ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING.

Behavior of Normal and High-Strength Confined Concrete Under Compression Load

Amare Gossaye GSR/3973/05

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By

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Behavior of Normal and High Strength Confined Concrete Under Compression Load

A Thesis Submitted To The School of Graduate Studies of AAiT In Partial Fulfillment of The Requirement For The Degree of Master of Science In Structural Engineering

By

Amare Gossaye

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Abstract

In this study high strength concrete with a specific compressive control cube strength at 28days of age f_{cu}=50MPa, and normal-strength concrete with a specific compressive control cube strength at 28 days of age f_{cu}=41MPa are considered to study the confined property of high-strength and normal-strength concrete under axial compression load. Material used for high-strength concrete are; OPC Derba cement, basaltic coarse aggregate, crushed sand, water, and conplast SP430 chemical admixture. And material used for normal-strength concrete are; OPC Derba cement, crushed sand, river sand, basaltic coarse aggregate and water. The mix design for high-strength concrete was designed to obtain f_{cu}=60Mpa, but from the test result it is obtained f_{cu}=50MPa, and this compressive strength of concrete is considered to study the behavior of high-strength concrete in this research. Deformed reinforcing bar diameter 8mm with yield strength about 503MPa and 580Mpa were used to confine the specimen. The reinforced specimens contained rectilinear lateral steel ties, and four diameter 10mm longitudinal reinforcement with yield strength about 628MPa was used in the tested specimens.

Test can be performed on 18 prismatic high-strength concrete specimens and 18 prismatic normal-strength concrete specimens having a size of (150mm×150mm×300mm) with three steel tie spacing (s=54mm,68mm,90mm). The test specimen include 6 plain unreinforced prismatic specimens; 3 for high strength and 3 for normal strength concrete. Specimens were tested by compression testing machine having a capacity of 3000KN subjected to generalized compression load with rate of loading 0.28MPa/s.

The test parameters considered in this study are; concrete compressive strength, volumetric ratio and spacing of transverse reinforcement and yield strength of transverse reinforcement. The models proposed by previous researchers were used in addition to the test result to study the effect of test parameters. Finally the influence of confinement and concrete compressive strength on the behavior of high-strength and normal-strength concrete specimens confined by rectilinear steel tie bars were examined. From the result obtained in the study the effect of volumetric ratio and spacing of transverse reinforcement has more pronounced effect on the behavior of normal and high-strength column specimens as compared to the other test parameters, which is agreed with the result of previous researchers.

Table of Contents

Pages

Acknowledgments……..…iii
Abstract……...iv
Table of Contents……v
List of Figures ……..……...……vii
List of Tables ……..……..……..ix
Notation…… ……...……..……...……x
1. Introduction……...……...……..……1
1.1 General……...…...……...….1
1.2 Objectives…….……...…2
2. Literature Review …….....3
2.1 General…….…...……3
2.2 Research on Confined Normal-Strength Concrete……..……...……3
2.2.1 Mander, Priestly, and Park(1988)……..……..……...3
2.2.2 Razvi and Saatcioglu(1992)……..……4
2.2.3 Riyad Zeidan(2005)…….……4
2.2.4 Melat Ayele (2010)…….……...……5
2.2.5 Tavio, Benny Kusuma and Priyo Suprobo (2012)…….…...……7
2.2.6 Shafqat A & Ali A. (2012)……....…9
2.3 Research on Confined High-Strength Concrete……..……11
2.3.1 Cusson and Paultre (1995)…….…..……..…11
2.3.2 Razvi and Saatcioglu (1999)……....……...…11
2.3.3 Li. Bing, Park.R, and Tanaka.H (2001)……...…12
2.3.4 Umesh K. Sharma, Pradeep Bhargava and S.K.Kaushik (2005)…….....…13
2.3.5 Metin Husem and Selim Pul 2007……...…14
2.3.6 Antonius & Iswandi Imran (2012)……...15
2.4. Some of Conclusions Drawn From Previous Research…….……16
3. Experimental Program……...17
3.1 General…….……..…17

3.2 Detail of Test Specimen……..……...17
3.3 Material Property …….…….....19
3.3.1 Concrete……..19
3.3.2 Reinforcement…….20
3.4 Casting Test Specimen ……..…….21
3.5 Test Set up and Instrumentation……21
3.6 Test Procedure……..….22
4 Experimental Result and Discussion…… …….……....23
4.1 General …….……....23
4.2 Observed Behavior……..…….23
4.3 Effects of Test Parameters……29
4.3.1 Effect of Compressive Strength of Concrete…..…….29
4.3.2 Effect of Volumetric Ratio and Spacing of Transverse Reinforcement……..33
4.3.3 Effect of Yield Strength of Transverse Reinforcement……...42
5. Conclusions and Recommendations…….……....46
5.1 Conclusions……..46
5.2 Recommendations…….……..……...….47

References……48

List of Figures **Page**

Fig. 2.1 Size of specimen and arrangement of transverse reinforcement considered by Riyad (2005)……..…..5

Fig. 2.2 Different geometric configuration of reinforcement considered by Melat 2010……..…6

Fig. 2.3(a). Different layer of wire mesh on circular column considered by Melat 2010…….....6

Fig. 2.3(b). Different layer of wire mesh on square column considered by Melat 2010……..7

Fig. 2.4 Detail of test specimen, reinforcement configuration and location of strain gage considered by Tavio, Benny Kusuma and Priyo Suprobo(2012)……8

Fig. 2.5 Detail of test specimen considered by Shafqat A & Ali A. 2012…….....10

Fig. 2.6 Short column with axial compressive loading ; principal dimensions; test setup; instrumentation; and position of strain gages considered by Li. Bing Park.R, and Tanaka. H (2001)……...12

Fig. 2.7 Detail of column specimens, reinforcement arrangement and location of strain gages considered by Umesh K. Sharma, Pradeep Bhargava and S.K. Kaushik (2005)……14

Fig. 2.8 Detail of test specimen and instrumentation considered by Antonius & Iswandi Imran (2012)…….…15

Fig. 3.1 Detail of tst specimens…….…….…….....18

Fig. 3.2 Schematic representation of test set up…….……..…….....21

Fig. 3.3 Overall view of test set up…….……..……22

Fig. 4.1 Appearance of confined test specimens at different loading stages…….……..24

Fig. 4.2 Typical inclined vertical cracks for well confined concrete…….……24

Fig. 4.3 Appearance of test specimens at post peak loading (s=90mm) ……..25
(a) Normal- strength concrete column specimen and
(b) High -strength concrete column specimen.

Fig. 4.4 Appearance of test specimens at post peak loading (s=68mm) ……..25
(a) Normal-strength concrete column specimen and
(b) High-strength concrete column specimen.

Fig. 4.5 Appearance of test specimens at post peak loading (s=54mm) ……...……26

(a) Normal- strength concrete column specimen and

(b) High- strength concrete column specimen.

Fig. 4.6 Stress-Strain relationship of confined concrete specimen: ……..27

(a) Normal- strength concrete column specimen and,

(b) High-strength concrete column specimen, with all other parameters are constant.

Fig. 4.7 Stress-Strain relationship of confined concrete specimen:…….....28

(c) Normal-strength concrete column specimen and,

(d) High-strength concrete column specimen, with all other parameters are constant.

Fig. 4.8 Effect of compressive strength of concrete on confined; ……...……33

(a) Normal-strength concrete

(b) High- strength concrete.

Fig. 4.9 Effectively confined core for rectangular tie reinforcement and arching action……34

Fig. 4.10 Test specimen cross section……..….35

Fig. 4.11 Important characteristics of Load-Deflection curve, (ASTM C1018)…….38

Fig. 4.12 Ductility index versus effective confinement index for normal-strength concrete columns…….……40

Fig.4.13 Ductility index versus effective confinement index for high-strength concrete columns…….……..…41

Fig. 4.14 Effect of yield strength on normal-strength concrete columns …….…….43

(a) Yield strength of transverse reinforcement =580MPa, and

(b) Yield strength of transverse reinforcement =503MPa.

Fig. 4.15 Effect of yield strength on high-strength concrete columns ……..44

(c) Yield strength of transverse reinforcement =580MPa, and

(d) Yield strength of transverse reinforcement =503MPa.

List of Tables **Page**

Table 3.1 Mix proportions for normal and high-strength concrete……...…19
Table 3.2. Summary of test result for normal-strength concrete,28 days control cube compressive strength ……20
Table 3.3. Summary of test result for high-strength concrete,28 days control cube compressive strength……..……..20
Table 3.4. Mechanical properties of longitudinal and lateral reinforcement ……...….20
Table 4.1 Strength enhancement in normal strength concrete column specimen, (C41)……..…31
Table 4.2 Strength enhancement in high strength concrete column specimen, (C50)……..32
Table. 4.3 Computation of confinement effectiveness index and ductility index for normal strength concrete columns ……..…..39
Table. 4.4 Computation of confinement effectiveness index and ductility index for high strength concrete columns……40
Table. 4.5 Effective confinement index, $k_e \rho_s f_{yt}/f'_c$ (%) and ductility index, I_{10}…..……..41

Notation

A_s =area of one leg of transverse reinforcement

A'_s =area of one leg of longitudinal reinforcement

A_{sx} =the total area of transverse bars running in the x directions

A_{sy} =the total area of transverse bars running in the y directions

b_c =core dimension measured center-to-center of perimeter hoops

b_{cx} =core dimensions to the centerlines of perimeter hoop in x directions

b_{cy} =core dimensions to the centerlines of perimeter hoop in y directions

d_b = diameter of transverse reinforcement

d_l = diameter of longitudinal reinforcement

E_s = modulus of elasticity of transverse steel

$f'c$ = standard cylinder compressive strength of concrete at the age of 28 days

f_{cu} = standard cube compressive strength of concrete at the age of 28 days

f'_{cc} = confined concrete compressive strength in member

f'_{co} = unconfined concrete compressive strength in member

f_l = average confined pressure

f_{le} =equivalent uniform lateral pressure that produces same effect as non uniform pressure

f_s = tensile stress in transverse reinforcement at peak concrete stress

f_{yt} = yield strength of transverse reinforcement

k_1 = coefficient that relates confinement pressure to strength enhancement

k_2 = coefficient that relates efficiency of confinement reinforcement

k_e = confinement effectiveness coefficient

q =number of tie legs that cross side of core concrete for which average lateral pressure f_l is being computed

s = spacing of transverse reinforcement

s_l = spacing of longitudinal reinforcement

s' =interior spacing between set of ties

w_i = the i^{th} clear distance between adjacent longitudinal bars,

α =angle between leg of transverse reinforcement and core side crossed by same leg

ρ_{cc}=ratio of area of longitudinal steel to area of core of section

ρ_s=ratio of the volume of transverse confining steel to the volume of confined concrete core

1. Introduction

1.1 General

The behavior of confined concrete is depend up on the level of confinement. Confinement increases the strength and ductility of concrete. The basic philosophy for the use of confined concrete in seismically resistant designed structures, requires that confinement is capable of increasing the capacity of the concrete structures to sustain large deformations in the post elastic range without a sustainable strength loss [2]. It is now well documented that the desired ductility can be attained in case of normal-strength concrete columns by providing well-detailed lateral reinforcement [4]. However, the gradual development of concrete technology has promoted the use of high-strength concrete owing to its wide range of advantages over normal-strength concrete.

The use of high strength concrete is increasing rapidly in most of construction projects around the world especially in high rise buildings. This increase is because HSC has an advantage which enables a reduction in the cross section and thus weight of construction members. This reduction in cross section and dead load leads to greater floor space in the case of high rise buildings and reduce construction costs. High strength concrete is inherently more brittle than normal strength concrete. As the strength and therefore brittleness of concrete increase the ductility of the concrete will decrease [7]. It is generally accepted that confined concrete shows increased ductility and strength, there is a difference of opinion on both the enhancement of ductility and strength, in confined high strength concrete.`

Many researchers have reported the lack of ductility and deformation capacity of HSC columns [1,10]. The ductility of reinforced concrete columns depends on the confinement provided by confining steel. Therefore, concrete confinement is a critical issue for HSC columns in seismic regions [10].

The aim of this thesis is to evaluate the influence of compressive strength of concrete, the amount of lateral reinforcement, spacing of lateral reinforcement and yield strength of lateral reinforcement on the behavior of normal and high-strength concrete specimens confined by rectilinear steel ties under compression load. `

1.2 Objectives

General objective

To study the behavior of normal and high-strength confined concrete under generalized compression loads.

The specific objective of this thesis is:

- To evaluate the influence of volume of lateral reinforcement on the axial strength and ductility of normal and high-strength concrete specimens confined by rectilinear steel ties.
- To evaluate the influence of concrete compressive strength on the axial strength and ductility of normal and high-strength concrete specimens confined by rectilinear steel ties.
- To evaluate the influence of yield strength of transverse reinforcement on the behavior of confined normal and high-strength concrete column specimen.

2. Literature Review

2.1 General

Characteristics of confined concrete have been researched extensively during the last four decades. Different researchers have been made numerous analytical and experimental studies on normal and high-strength confined concrete under compression load. Many researchers proposed different model of study on the behavior of confined concrete and they have drawn conclusions and recommendations based on the results they obtained.

The main parameters involved in the confinement are the ratio of transverse reinforcement i.e. the ratio of volume of hoops to the volume of confined core of the member, the yield strength of the transverse reinforcement, the compressive strength of concrete, the spacing of hoops, the longitudinal reinforcement and hoop pattern.

2.2 Research on Confined Normal Strength Concrete

2.2.1 Mander, Priestly, and Park(1988)

A stress strain model is developed for concrete subjected to uni- axial compressive loading and confined by transverse reinforcement. The concrete section may contain any general type of confining steel; either spiral or circular hoops; or rectangular hoops with or without supplementary cross ties. These cross ties can have either equal or unequal confining stresses along each of the transverse axes. A single equation is used for the stress-strain equation. The model allows for cyclic loading and includes the effect of strain rate. The influence of various type of confinement is taken into account by defining an effective lateral confining stress, which is dependent on the configuration of the transverse and longitudinal reinforcement. An energy balance approach is used to predict the longitudinal compressive strain in the concrete corresponding to first fracture of the transverse reinforcement by equating the strain energy capacity of the transverse reinforcement to the strain energy stored in the concrete as a result of the confinement.

2.2.2 Razvi and Saatcioglu (1992)

An analytical model is proposed to construct a stress-strain relationship for confined concrete. The model consists of a parabolic ascending branch, followed by a linear descending segment. It is based on calculation of lateral confinement pressure generated by circular and rectilinear reinforcement, and the resulting improvements in strength and ductility of confined concrete. A large volume of test data, including poorly confined and well confined concrete was evaluated to establish the parameters of the analytical model. Confined concrete strength and corresponding strain are expressed in terms of equivalent uniform confinement pressure provided by the reinforcement cage. The equivalent uniform pressure is obtained from average lateral pressure computed from section and material properties. Confinement by a combination of different types of lateral reinforcement is evaluated through superposition of individual confinement effects. The descending branch is constructed by defining the strain corresponding to 85% of the peak stress. This strain level is expressed in terms of confinement parameters. A constant residual strength is assumed beyond the descending branch, at 20% strength level. The model is compared against a large number of column tests. Circular, square, and rectangular columns, with spiral and rectilinear reinforcements, as well as welded wire fabric, are used for comparison. Comparisons include concentric and eccentric loadings, as well as slow and fast strain rates.

2.2.3 Riyad Zeidan (2005)

The effectiveness of transverse reinforcement is investigated analytically and experimentally. A total of 60 concrete columns with cross-section of 150×150×310mm and concrete control cube strength (C-25) with the same size of the specimen without tie were tested in order to investigate the enhancement in strength and ductility caused by rectilinear ties. The importance of the spacing of lateral ties, the amount of stirrups, the yield strength of stirrups and the amount of longitudinal reinforcement bars are evaluated. The confinement models proposed by various researchers were used to predict the results of the test conducted and are compared with the experimental results. Detail of test specimen is shown by **Fig.** 2.1.

