

Plate (3-4): Mini slump flow test**.**

3.5.2. V-funnel Test

By calculating how long the slurry will take to pass through the inspection device's funnel gate, this test can estimate the slurry's viscosity. Time is a measure of the flow rate, not the viscosity. Viscosity decreases when slurry penetration time decreases, and vice versa. The tool consists of a bucket, a scoop, a trowel, a V-shaped funnel, and a timer as shown in the Plate (3-5).

It takes about one liter of mortar to complete this test. The lower gate and internal walls of the funnel are moistened before being set down on a level surface. Close the bottom gate, set the bucket entirely below it, and begin scooping mortar into the funnel before using a trowel to level the surface. Ten seconds after the mortar has been poured into the funnel, the bottom gate opens, and the timer is activated to determine how long it will take for the slurry to discharge from the funnel to the bucket. It is known that when the light was noticed in the funnel from above, the slurry had already been entirely drained. Seven to ten seconds have been proven to be the ideal flow time for SIFCON slurry **(EFNARC, 2002).** The V-funnel time was 10 seconds.

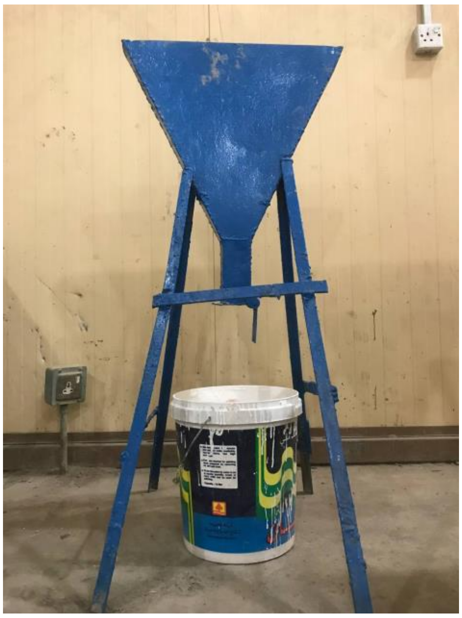


Plate (3-5): V-funnel test**.**

3.6. Test for Fresh NSC

The most popular technique for determining the consistency of concrete is the slump test, which may be done both in a lab and on the work site according to **(ASTM C143-15)**. The test result of slump was (87mm) as shown in plate (3-6).

Plate (3-6): Slump test.

3.7. Trial Mixes of SIFCON

The high-range water reduction admixture (HRWR) can be viewed as the most crucial element in achieving a homogenous mixture that has the low w/cm ratio needed for SIFCON mortars. In order to ensure that the dosage is correct and in complied with the other mortar components, the HRWR used for this study is (Glenium 54) from the Master Builders Solutions company. In order to achieve the best fresh properties for SIFCON mortars with mini slump flow range between (240 - 260) mm and V - funnel time range between (7 - 11 seconds), as well as to achieve easy and complete penetration of prepared mortars through the steel fiber network, numerous trial slurry mixes have been created. The process for figuring out how much HRWR is needed for SIFCON mortars involves measuring the slump flow with varying amounts of HRWR until the target value of (240 - 260) mm is obtained, and then timing how long the V-funnel takes to form. In this case, the fiber may be examined for infiltration after the small slump flow test, which is the easiest and fastest test. The **Table (3-14)** displays specifics on the test mixes. In that table, a few adjectives were used to describe the slurry's effectiveness. The terms (Bad) and (Good) reflect whether the slurry successfully penetrated any of the fiber forms employed in this investigation, respectively, where (Bad) indicates that the slurry does not penetrate the fiber completely and (Good) indicates that the slurry penetrates the fiber completely.

Table (3-14): Trial mixes of SIFCON slurry.

Dosage of HRWR (%) by weight of cement	w/cm ratio	The infiltration of slurry through fiber
2	0.25	Bad
2.2	0.28	Bad
2.4	0.28	Good

3.8. Mix Proportions

In order to create a concrete mixture, it is first required to select the raw ingredients and figure out the proper mixing ratios in order to produce a mixture with the suitable viscosity, good liquidity, and workability to prevent segregation or bleeding in the concrete. Because there are still no established standards for SIFCON, the mixing ratios listed in **Table (2-1)** of Chapter two were chosen based on prior research. The typical ratios of cement to sand are (1:1, 1:1.5 and 1:2), but it was discovered that increasing the amount of sand reduces the strength, thus the (1:1) ratio was used in this study. The amount of cement used ranges between (800–1000) kg/m^3, and the water to binder ratio (w/b) should not exceed 0.4. SIFCON shell was poured around NSC columns using hybrid fibers with volume fraction of 4% (2% polypropylene +2% steel fiber with hooked ends) and 6% (2%

polypropylene+ 4% hooked end steel fiber) and 6% steel fiber only. In order to produce concrete with a grade of 35, the mixing ratios for normal concrete are calculated using the American mix design method **(ACI 211.1-91)**. The mixing ratios of SIFCON and NSC are displayed in **Table (3–15)**.

Table (3–15): Mixing ratios of SIFCON and NSC**.**

Mix type	**Mix proportion**						
	Blended cement (kg/m^3)	**Sand (kg/m^3)**	**Silica fume (kg/m^3) 10% rep.**	**Gravel (kg/m^3)**	**Ratio of fiber (by volume mix) %**	**w/cm or w/c ratio**	**SP (by wt. of binder) %**
SIFCON	872.1	969	96.9	—	4 & 6	0.28	2.4
NSC	518	704	—	1129.66	—	0.61	—

3.9. Description of The Samples of The Tested Columns

The test program consists of 22 NSC column samples. All the columns were poured into the laboratory, eighteen of which were coated with SIFCON shell with (20, 30) mm thick on all sides and the remaining four were considered as a reference of comparing the results with them. The dimensions were fixed for all the columns, as they were 800 mm high. The shape of the cross-section of the columns is shown in **Figure (3-2).** Each NSC column was reinforced with 4Ø6 mm for longitudinal reinforcement and Ø4 mm for transverse reinforcement at a spaces of (80, 160) mm and (90, 180) mm between the ties of the square and circular columns respectively.

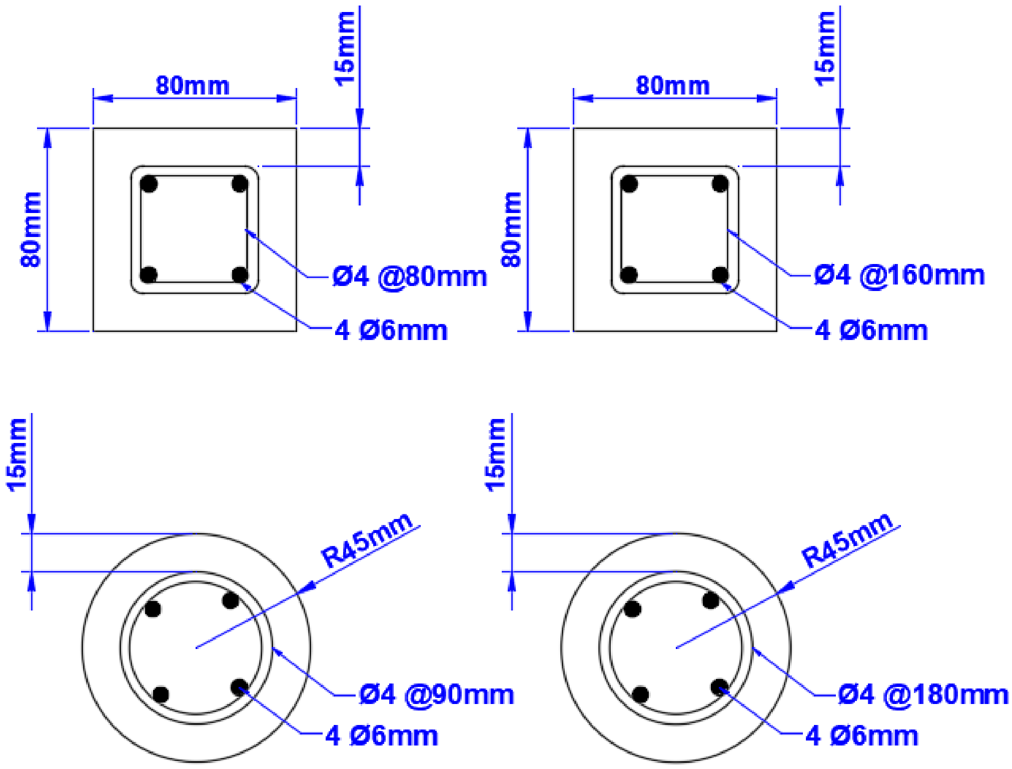


Figure (3-2): Shape of the cross-section of the columns.

3.10. Mixing Technique

To obtain the desired performance and homogeneity of SIFCON mortars, adequate mixing is required. In order to thoroughly dispose of silica fume and enable the HRWR to reach its full potential, it is also crucial to extend the mixing period by breaking up any agglomerated particles. As indicated in Plate (3-7), the specimen mixes were carried out in a horizontal rotary mixer with a capacity of (0.09 m^3), whereas the trial mixes were carried out in a tiny rotary mixer with a (0.01m^3) capacity. Before operating the concrete mixer, any leftover concrete from a previous batch must be scraped up. The concrete mixer's blades and pan are cleaned with a wet cloth.

The methodology used in this study is based on previous studies and trial mixtures to give results that are suitable and workable. The mixing processes are summarized as follows:

1. Prior to mixing, the mixer was cleaned of any remaining fresh or dried components (from previous combinations).

2. For about 0.5 minute, the entire amount of HRWR was mixed separately with (1/3) of mixing water.

3. To create the SIFCON slurry, the cement and silica fume (SF) binder material was first mixed for one minute in a mixer to distribute the SF particles throughout the cement particles. Then, sand was added and the mixing was continued for two more minutes.

4. The rotating drum was then filled with (2/3) of mixing water, which was then blended for 1 minute. After adding 1/3 of the mixing water, HRWR was fed into the mixer and blended for 3 minutes.

5. The mixer is then stopped, and hand mixing is carried out for the area where the mixer blades were unable to reach.

6. The mortar components are then blended for an additional (1) minute to get the desired smoothness.

3.11. The Definition of Column Samples

Because of the large number of column samples in this research, and also to facilitate comparison between these columns, each column is defined by four symbols as shown in **Table (3-16)**. Where the first letter (N) symbolizes the type of concrete from which the column is made, which is NSC. The second letter symbolizes the type of cross-section of the column, either square (S) or circular (C), and the third letter (Hy) represents hybrid fiber or (H) represents steel fiber. While the numbers (8, 9, 16, 18) represent spacing between ties. The percentages (4, 6) % represent fiber ratio and the numbers (2, 3) represent SIFCON shell thickness. **Figure (3-3)** summarizes the definition of column samples.

Table (3-16): The definition of column samples.

Type of column concrete	Columns Symbol
NSC	NS8
	NS16
	NC9
	NC18
NSC strengthened with SIFCON shell	N2CHy-18 (4%)
	N2CHy-18 (6%)
	N2CHy-9 (4%)
	N2CHy-9 (6%)
	N2SHy-16 (4%)
	N2SHy-8 (4%)
	N2SHy-8 (6%)
	N2SHy-16 (6%)
	N3SCHy-18 (4%)
	N3SCHy-18 (6%)
	N3SCHy-9 (4%)
	N3SCHy-9 (6%)
	N3SSHy-16 (4%)
	N3SSHy-8 (4%)
	N3SSHy-8 (6%)
	N3SSHy-16 (6%)
	N2SSH-8 (6%)
	N2SCH-9 (6%)

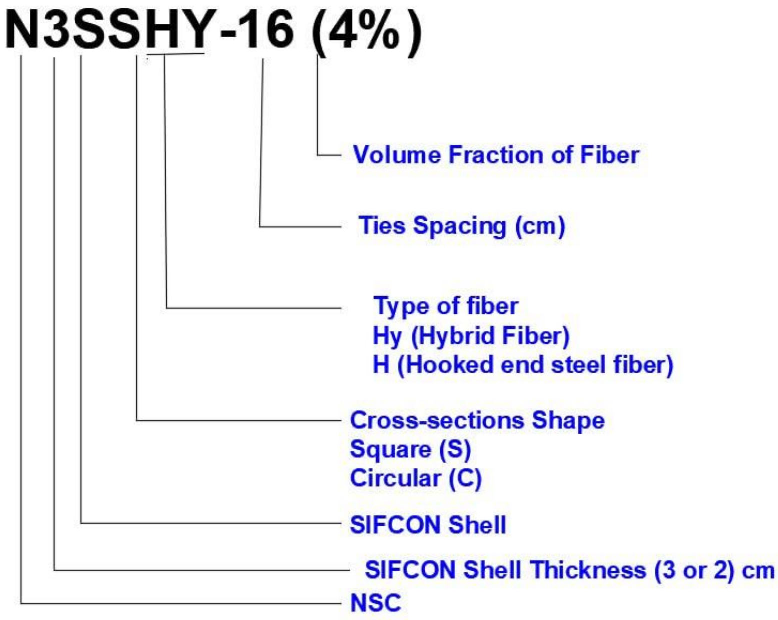


Figure (3-3): The definition of column samples method.

3.12. Columns Molds

Square and circular NSC columns were vertically poured using iron molds for square and circular columns with a cross section (80x80) mm and the a diameter of 90 mm as formwork in this study. Iron molds were also used to pour the SIFCON shell where circular iron molds have a (130 and 150) mm diameter, while square iron molds have a cross section of (120x120) mm and (140x140) mm (see Plate (3-7)). All of the molds have an 800 mm height. The iron molds are vertically separated into two pieces. To manage the casting process, the second vertical part is separated horizontally into three pieces, whereas the first vertical section is one piece measuring 800 mm in length.

3.13. Procedures for Casting and Curing Specimens

The ingredients were chosen and weighted in accordance with the volume of the mixture before casting. Two columns may be cast from each batch that came out of the mixer. The casting of columns is demonstrated in Plate (3-

8) and the casting of SIFCON samples (cubes, cylinders and prisms) is demonstrated in Plate (3-9).

The following phases are outlined in the casting process:

1. To prevent the concrete from sticking to the mold after it has hardened and to make it easier to remove from the mold, clean the molds then paint the inner sides with a thin layer of oil.

2. Using a horizontal rotating mixer to create normal concrete by combining cement, sand, gravel, and water.

3. After pouring concrete into the mold, level the top using a trowel and left the columns in the mold for 24 hours at room temperature.

4. For 28 days of curing, leave the square and circular NSC columns in the water.

5. After 28 days, the NSC columns are removed and left to dry and then roughed the surface to increase the bonding between normal and SIFCON concrete.

6. Cleaning the iron molds and painting their internal sides with a light layer of oil, placing the molds on a flat ground and adjusting their horizontality and verticality.

7. Mixing materials to form slurry by horizontal rotary mixer according to the mixing steps mentioned earlier in section 3-10.

8. To prevent the NSC columns from shifting while the SIFCON shell is being poured and to provide good bonding between SIFCON and NSC concrete, epoxy should be applied to the base and all sides of each column before placing it in the center of iron mold and allowing it to cure.

9. Pour the SIFCON shell based on the multi-layer technology, where each layer was poured 10 cm thick. Firstly distributing the fiber randomly, and then pouring the slurry over it with the aid of a metal rod to give the concrete compacting and prevent gaps or segregation.

10. After giving the columns a 24-hour rest, remove the molds, and put the columns in a water tank to cure for 56 days at a temperature of (23±2 °C).

The SIFCON samples (cubes, cylinders, and prisms) were poured using the same method as the columns and then left in the water tank for 56 days at a temperature of (23±2 °C).

Plate (3-7): Square and circular molds.

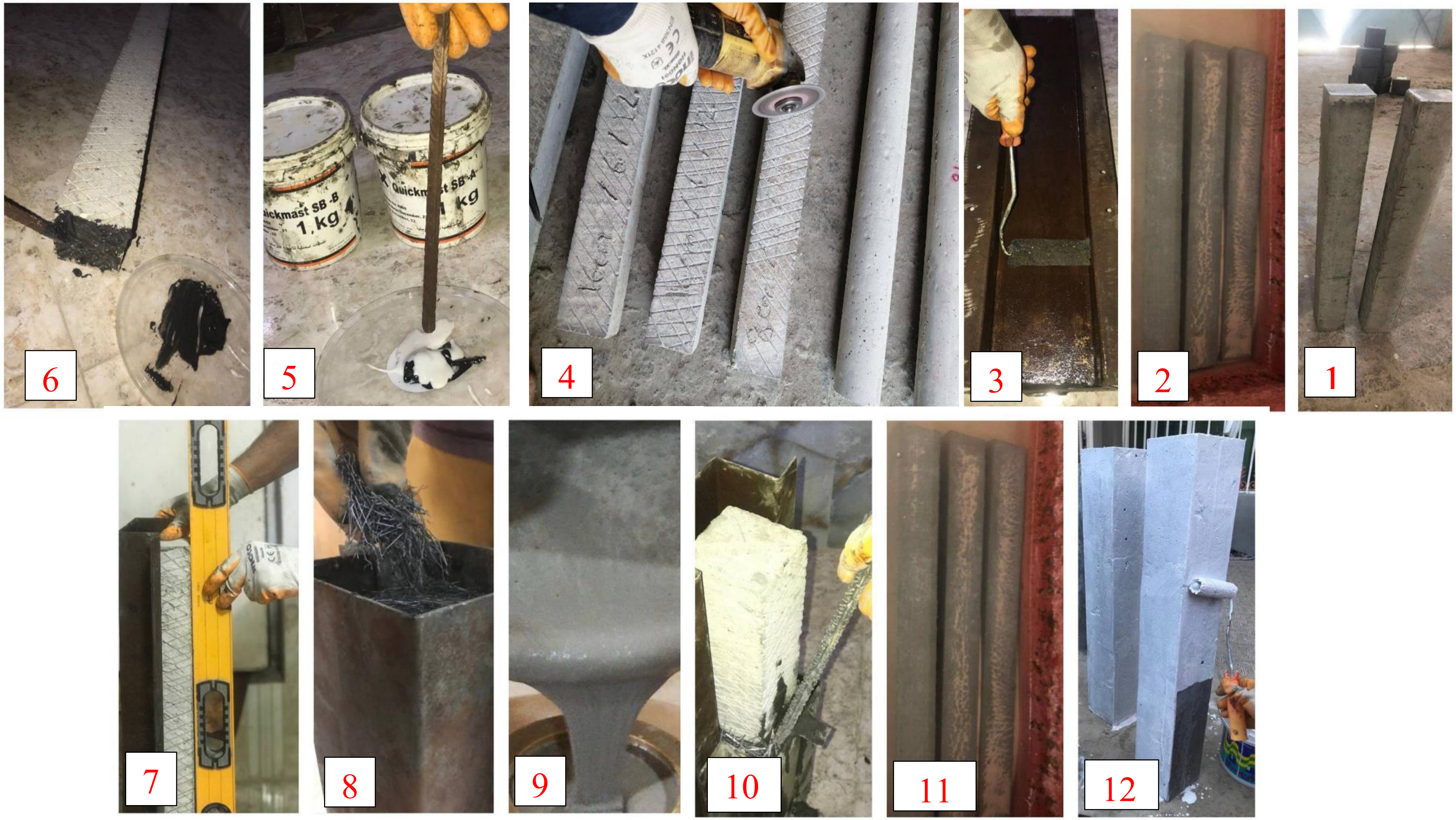


Plate (3-8): Procedures of Casting and curing columns.