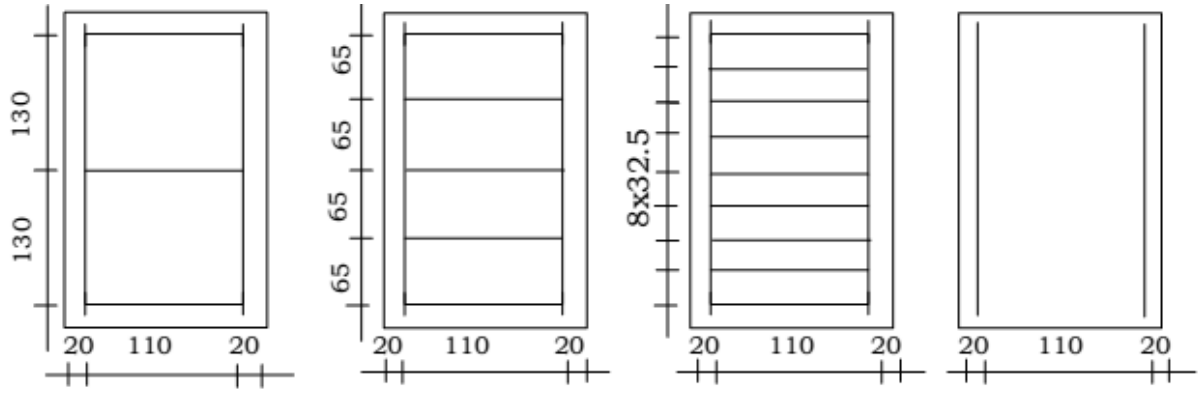


Fig. 2.1 Size of specimen and arrangement of transverse reinforcement, considered by Riyad (2005)

He reported as observation on the test results indicates that transverse reinforcement results in significant enhancement in the ductility of concrete column. However, the compression strength enhancement was found to be little. The spacing of stirrups is of the greatest importance for the post-peak behavior of concrete column under axial load. Due to size limitation of the specimen and lack of uniformly distributed longitudinal reinforcement, none of the predicted responses from the confinement model proposed by various researchers showed satisfactory agreement with the experimental result.

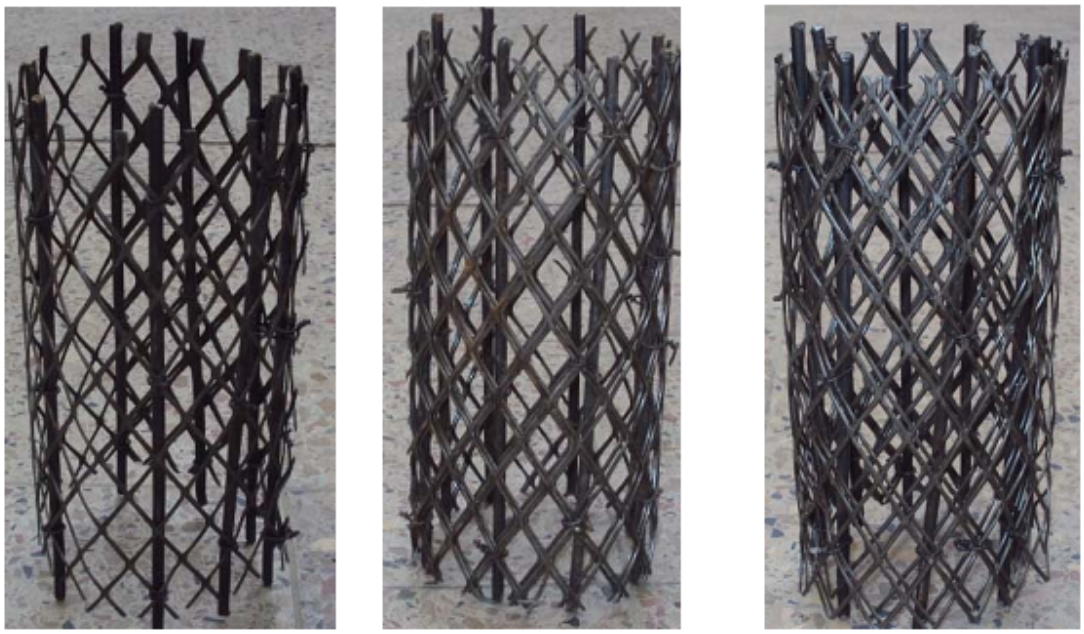
2.2.4 Melat Ayele (2010)

An experimental investigation was conducted to examine the effect of confinement in normal strength concrete columns subjected to axial loading. The experimental program include 33 small scale concrete column with size of 150mm*150mm*300mm and 150mm diameter of circular column specimen. Three type of different geometric arrangement of transverse tie (cross tie, normal and overlapping) of square column, and with three different number of layer of wire mesh square and circular column. Normal strength concrete with control cube strength of 30Mpa is used for the experiment. Detail of test specimen is shown by **Fig**. 2.2, **Fig**. 2.3(a) & **Fig**. 2.3(b).



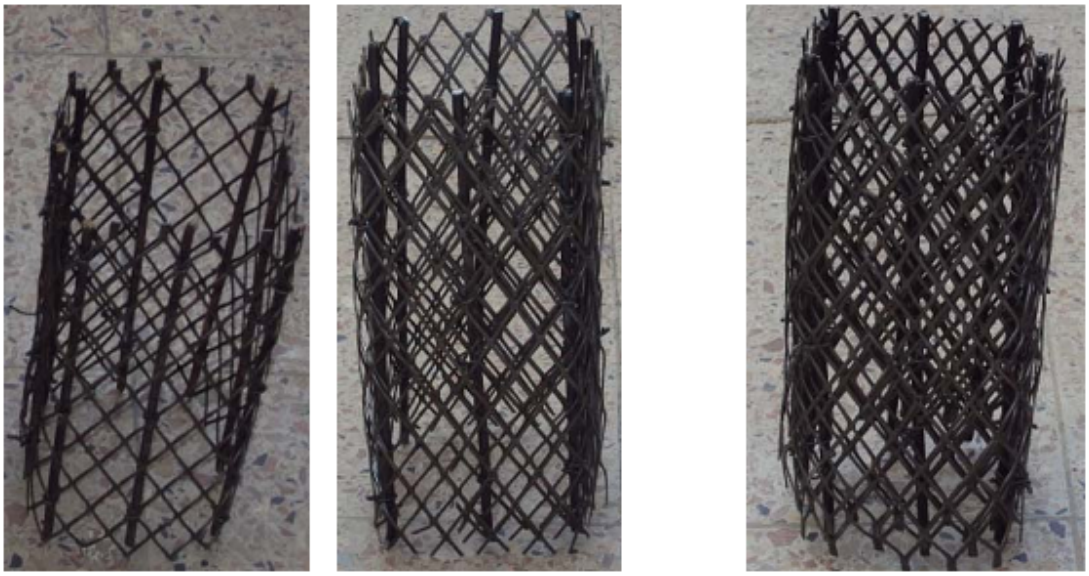
(a). normal tie configuration (b). overlapping configuration (c). cross tie configuration

Fig. 2.2 Different geometric configuration of reinforcement, considered by Melat 2010



One layer two layers three layers

Fig. 2.3(a). Different layer of wire mesh on circular column, considered by Melat 2010



One layer two layers three layers

Fig. 2.3(b). Different layer of wire mesh on square column, considered by Melat 2010

She has reported that the strength of column confined by cross tie, overlapping three layers square and circular specimens confined by wire mesh shows enhancement in strength very significantly. Significant enhancement in peak strain and ductility was observed in specimens confined by wire mesh and cross tie configuration especially specimen having circular cross section confined by three layers of wire mesh. Circular and cross tie type of confinement preserve the strength in the descending region of the stress-strain curve and prevent the column from sudden failure after peak load. From all specimens the test result indicates that the cross tie configuration give higher strength and ductility.

2.2.5 Tavio, Benny Kusuma and Priyo Suprobo (2012)

An experimental study was carried out to investigate the behavior of normal-strength concrete short columns confined by welded wire fabric as transverse reinforcement under monotonically increasing concentric compression. A total of 22 short concrete columns (with size of 180mm×180mm×720mm) reinforced with longitudinal steel and welded wire fabric or conventional ties under axial compression are considered. The parameters studied in this research included the volumetric ratio, spacing and lateral steel configuration, and distribution of

longitudinal steel around the core perimeter or longitudinal reinforcement ratio. The effect of these variables on the uni-axial behavior of reinforced concrete columns are presented and discussed. The performance of columns laterally reinforced with welded wire fabric was compared with that of columns laterally reinforced with conventional tie. The results indicate that welded wire fabric can be effective in confining the core concrete, resulting in significant improvements in the strength and ductility of columns. Strength increases of at least 17% and ductility increases of 130% were observed when compared with the corresponding specimens with conventional ties. An increase of longitudinal reinforcement and decrease of transverse reinforcement spacing effectively improved the ductility of confined concrete columns. Columns with four longitudinal reinforcement bars exhibited much less ductile than columns with eight or 12 longitudinal reinforcing bars. In addition, welded grids can be useful to reduce the congestion of reinforcement and improve the concrete quality in the members. Detail of test specimen, reinforcement configuration and location of strain gage is shown by **Fig**.2.4.

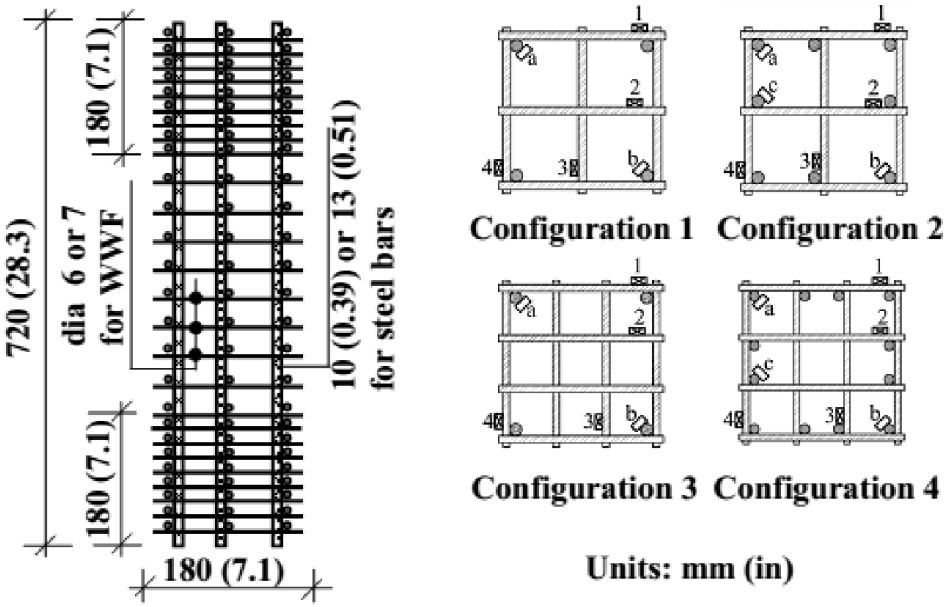
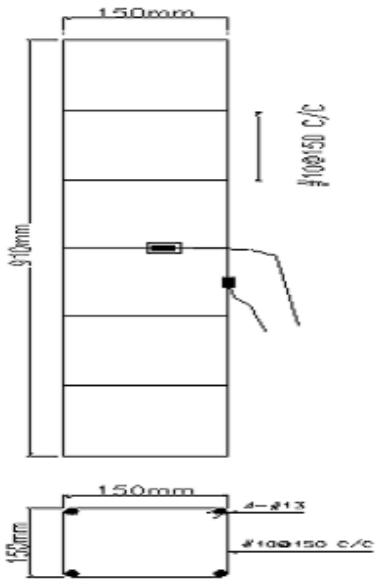


Fig. 2.4 Detail of test specimen, reinforcement configuration and location of strain gage considered by Tavio, Benny Kusuma and Priyo Suprobo(2012).

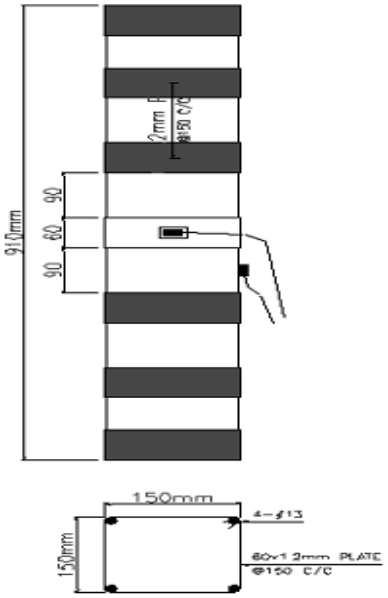
2.2.6 Shafqat A & Ali A. (2012)

Experimental investigation have been made by changing the conventional lateral ties of rectangular RC column core to special confinement using the equivalent area of thin steel plates. Three columns were casted using different confining steel with compressive strength of 18MPa. Each columns having the same size of 150mm square cross section and 910mm height with the following ties configuration having the same cross sectional area. 1. Concrete column confined with conventional steel tie, 2. concrete column confined with 2mm thick steel strips and 3.concrete column confined with 1.2mm thick steel strips. Experimentation was done on these columns to check the maximum axial capacity along with study of mode of failure and toughness. Detail of test specimen is shown by **Fig**. 2.5.

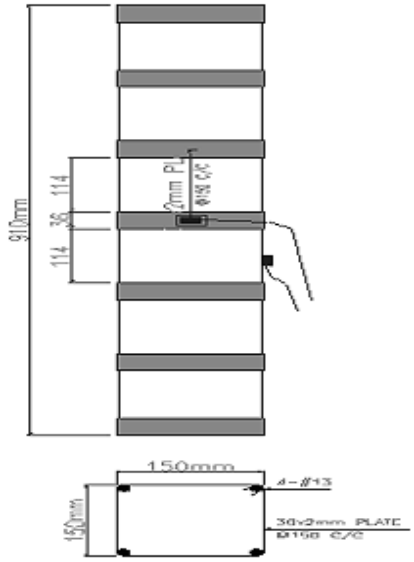
Experimental work on a tied column showed that strain in confining reinforcement was only 20% of main reinforcing steel strain at first peak and stress level in confining steel was only 28.45% of its yield stress for controlled column using normal tie. At the time of maximum load stresses in confining steel are significantly lesser than its capacity. So this reserve capacity can be utilized by spreading the area of lateral reinforcement over the longitudinal steel bar in order to reduce the effective length. Axial capacity of column confined with 2mm steel strips was approximately 78% more as compared to column confined with conventional steel tie, and column confined with 1.2mm steel strips showed only 15.8% greater capacity relative to the conventional steel tie. The peak strength and corresponding strain of confined concrete could be affected by the configuration and shape of lateral confinement.



(a). Concrete column confined by conventional steel



(b) .Concrete column confined by 2mm thick steel strips



(c) Concrete column confined by 1.2mm thick steel strips

Fig. 2.5 Detail of test specimen considered by Shafqat A & Ali A. 2012

2.3 Research on Confined High Strength Concrete

2.3.1 Cusson and Paultre (1995)

A stress-strain model for confined high-strength concrete has been developed and calibrated against the test results from 50 large-scale high-strength concrete tied columns tested under concentric loading (size of specimen 225mm×225mm×715mm). The effects of the concrete compressive strength, tie yield strength, tie configuration, transverse reinforcement ratio, tie spacing, and longitudinal reinforcement ratio are accounted for in the proposed stress strain model. The determination of the strength and ductility of confined concrete is based on the computation of the effective confinement pressure, which depends on the stress in the transverse reinforcement at maximum strength of confined concrete, and on the effectively confined concrete area.

They reported that using high-strength steel ties in lightly confined specimens does not translate into strength and ductility gains. The failure of high-strength columns is characterized by the formation of an inclined shear failure plane, separating the concrete core into two wedges laterally restrained by the reinforcement cage. Measured from the vertical axis, the inclination angle of the shear failure plane varies from 25° for lightly confined specimens to 45° for highly confined specimens. Confined high-strength concrete columns display a stress-strain relationship with a flat top and very ductile post peak response.

2.3.2 Razvi and Saatcioglu (1999)

A mathematical model is developed to express the stress-strain relationship of high-strength concrete confined by transverse reinforcement. The model is applicable to both normal-strength and high-strength concretes, covering a strength range between 30 and 130MPa. It incorporates all the relevant parameters of confinement that have been observed to play important roles in column tests. These parameters include the type, volumetric ratio, spacing, yield strength, and arrangement of transverse reinforcement as well as concrete strength and section geometry. It can be used for concrete confined by spirals, rectilinear hoops, cross ties, welded wire fabric, and combination of these reinforcements. It has been verified extensively against data obtained from column tests under concentric and eccentric loads, as well as slow and fast strain rates. It also

incorporates the effect of high-strength transverse reinforcement, with up to 1400MPa yield strength.

2.3.3 Li. Bing, Park.R, and Tanaka.H (2001)

An experimental study of a number of quasi-statics axial loading test on high-strength concrete specimens confined by various amounts of transverse reinforcement is described. Size of specimen is 240mm×240mm×720mm for square cross section and 240mm diameter by 720mm height for circular section. The main parameters were concrete strength ranging from 35.2 to 82.5MPa and yield strength of grade 430 and 1300 transverse reinforcement. A stress-strain relationship for confined high-strength concrete is proposed that is found to give reasonably good prediction of the experimental behavior of circular and square specimens with high-strength concrete confined by either normal or ultra-high–yield-strength with various configurations. An empirical formula for the ultimate longitudinal strain of confined high-strength concrete corresponding to the first hoop or spiral fracture is also proposed. Detail of test specimen, test setup and instrumentation is shown by **Fig**. 2.6.