Plate (3-9): Procedures of Casting samples.

3.14. Testing Procedure for Column Samples

Using a standardized electro-hydraulic testing device with a maximum capacity of 600 kN in the structural lab of the University of Babylon, all NSC columns strengthened with SIFCON shell were tested at the age of 56 days, while the unstrengthened NSC columns were tested at the age of 84 days up failure. The columns were taken ou of the molds, left to dry completely, then their surface was levelled, dyed and then tested until failure. On the test stand, the columns were positioned so that the boundary conditions at the column ends are simply supported while also ensuring that the columns are vertical. For the axially loaded columns, the load was applied through a bearing plate, and for the line load simulation, through a cylindrical roller attached to the top of the bearing plates. Using load control, the load was applied at a rate of 1 kN/s, and readings were taken every 10.0 kN load until failure. The load was maintained constant between each increment until the necessary measurements were taken and recorded. Testing went on until the column's load capacity decreased as deformation increased. Utilizing dial gauges with an accuracy of 0.001 mm per division, a capacity of 30 mm, and a maximum sensor length of 50 mm, the axial and mid-high lateral displacement of the specimens were measured. To measure the lateral deflection, these dial gauges were installed at mid-height along the vertical midline side of each column. As shown in **Figure (3-4)** and Plate (3-10), a dial gauge was used to measure the axial displacement of each column while being fixed on the top surface of the machine piston. Small cameras that were connected to the laptop that was recording the screen were used to monitor the dial gauge's value. This technique protects workers from the SIFCON column's explosion and fragmentation.

Plate (3-10): Electro hydraulic testing device of columns.

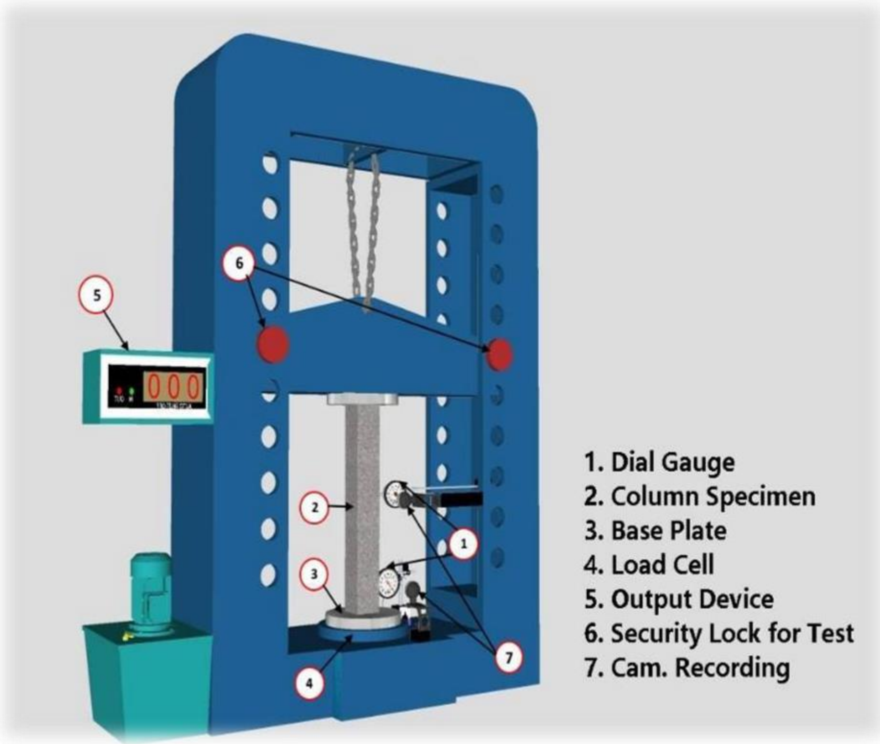


Figure (3-4): 3D drawing of the columns test device.

3.15. Tests of Hardened SIFCON Samples

These tests included compressive strength, elastic modulus, splitting tensile strength and flexure strength. The Babylon University College of Engineering's Civil Department's laboratory served as the site for all of the testing.

3.15.1. Test of Compressive Strength

The compressive strength is a recognized indicator of one of the crucial engineering characteristics of concrete that can give a broad image of the concrete's quality. Three cubes (100x100x100) mm and three cylinders (100x200) mm were cast in the same way for each fiber ratio (4% and 6%) in order to determine the compressive strength. The average value of these cubes and cylinders was obtained using **(BS. EN 12390: part 3).** They were crushed at ages (7, 28, and 56) days to evaluate the compressive strength using a digital testing machine with a capacity of 1900 kN, and a loading rate of 0.3 MPa/sec. The compressive strength testing device is depicted on Plate (3-11).

Plate (3-11): Compressive strength testing machine.

3.15.2. Static Modulus of Elasticity

Concrete's static modulus of elasticity was tested on cylindrical specimens of (100 mm * 200 mm), and in accordance with (**ASTM C469, 2014**). To prevent any loss of strength, the top surface of the cylinder was carefully polished and smoothed using an electric grinding machine. The test was conducted on the samples using a hydraulic device with a capacity of (1900 kN). As depicted in Plate (3-12), 40% of the concrete sample's ultimate compressive strength was applied to the concrete cylinders in order to conduct the elastic module test. The average of each of the three samples, which were evaluated at ages (7, 28, and 56) days, was taken into account. The following equation was used to calculate the static modulus of elasticity:

$$Es = S_2 - S_1 / e_2 - 0.00005 \quad \ldots\ldots \text{Eq. (3-1)}$$

Es: static modulus of elasticity, (MPa).

S_2: stress corresponding to 40% of ultimate load, (MPa).

S_1: stress corresponding to a longitudinal strain (0.00005), (MPa).

e_2: longitudinal strain produced by stress S_2.

Plate (3-12): Modulus of elasticity testing machine.

3.15.3. Splitting Tensile Strength:

Cylindrical specimens of 100 mm x 200 mm were used to conduct a splitting tensile strength test. Three samples were collected at (7, 28, and 56) days to get an average result. As stated in Plate (3-13**)**, the test was carried out in accordance with **ASTM C496 / C496M, 2017** utilizing a digital testing equipment with a capacity of 1900 kN and a loading rate of 0.3 MPa / sec.

The following equation can be used to get the specimen's splitting tensile strength:

$f_{sp} = 2P / \pi DL$ **……. Eq. (3-2)**

f_{sp}: Splitting tensile strength (MPa).

P: Maximum applied load in splitting test (N).

D: Diameter of cylinder (mm).

L: Length of cylinder (mm).

Plate (3-13): Splitting tensile strength testing machine.

3.15.4. Test of Flexural Strength (Modulus of Rupture)

Three prisms made of concrete measuring (100x100x400) mm were cast using the **(ASTM C78, 2010)** process. With a maximum capacity of 2000 kN, a universal hydraulic machine was used to test the prisms. Up to failure, the load was constantly applied and steadily increased at a consistent speed. That was offered in the Civil Engineering Department's Structural Laboratory at the University of Babylon.

Utilizing the outcomes of a basic prism under two-point load as shown in Plate (3-14), flexural strength expressed as the modulus of rupture (fr) was computed. The following formula was used to calculate the specimens' flexural strength to the nearest 0.01 MPa:

$fr = PL / bd^2$ ………… Eq. (3-3)

Where:

fr: The modulus of rupture (MPa),

P: The total ultimate load (N)

L: The length of span (mm) [in this test, L=300 mm],

b: The average width of the specimen (mm),

d: The average depth of specimen (mm).

Plate (3-14): Flexural strength testing machine.

3.16. Test for Hardened Normal Strength Concrete:

Compressive Strength Test: Cubes with dimensions of (150*150*150) mm are loaded uniaxially by the compressive machine type CONTROLS to determine the compressive strength of standard concrete. Cubes were examined at different ages (7 and 28 days) to determine the value of f_{cu}, and the value of (**$fc_{cylinder}$**) was determined using the equation (3-4) in accordance with (**IRAQI Code 1/1987).**

$fc_{cylinder} = 0.8\ f_{cu}$ ……. Eq. (3-4)

CHAPTER FOUR

(TEST RESULTS AND DISCUSSION)

4.1. Introduction

The basic goal of this study is to evaluate the behavior of NSC columns encased with slurry infiltration fiber reinforced concrete (SIFCON) subjected to concentric load and compare them with NSC columns using experimental tests. This chapter presents the test results of experimental program. The test results from the companion specimens, which were tabulated and utilized to describe the mechanical properties of the SIFCON, are presented at the beginning of the chapter. To determine the significance of the taken into consideration experimental variables, the experimental results were compared with one another. The experimental variables test results were mechanical properties of hardened SIFCON (compressive strength, static modulus of elasticity, splitting tensile strength and flexural strength). For columns, the ultimate load carrying capacity, and the load displacement relationships were evaluated. Based on the estimated load-displacement relationships, energy absorption was calculated for strengthened columns and compared with NSC columns. The considered experimental variables were cross section shape (circular and square columns), ties spacing (80, 160) mm for square columns and (90, 180) mm for circular columns, thickness of SIFCON shell (20, 30) mm, and; fiber type and volume fraction (4%, 6%).

4.2. A summary of Samples Test Results

In this section, a summary of the mechanical properties of hardened concrete, which include compressive strength, modulus of elasticity, splitting tensile strength and flexure strength for different ratios of hybrid fiber (hooked end steel fiber (HS) and polypropylene(PP)). **Table (4-1) and Table (4-2)** summarizes the results of these tests and each result in this table is an average of testing three samples.

Table (4-1): Summary of the tests results for hybrid and steel fiber**.**

Fiber ratio	**4% (2% HS+ 2% PP)**			**6% (4% HS+ 2% PP)**		
	7 days	**28 days**	**56 days**	**7 days**	**28 days**	**56 days**
Compressive strength for cube (MPa)	45.45	53.01	56.31	60.55	73.52	78.56
Compressive strength for cylinder (MPa)	31.52	46.9	50.21	49.57	56.7	63.12
Elastic modulus (GPa)	15.21	19.8	23.2	18.4	22.2	26.4
Splitting tensile strength (MPa)	9.18	12.27	13.52	15.41	16.32	17.29
Flexural strength (MPa)	11.15	13.49	14.08	18.19	20.64	
Fiber ratio	**4% HS**			**6% HS**		
	7 days	**28 days**	**56 days**	**7 days**	**28 days**	**56 days**
Compressive strength for cube (MPa)	43.76	65.3	75.65	54.70	69.51	90.51
Compressive strength for cylinder (MPa)	34.89	49.34	57.12	42.82	54.27	78.03

Table (4-1): Continued.

Fiber ratio	4% HS			6% HS		
	7 days	28 days	56 days	7 days	28 days	56 days
Elastic modulus (GPa)	16.73	21.13	25.41	19.7	24.29	28.03
Splitting tensile strength (MPa)	10.21	11.35	11.94	12.45	14.09	14.79
Flexural strength (MPa)	16.67	19.47	21.56	22.34	25.12	26.38

Table (4-2): Mechanical properites of NSC.

Mechanical propereties	Strength (Mpa) at 7 days	Strength (Mpa) at 28 days
Cube compressive strength	21.33	35
Cylinderical compressive strength	16.67	28

4.2.1 Compressive strength

The compression strength test is the most common test performed on hardened concrete. This test is used to determine the concrete's potential strength. Utilizing (100x100x100) mm cubes and (100x200) mm cylinders that had been cured at ages of (7, 28, and 56) days, respectively, the compressive strength test for SIFCON was conducted. **Figures (4-1) and (4-2)** display the data and shows how the fiber percentages utilized (4% and 6%) affected the compressive strength of SIFCON at different ages. The test results demonstrate that specimens with a 6% volume fraction of fiber exhibit a much higher compressive strength than specimens with a 4% volume fraction of fiber. It is clearly apparent that SIFCON specimens made with steel fibers exhibit higher strength. This is because the hooked ends fibers work together to bridge the development of micro cracks and produce a stronger bond between the fibers and the matrix, which in turn increases the strength of the SIFCON mixes. This is consistent with the findings of **(Qian and Stroeven, 2000),** who discovered that the incorporation of steel fibers led to significant enhancements in fiber reinforced concrete. A comparison between the findings of the current study and those of other researchers is shown in **Figure (4-3)**. Due to the fact that the concrete served as reinforced concrete elements and the fiber created a strong link between the concrete particles, the compressive strength increased as the fiber ratio increased up to 12% fiber ratio from mix volume **(Ali and Riyadh, 2018).** The greater bond between the fiber/matrix interfaces that results from increasing fiber volume fractions is what causes the rise in compressive strength. This increase in SIFCON compressive strength can be seen in the fibers' capacity to limit fracture extension, vary crack orientation, and postpone crack growth rate depending on the characteristics of each fiber type. By acting as a bridge for the crack in the two sides, a rise in steel fibers led to a reduction in the number of cracks and the crack's width, increasing strength in the system **(Naser and Abeer, 2020).** A particularly reactive pozzolana substance called silica fume combines with calcium hydroxide to produce calcium silicate hydrate, another type of binder that is comparable to the calcium silicate hydrate found in Portland cement. The integration of silica fume (as a partial replacement by weight of cement) results in a small increase in the compressive strength. The high surface area of silica fume, which fills in the pores between cement grains, is what has the impact of making SIFCON mixtures' compressive strength higher. This phenomenon is known as (particle packing). By providing nucleation sites where the cement's hydration products can more easily settle from solution and create a denser microstructure, silica fume also helps cement hydrate faster while also enhancing the cohesive force between the fiber and matrix **(S. Salih et al., 2018).**

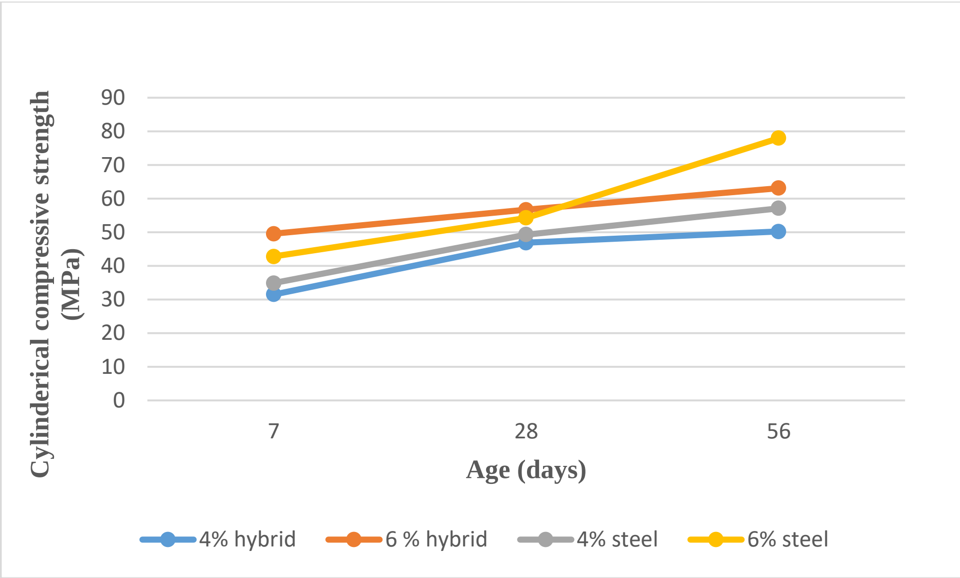


Figure (4-1): Cylindrical compressive strength of SIFCON for hybrid fiber and steel fiber.

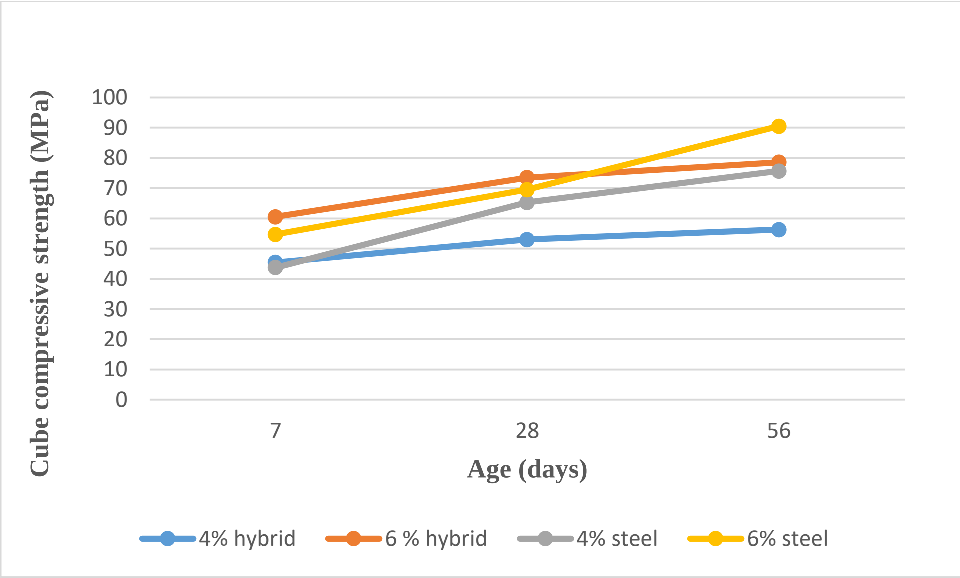


Figure (4-2): Cubes compressive strength of SIFCON for hybrid fiber and steel fiber.

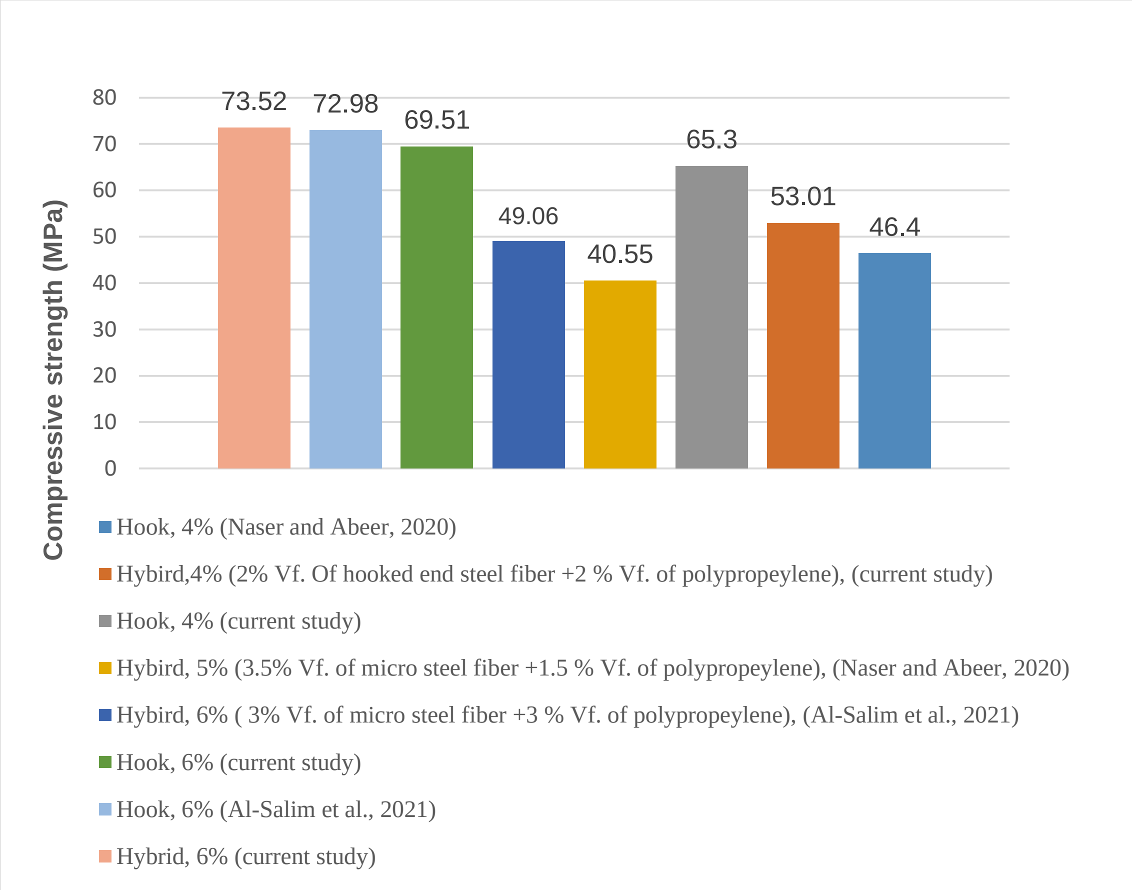


Figure (4-3): Comparison of compressive strength of SIFCON from current study and other studies at 28 days.

4.2.2. Static Elastic Modulus

One of the most crucial characteristics of solid materials is the static modulus of elasticity (Ec), which is a characteristic of the material that describes its stiffness. The concrete ingredients and their proportions have a significant effect on the modulus of elasticity. With an increase in compressive strength, an increase in the modulus of elasticity is expected since the stress-strain diagram's ascending branch's slope gets wider **(Ramezanianpour et al., 2009).** Three (100x200) mm cylinders that had been aged for (7, 28 and 56) days that used in this test for each volume fraction of fiber. The test results showed increasing in modulus of elasticity, when volume fraction of fiber was 6% higher than 4% as shown in **Figures (4-4)** and **(4-5),** because the modulus of elasticity is a function of compressive strength, and because compressive strength increases with an increase in fiber volume fraction, there for modulus of elasticity increases. This occurs as a result of an increase in steel fibers that lower the number and width of cracks by acting as a bridge between their opposing sides. The presence of silica fume in the specimen causes a reduction in crack distribution and intensity **(Ali and Riyadh, 2018)**.

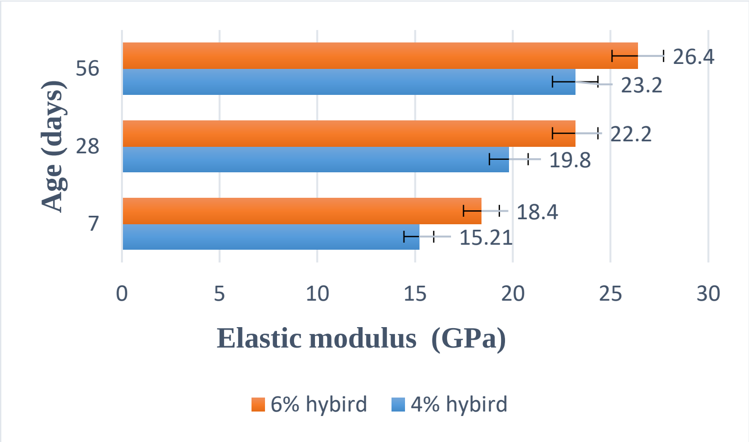


Figure (4-4): Static modulus of elasticity of SIFCON for hybrid fiber.

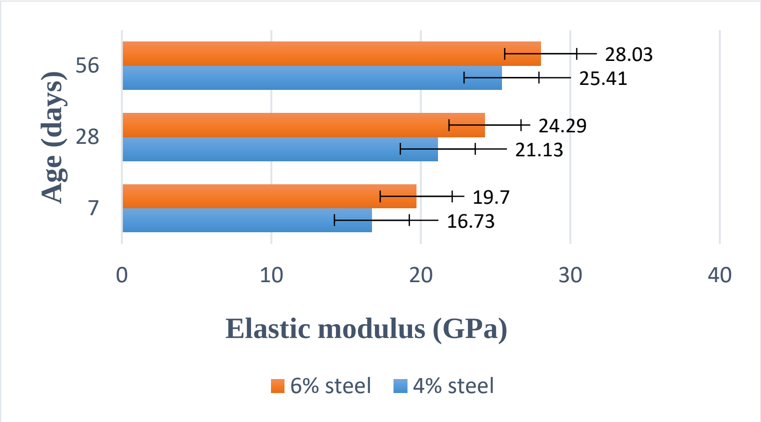


Figure (4-5): Static modulus of elasticity of SIFCON for steel fiber.

4.2.3 Splitting Tensile Strength

It controls the cracking behavior and influences the stiffness and durability of SIFCON. The results show that the splitting tensile strengths of SIFCON often rise with aging. The improvement of the matrix's hydration process through completion of its internal microstructure results in an increase in the composite material's strength over time as well as an improvement in the bond strength between the fibers and matrix **(Ali and Riyadh, 2018)**. The SIFCON's splitting tensile strength test results, shown in **Table (4-1)**. The results showed increasing in the strength with increasing fibers ratio where 6% fiber volume fraction showed higher tensile strength than 4% fiber volume fraction as shown in **Figure (4-6)** and **Figure (4-7)**, because the tensile strength of steel and polypropylene fibers is high, the tensile strength of concrete increased in the presence of these fibers so that the cracking load becomes more. This behavior is caused by steel fiber's ability to stop both macro cracks and micro cracks. Using steel fiber with a hooked end also improves the bond, which in turn improves the mechanical properties. The tensile strength increased with the addition of silica fume. As it was mentioned that the filler effect, pozzolanic effect and the enormous surface area of silica fume enhance the bond between fiber and matrix interface in addition to the growth restricting for micro cracks, this explains the improved mechanical properties **(S. Salih et al., 2018). Figure (4-8)** shows a comparison of splitting tensile strength of SIFCON from current study and other studies at 28 days.

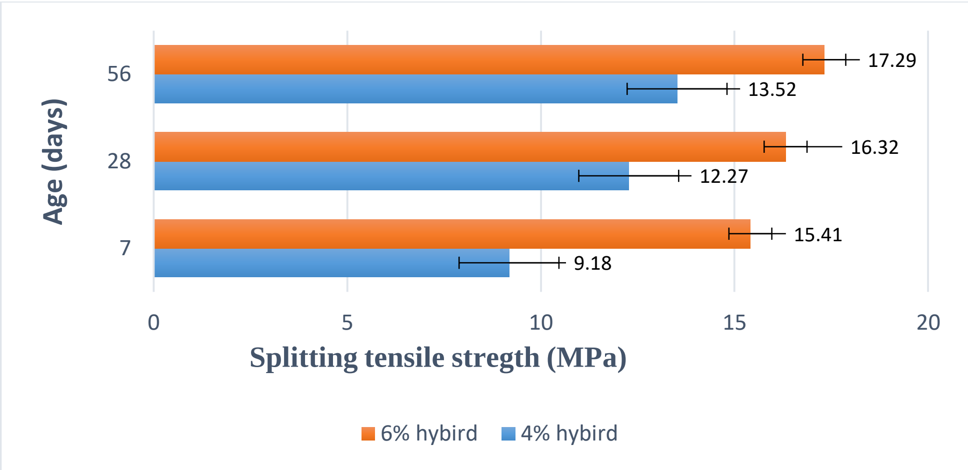


Figure (4-6): Splitting Tensile Strength of SIFCON for hybrid fiber.

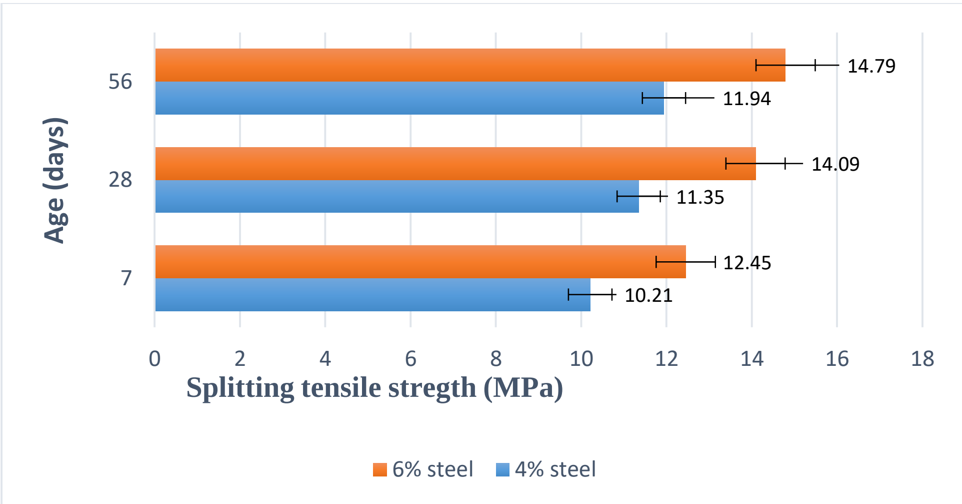


Figure (4-7): Splitting Tensile Strength of SIFCON for steel fiber.

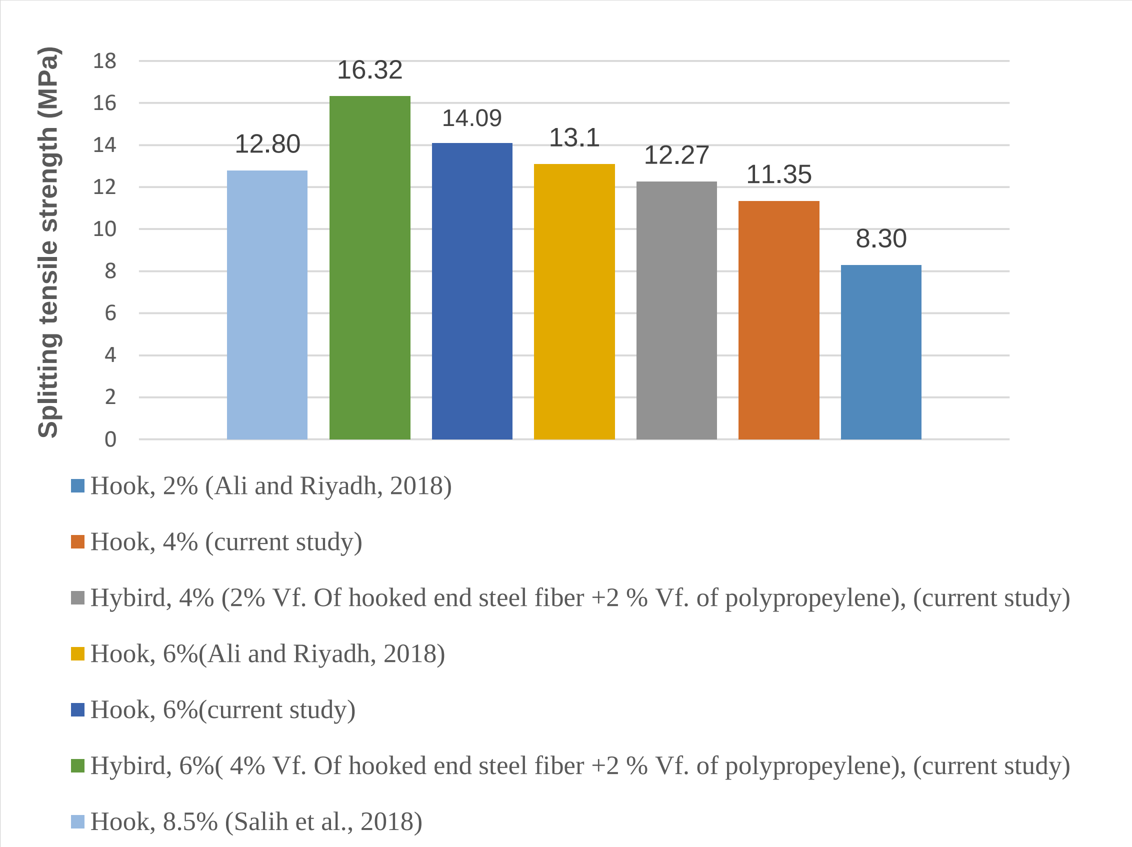


Figure (4-8): Comparison of splitting tensile strength of SIFCON from current study and other studies at 28 days.

4.2.4. Modulus of Rupture

Testing prisms with dimensions of (100x100x400 mm) for fibers ratio of (4% and 6%) hybrid or steel fiber, at age of (7, 28, 56) days, is done to determine the SIFCON modulus of rupture values. All mixes with 6% volume fraction of fibers have a higher modulus of rupture (fr) value than mortar with 4% fibers ratio as shown in **Figure (4-9)** and **Figure (4-10)**. Therefore, the fr value grew significantly as the volume proportion of fiber increased. The addition of fiber to SIFCON mixtures enhances their flexural strength, which increased as the volume fraction of fiber increased. As an additional benefit, silica fume improves flexural strength. The high surface area of silica fume replacement, which fills the voids between cement grains, is what enables it to have such a favorable effect on the flexural behavior of

SIFCON. This leads to an enhancement in the matrix phase, which enhances the flexural strength and the binding strength between the fibers and matrix. The stronger interface zone between the binder and the fibers, which strengthens the connection and slows the growth of micro cracks that cause flexural failure, is responsible for the increase in flexural strength **(S. A. Salih et al., 2018).** In general, using hybrid fiber in mortar has a big impact since it gives the SIFCON section a more uniform spread of fiber. When compared to reference mix, the use of steel fibers in SIFCON increases the strength of SIFCON more than hybrid fibers. The fact that polypropylene fibers resist the micro cracks created for a shorter amount of time during the development of cracks has led to a lower flexural strength as well as lower tensile strength compared to other types of fiber utilized in SIFCON, which is the cause of this tiny increase. However, it has been demonstrated that employing these fibers has advantages beyond corrosion resistance, such as a significant reduction in density. The macro hooked end steel fiber and polypropylene fiber combination increased the strength noticeably. This is because when micro- and macro-cracks emerge, the impacts of the fiber composition, strength, and length strengthen the link between the fibers and mortar contact **(Naser and Abeer, 2020)**. **Figure (4-11)** shows a comparison of flexural strength of SIFCON from current study and other studies at 28 days.

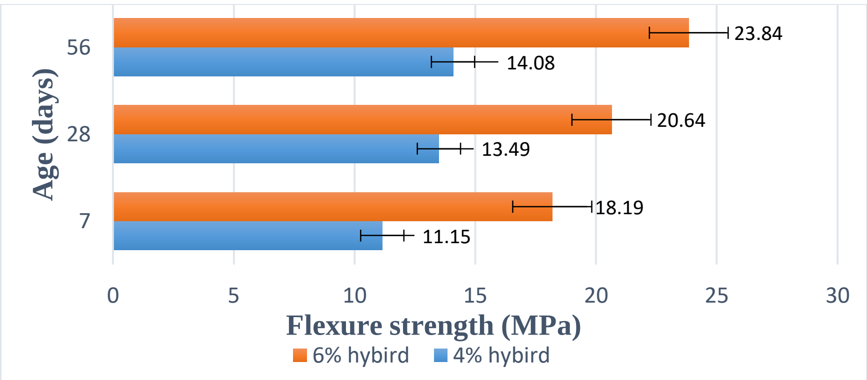


Figure (4-9): Flexural Strength of SIFCON for hybrid fiber.

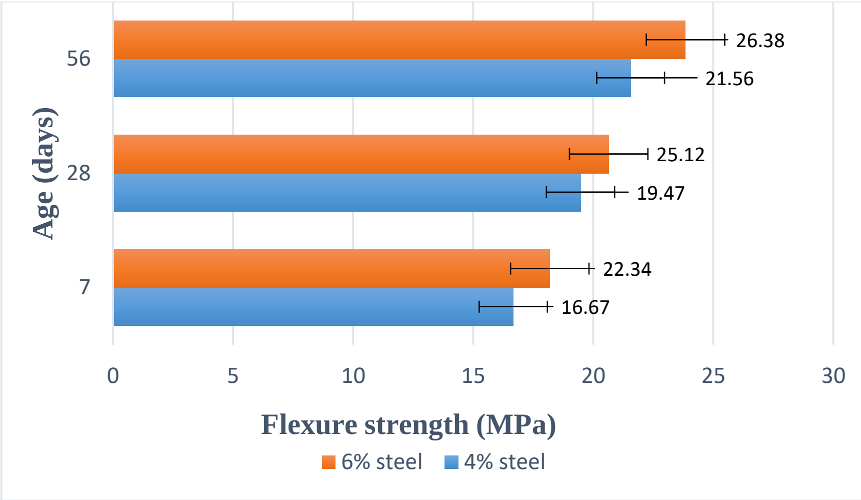


Figure (4-10): Flexural Strength of SIFCON for steel fiber.