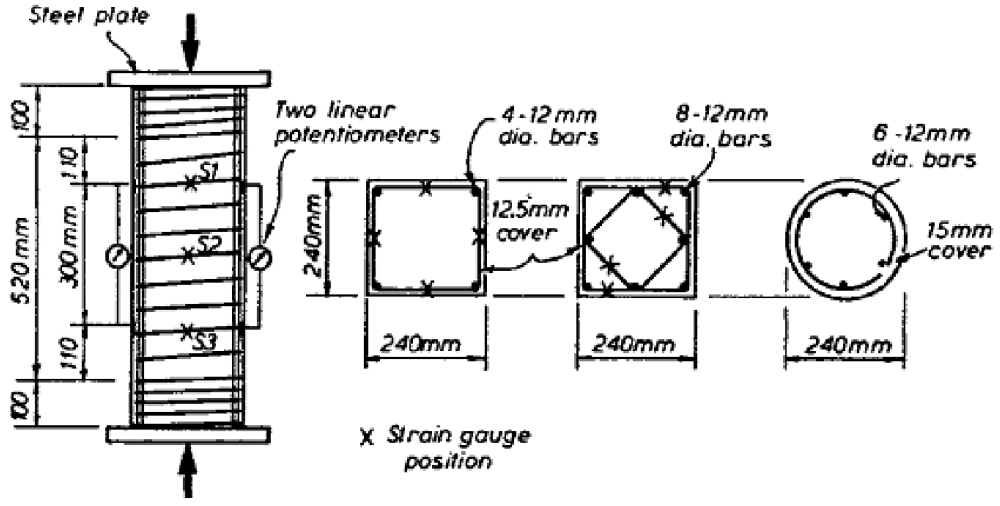


Fig. 2.6 Short column with axial compressive loading ; principal dimensions; test setup; instrumentation; and position of strain gages considered by Li. Bing Park.R, and Tanaka. H (2001)

They reported that the most significant parameters affecting the shape of the stress-strain curve of confined high-strength concrete for all section shapes are the volumetric ratio and the yield strength of the confining reinforcement. As the yield strength of the confining reinforcement increases, the strength of the confined concrete also increases. The ultimate longitudinal strain was defined as the strain at the first hoop or spiral fractured. The influence of concrete compressive strength on the degree of column ductility is significant, particularly for concrete compressive strengths exceeding 60MPa. Regardless of the concrete compressive strength, however, an increase in the confinement ratio increases the peak stress attained, increases the ultimate strain at first hoop or spiral fracture, and decreases the slope of the descending branching branch. An increase in the spacing of transverse reinforcement tends to reduce the efficiency of the confinement.

2.3.4 Umesh K. Sharma, Pradeep Bhargava and S.K.Kaushik (2005)

An experimental study was carried out to investigate the behavior of high-strength concrete short columns confined by circular spirals and square ties under monotonically increasing concentric compression. Size of specimens is 150mm×150×600mm for square cross section and 150mm diameter with height of 600mm for circular section is considered. The test variables included volumetric ratio, spacing and yield strength of transverse reinforcement, longitudinal reinforcement ratio, lateral steel configuration, shape of cross section and concrete compressive strength. The effects of these variables on the uni-axial behavior of high strength concrete columns are presented and discussed. The results indicate that more confinement is required in columns of high strength concrete than in columns of low strength concrete to achieve the desired post-peak deformability. The behavior of high-strength concrete columns is characterized by the sudden spalling of concrete cover, leading to a loss of axial capacity. Detail of test specimen and location of strain gage is shown by **Fig**.2.7.

They conclude that a higher degree of confinement is required in columns with higher concrete strength than in a column with lower concrete strength to achieve similar advantage. Among the test variables studied, volumetric ratio and spacing of lateral steel has a more pronounced effect on the behavior of confined columns than the other parameters like yield strength of lateral steel, longitudinal steel ratio and configuration of lateral steel through, improvement in each of the

variables considered, translated into enhancements in strength and ductility. However, increasing the yield strength of lateral steel seems to give benefits only when a column has high volumetric ratio and efficient arrangement of lateral steel.

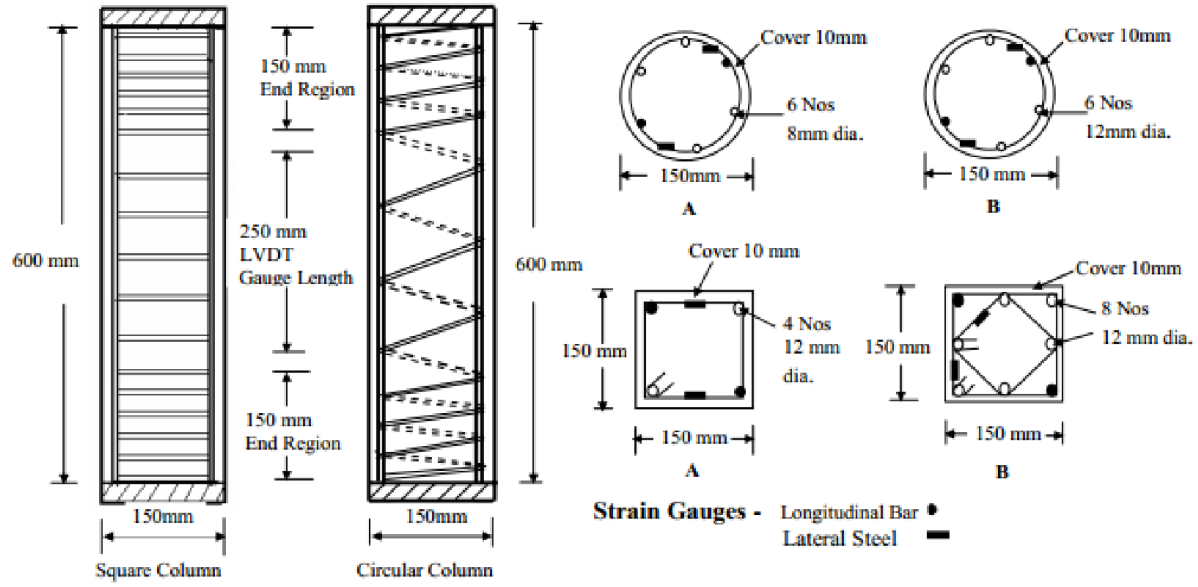


Fig. 2.7 Detail of column specimens, reinforcement arrangement and location of strain gages considered by Umesh K. Sharma, Pradeep Bhargava and S.K. Kaushik (2005)

2.3.5 Metin Husem and Selim Pul (2007)

The effects of confinement reinforcement on the behavior of high-strength concrete columns are investigated for which prismatic experimental specimens (with size of 150mm×150mm×300mm) were prepared. In the experiment specimens, four longitudinal reinforcement and confinement reinforcement were used. For each experiment, stress-strain relationship of concrete was obtained and compared with models proposed earlier. The results show that confinement reinforcement improved the ductility of high-strength concrete.

The researcher's reported that, in the high strength concrete which is more brittle than ordinary concrete, using confinement reinforcement, ductility is increased to a great extent. When confinement reinforcement spacing is decreased to half, ductility improved twice. As a result, by decreasing confinement reinforcement spacing, the earthquake behavior of high-strength

concrete can be improved. Decreasing confinement reinforcement spacing has increased the compressive strength of confined concrete to a maximum of 19%.

2.3.6 Antonius & Iswandi Imran (2012)

An experimental study of 23 low, medium, and high-strength concrete columns (with size of 100mm×100mm×500mm) is presented in the study. Square confined concrete columns without longitudinal reinforcement were designed, and tested under concentric axial compression. The columns were made of concrete with a compressive strength ranging between 30MPa and 70MPa. The test parameters in the study are concrete compressive strength and confining steel properties, i.e. spacing, volumetric ratio, and configurations. The effects of these parameters on the strength and ductility of square-confined concrete were evaluated. Of the specimens tested in the study, the columns made with higher strength concrete produced less strength enhancement and ductility than those with lower strength concrete. The steel configuration were found to have an important role in governing the strength and ductility of the confined high-strength concrete. Detail of test specimen and instrumentation is shown by **Fig**. 2.8.

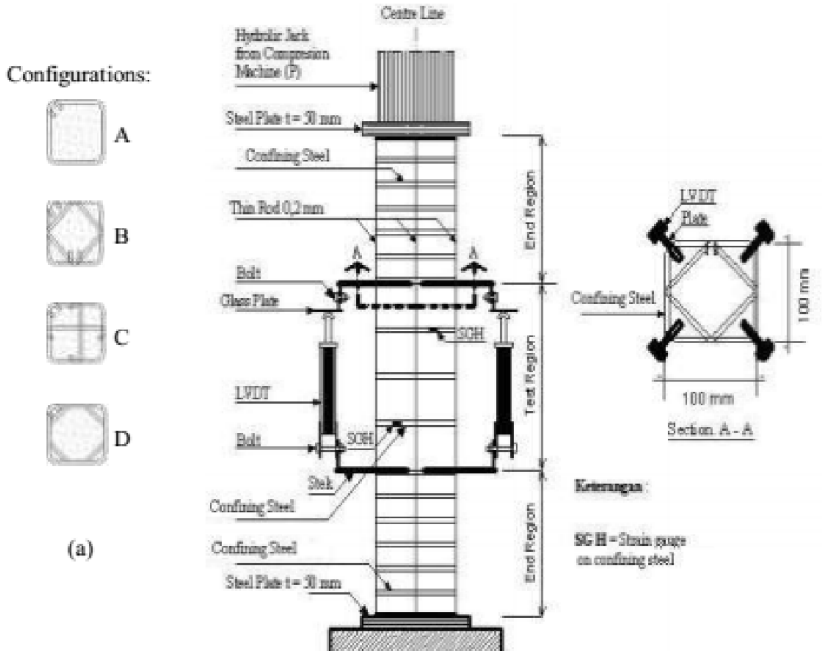


Fig. 2.8 Detail of test specimen and instrumentation considered by Antonius & Iswandi Imran (2012)

They reported that Strength enhancement and ductility of confined concrete tend to decrease as the concrete strength increases which means that strength and ductility diminish in confined high-strength concrete. The effectiveness of the confining steel diminishes quickly as the tie spacing increases. Specimens with a tie spacing similar to the core dimension cannot develop confinements, so that the behavior produced is similar to that of unconfined concrete.

The tensile force developed in confining steel for high-strength concrete is indirectly proportional to the amount of confining reinforcement, such as the volumetric ratio. The volume expansion of high-strength concrete is smaller than that of low-strength concrete. This phenomenon delays the yielding of the confining steel to the post-peak response of the confined column. This influences the effectiveness of reinforcement in confining the concrete core.

2.4. Some of Conclusions Drawn From Previous Researchers

-Strength and ductility of confined concrete increase with increasing volumetric ratio of confinement steel. This is true for both normal and high- strength concrete. However, higher volumetric ratio is required for high-strength concrete columns to achieve similar ductility expected of normal-strength concrete columns.

- Rectangular columns with tie spacing equal to the lateral dimension of the columns show no confinement effect.

- The spalling of the cover concrete tends to occur at below 85% of the unconfined concrete strength in columns with higher concrete strength and closely spaced transverse reinforcement.

- Previous research indicates conflicting views on the use of high strength steel for column confinement. Some researchers believe that extra strength present in high strength steel can not be used prior to the peak load of column. Therefore, these researches suggested limits on yield strength. Others suggest that the use of high strength steel is necessary to produce ductility behavior of high-strength concrete columns, although very high-strength steel does not yield at the peak load. However, there is strong evidence that the behavior of column with closely spaced transverse reinforcement improves significantly with the use of high-strength confinement steel.

- The use of larger size longitudinal reinforcement produces little beneficial effect on the ductility of column.

3. Experimental Program

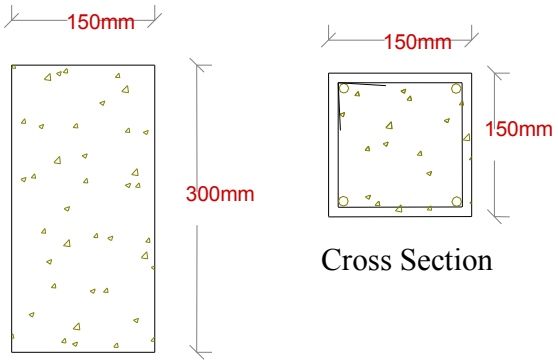
3.1 General

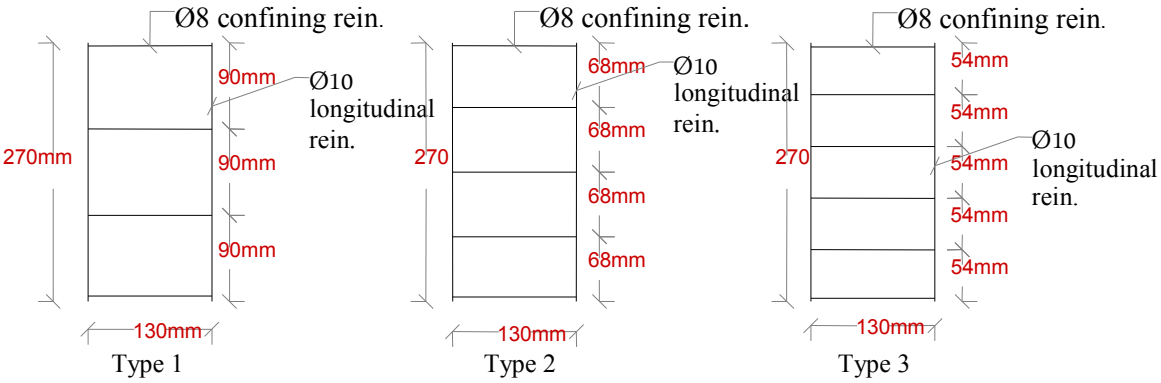
The primary focus of this experimental program is to study the behavior of normal and high-strength columns confined with rectilinear reinforcement. The experimental program included testing of eighteen high-strength confined column specimen, three high-strength unconfined column specimen, eighteen normal-strength confined column specimen and three unconfined normal-strength column specimen subjected to axial compression. Detail of the test specimen, material properties, test set up, instrumentation, and test procedure are presented in this section.

The test parameters are included compressive strength of the concrete (two target strength), spacing of transverse reinforcement (three different spacing), and yield strength of lateral reinforcement (two different yield strength).

3.2 Detail of Test Specimen

Size of concrete column specimens used for experiment is 150mm×150mm cross section in area and 300mm in height with three steel tie spacing (54mm, 68mm and 90mm). Since the specimens would be tested by Compression Testing Machine Controls solution under compression to failure, the capacity of the test machine became a factor in setting the size of the specimens. Test were performed on eighteen prismatic high-strength concrete specimens and eighteen prismatic normal- strength concrete specimens. The test specimen include six plain unreinforced prismatic specimens; three for high-strength and three for normal-strength concrete. A total of thirty six reinforced and six unreinforced specimens were used for the experiment. The maximum spacing of transverse reinforcement used in the experiment is selected to full fill the required spacing which is set in the code. Transverse reinforcement with 90° hoop bend is applied in the test. The size of specimen and detail of reinforcement is shown in **Fig. 3.1**





Reinforcement detail



Fig. 3.1 Detail of test specimens

3.3 Material Properties

3.3.1 Concrete

The high-strength concrete mixture was designed in order to obtain a specific compressive control cube strength at 28 days of age (f_{cu}=60Mpa), with material composition; OPC Derba cement, crushed sand, basaltic coarse aggregate, water, Conplast SP 430 chemical admixture. But from the test result it is obtained (f_{cu}=50MPa), and this compressive strength of concrete is considered to study the behavior of high-strength concrete in this research. The maximum size of the coarse aggregate was 19mm.

The normal-strength concrete mixture was designed in order to obtain a specific compressive control cube strength at 28 days of age ($f_{cu}\cong$41MPa). With material composition; OPC Derba cement, river sand, crushed sand, basaltic coarse aggregate and tap water for curing and mixing. The maximum size of the coarse aggregate was 25mm. In order to determine concrete strength standard control cube were used for each type of concrete mix. The specimens has been cured by water for about 28 days. Mix proportions for normal and high-strength concrete and, summary of the test result of control cube strength for normal and high-strength concrete is shown in Table 3.1, Table 3.2 and Table 3.3 respectively.

Table 3.1 Mix proportions for normal and high-strength concrete

Content	Weights/m^3	
	f'_{cu}=41Mpa	f'_{cu}=50Mpa
25mm coarse aggregate	916Kg	–
19mm coarse aggregate	–	824Kg
10mm Coarse Aggregate	174Kg	206Kg
Crushed sand	220Kg	682Kg
River sand	501Kg	_
Derba Cement	372Kg	550Kg
Water	186lit.	159lit.
Super plasticizer Conplast SP430	–	11Kg
Water-Cement ratio	0.5	0.29

Table 3.2. Summary of test result for normal-strength concrete,28 days control cube compressive strength

Specimen no.	Dimensions(cm)			Area(cm^2)	Weight(gm)	Loading Rate (Mpa/s)	Load (KN)	Compressive Strength (Mpa)	Average Comp. Strength(Mpa)
	L	W	H						
1	15	15	15	225	8570	0.28	942.1	41.87	41
2	15	15	15	225	8671	0.28	899.8	39.99	
3	15	15	15	225	8399	0.28	941.8	41.86	

Table 3.3. Summary of test result for high-strength concrete,28 days control cube compressive strength

Specimen no.	Dimensions(cm)			Area(cm^2)	Weight(gm)	Loading Rate (Mpa/s)	Load (KN)	Compressive Strength (Mpa)	Average Comp. Strength(Mpa)
	L	W	H						
1	15	15	15	225	8420	0.28	1061.1	47.16	50
2	15	15	15	225	8437	0.28	1133.5	50.37	
3	15	15	15	225	8362	0.28	1172.4	52.11	

3.3.2 Reinforcement

Local product (Apollo Steel product) of deformed reinforcing bar diameter 8mm with yield strength about 503MPa,and imported product of deformed reinforcing bar diameter 8mm with yield strength about 580Mpa were used to confine the specimen. The reinforced specimens contained rectilinear lateral steel ties, and four diameter 10mm longitudinal reinforcement with yield strength about 628MPa was used in the specimens. Some mechanical properties of reinforcement obtained from laboratory test are show in Table 3.4.

Table 3.4. Mechanical properties of longitudinal and lateral reinforcement

Sample	Diameter		Average Diameter (mm)	Area (mm^2)	Yield load (KN)	Failure load (KN)	Elong-ation (cm)	Mass/ m (Kg)	Length (cm)	Yield Stress (Mpa)	Tensile Stress (Mpa)	Strain (%)	Average yield stress (Mpa)	Average Tensile stress (MPa)
	D1 (mm)	D2(mm)												
ϕ8,1	7.54	9.23	8.39	55.22	33.90	37.90	3.80	0.43	35.00	613.91	686.35	10.86	579.57	652.47
ϕ8,2	7.67	9.00	8.34	54.56	26.40	30.40	3.80	0.43	40.00	483.84	557.15	9.50		
ϕ8,3	7.09	8.98	8.04	50.71	32.50	36.20	3.80	0.40	35.00	640.95	713.92	10.86		
ϕ8,1'	6.96	9.16	8.06	51.02	24.00	33.00	7.00	0.40	45.00	470.38	646.78	15.56	502.71	678.46
ϕ8,2'	6.96	8.60	7.78	47.54	23.40	32.10	6.00	0.37	35.00	492.23	675.24	17.14		
ϕ8,3'	6.81	8.77	7.79	47.66	26.00	34.00	5.00	0.37	35.00	545.52	713.37	14.29		
ϕ10,1	9.18	11.09	10.14	80.67	46.70	52.60	3.70	0.63	45.00	578.87	652.00	8.22	628.36	721.89
ϕ10,2	8.89	10.50	9.70	73.82	47.40	54.50	3.40	0.58	40.00	642.09	738.26	8.50		
ϕ10,3	8.57	10.46	9.52	71.11	48.20	56.30	3.60	0.56	30.00	677.86	791.77	12.00		

3.4 Casting Test Specimen

A total of four batches of concrete were used to cast both normal and high-strength concrete. That is two batches for each type of concrete. Because of the size of the mixer available at laboratory it is not possible to cast each type of concrete in one batch. All column specimens were casted vertically to simulate typical construction practice of column and compacted by vibrator. To control the strength of concrete for each batch a standard cube were casted together with the specimens. Both the column specimen and the cube were stripped and de-molded after 24 hrs, and then socked in to water for curing purpose, the curing lasted for 28 days.

3.5 Test Set Up and Instrumentation

Four linear voltage displacement transducers (LVDT) located at the mid height of each test specimen to measure the axial deflection of the specimen. Two of the LVDT were attached to the surface of the specimen in opposite direction and the other two were attached to the bottom of the top steel collar and the top of the bottom steel collars in opposite direction to provide continuous data recording, even after the spalling of cover concrete. The history of experimentally measured axial strain of confined concrete can be obtained from the average axial shortening readings from LVDT divided by the vertical length of the test region.

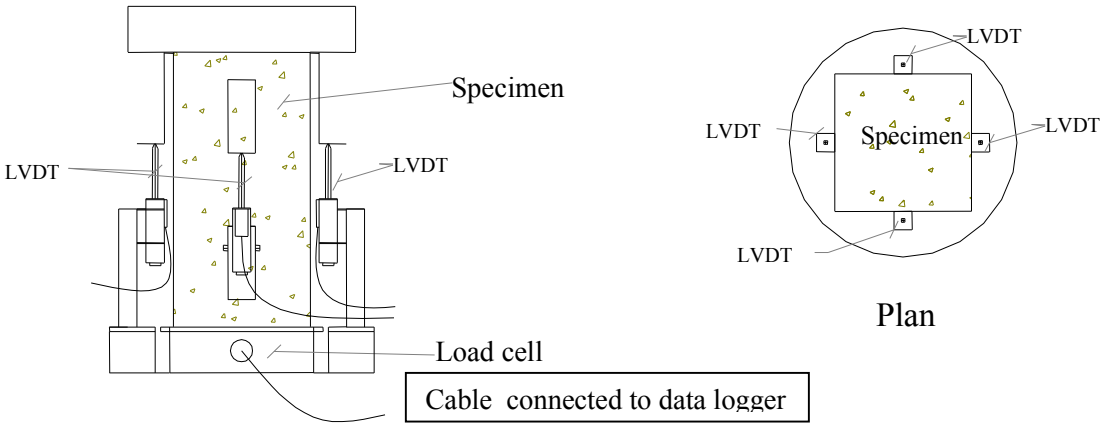


Fig. 3.2 Schematic representation of test set up

3.6 Test Procedure

All column specimen were tested under axial compression produced by Compression Testing Machine controls solution with a capacity of 3000KN at 0.28MPa/s loading rate. In order to see the post peak behavior of testing specimen the peak sensitivity of the machine is converted to 500KN. The specimen is directly placed on load cell and then transducers (LVDT) were placed at required positions. After correctly positioning the specimen and the transducer, test should be started equally on machine, data logger and LVDT channel. The axial deflection data from the four LVDTs and the corresponding applied compression load is recorded at every five second with the help of load cell, data logger and LVDT channel. These data's were fed to a data acquisition system and stored in a computer. Picture for the failure pattern of the specimen due to the applied axial compression load is taken by pocket camera for further information. Overall view of the test setup is shown in **Fig. 3.3**



Fig. 3.3 Over all view of test set up

4. Experimental Results and Discussion

4.1 General

This section summarizes the measured behavior of normal and high-strength confined concrete column specimens during testing observation and the raw data recorded. Typical behavior including the axial load shortening relationship, the confinement effectiveness of transverse reinforcement and ductility of confined concrete columns were discussed. Because of the limitation of measurement of all the required data during testing, models proposed by previous researcher were used together with the test data to see the complete behavior of the columns in this study.

4.2 Observed Behaviors

The confined column specimens were characterized sequentially under the application of axial load by the development of surface cracks (vertical cracks), cover spalling and buckling of longitudinal bars for the specimens with larger spacing. First of all vertical longitudinal cracks were noticed for all normal and high-strength column specimens just before cover spalling. These vertical cracks eventually led to the spalling of cover concrete. The vertical cracks were slightly inclined for well confined concrete specimens of normal and high-strength concrete as shown in **Fig. 4.2** The cover spalling was comparatively more sudden and explosive for high-strength concrete column specimens than the normal-strength concrete column specimens. **Fig.4.1** illustrates the appearance of a typical specimens at various loading stage. Also **Fig. 4.3,4.4**, and **Fig**. **4.5** illustrates the appearance of a typical specimens at the end of test for normal and high-strength confined concrete column specimens having the same yield strength of lateral steel bars and the same spacing of lateral steel bars.

Longitudinal reinforcement have buckled for larger spacing of transverse reinforcement, but for well confined specimen yielding of transverse reinforcement and buckling of longitudinal reinforcement was not observed. It is also observed that during testing, once the load reaches its maximum and decline to a certain level then the machine stopped. But reloading on this same concrete core the load can reaches up to 60-70% of the maximum load of the first loading. Most of the failure were seen at middle section of the specimen.



(a) Initial vertical cracking (b) Spalling of cover concrete (c) Complete spalling of cover concrete (d) End of testing

Fig. 4.1 Appearance of confined test specimens at different loading stages

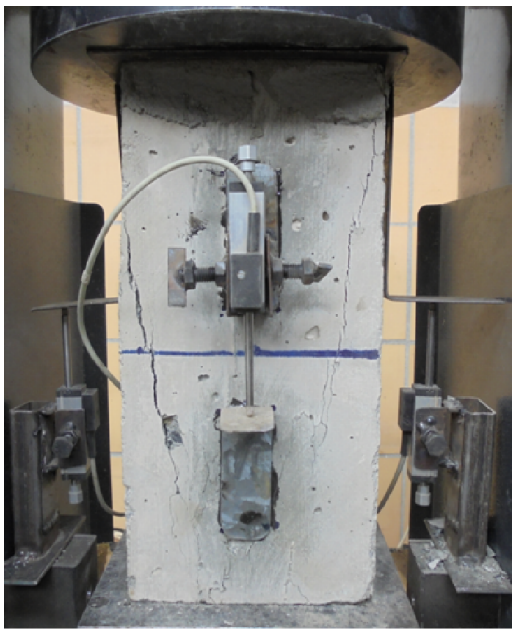


Fig. 4.2 Typical inclined vertical cracks for well confined concrete



(a) (b)

Fig. 4.3 Appearance of test specimens at post peak loading (s=90mm); (a) Normal strength concrete column specimen and, (b) High strength concrete column specimen.



(a) (b)

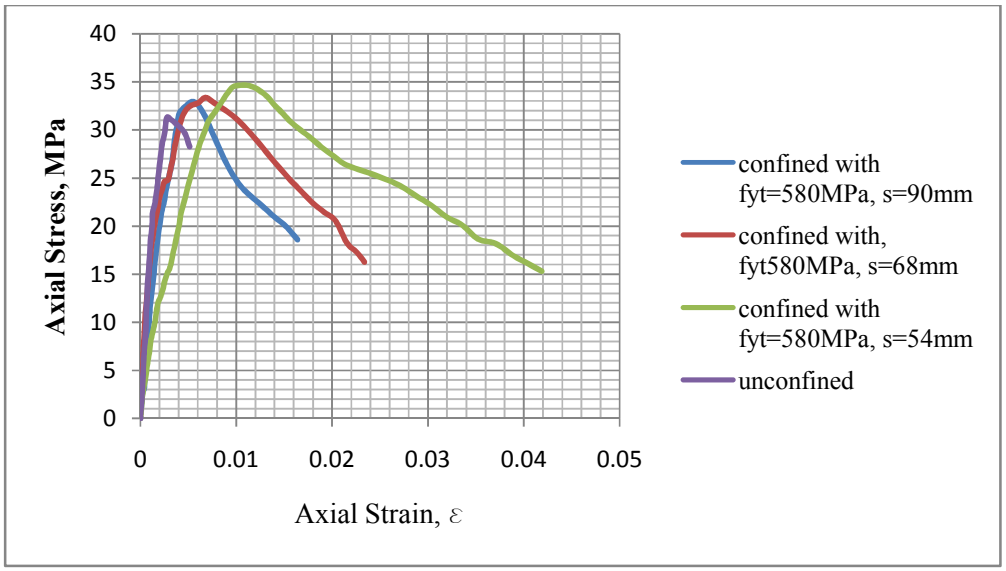
Fig. 4.4 Appearance of test specimens at post peak loading (s=68mm); (a) Normal strength concrete column specimen and, (b) High strength concrete column specimen.



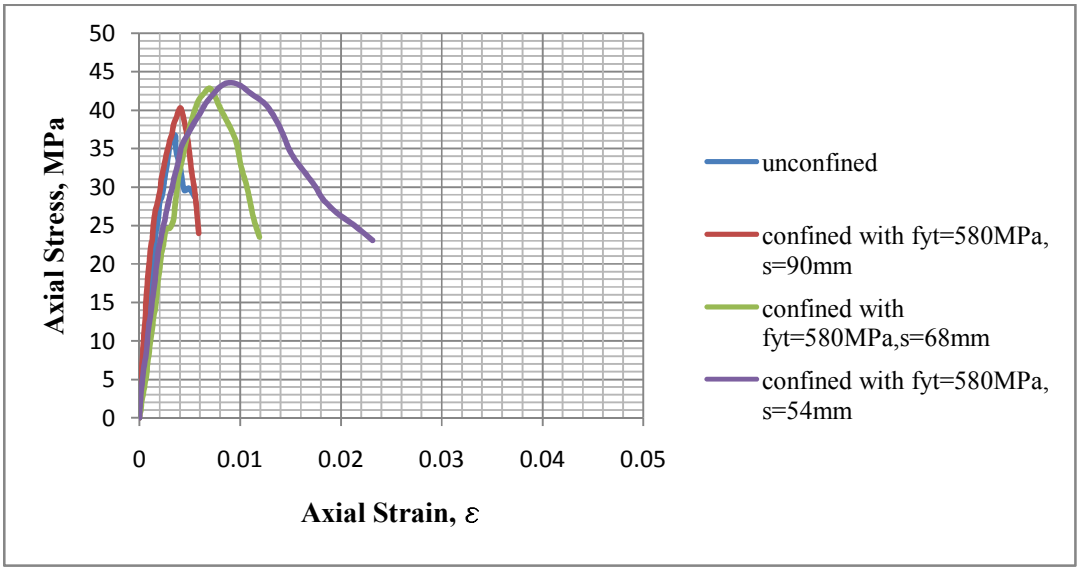
(a) (b)

Fig. 4.5 Appearance of test specimens at post peak loading (s=54mm); (a) Normal strength concrete column specimen and, (b) High strength concrete column specimen.

The tested column specimens initially behaved in a similar manner and exhibited relatively linear load deformation behavior in the ascending parts, which is typical of normal and high- strength concrete. The descending parts of the column with a higher strength concrete column are steeper than those with a lower strength concrete column. The unconfined column specimen had a sudden and explosive type of failure at maximum applied axial load, and with the present testing facility it is not possible to measure any data after the peak load. The strain corresponding to the peak load for unconfined normal-strength concrete were observed a value of 0.00275 and that of high-strength concrete were observed a value of 0.003563. **Fig. 4.6** and **Fig. 4.7** shows that the measured stress-strain results of the tested columns, and the contribution of load carrying capacity of longitudinal reinforcement is deducted while comparing the stress-strain behavior of the column specimens.

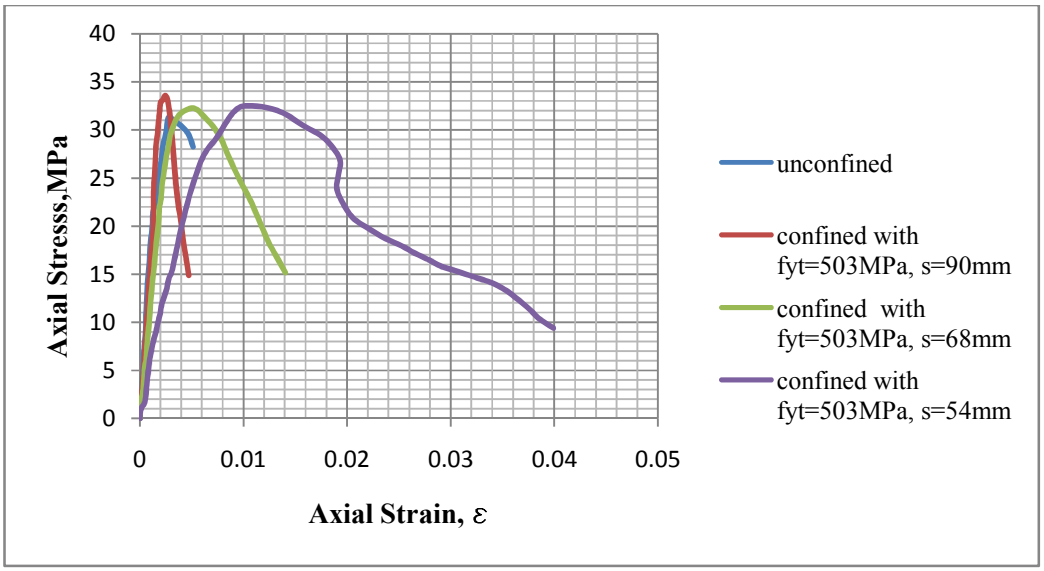


(a)

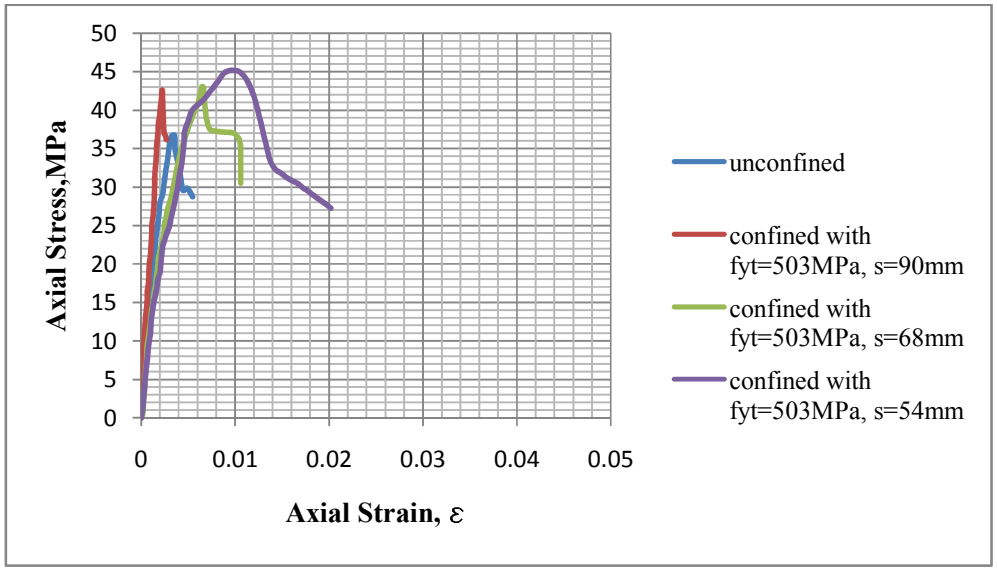


(b)

Fig. 4.6 Stress-Strain relationship of confined concrete specimen with yield strength of transverse reinforcement equals 580MPa; (a) Normal-strength concrete column specimen and, (b) High-strength concrete column specimen, with all other parameters are constant.