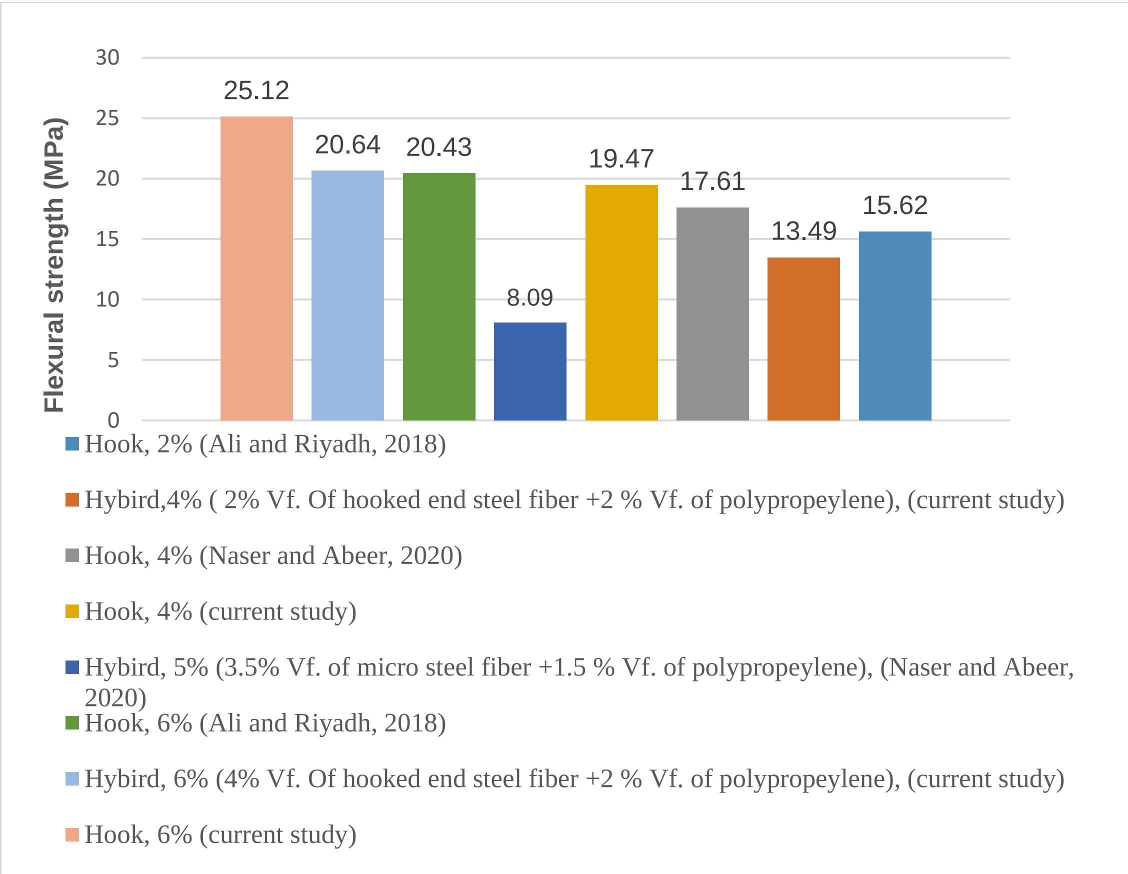


Figure (4-11): Comparison of flexural strength of SIFCON from current study and other studies at 28 days.

4.3. Details of the Column Samples Experimental Program

According to the type of concrete used (SIFCON or NSC), the tested column specimens are divided into two groups. These groups are then further divided into two main categories based on the type of column (square or circular). The columns strengthened with SIFCON are divided according to the ties spacing and the SIFCON shell thickness. In chapter three, these groups were looked through. The primary structural features seen and recorded throughout the test of each column specimen and at each step of loading were used to evaluate the structural behavior of the tested column specimens. The load on the concrete column specimens was applied using a 600 kN capacity electrohydraulic jack compression machine. Axial displacement, mid-height lateral displacement, and ultimate failure load are the measured features. **Table (4-3)** provides information about the results of tests performed on SIFCON and NSC columns, including the load carrying capacity of the columns, axial displacements measured over the height of the specimen, and comparable lateral displacements at the specimen's midpoint.

4.4. Load Carrying Capacity of Strengthened with SIFCON and NSC Columns

Four NCS column specimens were cast, tested, and compared to NSC columns that had been strengthened with SIFCON shell. The strengthened square columns outperformed circular columns with the same fiber ratio in terms of load-carrying capacity when compared to NSC columns. The results indicate that a thicker SIFCON shell gives a higher increase in load-bearing capacity, where higher increase in load was 49% and 50% for circular and square columns respectively as compared with columns strengthened with 20 mm SIFCON shell as shown in **Figures (4-12)** and

(4-13). The maximum load for NSC circular columns reinforced with SIFCON shell was 202% for N3CHy18-4% column as compared with NSC columns, while the maximum increase in load attained for N3SSHy16-4% square column strengthened with SIFCON shell of 30 mm and 4% hybrid fiber ratio is 223% as shown in **Figures (4-14)** and **(4-15)**. It was observed that, for square and circular columns, respectively, columns with the same reinforcement and fiber ratio strengthened with a SIFCON shell of steel fiber only had higher load-bearing capacity than those with hybrid fiber by roughly 34% and 41% respectively as shown in **Figure (4-16)**. According to the results, the highest increase in load capacity for square and circular NSC columns strengthened with SIFCON shell was when the fiber ratio is 4% (hybrid) because "the slurry strength, fiber volume fraction, fiber alignment and fiber type greatly influence the strength of SIFCON samples **(Thomas and Mathews, 2014)**". In addition, fibers cannot randomly organize themselves at mold interface as they can in places farther from the edges. Observations show that the fiber density is less dense near the specimen's edge than it is in the center. Mostly fiber ends or fibers that have been pushed into a vertical or horizontal alignment fill this edge area. As a result of the vertical or horizontal fibers at the edge spall off under compressive load and therefore do not contribute to the compressive strength **(Wang and Maji, 1994)**. In this study fiber orientation is random because the square section has sharp edges and the circular section has curvature edges, therefore, making it challenging for the fibers to reach the corners and edges unless they are spread vertically or horizontally. Due to the difficulties of fiber distribution in a horizontal or vertical direction when the fiber ratio is increasing within a tiny thickness in a square and circular sections, the edges' contribution to load bearing capability became unnoticeable. Additionally, perhaps the 4% fiber ratio distribution is more uniform than

6% through these thin thicknesses. A higher ratio of fiber may have accumulated in one location but not another, which made it not contribute to resisting loads. Because of this, square and circular columns perform better when the fiber volume fraction is 4% rather than 6%. **Table (4-3)** shows test results of columns.

Table (4-3): Test results of strengthened with SIFCON and unstrengthen NSC columns.

Type of Concrete of column		Columns Symbol	Ultimate Load(Pu) (kN)	Axial Displacement (mm)	Mid-height Lateral Displacement (mm)
NSC	Square	NS8	152.21	1.79	0.168
		NS16	147.33	1.98	0.158
	Circular	NC9	172.52	2.03	0.196
		NC18	131.17	1.64	0.182
NSC Strengthened with SIFCON shell	Circular	N2CHy18-4%	266.78	7.03	0.359
		N2CHy18-6%	248.18	5.84	0.217
		N2CHy9-6%	256.79	6.98	0.278
		N2CHy9-4%	294.17	8.51	0.372
		N2SCH9-6%	362.57	10.49	0.590
	Square	N2SHy16-4%	317.24	9.47	0.466
		N2SHy8-6%	244.88	5.78	0.203
		N2SHy8-4%	274.86	7.74	0.361
		N2SHy16-6%	282.3	7.23	0.368
		N2SSH8-6%	327.14	9.81	0.482
	Circular	N3SCHy18-4%	395.92	10.97	0.621
		N3SCHy18-6%	361.8	10.38	0.587
		N3SCHy9-6%	380.3	10.59	0.593
		N3SCHy9-4%	434.26	11.87	0.684
	Square	N3SSHy16-4%	475.86	12.16	0.705
		N3SSHy8-6%	359.19	10.24	0.576
		N3SSHy8-4%	402.81	11.28	0.648
		N3SSHy16-6%	410.45	11.41	0.667

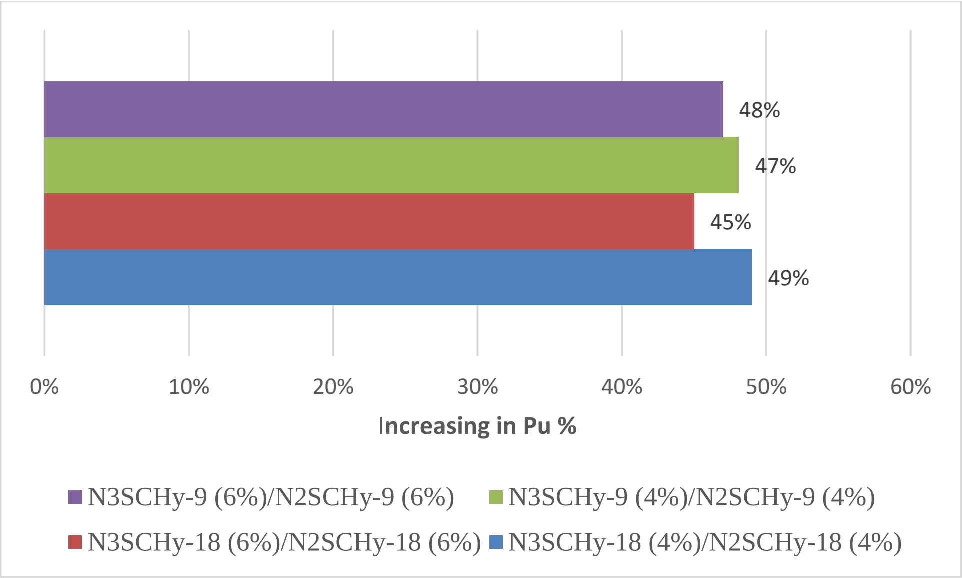


Figure (4-12): Ratio of increasing load bearing capacity of circular strengthened with SIFCON of 3cm columns to with 2cm columns *100%.

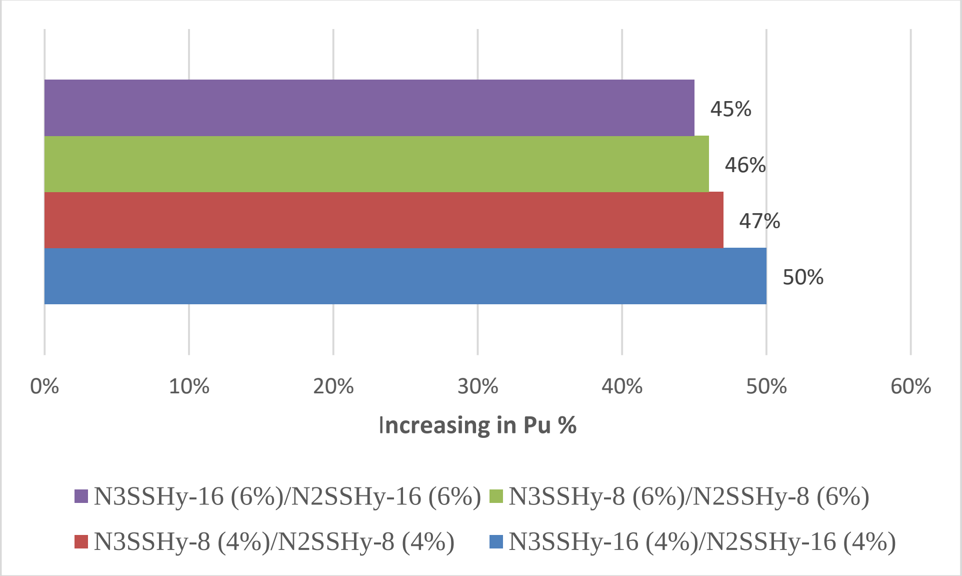


Figure (4-13): Ratio of increasing load bearing capacity of square strengthened with SIFCON of 3cm columns to with 2cm columns *100%.

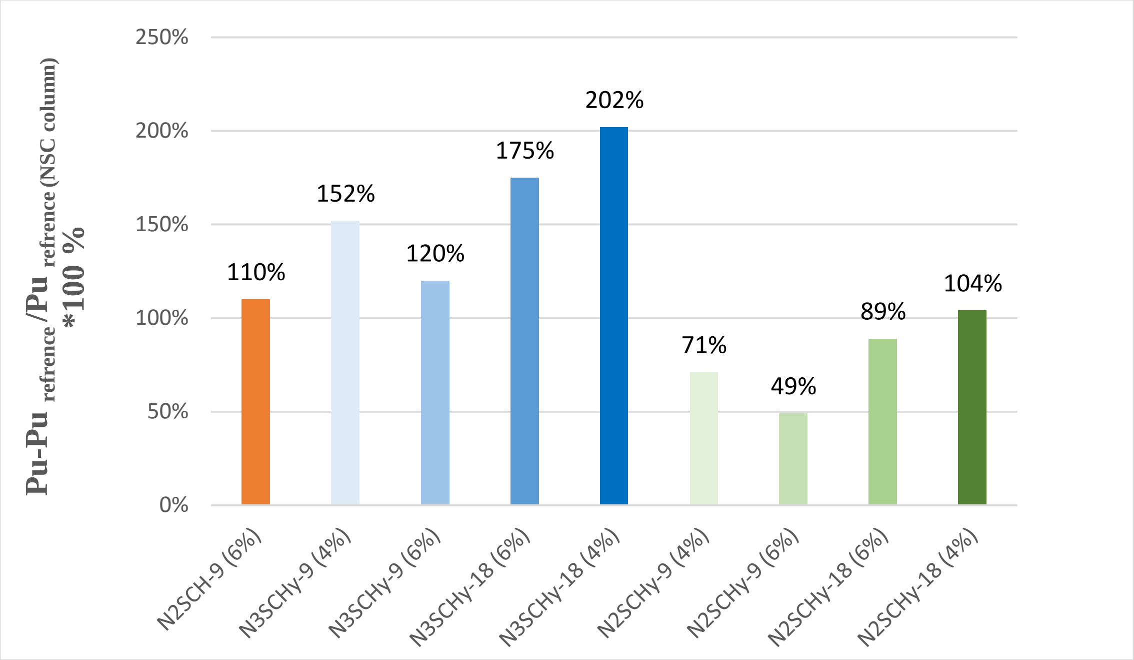


Figure (4-14): Ratio of increasing load bearing capacity of circular strengthened columns to circular unstrengthened columns (NSC columns)*100.

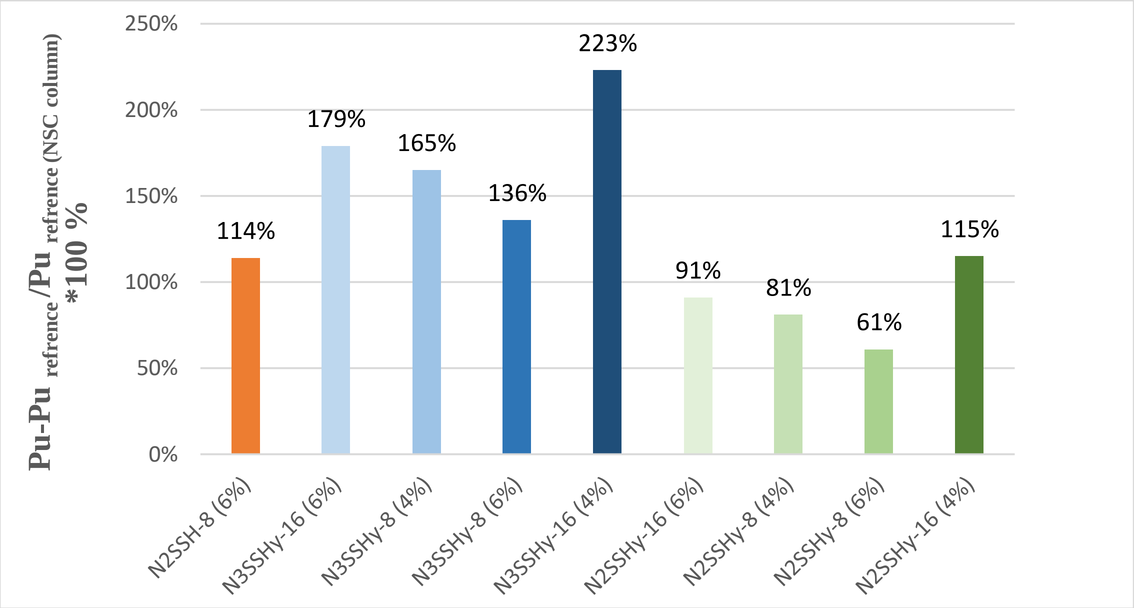


Figure (4-15): Ratio of increasing load bearing capacity of square strengthened columns to square unstrengthened columns (NSC columns)*100.

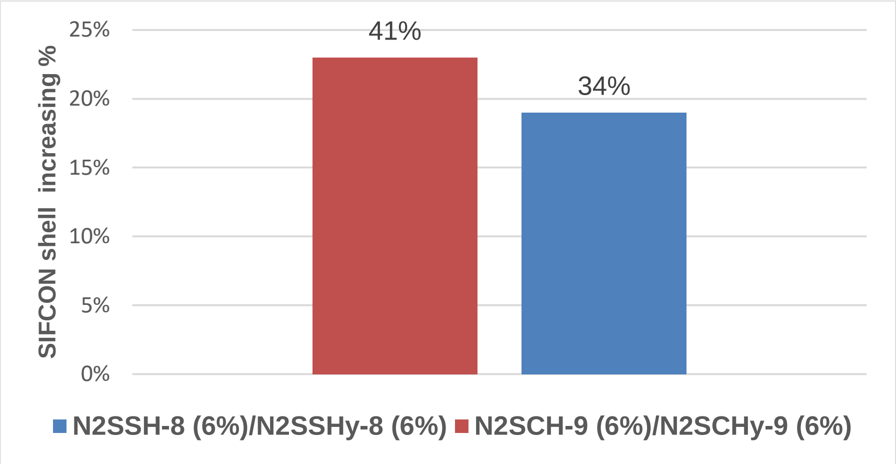


Figure (4-16): Ratio of increasing load bearing capacity of strengthened with steel fibers columns to strengthened with hybrid fibers columns *100%.