(c)



(d)

Fig. 4.7 Stress-Strain relationship of confined concrete specimen with yield strength of transverse reinforcement equals 503MPa: (c) Normal strength concrete column specimen and, (d) High strength concrete column specimen, with all other parameters are constant.

4.3 Effects of Test Parameters

4.3.1 Effect of Compressive Strength of Concrete

The concrete compressive strength is one of the primary variables investigated extensively in this study. Column specimens with the same spacing of lateral steel, longitudinal steel, yield strength and arrangement of reinforcement but with distinctly different concrete strength is compared to examine the effects of this parameter. **Fig 4.6** and **Fig. 4.7** shows comparisons of both normal and high-strength column specimens having the same number of longitudinal reinforcement, spacing of lateral steel tie and yield strength of lateral steel ties. The post peak curves of the higher strength concrete specimen are steeper indicating faster rate of strength decay as compared to the normal-strength concrete column specimens. Comparing **Fig. 4.6** (a)&(b) which have the same volumetric ratio, spacing of confining reinforcement and yield strength of confining reinforcement, but with different concrete compressive strength, the test results indicate that the confinement effectiveness in terms of axial strains was less with a higher concrete compressive strength. This is because the lateral dilation of high- strength concrete was smaller than that of the normal- strength concrete. **Fig. 4.7** (c) & (d) compare the results with same fashion to that of **Fig. 4.6.**

The model proposed by Saatcioglu and Razvi (1992) is selected to verify the results of the test data of this study against the model . The confinement model proposed by Saatcioglu and Razvi (1992) is based on the computation of equivalent uniform pressures that gives the same effect as the non-uniform confinement pressures. Saatcioglu and Razvi (1992) conclude that the absolute gain in strength was independent of concrete strength. Accordingly, the strength for both confined normal-strength and high-strength concrete can be computed by the following equations.

$$f'_{cc} = f'_{co} + k_1 f_{le} \quad \ldots\ldots (4.1)$$

$$k_1 = 6.7 f_{le}^{-0.17} \quad \ldots\ldots (4.2)$$

$$f_{le} = k_2 f_l \quad \ldots\ldots (4.3)$$

$$f_l = \frac{\sum_{i=1}^{q} (A_s f_s \sin\alpha) i}{S b_c} \quad \ldots\ldots (4.4)$$

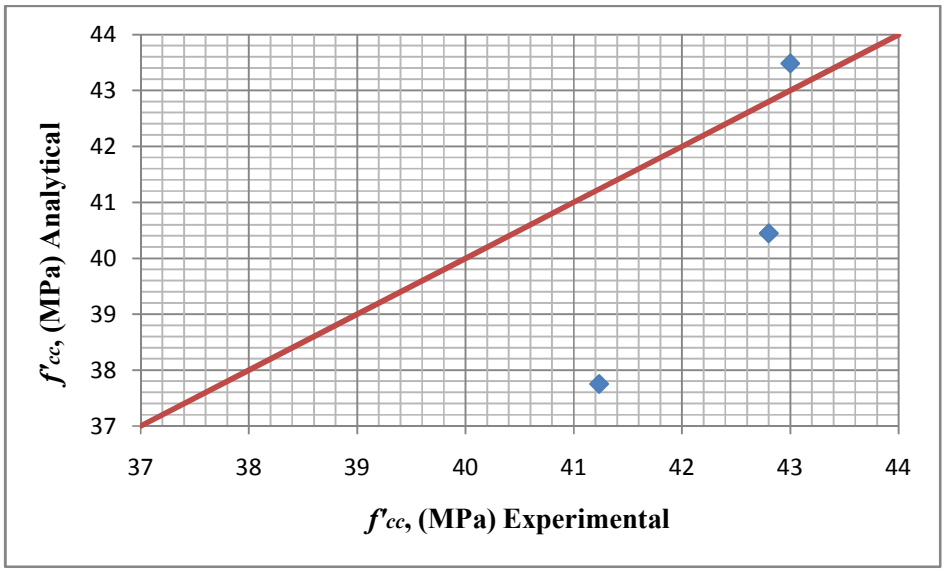
$$f_s = E_s\left(0.0025 + 0.04\sqrt[3]{\frac{K_2\rho_s}{f'_{co}}}\right) \leq f_{yt} \ldots\ldots\ldots\

Table 4.1 Strength enhancement in normal strength concrete column specimen, (C41)

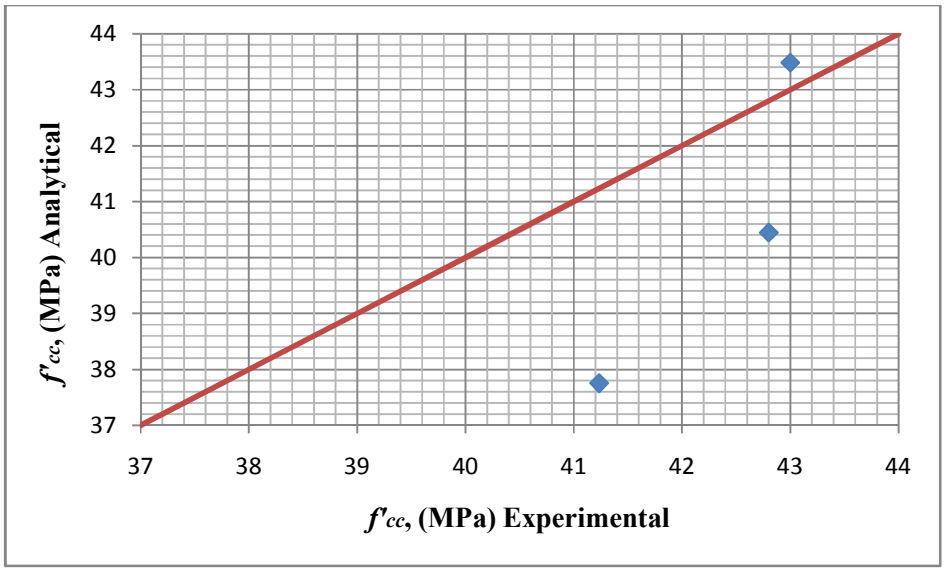
Specimen label	No. of longitudinal reinforcement	b_c (mm)	d_b (mm)	s_1 (mm)	s (mm)	f_{yt} (Mpa)	f_s (Mpa)	f_l (Mpa)	k_1	k_2	f'_{co} (Mpa)	f'_{cc} (Mpa)		Analytical /Experimental
												Experimental	Analytical	
1N11	4	121.75	8.25	104	90	580	580	5.06	6.75	0.19	31.3	41.1	37.75	0.92
1N12	4	121.75	8.25	104	90	580	580	5.06	6.75	0.19	31.3	41.1	37.75	0.92
1N13	4	121.75	8.25	104	90	580	580	5.06	6.75	0.19	31.3	41.5	37.75	0.91
1N21	4	121.75	8.25	104	68	580	580	6.70	6.29	0.22	31.3	42.2	40.44	0.96
1N22	4	121.75	8.25	104	68	580	580	6.70	6.29	0.22	31.3	41.3	40.44	0.98
1N23	4	121.75	8.25	104	68	580	580	6.70	6.29	0.22	31.3	44.9	40.44	0.90
1N31	4	121.75	8.25	104	54	580	580	8.44	5.93	0.24	31.3	43.9	43.48	0.99
1N32	4	121.75	8.25	104	54	580	580	8.44	5.93	0.24	31.3	41.7	43.48	1.04
1N33	4	121.75	8.25	104	54	580	580	8.44	5.93	0.24	31.3	43.4	43.48	1.00
2N11	4	122.12	7.88	104	90	503	503	3.99	7.03	0.19	31.3	38.1	36.61	0.96
2N12	4	122.12	7.88	104	90	503	503	3.99	7.03	0.19	31.3	42.3	36.61	0.87
2N13	4	122.12	7.88	104	90	503	503	3.99	7.03	0.19	31.3	40.2	36.61	0.91
2N21	4	122.12	7.88	104	68	503	503	5.28	6.54	0.22	31.3	42	38.83	0.92
2N22	4	122.12	7.88	104	68	503	503	5.28	6.54	0.22	31.3	42.1	38.83	0.92
2N23	4	122.12	7.88	104	68	503	503	5.28	6.54	0.22	31.3	41.6	38.83	0.93
2N31	4	122.12	7.88	104	54	503	503	6.65	6.17	0.24	31.3	42.3	41.33	0.98
2N32	4	122.12	7.88	104	54	503	503	6.65	6.17	0.24	31.3	42.8	41.33	0.97
2N33	4	122.12	7.88	104	54	503	503	6.65	6.17	0.24	31.3	38.3	41.33	1.08

Table 4.2 Strength enhancement in high strength concrete column specimen, (C50)

Specimen label	No. of longitudinal reinforcement	b_c (mm)	d_b (mm)	s_1 (mm)	s (mm)	f_{yt} (Mpa)	f_s (Mpa)	f_l (Mpa)	k_1	k_2	f'_{co} (Mpa)	f'_{cc} (Mpa)		Analytical /Experimental
												Experimental	Analytical	
1H11	4	121.75	8.25	104	90	580	580	5.06	6.75	0.189	39.07	49.6	45.52	0.92
1H12	4	121.75	8.25	104	90	580	580	5.06	6.75	0.189	39.07	49.05	45.52	0.93
1H13	4	121.75	8.25	104	90	580	580	5.06	6.75	0.189	39.07	49.47	45.52	0.92
1H21	4	121.75	8.25	104	68	580	580	6.70	6.29	0.217	39.07	50.76	48.21	0.95
1H22	4	121.75	8.25	104	68	580	580	6.70	6.29	0.217	39.07	52.3	48.21	0.92
1H23	4	121.75	8.25	104	68	580	580	6.70	6.29	0.217	39.07	50.74	48.21	0.95
1H31	4	121.75	8.25	104	54	580	580	8.44	5.93	0.244	39.07	50.61	51.25	1.01
1H32	4	121.75	8.25	104	54	580	580	8.44	5.93	0.244	39.07	52.21	51.25	0.98
1H33	4	121.75	8.25	104	54	580	580	8.44	5.93	0.244	39.07	54.38	51.25	0.94
2H11	4	122.12	7.88	104	90	503	503	3.99	7.03	0.189	39.07	46.2	44.38	0.96
2H12	4	122.12	7.88	104	90	503	503	3.99	7.03	0.189	39.07	56.1	44.38	0.79
2H13	4	122.12	7.88	104	90	503	503	3.99	7.03	0.189	39.07	51.2	44.38	0.87
2H21	4	122.12	7.88	104	68	503	503	5.28	6.54	0.218	39.07	58.7	46.60	0.79
2H22	4	122.12	7.88	104	68	503	503	5.28	6.54	0.218	39.07	54.9	46.60	0.85
2H23	4	122.12	7.88	104	68	503	503	5.28	6.54	0.218	39.07	51.1	46.60	0.91
2H31	4	122.12	7.88	104	54	503	503	6.65	6.17	0.244	39.07	52.8	49.10	0.93
2H32	4	122.12	7.88	104	54	503	503	6.65	6.17	0.244	39.07	53.9	49.10	0.91
2H33	4	122.12	7.88	104	54	503	503	6.65	6.17	0.244	39.07	53.35	49.10	0.92



(a)



(b)

Fig. 4.8 Effect of compressive strength of concrete on confined; (a) Normal-strength concrete, (b) High-strength concrete.

4.3.2 Effect of Volumetric Ratio and Spacing of Transverse Reinforcement

The volume of transverse reinforcement and spacing of confining transverse steel as a factor that affects the behavior of confined concrete is well recognized. Increasing the volume of transverse steel is directly related to a proportional increase in confining pressure. The spacing of transverse reinforcement is an important parameter that affects the distribution of confinement pressure on the confined core in addition to the stability of longitudinal reinforcement. In this study three different types of lateral reinforcement spacing is considered. In both normal and high-strength concrete columns, increasing the volumetric ratio or the closer spacing of lateral steel bars, the behavior of column is more ductile as expected. The columns with low volumetric ratio or increased the spacing of lateral steel bars exhibit brittle behavior and showing faster rate of strength decay after the peak load. **Fig.4.6** & **Fig. 4.7** illustrates the effect of volumetric ratio of confining reinforcement on the behavior of confined normal and high-strength concrete columns tested by this study.

The effect of volumetric ratio and spacing of lateral reinforcement on the behavior of column has extensively studied by computing the effective confinement index and the ductility index of the

confined columns with the help of models proposed by Mander et.al (1988) and Paultre et.al (1995). **Fig. 12** & **Fig. 4.13** together with the test data are used to compute the confinement effectiveness index and ductility index of the columns.