4.5 Column Specimen Load-Displacement Relationships

The vertical displacement and the mid-height lateral displacement of these columns were recorded immediately after the load was applied in order to be able to study the behavior of strengthened with SIFCON columns with various parameters and to determine the deformation properties of strengthened with SIFCON and NSC columns. These characteristics are significant in introducing the energy dissipation characteristics of concrete columns. The columns' ultimate displacements and lateral displacements at mid height are shown in **Table (4-3)**. The test results revealed that, columns strengthened with SIFCON have a much higher ultimate axial displacement than NSC columns. It also demonstrated that the NSC specimens' ascending portion of the curve is linear whereas the curve's descending part rapidly drops within a small range of deformation. **Figures (4-17)** show that the SIFCON curves, unlike NSC columns, do not descend once they reach their maximum strength as compared with NSC columns. It is also evident from the experiment results that the strengthened with SIFCON columns' ultimate mid-height lateral displacement is higher than that of the NSC columns. This may be because of the high deformation of the strengthened with SIFCON columns prior to failure **(Khamees et al., 2021).**

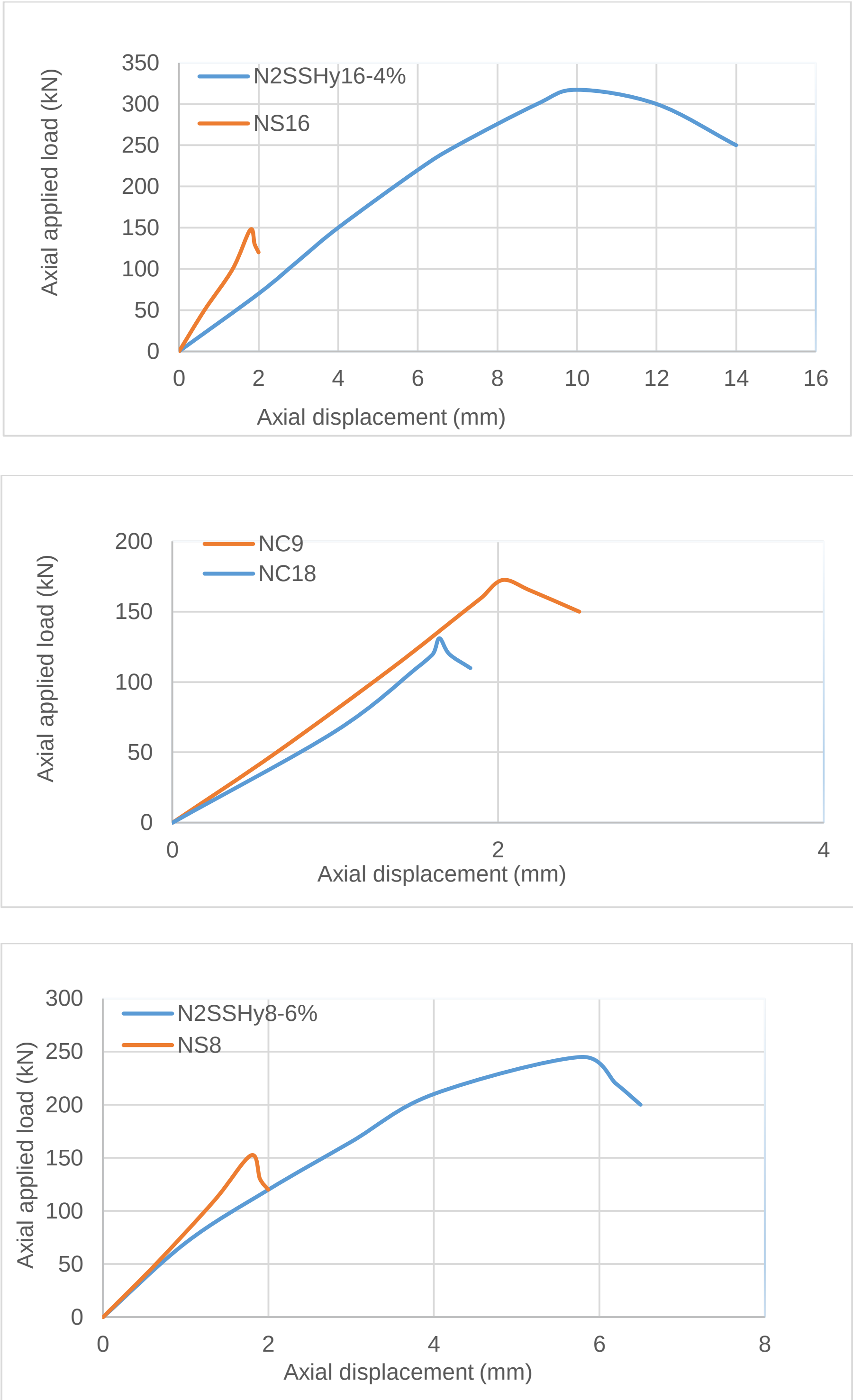


Figure (4-17-a): Load-axial displacement relationship of NSC columns and strengthened with SIFCON column.

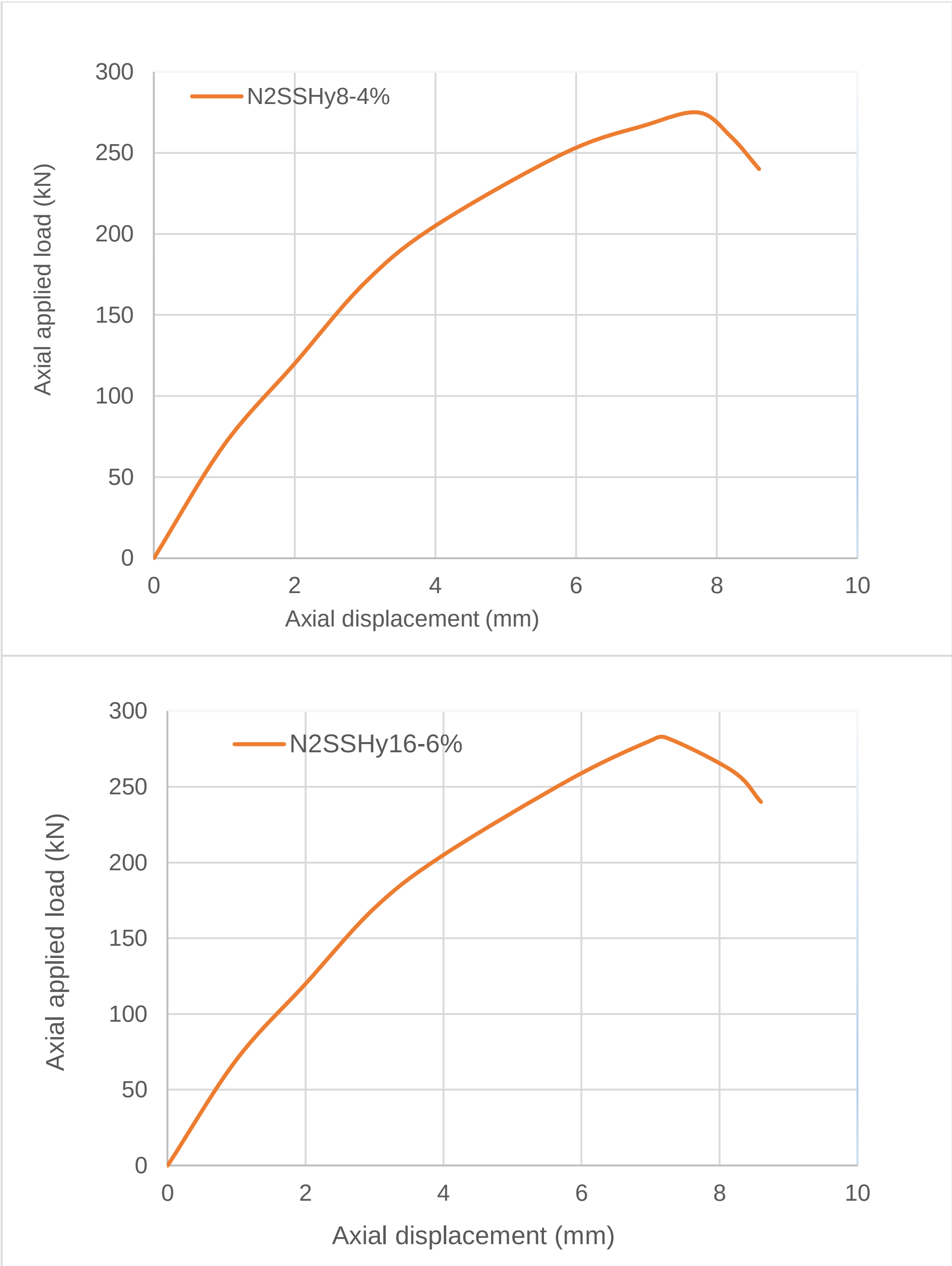


Figure (4-17-b): Load-axial displacement relationship of square NSC columns strengthened with 2 cm hybrid fiber SIFCON shell

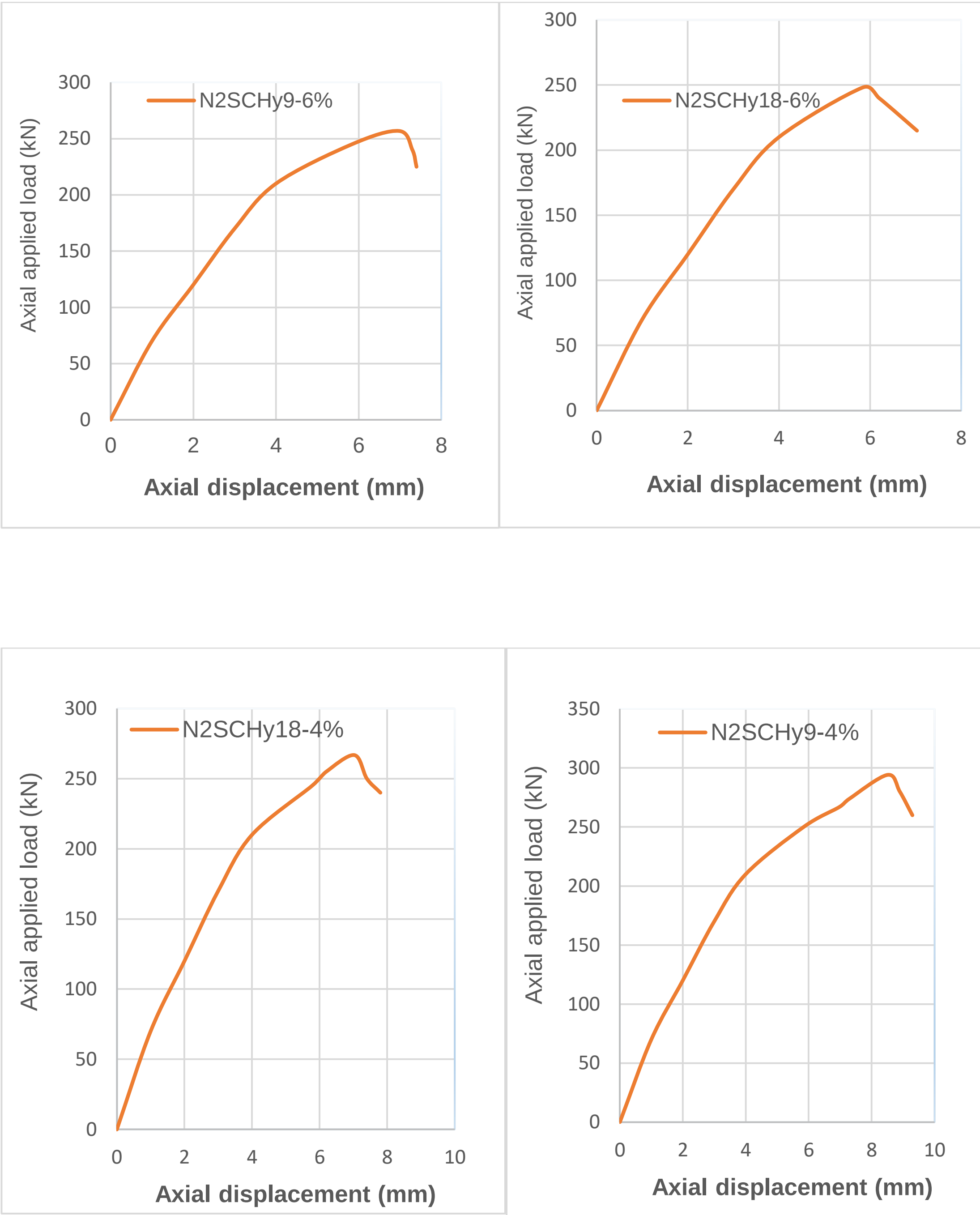
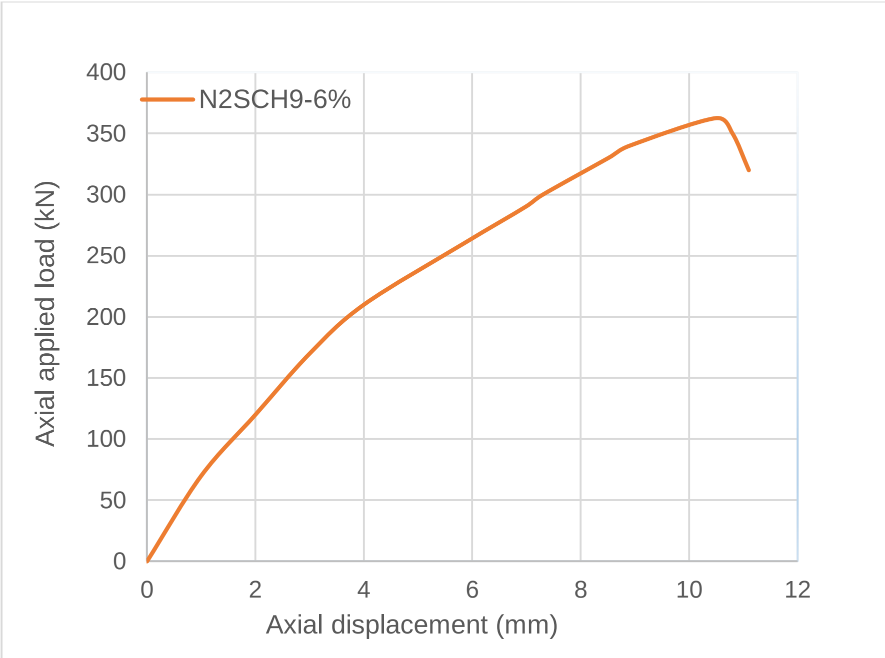


Figure (4-17-c): Load-axial displacement relationship of circular NSC columns strengthened with 2 cm hybrid fiber SIFCON shell.



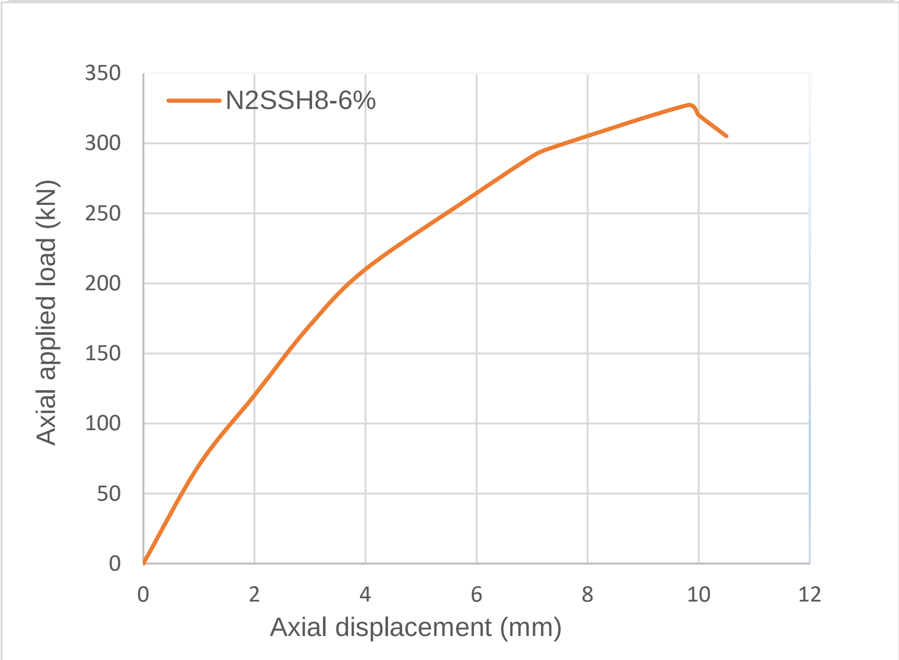


Figure (4-17-d): Load-axial displacement relationship of NSC square and circular columns strengthened with 2 cm steel fiber SIFCON shell.