Confinement effectiveness for rectangular cross sections confined by rectangular hoops can be discussed with the help of **Fig. 4.9** & **Fig. 4.10.**

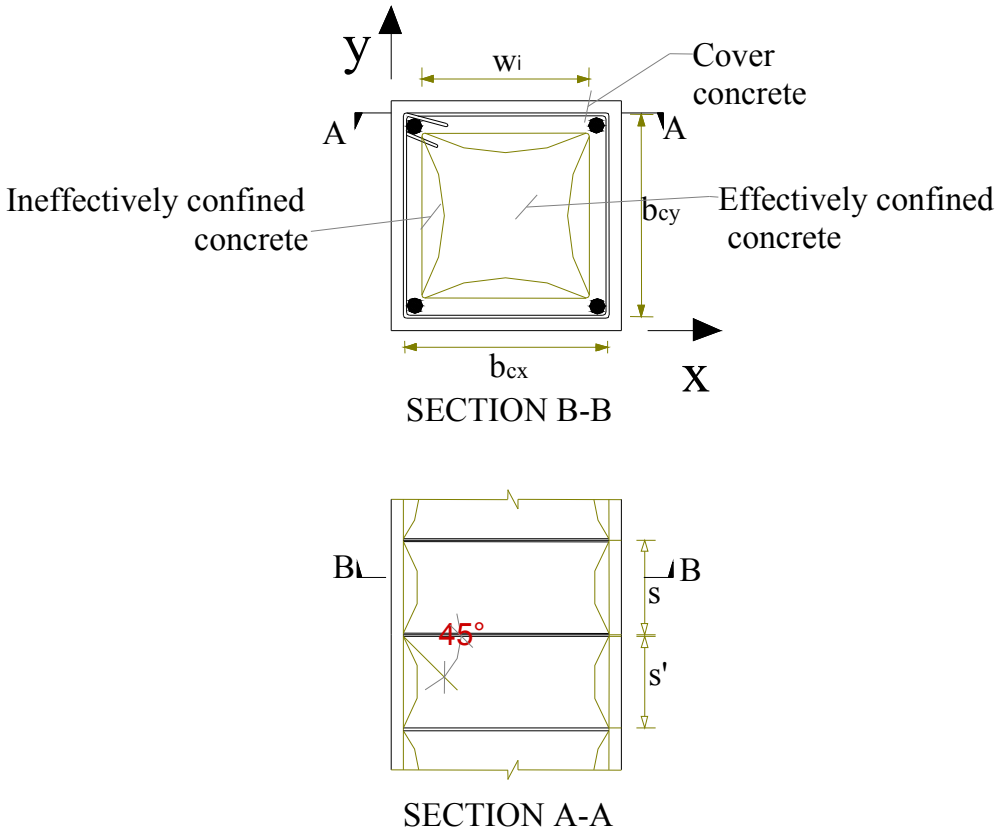


Fig. 4.9 Effectively confined core for rectangular tie reinforcement and arching action

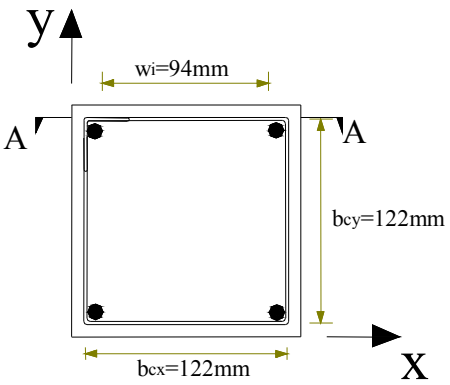


Fig. 4.10 Test Specimen Cross Section

In **Fig. 4.9** the arching action is assumed to act in the form of second degree parabolas with an initial tangent slope of 45°. Arching occurs vertically between layers of transverse hoop bars and horizontally between longitudinal bars. The confinement effectiveness coefficient can be computed by the following expression.

$$k_e = \frac{\left(1 - \sum_{i=1}^{n} \frac{(w_i)^2}{6b_{cx}b_{cy}}\right)\left(1 - \frac{s'}{2b_{cx}}\right)\left(1 - \frac{s'}{2b_{cy}}\right)}{(1 - \rho_{cc})} \quad \ldots\ldots\ldots\

It is possible for rectangular reinforced concrete members to have different quantities of transverse confining steel in the x and y directions, this may be expressed as, (Mander et. al. 1988)

$$\rho_x = \frac{A_{sx}}{sb_{cy}} \quad \ldots\ldots (4.9)$$

and

$$\rho_y = \frac{A_{sy}}{sb_{cx}} \quad \ldots\ldots (4.10)$$

Where, s =center-to- center spacing between set of ties, A_{sx} and A_{sy} =the total area of transverse bars running in the x and y directions, respectively, ρ_s=ratio of the volume of transverse confining steel to the volume of confined concrete core,

(See **Fig. 4.10**) in the case of this research the cross section of the column specimen is a square $A_{sx}=A_{sy}=2A_s$ and $b_{cx}=b_{cy}=b_c$,where A_s is area of a single lateral reinforcing bar. therefore the lateral reinforcement ratio becomes,

$$\rho_x = \frac{A_{sx}}{sb_{cy}} = \frac{2A_s}{sb_c} \quad \ldots\ldots (4.11)$$

And

$$\rho_y = \frac{A_{sy}}{sb_{cx}} = \frac{2A_s}{sb_c} \quad \ldots\ldots (4.12)$$

$$\rho_s = \rho_x + \rho_y = \frac{2A_s}{sb_c} + \frac{2A_s}{sb_c} = \frac{4A_s}{sb_c} \quad \ldots\ldots (4.13)$$

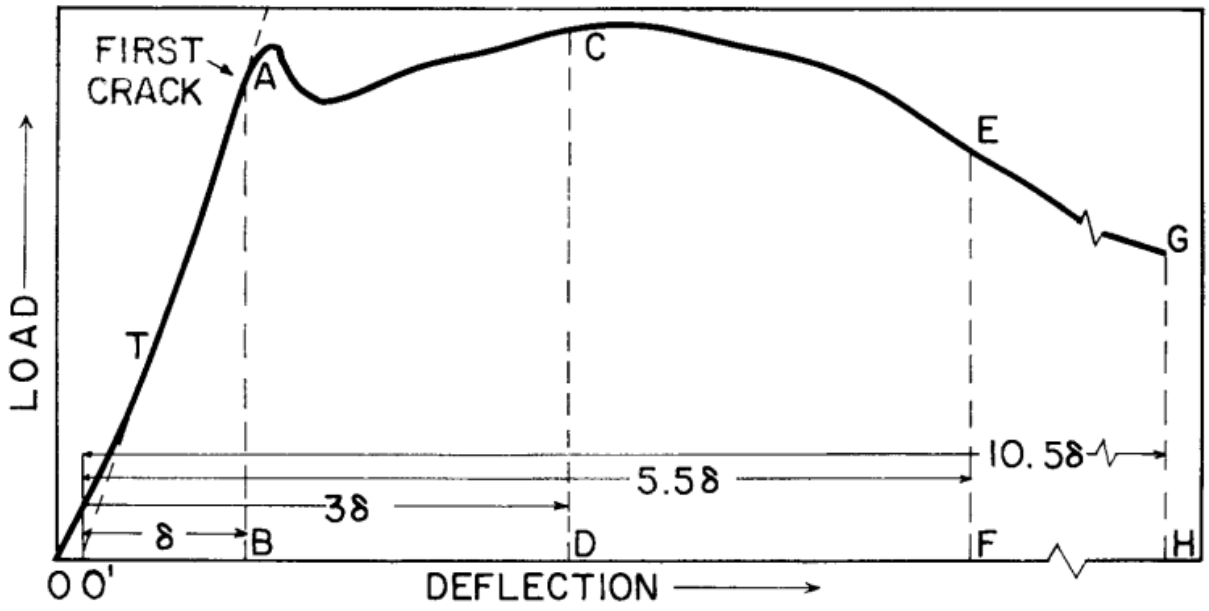
$$Effective\ confinement\ index = \frac{k_e \rho_s f_{yt}}{f_c'} \quad \ldots\ldots (.14)$$

To quantify the effect of test variables on the post-peak deformability of confined normal-strength and high-strength concrete columns more effectively I_{10} ductility index can be used. The definition of I_{10} ductility index is adopted from ASTM C1018 for the measurement of toughness. The I_{10} ductility index can be determined under the area load-deflection curve up to a

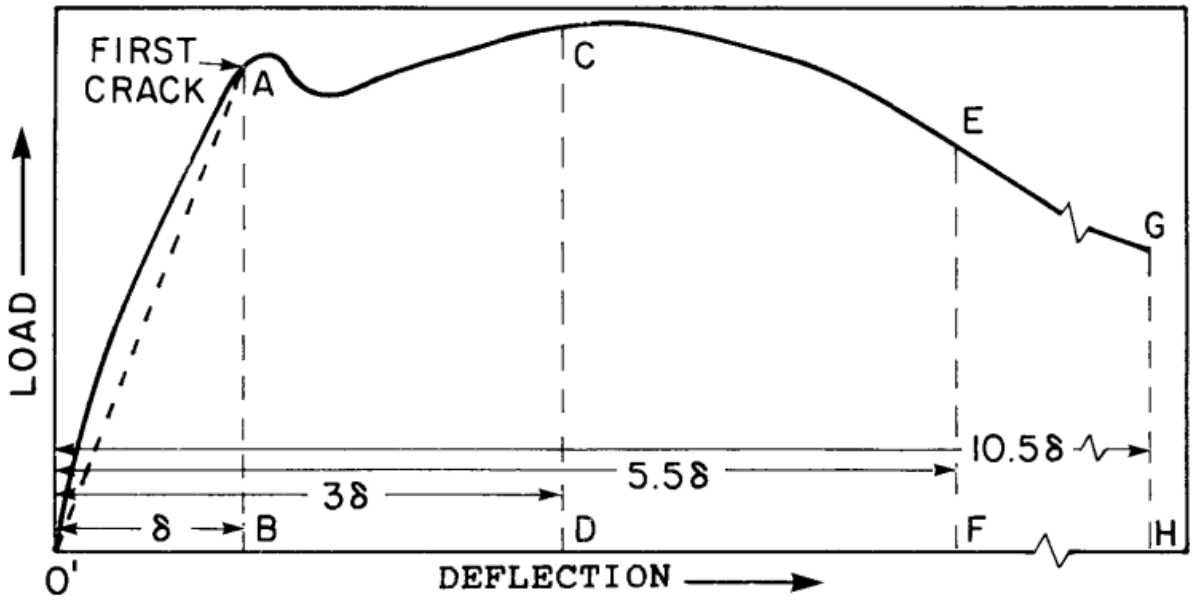
deflection of 5.5 times the first crack deflection (yield strain) area O'AEF in **Fig. 4.11** divided it by the area of first crack (yield strain) area O'AB. The significance of taking area under the curve up to 5.5 times the first crack (the yield strain) is that for a perfectly elasto-plastic material I_{10} =10, while for a perfectly elastic-brittle material I_{10}=1. Determination of the irregularly shaped area requires a planimeter, or application of Simpson's rule, or the counting of squares or other suitable elements of known area.

A number of past studies (Sheikh & Uzumeri, 1980, Mander et.al. 1988, Razvi & Saatcioglu 1995, Foster & Attard, 2001) have indicated that ductility is a function of effective confinement index. In this study ductility index I_{10} can computed from the expression developed by Foster & Attard, 2001 which is obtained from the plot of best fit relationship between ductility index I_{10} and effective confinement index and is given by;

$$Ductility\ index, I_{10} = 2.89 \ln\left(\frac{k_e \rho_s f_{yt}}{f_c'}\right) - 0.45 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.15)$$



(a) Concave upwards to first crack



(b) Convex upwards to first crack

Fig. 4.11 Important characteristics of Load-Deflection curve, (ASTM C1018)

The values of confinement effectiveness index and ductility index from the test result and theoretical expressions (Umesh K. Sharma et.al. , ASTM C1018) are given in Table 4.3 and Table 4.4 for normal-strength and high-strength concrete columns respectively. From the result that is obtained, both the values of confinement effectiveness index and ductility index increases for decreasing the spacing of confinement reinforcement for both normal and high-strength concrete columns. But the values of confinement effectiveness index and ductility index in normal-strength concrete column is greater than that of high-strength concrete. Therefore, if the same levels of strength and ductility enhancements are desired, higher strength concrete columns shall require more confinement than lower strength concrete.

In normal-strength concrete specimen, as the volumetric ratio of transverse reinforcement increases from 1.8% to 2.4% I_{10} increases by 26% for higher yield strength of transverse reinforcement and 28% for lower yield strength, and as the volumetric ratio increases from 2.4% to 3.1% I_{10} increases by 15% for higher yield strength of transverse reinforcement and 16% for lower yield strength.

In high-strength concrete specimen, as the volumetric ratio of transverse reinforcement increases from 1.8% to 2.4% I_{10} increases by 29% for higher yield strength of transverse reinforcement

and 32% for lower yield strength, and as the volumetric ratio increases from 2.4% to 3.1% I_{10} increases by 16% for higher yield strength of transverse reinforcement and 17% for lower yield strength.

Both ductility index and effective confinement index increases linearly for the increase in volumetric ratio and for the decrease in spacing of transverse reinforcement in both normal and high-strength confined concrete specimen, as shown in **Fig.4.12, Fig. 4.13** and Table 4.5.

Table. 4.3 Computation of confinement effectiveness index and ductility index for normal strength concrete columns

Specimen label	b_c (mm)	s (mm)	s' (mm)	d_b (mm)	d_l (mm)	w_i (mm)	A_s (mm^2)	A'_s (mm^2)	f_{yt} (Mpa)	f_{cu} (Mpa)	f'_c (Mpa)	ρ_{cc}	ρ_s	k_e	$k_e\rho_s f_{yt}/f_c'$	I_{10}
1N11	122	90	82	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0183	0.27	0.0875	5.82
1N12	122	90	82	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0183	0.27	0.0875	5.82
1N13	122	90	82	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0183	0.27	0.0875	5.82
1N21	122	68	60	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0242	0.348	0.1493	7.36
1N22	122	68	60	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0242	0.348	0.1493	7.36
1N23	122	68	60	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0242	0.348	0.1493	7.36
1N31	122	54	46	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0305	0.404	0.2178	8.45
1N32	122	54	46	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0305	0.404	0.2178	8.45
1N33	122	54	46	8	10	94	50.27	78.54	580	41	32.8	0.014	0.0305	0.404	0.2178	8.45
2N11	122	90	82	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0183	0.27	0.0759	5.41
2N12	122	90	82	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0183	0.27	0.0759	5.41
2N13	122	90	82	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0183	0.27	0.0759	5.41
2N21	122	68	60	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0242	0.348	0.1295	6.95
2N22	122	68	60	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0242	0.348	0.1295	6.95
2N23	122	68	60	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0242	0.348	0.1295	6.95
2N31	122	54	46	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0305	0.404	0.1889	8.04
2N32	122	54	46	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0305	0.404	0.1889	8.04
2N33	122	54	46	8	10	94	50.27	78.54	503	41	32.8	0.014	0.0305	0.404	0.1889	8.04

Table. 4.4 Computation of confinement effectiveness index and ductility index for high strength concrete columns.

Specimen label	b_c (mm)	s (mm)	s' (mm)	d_b (mm)	d_l (mm)	w_i (mm)	A_s (mm^2)	A'_s (mm^2)	f_{yt} (Mpa)	f_{cu} (Mpa)	f'_c (Mpa)	ρ_{cc}	ρ_s	k_e	$k_e\rho_s f_{yt}/f_c'$	I_{10}
1H11	122	90	82	8	10	94	50.27	78.54	580	50	40	0.014	0.0183	0.27	0.0717	5.24
1H12	122	90	82	8	10	94	50.27	78.54	580	50	40	0.014	0.0183	0.27	0.0717	5.24
1H13	122	90	82	8	10	94	50.27	78.54	580	50	40	0.014	0.0183	0.27	0.0717	5.24
1H21	122	68	60	8	10	94	50.27	78.54	580	50	40	0.014	0.0242	0.348	0.1225	6.79
1H22	122	68	60	8	10	94	50.27	78.54	580	50	40	0.014	0.0242	0.348	0.1225	6.79
1H23	122	68	60	8	10	94	50.27	78.54	580	50	40	0.014	0.0242	0.348	0.1225	6.79
1H31	122	54	46	8	10	94	50.27	78.54	580	50	40	0.014	0.0305	0.404	0.1786	7.88
1H32	122	54	46	8	10	94	50.27	78.54	580	50	40	0.014	0.0305	0.404	0.1786	7.88
1H33	122	54	46	8	10	94	50.27	78.54	580	50	40	0.014	0.0305	0.404	0.1786	7.88
2H11	122	90	82	8	10	94	50.27	78.54	503	50	40	0.014	0.0183	0.27	0.0622	4.83
2H12	122	90	82	8	10	94	50.27	78.54	503	50	40	0.014	0.0183	0.27	0.0622	4.83
2H13	122	90	82	8	10	94	50.27	78.54	503	50	40	0.014	0.0183	0.27	0.0622	4.83
2H21	122	68	60	8	10	94	50.27	78.54	503	50	40	0.014	0.0242	0.348	0.1062	6.38
2H22	122	68	60	8	10	94	50.27	78.54	503	50	40	0.014	0.0242	0.348	0.1062	6.38
2H23	122	68	60	8	10	94	50.27	78.54	503	50	40	0.014	0.0242	0.348	0.1062	6.38
2H31	122	54	46	8	10	94	50.27	78.54	503	50	40	0.014	0.0305	0.404	0.1549	7.47
2H32	122	54	46	8	10	94	50.27	78.54	503	50	40	0.014	0.0305	0.404	0.1549	7.47
2H33	122	54	46	8	10	94	50.27	78.54	503	50	40	0.014	0.0305	0.404	0.1549	7.47

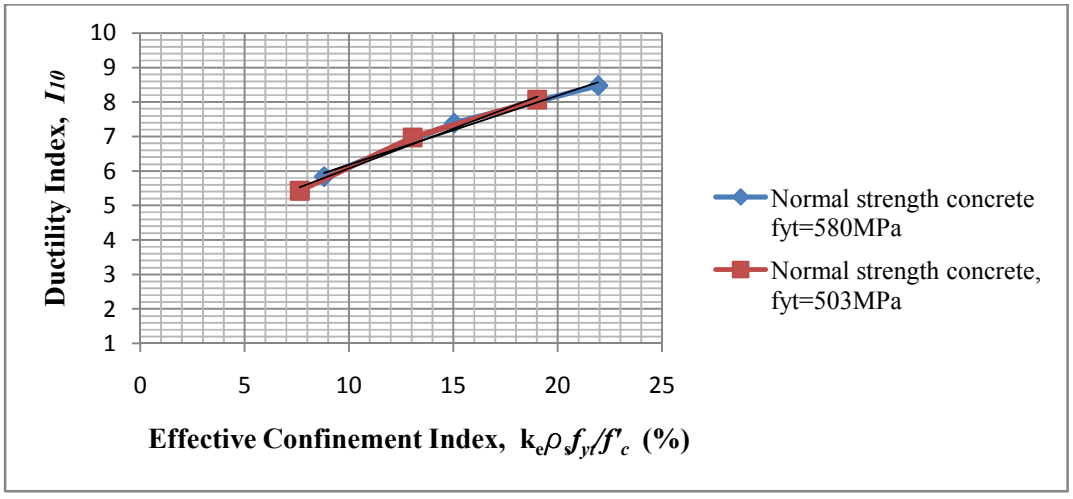


Fig. 4.12 Ductility index versus effective confinement index for normal-strength concrete columns

Table. 4.5 Effective confinement index, $k_e\rho_s f_{yt}/f'_c$ (%) and ductility index, I_{10}

Specimen label	f_{yt} (Mpa)	$k_e\rho_s f_{yt}/f_c'$	I_{10}	$k_e\rho_s f_{yt}/f_c'$(%)
1N11	580	0.0881	5.84	8.81045
1N12	580	0.0881	5.84	8.81045
1N13	580	0.0881	5.84	8.81045
1N21	580	0.1504	7.38	15.0431
1N22	580	0.1504	7.38	15.0431
1N23	580	0.1504	7.38	15.0431
1N31	580	0.2194	8.47	21.9355
1N32	580	0.2194	8.47	21.9355
1N33	580	0.2194	8.47	21.9355
2N11	503	0.0764	5.43	7.64078
2N12	503	0.0764	5.43	7.64078
2N13	503	0.0764	5.43	7.64078
2N21	503	0.1305	6.97	13.046
2N22	503	0.1305	6.97	13.046
2N23	503	0.1305	6.97	13.046
2N31	503	0.1902	8.06	19.0234
2N32	503	0.1902	8.06	19.0234
2N33	503	0.1902	8.06	19.0234

Specimen label	f_{yt} (Mpa)	$k_e\rho_s f_{yt}/f_c'$	I_{10}	$k_e\rho_s f_{yt}/f_c'$(%)
1H11	580	0.0722	5.26	7.2246
1H12	580	0.0722	5.26	7.2246
1H13	580	0.0722	5.26	7.2246
1H21	580	0.1234	6.81	12.335
1H22	580	0.1234	6.81	12.335
1H23	580	0.1234	6.81	12.335
1H31	580	0.1799	7.9	17.987
1H32	580	0.1799	7.9	17.987
1H33	580	0.1799	7.9	17.987
2H11	503	0.0627	4.85	6.2654
2H12	503	0.0627	4.85	6.2654
2H13	503	0.0627	4.85	6.2654
2H21	503	0.107	6.4	10.698
2H22	503	0.107	6.4	10.698
2H23	503	0.107	6.4	10.698
2H31	503	0.156	7.49	15.599
2H32	503	0.156	7.49	15.599
2H33	503	0.156	7.49	15.599

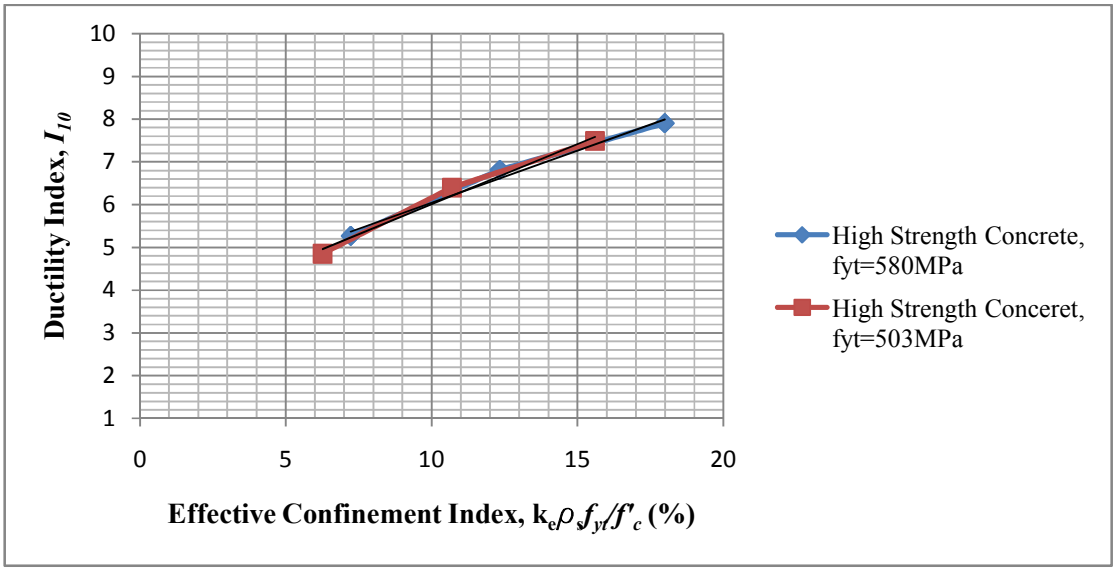
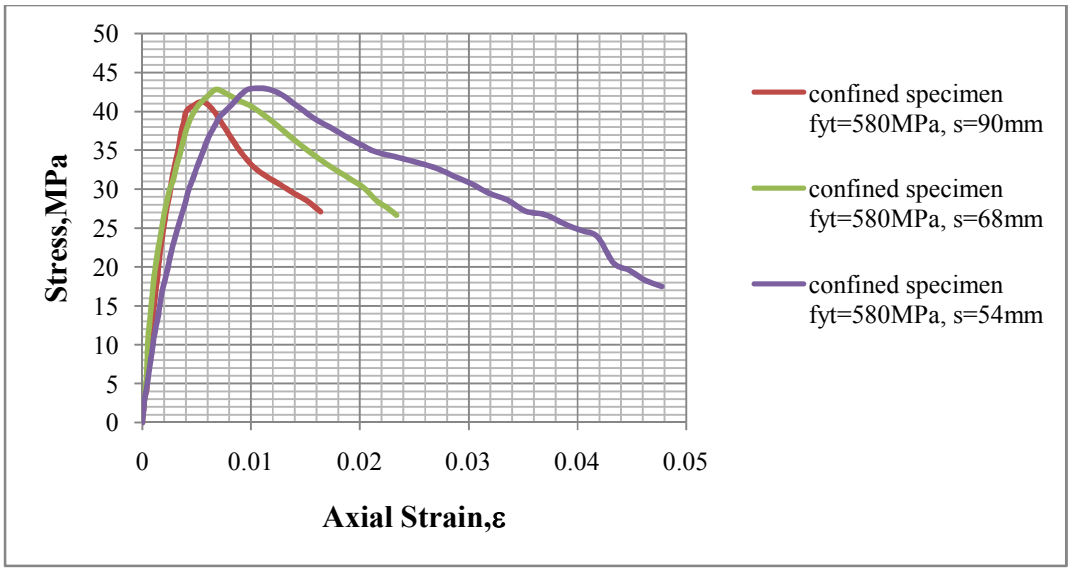


Fig.4.13 Ductility index versus effective confinement index for high-strength concrete columns

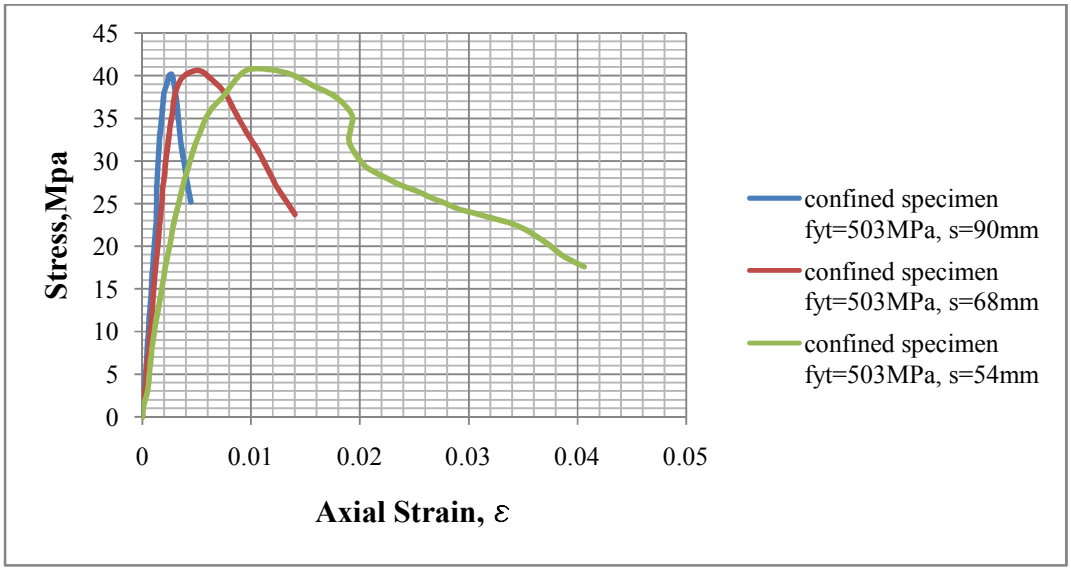
4.3.3 Effect of Yield Strength of Transverse Reinforcement

The effect of yield strength of transverse confining steel was investigated by comparing results of pair of columns specimens having the same concrete compressive strength, same volumetric ratio and the same spacing of lateral confining reinforcement with different yield strength of lateral reinforcement for both normal and high-strength confined concrete columns. In general, it is observed that as the yield strength of transverse reinforcement increases from 503MPa to 580MPa, the strength and deformability of confined concrete get improved. **Fig.14(a) & (b)**, and Table 4.5 compares the results of normal-strength concrete column specimens. For the steel grade used in this study, as the yield strength of transverse reinforcement increases from 503MPa to 580MPa, well confined column specimens of normal-strength concrete increases ductility I_{10} by 5.1%, and specimen with larger spacing increases ductility I_{10} by 7.6%, but gain in strength is insignificant. **Fig. 15 (c) & (d),** and Table 4.5 compares the results of high-strength concrete column specimens. As the yield strength of transverse reinforcement increases from 503MPa to 580MPa, well confined column specimens of high-strength concrete can gain a ductility of I_{10}=5.5% and specimen with larger spacing increases ductility I_{10} by 8.5%, gain in strength for high strength column specimen is also insignificant. From the result it has been observed, increasing the yield strength of confining reinforcement can improve ductility better than strength.

As the yield strength of transverse reinforcement increases from 503MPa to 580MPa in normal-strength concrete, the strain value of larger spacing specimen (s=90mm) corresponding to the peak load were increases from 0.002719 to 0.005563, and that of closer spacing (s=54mm) increases from 0.010042 to 0.010708. For high- strength concrete as the yield strength increases, the corresponding strain value at peak load increases from 0.002255 to 0.004104 for larger spacing (s=90mm), and for closer spacing (s=54mm) strain value increases from 0.008938 to 0.009479 at peak load. Therefore, the increase in yield strength of transverse reinforcement increases the strain values at peak load for both normal and high- strength concrete specimens.

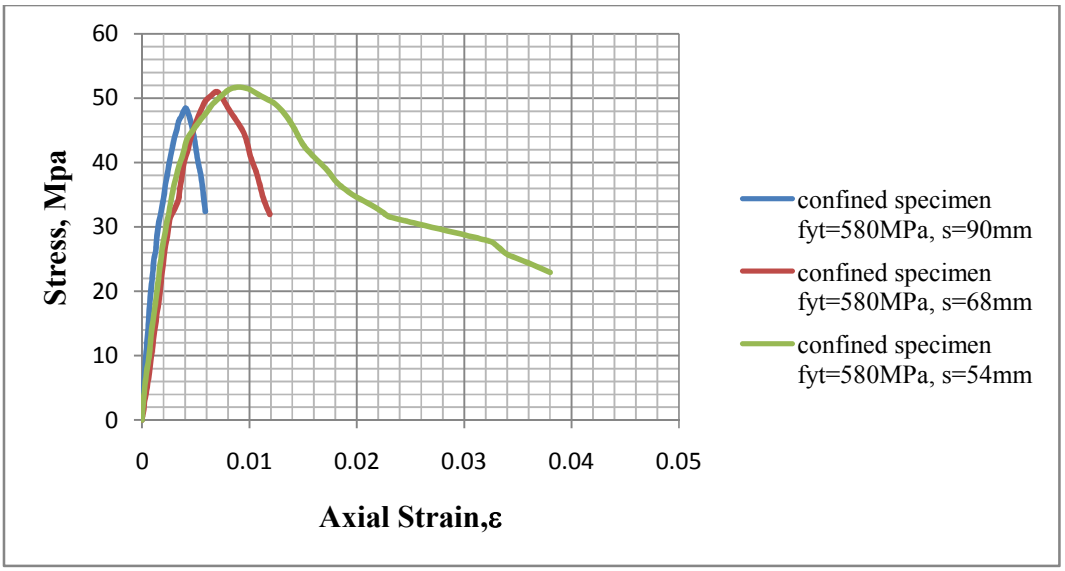


(a)

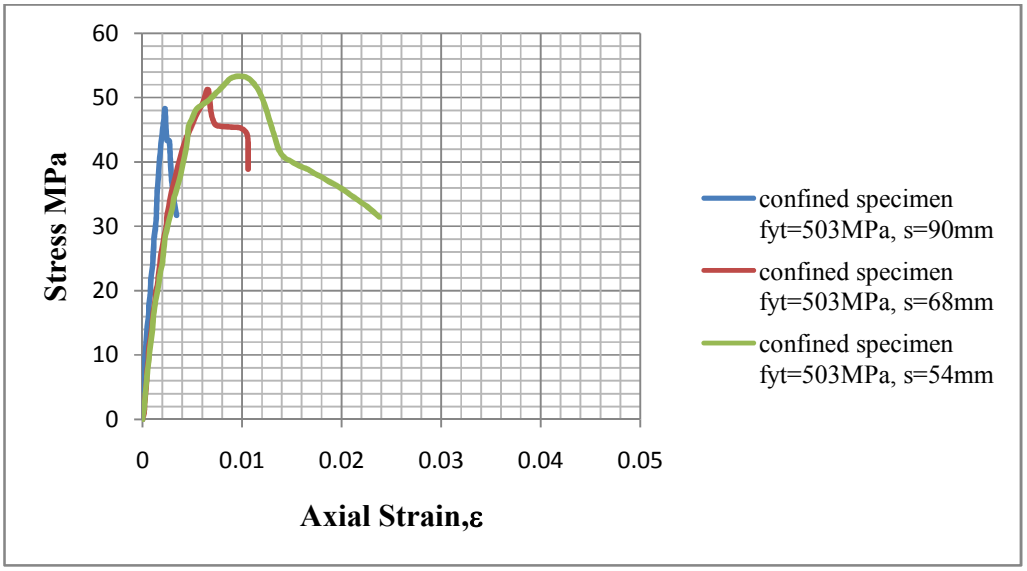


(b)

Fig. 4.14 Effect of yield strength on normal-strength concrete columns (a) Yield strength of transverse reinforcement =580MPa, and (b) Yield strength of transverse reinforcement=503MPa.



(c)



(d)

Fig. 4.15 Effect of yield strength on high-strength concrete columns (c) Yield strength of transverse reinforcement =580MPa, and (d) Yield strength of transverse reinforcement=503MPa.

From stress-strain diagram of the test result as shown in **Fig. 4.14** & **Fig. 4.15** the descending part of the graph in both normal and high- strength concrete column specimens is steeper for the lower yield strength reinforcement than the higher yield strength of transverse reinforcement. The strain value corresponding to the peak load in normal-strength concrete column specimen is greater than the higher strength concrete column specimen for the same yield strength of transverse reinforcement. Therefore, the effect of yield strength of transverse reinforcement has more pronounced effect in normal-strength concrete column specimen than high- strength concrete column specimen.

5. Conclusions and Recommendations

5.1 Conclusions

This research presents the behavior of normal and high-strength concrete column specimens confined by rectilinear steel under the action of axial compression load. The test variables are compressive strength of concrete, volumetric ratio and spacing of transverse reinforcement, and yield strength of transverse reinforcement. The result of test for both normal and high-strength concrete column specimen is compared and reported with present testing facilities. The following conclusions can be made based up on this research.

1. Strength enhancement and deformability of confined column specimen decreases as the concrete strength increases. The post peak curves of the higher strength concrete specimens are steeper, indicating faster rate of strength decay as compared to the normal-strength concrete column specimens.
2. The effect of volumetric ratio and spacing of transverse reinforcement has more pronounced effect on the behavior of normal and high-strength column specimens as compared to the other test parameters. Both ductility index and effective confinement index increases linearly for the increase in volumetric ratio and for the decrease in spacing of transverse reinforcement in both normal and high-strength confined concrete specimen.
3. The increase in yield strength of transverse reinforcement increases the strain values at peak load for both normal and high-strength concrete specimens. From stress-strain diagram of the test result, the descending part of the graph in both normal and high-strength concrete column specimens is steeper for the lower yield strength reinforcement than the higher yield strength of transverse reinforcement.
4. The influence of the test parameters on the ascending portion of the stress strain diagram is almost the same for both normal and high-strength concrete, but it have significant influence on the descending portion of the curve.
5. Vertical cracks were observed for larger spacing of confined concrete column specimen at the time of loading in case of both normal and high-strength concrete, but these vertical cracks were slightly inclined for well confined specimen.