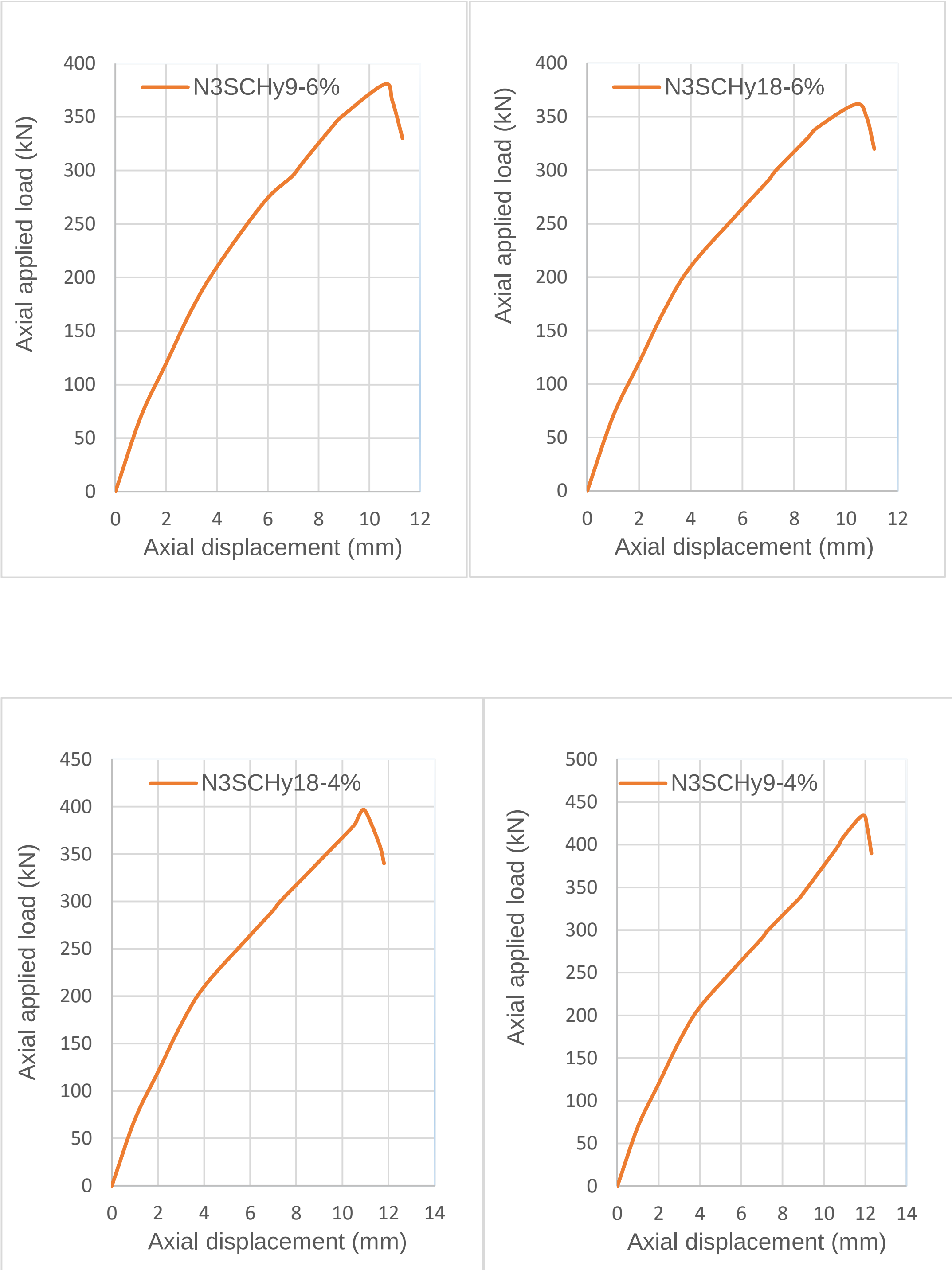


Figure (4-17-e): Load-axial displacement relationship of NSC circular columns strengthened with 3 cm hybrid fiber SIFCON shell

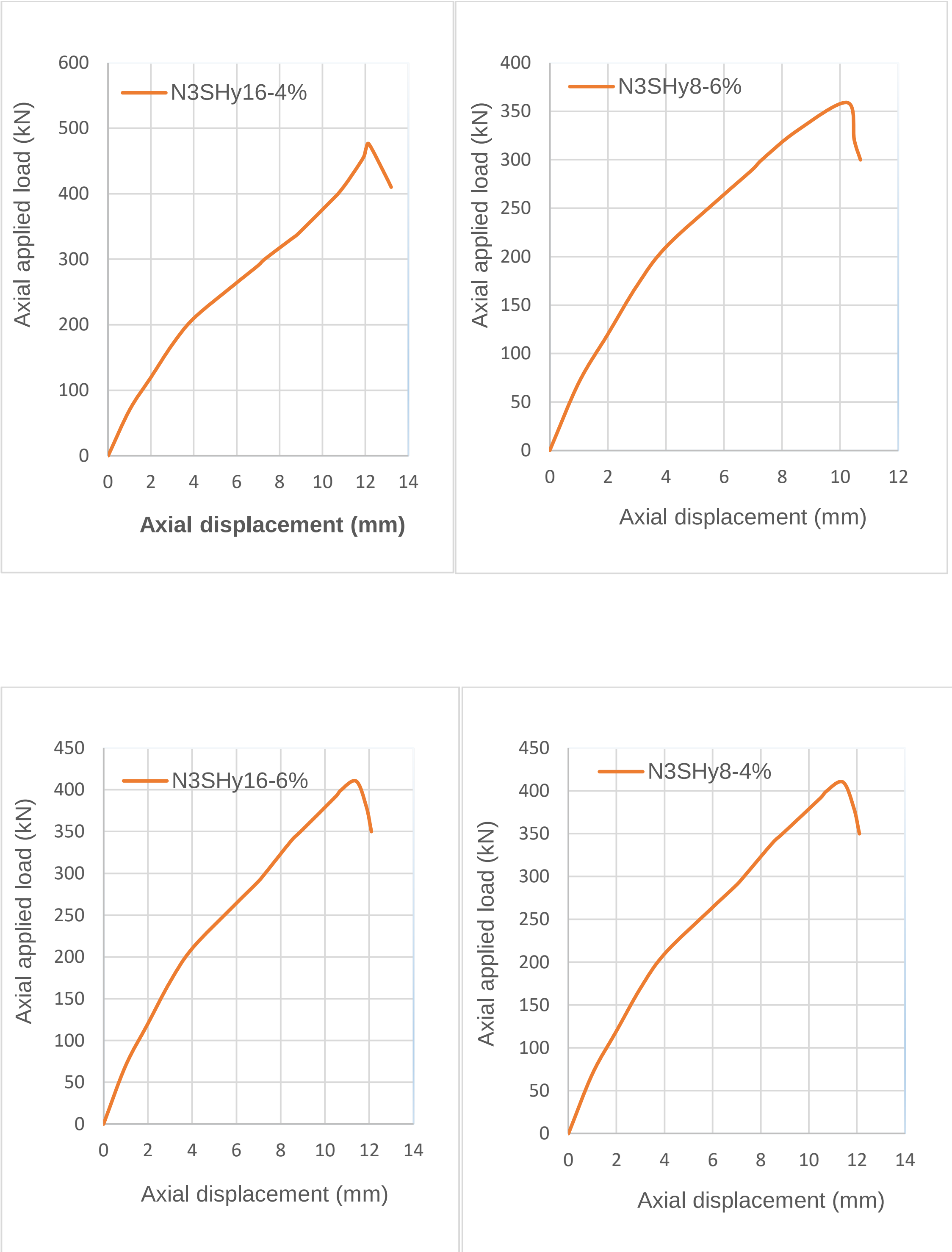


Figure (4-17-f): Load-axial displacement relationship of NSC square columns strengthened with 3 cm hybrid fiber SIFCON shell.

4.6. Energy Absorption Capacity of Column Specimens

The area enclosed by the load-displacement curve until the maximum load is utilized to describe the concrete column's energy absorption capacity. This area represents the maximum amount of energy that a concrete column could absorb before significantly reducing its capacity to carry loads **(Abdulraheem and Kadhum, 2017; Barros et al., 2007).** The energy absorption capacity for strengthened with SIFCON and NSC columns was measured and the results are given in **Table (4-4)**. From that table, it can be observed that the energy absorption capacity is constantly rising, reaching a maximum increase of around 16 times for strengthened with SIFCON square column (N3SSHy16-6%) and 15 times for strengthened with SIFCON circular column (N3SCHy18-4%) as compared with NSC column of the same characteristics as shown in **Figures (4-18)** and **(4-19)**. Due to the SIFCON shell's high fiber content and fibers' ability to transfer loads across broken sections, concrete's ability to absorb energy in a hardened condition is increased **(Dahake and Charkha, 2016)**. On the other hand, SIFCON columns have a larger energy absorption capacity due to their high fiber/matrix bonding **(Pakravan et al., 2012)**. **Figure (4-20)** shows an example of area under curve to describe energy absorption capacity.

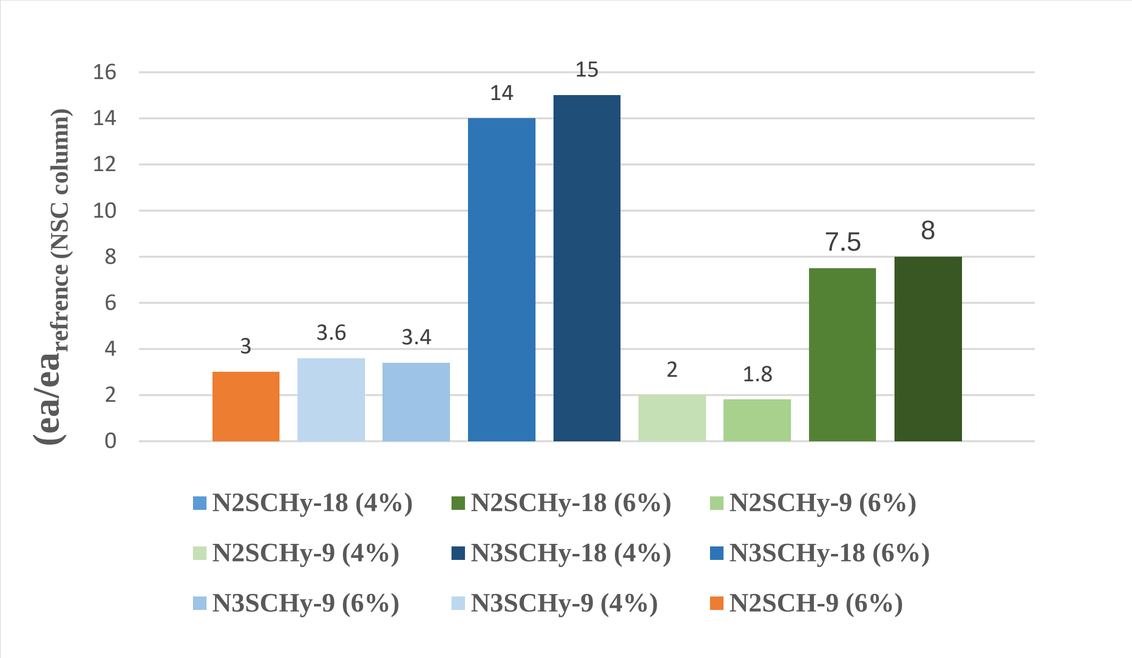


Figure (4-18): Ratio of increasing in energy absorption of circular strengthened columns to circular unstrengthened columns (NSC columns).

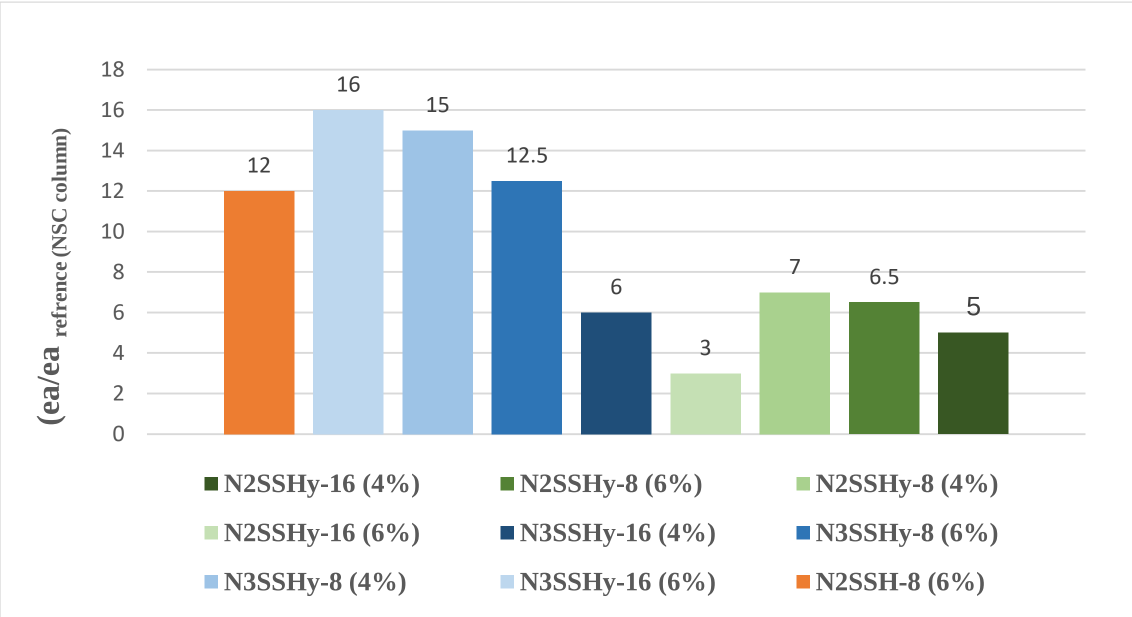


Figure (4-19): Ratio of increasing in energy absorption of square strengthened columns to square unstrengthened columns (NSC columns).

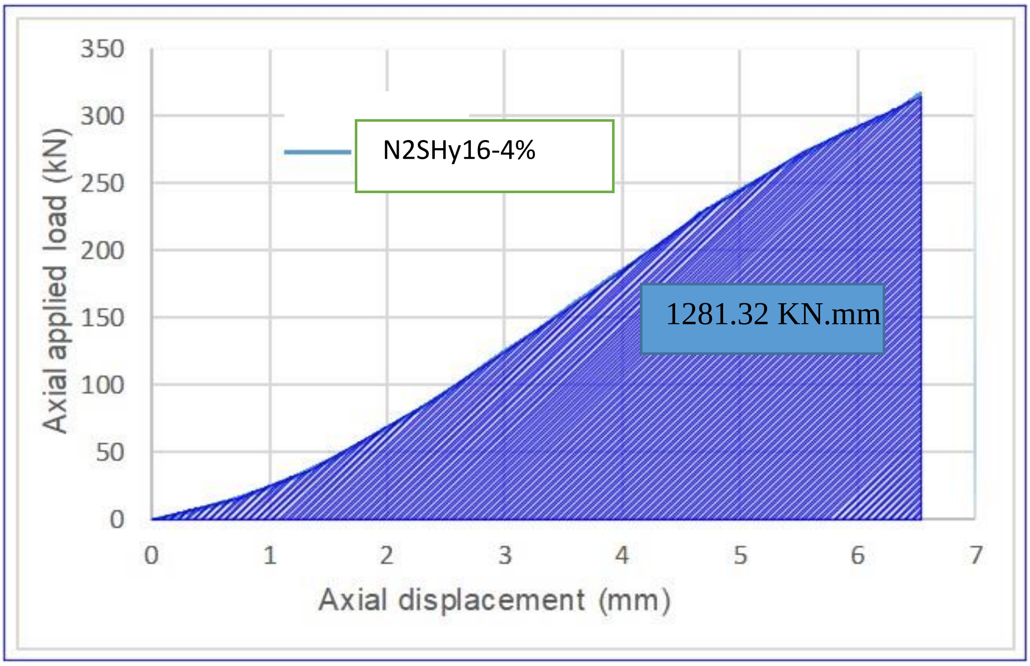


Figure (4-20): An example of area under curve to describe energy absorption capacity

Table (4-4): Test results of energy absorption of strengthened with SIFCON and unstrengthen NSC columns.

Columns Symbol	Energy absorption capacity (ea) (kN.mm)	Increasing in (ea) of strengthened column as compared with NSC column %
NS8	110.345	…..
NS16	260.823	……
NC8	424.682	……
NC18	97.367	……
N2Chy%4-18	782.399	704
N2Chy%6-18	733.445	653
N2Chy9-6%	778.927	83
N2Chy9-4%	956.436	125
N2SCH9-6%	1403.08	230
N2Shy%4-16	1281.321	391
N2Shy8-6%	723.763	556
N2Shy8-4%	785.682	612
N2Shy%6-16	883.310	239
N2SSH8-6%	1349.87	1123

Table (4-4): Continued.

Columns Symbol	Energy absorption capacity (ea) (kN.mm)	Increasing in (ea) of strengthened column as compared with NSC column %
N3SCHy18-4%	1451.240	1390
N3SCHy18-6%	1396.050	1334
N3SCHy9-6%	1423.310	235
N3SCHy9-4%	1516.590	257
N3SSHy16-4%	1563.920	500
N3SSHy8-6%	1378.560	1149
N3SSHy8-4%	1476.080	1238
N3SSHy16-6%	1496.080	474

4.7. Discussions on the Column Failure Process

In concrete structural systems, columns play a crucial role. In the majority of real-world situations, they experience axial compressive force coupled with bending. One column's failure in a crucial point might result in the progressive collapse of the entire structure to which it is connected since columns are compression elements. Because columns can fail with little visual warning and result in severe financial and human damage, extreme care needs to be taken in their analysis and design. All NSC columns had slow failure during testing, beginning with the collapse of a huge piece of concrete and the appearance of steel reinforcement until a localized failure occurred. For NSC columns, the longitudinal reinforcement buckled and the cover spalled, as shown in Plate (4-1-d). As illustrated in Plate (4-1), strength

ened with SIFCON columns do not exhibit noticeable spalling. The minor cracks on the columns' surface may be the result of the strong adhesion between fibers. A massive explosion that takes place at failure is one of the most frequent characteristics that set SIFCON columns apart from NSC columns. Due to the lack of confinement and the occurrence of fragmentation at the time of explosion, the SIFCON concrete absorb extremely high energy and cause the explosion.

(a)

(b)

(c)

(d)


(e) **(f)**


(g) (h)

Plate (4-1): Examples of the Failure pattern of NSC columns and strengthened with SIFCON column.

CHAPTER FIVE

(NUMERICAL MODEL)

"Proposed Equations for Predicting the Cube Compressive Strength of SIFCON and Axial Load Carrying Capacity of Reinforced Concrete Columns Strengthened by SIFCON Shell".

5.1. Introduction

The mathematical models presented in this section are to predict the compressive strength of SIFCON containing hooked end steel fiber at ages 7 and 28 days. To predict the ultimate loading capacity of square and circular NSC columns strengthened with SIFCON of hybrid fibers (hooked-end steel fibers and polypropylene) modified ACI and B.S. code equations are suggested. The results of this study are taken into consideration as the database for columns, whereas the database for the compressive strength model is based on previous studies.

5.2. Determination Coefficient (R^2)

R^2 is a statistical ratio that compares the accuracy of models to the accuracy of the simplest model, which simply forecasts all records using the mean of all goal values. The more this ratio approaches 1, the more accurate the model is. A poor model is indicated by small positive values close to zero. The R^2 ratios for compressive strength at 7 and 28 days are 0.91 and 0.94, respectively **(Web page)**.

5.3. Proposed Equations for Predicting the Compressive Strength of SIFCON Cubes.

A mathematical study has been made to predict the compressive strength of SIFCON. The database that is used in this model depends on previous researches as given in **Table (5-1)**.

Table (5-1): The database of compressive strength from pervious researches.

Vf (%)	Average of fcu at (7d) (MPa)	Average of fcu at (28d) (MPa)	No. of samples	References
4	------	46.4	36 cubes	**(Naser and Abeer, 2020)**
4	54.7	69	3 cubes	**(Al-Baghdadi et al., 2021)**
4	43.76	65.3	3 cubes	**(Al-Baghdadi et al., 2021)**
4	62.19	85.76	3 cubes	**(Giridhar et al., 2015)**
5	34.2	39.8	3 cubes	**(Thomas and Mathews, 2014)**
5	50	69	3 cubes	**(Ali et al., 2022)**
6	45.7	65.5	3 cubes	**(Khamees et al., 2021)**
6	------	56.5	12 cubes	**(Ali and Riyadh, 2018)**
6	69.5	78.7	3 cubes	**(Salih et al., 2018)**
6	------	72.98	3 cubes	**(Al-Salim et al., 2021)**
6	66.85	89.81	3 cubes	**(Al-Salim et al., 2021)**
6	------	109.2	3 cubes	**(Giridhar et al., 2015)**
6	------	98.41	3 cubes	**(Hashim and Kadhum, 2020)**
6	54.7	69.51	3 cubes	**(Al-Baghdadi et al., 2021)**
7	62.22	80	3 cubes	**(Al-Baghdadi et al., 2021)**
7.5	68	79	3 cubes	**(Ali et al., 2022)**
8	------	76.7	12 cubes	**(Ali and Riyadh, 2018)**
8	71.4	81	3 cubes	**(Salih et al., 2018)**
10	58	79	3 cubes	**(Ali et al., 2022)**
10	40	45.33	3 cubes	**(Kumar and Rajasekhar, 2017)**
11	74.4	83.7	3 cubes	**(Salih et al., 2018)**
12	42.67	48.9	3 cubes	**(Kumar and Rajasekhar, 2017)**
12	------	38	3 cubes	**(Vijayakumar and Kumar, 2017)**

The fiber volume fraction varies from 4% to 12%, which is the practical fiber ratio used in SIFCON. Compressive strength values are different from one research study to another for many reasons, such as mix proportions and sample dimensions. The researchers used a database for compressive strength with a (1:1) mix proportion and 10% silica fume replacement by cement weight. Two equations have been proposed (**Eq.1.** and **Eq.2**.) to predict SIFCON compressive strength at 7 and 28 days, respectively.

A graphical relationship was drawn between compressive strength and fiber ratio for the age of 7 and 28 days and it was a non-linear relationship and then the curve equation was found using Excel- 2020 software. The following equations relates the compressive strength with fiber volume fraction (vf) multiplied by fiber density (ρ) and fiber length (L_f):

fcu (MPa) = $-1.13x^6*10^{26} + 1.4x^5*10^{23} - 6.68x^4*10^{19} + 1.67x^3*10^{16} - 2x^2*10^{12} + 1.54x*10^8 - 4157$ …………..eq.1 (7day)

fcu (MPa) = $-2.3x^6*10^{25} + 1.7x^5*10^{22} - 1.8x^4*10^{18} - 1.56x^3*10^{15} + 5.47x^2*10^{11} - 6.64x*10^7 + 2855.25$ .... eq. 2 (28day)

Where:

x is (V_f **(%)***ρ ***L_f*10^{-8}).**

V_f = *fiber volume fraction*

ρ = *fiber density (kg/m^3)*

L_f = *fiber length (mm)*

It should be noted that these equations are applicable to 100 mm SIFCON cubes that contain steel fiber with hooked ends. When deriving such equations that predict compressive strength values at 7 and 28 days, the average of the database was considered, and the relationship between the fiber ratio and compressive strength was drawn in Figure (5-1). **Table (5-2)** displays a model application with accuracy for SIFCON compressive strength at 7 and 28 days of 91% and 94%, respectively. **Figure (5-1)** shows curve fitting obtained from derived equations for compressive strength at 7 and 28 days.

Table (5-2): The calculations of compressive strength (MPa).

V_f (%)	V_f (MPa) $=V_f (\%) * \rho * L_f * 10^{-8}$	Average of cube compressive strength (fcu) at 7 days	Average of cube compressive strength (fcu) at 28 days	Cube compressive strength at 7days from eq.1	Cube compressive strength at 28 days from eq.2
		From previous studies			
4	0.000109	53.55	70.40	53.357	70.146
5	0.000137	42.10	54.40	44.162	56.062
6	0.000164	59.20	80.10	54.034	75.943
7	0.000191	62.22	80.00	68.096	84.604
7.5	0.000205	68.00	79.00	69.429	81.129
8	0.000218	71.40	78.85	65.775	74.169
10	0.000273	49.00	62.17	50.011	63.868
11	0.0003	74.40	81.00	72.132	80.251
12	0.000328	42.67	48.90	41.251	49.272

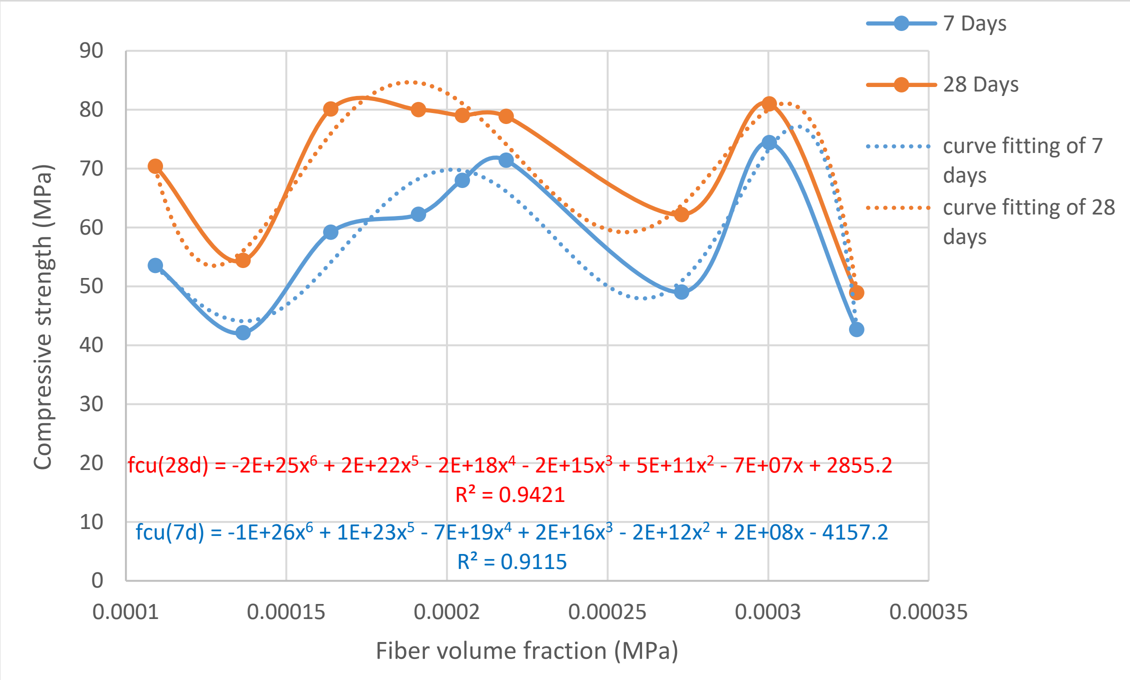


Figure (5-1): A curve fitting obtained from derived equations for compressive strength of SIFCON cubes at 7 and 28 days.

5.4. Proposed Equations for Axial Load Carrying Capacity of Reinforced concrete Columns Strengthened by SIFCON Shell

The axial load carrying capacity of NSC columns strengthened with SIFCON shell is predicted, in the present study through suggesting two equations. The two equations that are suggested are extensions of the equations of the most respectful codes which are ACI and B.S codes and made some modifications to it to fit NSC columns strengthened with SIFCON shell. This modification includes adding a limit for the SIFCON concrete, which is the area of SIFCON multiplied by its compressive strength multiplied by a certain coefficient obtained from the way of trial and error. The results from applying these equations are compared with the previous experimental results. The majority of construction codes recommended using the formulae (**eq.3** and **eq.4**) to calculate the axial load carrying capacity of the NSC reinforced columns. The suggested equations (**eq.5** and

eq.6) are the equations that have been modified to predict axial load carrying capacity of NSC columns strengthened with SIFCON shell.

$Pn=0.8 \times (0.85fc' \times An + fy \times Ast)$….**eq.3** (ACI 318M-14, Code)

$Pn=0.4fcu \times An + 0.75fy \times Ast$ ….**eq.4** (B.S 8110-1:97, Code)

$Pn=0.8 \times (0.85fc' \times An + fy \times Ast + 0.45\, fc'_{SIFCON} \times A_{SIFCON})$ ….**eq.5** (Modified ACI 318M-14, Code equation)

$Pn=0.4fcu \times An + 0.75fy \times Ast + 0.35\, fcu_{SIFCON} \times A_{SIFCON}$ ….**eq.6** (Modified B.S 8110-1:97, Code equation)

Where:

fc' = concrete cylinder compressive strength, (MPa).

fcu= concrete cube compressive strength,(MPa).

An = Net normal strength concrete area =Ag-Ast, mm^2.

Ast = Total area of longitudinal steel reinforcement, mm^2.

fy = yield strength of longitudinal reinforcing steel bars, (MPa).

fc'_{SIFCON} =SIFCON cylinder compressive strength, (MPa).

fcu_{SIFCON} =SIFCON cube compressive strength, (MPa).

A_{SIFCON} = Net SIFCON area, mm^2.

Table (5-3) and Figures (Figure (5-2) and Figure (5-3)) show a comparison between experimental ultimate load and that obtained from modified equations (eq.5 and eq.6) for both square and circular columns. It is clear that the ratio of experimental capacity to estimated (from equations) ranges from 0.88 to 1.3 for strengthened square column according to modified ACI equation and 0.87 to 1.32 according to modified BS equation. On the other hand, for strengthened circular columns this ratio is ranged from 0.78 to 1.08 according to modified ACI equation and from 0.79 to 1.14 according to modified BS equation. Such differences are seemed acceptable and really good in comparison with those obtained for unstrengthened columns (NS8, NS16, NC9 and NC18) in comparison with original ACI and BS from (range 0.77-1.51).

Table (5-3): A comparison between the results of the experimental load carrying capacity and the estimated load carrying capacity from modified equations.

Columns symbol	Exp.P_n (kN)	Modified ACI(eq.5) P_n (kN)	Modified BS (eq.6) P_n (kN)	(Exp.P_n/ eq.(5) P_n)	(Exp.P_n/ eq.(6) P_n)
NS8	152.21	133.98	101.08	1.14	1.51
NS16	147.33	133.98	101.08	1.10	1.46
N2SHy 16-4%	317.24	274.57	258.75	1.16	1.23
N2SHY 8-4%	244.88	274.57	258.75	0.89	0.95
N2SHy 8-6%	274.86	310.72	321.05	0.88	0.86
N2SHy 16-6%	282.30	310.72	321.05	0.91	0.88
N3SSHy 16-4%	475.86	365.95	361.23	1.30	1.32
N3SSHy 8-4%	359.19	365.95	361.23	0.98	0.99
N3SSHy 8-6%	402.81	425.60	464.02	0.95	0.87
N3SSHy 16-6%	410.45	425.60	464.02	0.96	0.88
NC9	172.52	169.73	124.88	1.02	1.38
NC18	131.17	169.73	124.88	0.77	1.05
N2CHy 18-4%	266.78	287.81	261.09	0.93	1.02
N2CHY18-6%	248.18	319.04	314.91	0.78	0.79
N2CHy 9-4%	256.97	287.81	261.09	0.89	0.98
N2CHy 9-6%	294.17	319.04	314.91	0.92	0.93

Table (5-3): Continued.

Columns symbol	Exp.P_n	Modified ACI(eq.5) P_n (kN)	Modified BS (eq.6) P_n (kN)	(Exp.P_n/ eq.(5) P_n)	(Exp.P_n/ eq.(6) P_n)
N3SCHy 18-4%	395.92	365.10	347.77	1.08	1.14
N3SCHy 18-6%	361.80	416.21	435.85	0.87	0.83
N3SCHy 9-4%	380.30	365.10	347.77	1.04	1.09
N3SCHy 9-6%	434.26	416.21	435.85	1.04	1.00

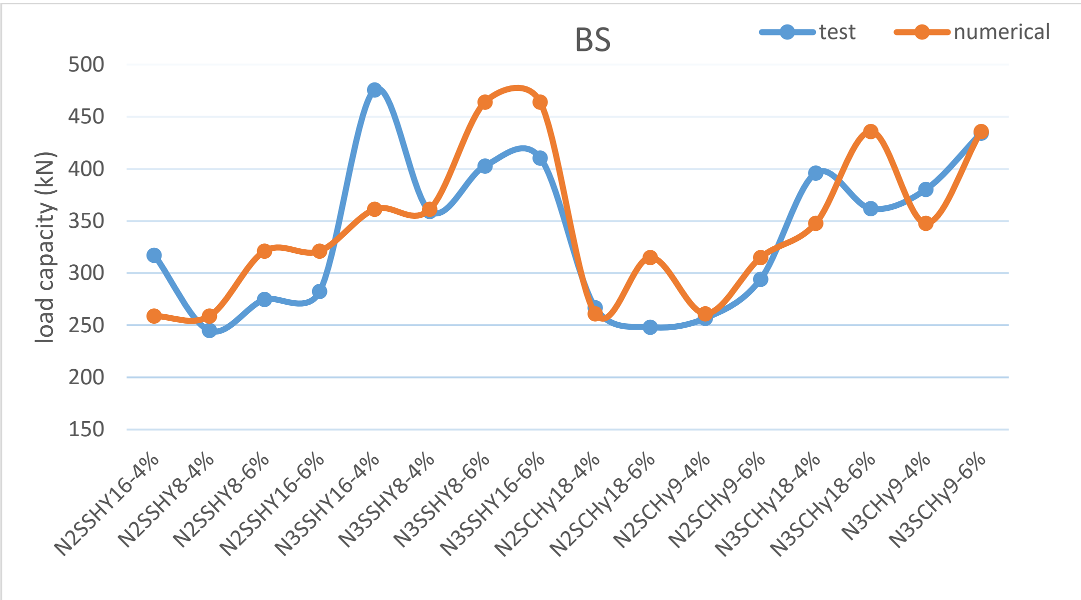


Figure (5-2): A comparison between columns bearing load of experimental results and that obtained from modified B.S. code equation.

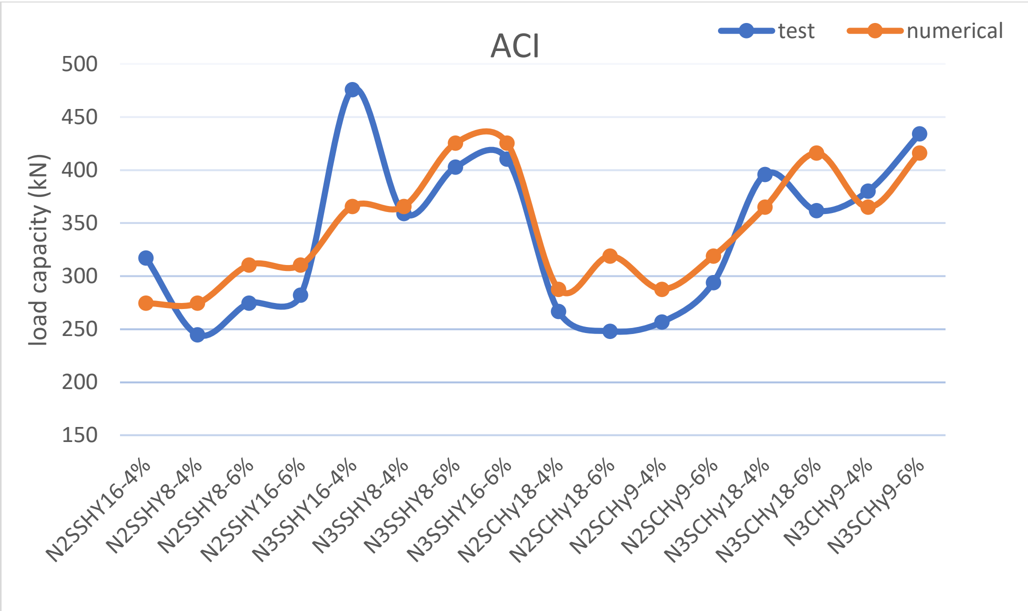


Figure (5-3): A comparison between columns bearing load of experimental results and that obtained from modified ACI code equation.

CHAPTER SIX

(Conclusions and Recommendations)

Conclusions and Recommendations

6.1. Introduction

The major goal of this thesis is to examine the behavior of columns made of normal strength reinforced concrete (NSC) strengthened with slurry infiltration fiber reinforced concrete (SIFCON) shell and compare with the behavior of unstrengthened columns.

6.2. Major Findings

There are several conclusions that can be derived about the structural behavior of concrete column specimens based on the variables that were explored in this study:

6.2.1. Mechanical Characteristics of SIFCON

1. The experimental results unambiguously show that the fiber volume fraction has a substantial impact on the compressive strength, splitting tensile strength, flexural strength, and elastic modulus, with values of 6% fiber ratio higher than 4%.

2. It was discovered that using hybrid fibers made of hooked end steel fiber and polypropylene produced good results with decreased dead weight, lower cost and reduced corrosion.

3. Using steel fibers only give higher results in the term of compressive strength, splitting tensile strength, flexural strength, and elastic modulus than hybrid fibers (hooked end steel fibers and polypropylene) by about (34 %, 17 %, 53% and 10 %) respectively.

4. Two equations are suggested in the present study to predict the compressive strength of SIFCON with steel fiber only at 7 days and 28 days respectively with very good accuracy based on previous studies as follows:

fcu = $-1.13x^6*10^{26} + 1.4x^5*10^{23} - 6.68x^4*10^{19} + 1.67x^3*10^{16} - 2x^2*10^{12} + 1.54x*10^8 - 4157$ …………..eq.1 (7day)

fcu= $-2.3x^6*10^{25} + 1.7x^5*10^{22} - 1.8x^4*10^{18} - 1.56x^3*10^{15} + 5.47x^2*10^{11} - 6.64x*10^7 + 2855.25$ .... eq. 2 (28day)

Where **x** is **(V_f (%)*ρ *L_f *10^{-8}).**

6.2.2. Behavior of Axially loaded Reinforced Concrete Columns Strengthened by SIFCON Shell.

The effect of different SIFCON shell thicknesses, fiber volume fractions, fibers type, and distance between ties of NSC columns strengthened with SIFCON shell as compared with NSC columns were experimentally investigated. The following conclusions are drawn:

1. The performance of strengthened with SIFCON shell columns is significantly superior to NSC columns in terms of load-carrying capacity, and energy absorption capacity and this may reach about (49%-223%) and (83%-1390%) respectively.
2. Thicker SIFCON shell shows higher load carrying capacity as compared with NSC columns, where the max increase in load achieved is 223% and 202% for square and circular NSC column strengthened with SIFCON shell of 3cm respectively (as found experimentally).
3. Columns strengthened with SIFCON shell of steel fiber only show some higher load-bearing capacity by about 34% and 41% than that of hybrid fibers for square and circular columns respectively.
4. Strengthened with SIFCON shell columns absorb more energy than the NSC columns. The maximum energy absorption achieved is 16 times and 15 times of NSC columns for square and circular columns respectively. The high energy absorption of SIFCON concrete

increase the possibilities of employing this concrete in bridge columns and other constructions, particularly in seismic areas.

5. Using hybrid fiber (hooked end steel fiber and polypropylene) with 4% and 6% volume fraction in mortar have a significant impact through provide a perfect spread of fiber crossing the SIFCON section, reducing dead weight and prevent corrosion.
6. The 4% hybrid fiber ratio gives higher increase in term of load bearing capacity for circular columns and square columns as compared with 6% hybrid fiber ratio.
7. To obtained load bearing capacity of NSC columns strengthened with SIFCON shell, modified ACI and B.S. codes equations are suggested as follows:

   $Pn=0.8 \times (0.85fc' \times An + fy \times Ast + 0.45\ fc'_{SIFCON} \times A_{SIFCON})$… Modified from ACI 318M14, Code equation.

   $Pn=0.4fcu \times An + 0.75fy \times Ast + 0.35\ fcu_{SIFCON} \times A_{SIFCON}$…. Modified from B.S 8110-1:97, Code equation.

6.3. Recommendations for Future Research

The following suggestions for future studies may be taken into account in order to study the structural behavior of NSC reinforced with SIFCON shell columns:

1. Producing SIFCON shells purely from polypropylene to analyze the impact on mechanical properties and strengthening

2. Researching how different fiber volume fractions effect on SIFCON columns behavior.

3. Researching the impact of other fiber types, such as basalt fiber, on how SIFCON columns behave.

4. Studying NSC columns strengthened with SIFCON shell respond to eccentric loads of various eccentricities

5. Studying the effect of NSC columns strengthened with SIFCON shell exposed to fire flame.

6. Research the potential for using SIFCON to strengthen various types of concrete columns, such as those made of lightweight concrete.

7. Producing SIFCON with different mineral admixtures such as fly ash.

8. Changing the structural members.

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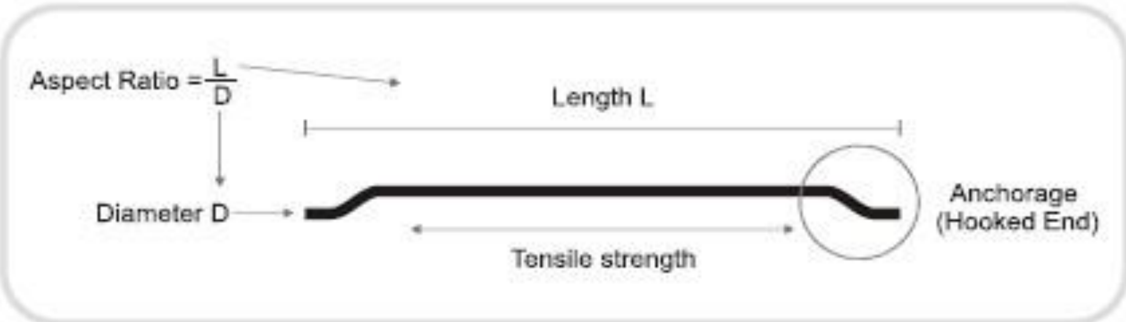
APPENDIX-A

Material Safety Datasheets

1. Data sheet of hooked end fibers provided by the manufacturer

Product Data Sheet



Material Properties

Material	Low Carbon Drawn Wire
Aspect Ratio	60
Length (mm)	35
Diameter (mm)	0.50 mm
Tensile Strength	> 1100 MPa
Appearance	Clear, bright, Loose unglued with hook end anchorage
Conforms to	EN 14889-1, ASTM A820 M04 Standards
Suitable Application	Tunnel Shotcrete, Slope Stabilization, Precast Pipes

Mixing

- Duraflex™ Steel fibers can be added before, during or after the batching of the concrete, as outlined by ASTM C-94 (4-5 minutes at mixing speed or approximately 60-70 revolutions).
- In the batch plant fibers can be added by a shaker or through a hopper to the aggregate on a conveyor belt during aggregate addition and mixed in the normal manner.
- If fibers are added in the mixer truck the drum should be rotating at maximum speed while fibers are slowly added. This is important to avoid clump avoiding balling effect.
- Depending on fiber type and dose rate the concrete slump should be increased by the addition of superplasticiser before fibers are added.
- Use of Micro Silica is beneficial along with steel fibers
- Do not use Steel fiber as a first component in the concrete mix.

Placing and Finishing

- Use of Internal and external vibrator (including vibrating screeds) is recommended.
- Finishing of the concrete surface is usually accomplished by using conventional power or hand equipment.
- The use of a surface hardener to achieve a smooth and hardened surface will also help to cover fibers close to the surface.
- Do not use Wood floats, Wood floats tend to tear the surface and should not be used.

Precaution

- To avoid chocking in the pumping operation of the concrete mix, please note that The Hose diameter should be approximately 50 % greater than the fiber length. Testing is recommended before execution

Safety & Handling

- It is recommended that gloves and appropriate eye protection must be used while using fibers.
- Fibers concretes/shotcretes contain Portland cement and thus normal safety precautions used when handling conventional cement based products should be followed.
- Store in dry place
- Do not use Hooks.
- No Stacking

Packaging

- Available in15/ 20/25 kg Non Woven HDPE Bags & Paper Laminated Bags.
- Palettes available on request.

KASTURI
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2. Data sheet of superplasticizer provided by the manufacturer

MASTER®
» BUILDERS
SOLUTIONS

MasterGlenium® 54

A high performance concrete superplasticiser based on modified polycarboxylic ether

DESCRIPTION

MasterGlenium 54 has been developed for applications primarily in precast but also readymix concrete industries where the highest durability and performance is required.

MECHANISM OF ACTION

MasterGlenium 54 is differentiated from conventional superplasticisers, such as those based on sulphonated melamine or naphthalene formaldehyde condensate as it is based on a unique carboxylic ether polymer with long lateral chains. This greatly improves cement dispersion. At the start of the mixing process the same electrostatic dispersion occurs but the presence of the lateral chains, linked to the polymer backbone, generate a steric hindrance which stabilises the cement particles capacity to separate and disperse.

This mechanism provides flowable concrete with greatly reduced water demand and enhanced early strength.

TYPICAL APPLICATIONS

The excellent dispersion properties of **MasterGlenium 54** make it the ideal admixture for precast or ready-mix where low water cement ratios are required. This property allows the production of very high early and high ultimate strength concrete with minimal voids and therefore optimum density. Due to the strength development characteristics the elimination or reduction of steam curing in precast works may be considered as an economical option.

- High workability without segregation or bleeding
- Less vibration required
- Can be placed and compacted in congested reinforcement
- Reduced labour requirement
- Improved surface finish

MasterGlenium 54 may be used in combination with **MasterMatrix** for producing Smart Dynamic Concrete (SDC). The technology produces advanced self-compacting concrete, without the aid of vibration. For economic, ecological and ergonomic ready-mix / precast concrete production.

MasterGlenium 54 can be used to produce very high early strength floor screeds. For screed mix designs consult Master Builders Solutions Technical Services.

PACKAGING

MasterGlenium 54 is available in 208 L drums and in bulk tanks upon request.

STANDARDS

ASTM C-494 Type F& G
BS EN 934-2

TYPICAL PROPERTIES*

Appearance	Whitish to straw coloured liquid
Relative density	1.07
pH value	4.0 - 7.0

APPLICATION GUIDELINES

MasterGlenium 54 is a ready to use admixture that is added to the concrete at the time of batching.

The maximum effect is achieved when the **MasterGlenium 54** is added after the addition of 70% of the water. **MasterGlenium 54** must not be added to the dry materials.

Thorough mixing is essential and a minimum mixing cycle, after the addition of the **MasterGlenium 54**, of 60 seconds for forced action mixers is recommended.

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MasterGlenium® 54

The normal dosage for **MasterGlenium 54** is between 0.50 and 1.75 L/100kg of cement (cementitious material). Dosages outside this range are permissible subject to trial mixes.

MIXING

MasterGlenium 54 is suitable for mixes containing all types of Portland cement and cementious materials as follows:

- Microsilica
- Fly ash (PFA)
- Ground granulated blast furnace slag GGBS

Note: **MasterGlenium 54** is not compatible with **MasterRheobuild** superplasticizers.

EFFECT ON HARDENED CONCRETE

- Increased early and ultimate compressive strengths
- Increased flexural strength
- Better resistance to carbonation
- Lower permeability
- Better resistance to aggressive atmospheric conditions
- Reduced shrinkage and creep
- Increased durability

STORAGE AND SHELF LIFE

MasterGlenium 54 should be stored above 5°C In closed containers or storage tanks to protect from evaporation and extreme temperatures.
The shelf life is 12 months when stored as above.

The occurrence of a surface layer with **MasterGlenium 54** is normal and will have no effect on the performance of the product.

HEALTH AND SAFETY

MasterGlenium 54 contains no hazardous substances requiring labelling. For further information refer to the Material Safety Data Sheet.

QUALITY AND CARE

All products originating from Master Builders Solutions Dubai, UAE facility are manufactured under a management system independently certified to conform to the requirements of the quality, environmental and occupational health & safety standards ISO 9001 and ISO 14001.

* Properties listed are based on laboratory controlled tests.

MBS_CC-UAE/Gl_54_09_07/v2/03_16/v3/01_23

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Disclaimer: the TUV mark relates to certified management system and not to the product mentioned on this datasheet

A brand of MBCC GROUP

3. Data sheet of silica fume provided by the manufacturer

Construction Chemicals

CON MIX

MegaAdd MS(D)

Densified Microsilica

DESCRIPTION

MegaAdd MS(D) is a very fine pozzolanic, ready to use high performance mineral additive for use in concrete. It acts physically to optimize particle packing of the concrete or mortar mixture and chemically as a highly reactive pozzolan.

MegaAdd MS(D) in contact with water, goes into solution within an hour. The silica in solution forms an amorphous silica rich, calcium poor gel on the surface of the silica fume particles and agglomerates. After time the silica rich calcium poor coating dissolves and the agglomerates of silica fume react with free lime ($CaOH_2$) to form calcium silicate hydrates (CSH). This is the pozzolanic reaction in cementitious system.

STANDARDS

ASTM C1240

USES

MegaAdd MS(D) can be used in a variety of applications such as concrete, grouts, mortars, fibre cement products, refractory, oil/gas well cements, ceramics, elastomer, polymer applications and all cement related products.

ADVANTAGES

- High to ultra high strength
- High resistance to chlorides and sulfates
- Protection against corrosion
- Increased durability, longer service life for structures
- Enhanced rheology, control of mixture segregation and bleed
- Greater resistance to chemicals

Element	Limit
SiO2	>85
CaO	<2,5
Na2O	<1.8
K2O	<2,5
Cl	<0,3
SO3	<1,5
MgO	<3,5
Fe2O3	<3,5
Al2O3	<2,2
Screen analysis, particles > 0,45µm	<40
Loss of ignition, (LOI)	<5
Free silicon <0,4	<0,4
Specific surface, BET	>15
Accelerated pozzolanic index	>95
Carbon is normally 0-0,2 % lower than LOI.	

COMPATIBILITY

MegaAdd MS(D) is suitable for use with all types of cement and cementitious materials.

With Admixtures:

MegaAdd MS(D) is compatible to use with all types of water reducing plasticisers / superplasticisers and poly carboxylate based superplasticiser.

DOSAGE

The normal dosage of **MegaAdd MS(D)** is 5 - 8% by weight of cement, but it can be used up to 10%. Site trials should be carried out to establish the optimum dosage for the mix to be used as the dosage varies depending on application.

CC/MAPDS08/Ver1/11/15

1/2 | Technical Datasheet

APPENDIX-B

Calculations and Design of NSC Columns

- **For NSC square column**

$p_{min} = \frac{A_{st}}{A_g}$

$A_{st} = p_{min} * A_g$

$A_{st} = 0.01 * 80^2 = 64$ mm^2

No. of bars= A_{st} A_{bar}

Use 6mm bar diameter

No. of bars = $64/\frac{\pi}{4} * 6^2$ = 2.26 then use 2

But in ACI 10.7.3.1 the minimum number of longitudinal bars

shall be 4, then use 4Ø6 mm

A_{st}= 113.097 mm^2

P_u= 0.8Ø [0.85 fc (A_g – A_{st}) +A_{st} fy]

Ø=0.65 for tied columns

P_u=0.8*0.65[0.85*35(80^2-113.097) +113.097*560]*10^{-3}=139.2 kN

For spacing, take the smallest number from the following calculations, according to the ACI:

S= 16 * Diameter of longitudinal reinforcement bars

S= 48 * Diameter of transverse reinforcement bars

S= The smallest dimension of cross-section

So S= 80 mm

- **For NSC circular column**

$p_{min} = \frac{A_{st}}{A_g}$

$A_{st} = p_{min} * A_g$

$A_{st} = 0.01 * \frac{\pi}{4} * 90^2 = 63.61$ mm^2

No. of bars= A_{st} /A_{bar}

Use 6mm bar diameter

No. of bars = $\frac{63.61}{\frac{\pi}{4}*6^2}$ = 2.25, use the same reinforcement of square column (4Ø6 mm)

∴ A_{st}= 113.097 mm^2
P_u= 0.8Ø [0.85 fc (A_g – A_{st}) +A_{st} fy]
Ø=0.65 for tied columns
P_u=0.8*0.65[0.85*35($\frac{\pi}{4}$*90^2-113.097) +113.097*560]*10^{-3}=129.57 kN

For spacing, take the smallest number from the following calculations, according to the ACI:

S= 16 * Diameter of longitudinal reinforcement bars
S= 48 * Diameter of transverse reinforcement bars
S= The smallest dimension of cross-section
So S= 90 mm.

الخلاصة

خرسانة الملاط المتخلل الألياف (السفكون) هي جيل متطور من الخرسانة المسلحة بالالياف لكنها تحتوي على نسبة الياف أعلى تصل إلى (٤-٢٠)٪. السفكون يوفر احتمالية أفضل لإستخدامهِ في المناطق التي تتطلب مطيلية عالية ومقاومة الصدمات خاصةً عندما يتم تصميم المنشأ لمقاومة الزلازل وإعادة تأهيل أو تقوية الاعضاء الإنشائية الخرسانية المسلحة. الجزء الأول من هذهِ الدراسة يتناول البرنامج العملي الذي يهدف لمعرفة سلوك الاعمدة ذات المقطع العرضي الدائري والمربع المنفذة من الخرسانة المسلحة ذات المقاومة الاعتيادية بعد تغليفها بقشرة السفكون ومقارنة سلوك هذهِ الاعمدة المقواة مع الاعمدة المنفذة من الخرسانة المسلحة غير المقواة. تمت دراسة تأثير اسماك مختلفة من قشرة السفكون (٢، ٣) سم، نوع الالياف ونسبتها (٤٪، ٦٪) والمسافات بين الاتاري التي هي (٨، ١٦) سم للأعمدة المربعة الشكل و (٩،١٨) سم للأعمدة الدائرية الشكل. إنَّ نوع الألياف المستخدمة هي ألياف البولي بروبلين وألياف الحديد ذات النهايات المعقوفة. تم صب وفحص ٢٢ عمود والتي بدورها صُنفت الى مجموعتين، المجموعة الأولى تتألف من ستة أعمدة غير مقواه المنفذة من الخرسانة المسلحة العادية وعمودين تم تقويتهما بقشرة سفكون سمكها ٢ سم بنسبة ٦٪ من الياف الحديد ذات النهايات المعقوفة. المجموعة الثانية تتألف من ١٦ عمود مقوى بقشرة سفكون تحتوي الياف مختلطة من الحديد والبولي بروبلين. إنَّ أبعاد الاعمدة المربعة تساوي (٨*٨*٨٠) سم بينما الاعمدة الدائرية قطرها ٩ سم وارتفاعها ٨٠ سم. تمت ملاحظة أنَّ الاعمدة المقواة بقشرة سفكون سمكها ٣ سم أعطت سعة تحمل الحمل وامتصاص طاقة أعلى مقارنةً بتلك المقواة بسمك ٢ سم. إنَّ اقصى حمل تم الحصول عليهِ هو ٢٢٣٪ و٢٠٢٪ أعلى من حمل الأعمدة المنفذة من الخرسانة المسلحة بعد تقويتها بقشرة السفكون ذات سمك ٣ سم ونسبة ألياف مختلطة ٤٪ ذات المقطع المربع الشكل والدائري على التوالي مقارنةً مع الأعمدة الغير مقواة. بينما اعلى امتصاص للطاقة كان تقريباً ١٦ مرة و١٥ مرة اعلى من الاعمدة الغير مقواة ذات المقطع المربع الشكل والدائري على التوالي.
الجزء الثاني من الدراسة يتضمن بعض المعادلات المقترحة للتنبؤ بمقاومة انضغاط مكعبات السفكون ومعادلات أخرى للتنبؤ بسعة تحمل الحمل المحوري المركزي للأعمدة المنفذة من الخرسانة العادية المسلحة بعد ما تم تقويتها بقشرة السفكون. معادلتين تم اقتراحهما للتنبؤ بمقاومة انضغاط مكعبات السفكون الحاوي على ألياف الحديد بعمر ٧ و ٢٨ يوم بدقة جيدة جداً إستناداً إلى الدراسات السابقة. بإلاضافة إلى ذلك، للحصول على سعة تحمل الحمل للأعمدة المنفذة من الخرسانة العادية بعد ما تم

تقويتها بقشرة السفكون، تم اقترح تعديل معادلات الكود الأمريكي والبريطاني. إنَّ الفرق بين الحمل الناتج من نتائج الفحص المختبري ومن المعادلات المقترحة للأعمدة المقواة يبدو مقبولاً وجيداً مقارنةً بالأعمدة الغير مقواه مقارنةً مع معادلات الكود الأمريكي والبريطاني الأصلية.

وزارة التعليم العالي والبحث العلمي

جامعـــــة بابـــل

كلية الهندســـــة / قسم الهندسة المدنية

سلوك الأعمدة الخرسانية المسلحة المقواة بإستخدام قشرة من خرسانة الملاط المتخلل للألياف (السفكون)

رسالة

مقدمه إلى كلية الهندسة / جامعة بابل

كجزء من متطلبات نيل درجة ماجستير في الهندسة / الهندسة المدنية / الانشاءات

من قبل

نور عدنان حواس

بكالوريوس هندسة مدني (2019)

بإشراف

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1445 A.H **2023 A.D**