6. Because of testing facilities and small number of test specimens, it is not possible to develop own model.

5.2 Recommendations

In this study only some of the confinement parameters that influences on the behavior of normal and high- strength concrete column specimens are considered because of financial constraint and testing facilities available at laboratory. The results were reported with the constraint of testing facilities, so that the test result and observations were reported by completing and comparing with the models proposed by earlier researchers. In order to study the complete behavior of confinement and propose own model, some of the area which requires further investigations are recommended.

- In order to know the actual behavior of confined concrete column and develop own local model, the size of test specimen shall be considered closer to the actual size of column.
- In order to see whether spacing or volume of confining reinforcement that has more influence on the behavior of confined concrete column, use the same volume of confining reinforcement but with different spacing. This can be done by varying the area of confining reinforcement.
- Since the range of high-strength investigated is narrow, (i.e. only 9MPa difference) investigating the behavior of confined concrete for higher strength is recommended.
- Since the range of yield strength of transverse reinforcement used in this study is small, use for higher range of transverse reinforcement to see the effect of yield strength of transverse reinforcement on confined concrete.
- The post peak behavior observed in this study is obtained by changing the peak sensitivity of the compression machine under load control approach, use of displacement controlled testing machine is to be used to record the post peak behavior.

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Mix proportioning for normal-strength concrete (C41)

i). Design stipulation for proportioning

-Grade designation……..……. C41

-Type of cement ……..……...OPC (Derba cement)

- Maximum nominal size of aggregate……..….25mm

-Minimum cement content…….……320Kg/m^3

- Maximum water -cement ratio……..…….0.54

- Workability…….50mm slump

- Exposure condition ……....severe (reinforced concrete)

- Type of aggregate……..crushed angular aggregate and river sand

- Maximum cement content……..…..450Kg/m^3

ii) Test data for materials

-Cement used…….…OPC (Derba cement)

- Specific gravity of cement……..3.15

- Bulk specific gravity of:

Coarse aggregate…….……2.61

Fine aggregate……...…….2.59

- Water absorption:

Coarse aggregate……2.786 %

Fine aggregate……..…….4.82 %

-Free (surface moisture):

Coarse aggregate…….……..Nil

Fine aggregate…….…….Nil

- Sieve analysis:

Coarse aggregate…….……conforming to Table A5.3 of ACI

Fine aggregate…….conforming to Zone IV of ACI

iii) Target strength for mix proportioning

$f'_{ck}=f_{ck}+ 1.65s$

where f'_{ck} =Target average compressive strength at 28 days

f_{ck} =Characteristic compressive strength at 28 days

s= standard deviation

from Table 1 of IS standard deviation, s= 5N/mm^2

therefore target strength =32.8+1.65×5=41N/mm^2

iv) Selection of water cement ratio

from table A1.5.3.4(a) maximum water cement ratio=0.54

based on experience adopt water cement ratio as 0.5, 0.5<0.54, hence ok

v) Selection of water content

- from TableA15.3.3, maximum water content =186 liter (for 25-50mm slump range and for 20mm aggregate)

vi) Calculation of cement content

-water cement ratio=0.5

-Cement content =186/0.5=372Kg/m^3

From table 5 minimum cement content for severe exposure condition =320 kg/m^3, 372Kg/m^3 >320Kg/m^3, hence ok.

vii) Proportion of volume of coarse aggregate and fine aggregate content.

-from table 5.3.6, volume of coarse aggregate corresponding to 20mm size aggregate and fine aggregate (Zone IV) for water cement ratio of 0.5=0.6

Volume of fine aggregate =1.0-0.6=0.40

viii) Mix calculation

the mix calculations per unit volume of concrete shall be as follows

a) Volume concrete=1m^3
b) Volume of cement=mass of cement/sp.gr. of cement
   ×1/1000=(372/3.15)×1/1000=0.118m^3
c) Volume of water=(186/1)×1/1000=0.186m^3
e) Volume of all in aggregate=a-(b+c)=1-(0.118+0.186)=0.696m^3
f) Volume of coarse aggregates
   e×volume of coarse aggregate ×specific gravity of coarse aggregate
   =0.0.696×0.6×2.61×1000=1090Kg
g) Volume of fine aggregate

e×volume of fine aggregate ×specific gravity of fine aggregate

=0.696×0.4×2.59×1000=721Kg

ix) Mix proportion for trial number 1

cement=**372kg/m^3**

water=**186liter/m^3**

fine aggregate=**721Kg**

coarse aggregate=**1090Kg**

water cement ratio=**0.5**

Mix proportioning for high-strength concrete (C60)

i). Design stipulation for proportioning

-Grade designation……..……. C60

-Type of cement ……..……...OPC (Derba cement)

- Maximum nominal size of aggregate……..….20mm

-Minimum cement content…….……400Kg/m^3

- Maximum water -cement ratio……..…….0.4

- Workability…….50mm slump

- Exposure condition ……....severe (reinforced concrete)

- Type of aggregate……....crushed angular aggregate

- Maximum cement content……..…..600Kg/m^3

- Chemical admixture …….conplast SP430

ii) Test data for materials

-Cement used……..…OPC (Derba cement)

- Specific gravity of cement……..3.15

- Chemical admixture ……..…conplast SP430

- Bulk specific gravity of:

Coarse aggregate…….……2.61

Fine aggregate……...…….2.59

- Water absorption:

Coarse aggregate……2.786 %

Fine aggregate……..…….4.82 %

-Free (surface moisture):

Coarse aggregate…….……..Nil

Fine aggregate…….…….Nil

- Sieve analysis:

Coarse aggregate…….……conforming to Table A5.3 of ACI

Fine aggregate…….conforming to Zone IV of ACI

iii) Target strength for mix proportioning

$f'_{ck}=f_{ck}+ 1.65s$

where f'_{ck} =Target average compressive strength at 28 days

f_{ck} =Characteristic compressive strength at 28 days

s= standard deviation

from Table 1 of IS standard deviation, s= 5N/mm^2

therefore target strength =60+1.65×5=68.25N/mm^2

iv) Selection of water cement ratio

from table A1.5.3.4(a) maximum water cement ratio=0.4

based on experience adopt water cement ratio as 0.29, 0.29<0.4, hence ok

v) Selection of water content

- from ACI 211.4RTable4.3.4, the mixing water is =174 (for 50-100mm slump range and for 20mm aggregate)

-as super plasticizer is used the water content can be reduced up to 20 percent and above.

Based on trials with SP water content reduction of 20 percent has been achieved.

Hence the water content arrived=199×0.8=159liter

vi) Calculation of cement content

-water cement ratio=0.29

-Cement content =159/0.29=550Kg/m^3

From ACI 211. 4R table 4.3.5(b) minimum cement content for severe exposure condition =400 kg/m^3, 600Kg/m^3 >550Kg/m^3, hence ok.

vii) Proportion of volume of coarse aggregate and fine aggregate content.

-from ACI 211.4R table 4.3.3, volume of coarse aggregate corresponding to 20mm size aggregate and fine aggregate (Zone IV) for water cement ratio of 0.5=0.6

In the present case w/c ratio =0.3 the volume of coarse aggregate is required to be increased to decrease the fine aggregate content. As w/c ratio is lower by 0.1 increase the coarse aggregate volume by 0.02 (at the rate of -/+0.01 for every +/-0.05 change in water cement ratio.)

Therefore corrected volume of coarse aggregate for w/c of 0.29=0.6

Volume of fine aggregate =1.0-0.6=0.4

viii) Mix calculation

the mix calculations per unit volume of concrete shall be as follows

h) Volume concrete=1m^3

i) Volume of cement=mass of cement/sp.gr. of cement ×1/1000=(550/3.15)×1/1000=0.174m^3

j) Volume of water=(159/1)×1/1000=0.159m^3

k) Volume of chemical admixture (2% by mass of cement)=(0.02×550)/1.18×(1/1000)=0.009m^3

l) Volume of all in aggregate=a-(b+c+d)=1-(0.174+0.159+0.009)=0.658m^3

m) Volume of coarse aggregates

e×volume of coarse aggregate ×specific gravity of coarse aggregate

=0.658×0.6×2.61×1000=1030Kg

n) Volume of fine aggregate

e×volume of fine aggregate ×specific gravity of fine aggregate

=0.658×0.4×2.59×1000=682Kg

ix) Mix proportion for trial number 1

cement=**550m^3**

water=**159liter/m^3**

fine aggregate=**682Kg**

coarse aggregate=**1030Kg**

chemical admixture=**11Kg=11liter**

water cement ratio=**0.29**

Test data for normal-strength concrete column specimen confined with yield strength of transverse reinforcement equals 580MPa

Specimen Lable																							
PN (unconfined)		1N1(confined)							1N2 (confined)							1N3 (confined)							
			Average Load(KN)			Average Stress (MPa)				Average Load(KN)			Average Stress (MPa)				Average Load(KN)			Average Stress (MPa)		
Strain	Ave. Str. (MPa)	Strain	Colu. Spec.	Long. Rein.	Conc.	Long. Rein.	Conc	Colu. spec.	Strain	Colu. spec.	Long. Rein.	Conc.	Long. Rein.	Conc	Colu. spec.	Strain	Colu. spec.	Long. Rein.	Conc.	Long. Rein.	Conc	Colu. spec.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.2	0	0.2	0	0.01	0.01	0	0.3	0	0.3	0	0.01	0.01	0	0.1	0	0.1	0	0	0
0	0.197	0	0.7	0	0.7	0	0.03	0.03	0	5.033	0	5.0333	0	0.23	0.22	0	0.2	0	0.2	0	0.01	0.01
0	0.4385	0	10	0	10	0	0.45	0.44	0	9.7	0	9.7	0	0.44	0.43	2E-05	5.6333	1.309	4.324	4.1667	0.19	0.25
6E-05	1.0311	4E-05	20.7	2.62	18.08	8.333	0.82	0.92	2E-05	22.1	1.309	20.791	4.167	0.94	0.98	6E-05	15.6	3.927	11.67	12.5	0.53	0.69
0.0002	2.4756	0.0001	49.33	9.16	40.17	29.17	1.81	2.19	0.0001	54.97	6.545	48.422	20.83	2.18	2.44	0.0001	36.767	7.854	28.91	25	1.3	1.63
0.0003	4.6163	0.0002	71.97	13.1	58.88	41.67	2.65	3.2	0.0002	97.2	13.09	84.11	41.67	3.79	4.32	0.0003	73.867	15.71	58.16	50	2.62	3.28
0.0004	6.7215	0.0004	94.6	24.9	69.73	79.17	3.14	4.2	0.0003	173.5	18.33	155.14	58.33	6.99	7.71	0.0005	120.23	31.42	88.82	100	4	5.34
0.0005	8.1852	0.0005	123.4	28.8	94.6	91.67	4.26	5.48	0.0004	207.4	23.56	183.84	75	8.29	9.22	0.0007	170.4	45.81	124.6	145.83	5.62	7.57
0.0006	9.6696	0.0005	157.6	34	123.5	108.3	5.57	7	0.0004	241.2	27.49	213.74	87.5	9.63	10.7	0.0009	208.57	57.6	151	183.33	6.8	9.27
0.0006	11.148	0.0006	191.5	40.6	150.9	129.2	6.8	8.51	0.0005	274.8	32.72	242.08	104.2	10.9	12.2	0.0011	243.57	66.76	176.8	212.5	7.97	10.8
0.0007	12.616	0.0008	225.3	48.4	176.8	154.2	7.97	10	0.0006	308	39.27	268.7	125	12.1	13.7	0.0013	277.43	79.85	197.6	254.17	8.91	12.3
0.0008	14.098	0.0008	259	52.4	206.6	166.7	9.31	11.5	0.0007	341.4	45.81	295.62	145.8	13.3	15.2	0.0015	311.13	92.94	218.2	295.83	9.83	13.8
0.0009	15.557	0.0009	292.4	58.9	233.5	187.5	10.5	13	0.0008	374.4	52.36	322.07	166.7	14.5	16.6	0.0016	344.7	103.4	241.3	329.17	10.9	15.3
0.001	17.027	0.001	325.8	64.1	261.7	204.2	11.8	14.5	0.0009	407.7	58.9	348.83	187.5	15.7	18.1	0.0018	378.3	113.9	264.4	362.5	11.9	16.8
0.001	18.486	0.0012	359.3	73.3	286	233.3	12.9	16	0.001	440.9	65.45	375.45	208.3	16.9	19.6	0.0021	411.43	130.9	280.5	416.67	12.6	18.3
0.0012	19.948	0.0013	392.6	81.2	311.4	258.3	14	17.4	0.0012	473.9	73.3	400.63	233.3	18.1	21.1	0.0023	444.33	146.6	297.7	466.67	13.4	19.7

0.0013	21.41	0.0014	425.8	89	336.8	283.3	15.2	18.9	0.0013	507.1	83.78	423.32	266.7	19.1	22.5	0.0025	477.1	159.7	317.4	508.33	14.3	21.2
0.0015	22.446	0.0015	459.1	95.6	363.5	304.2	16.4	20.4	0.0015	540.1	92.94	447.19	295.8	20.2	24	0.0028	509.83	175.4	334.4	558.33	15.1	22.7
0.0018	24.077	0.0016	492.1	103	388.7	329.2	17.5	21.9	0.0017	573.2	104.7	468.45	333.3	21.1	25.5	0.0031	542.63	193.7	348.9	616.67	15.7	24.1
0.0019	25.536	0.0018	525.3	113	412.7	358.3	18.6	23.3	0.0019	606.1	116.5	489.63	370.8	22.1	26.9	0.0034	575.07	197.3	377.8	628	17	25.6
0.0021	26.993	0.0019	558.1	122	436.4	387.5	19.7	24.8	0.002	638.7	127	511.73	404.2	23.1	28.4	0.0037	607.37	197.3	410.1	628	18.5	27
0.0023	28.433	0.0021	591	132	458.8	420.8	20.7	26.3	0.0023	671.3	142.7	528.59	454.2	23.8	29.8	0.004	639.83	197.3	442.5	628	19.9	28.4
0.0025	29.719	0.0023	622.2	141	480.8	450	21.7	27.7	0.0025	703.4	157.1	546.29	500	24.6	31.3	0.0043	672	197.3	474.7	628	21.4	29.9
0.0028	31.261	0.0025	656	156	500.3	495.8	22.5	29.2	0.0029	731	180.6	550.39	575	24.8	32.5	0.0046	704	197.3	506.7	628	22.8	31.3
0.0032	31.041	0.0026	688.6	166	522.4	529.2	23.5	30.6	0.0031	765.8	195	570.76	620.8	25.7	34	0.005	734.67	197.3	537.4	628	24.2	32.7
0.004	30.424	0.0028	721.2	178	543.2	566.7	24.5	32.1	0.0034	797.9	197.3	600.61	628	27.1	35.5	0.0054	766.13	197.3	568.8	628	25.6	34.1
0.0047	29.601	0.003	751.4	190	561.6	604.2	25.3	33.4	0.0036	828.2	197.3	630.87	628	28.4	36.8	0.0057	796.33	197.3	599	628	27	35.4
0.0051	28.244	0.0033	782.9	197	585.6	628	26.4	34.8	0.0039	856.6	197.3	659.27	628	29.7	38.1	0.0061	825.43	197.3	628.1	628	28.3	36.7
		0.0034	813.4	197	616.1	628	27.8	36.2	0.0042	884.1	197.3	686.81	628	31	39.3	0.0066	855.6	197.3	658.3	628	29.7	38
		0.0036	845.5	197	648.2	628	29.2	37.6	0.0047	906.2	197.3	708.91	628	32	40.3	0.0071	883.17	197.3	685.9	628	30.9	39.3
		0.0038	872.6	197	675.3	628	30.4	38.8	0.0053	918.6	197.3	721.31	628	32.5	40.8	0.0078	905.8	197.3	708.5	628	31.9	40.3
		0.0041	901	197	703.7	628	31.7	40	0.006	925	197.3	727.71	628	32.8	41.1	0.0086	930.73	197.3	733.4	628	33.1	41.4
		0.0047	916.8	197	719.5	628	32.4	40.7	0.0068	937.5	197.3	740.17	628	33.4	41.7	0.0091	948.1	197.3	750.8	628	33.8	42.1
		0.0056	927.8	197	730.5	628	32.9	41.2	0.0077	924.5	197.3	727.21	628	32.8	41.1	0.0097	963.2	197.3	765.9	628	34.5	42.8
		0.0066	902	197	704.7	628	31.8	40.1	0.0088	909.2	197.3	711.87	628	32.1	40.4	0.0107	966.53	197.3	769.2	628	34.7	43
		0.0078	842.1	197	644.8	628	29.1	37.4	0.0099	891	197.3	693.67	628	31.3	39.6	0.0115	964.37	197.3	767.1	628	34.6	42.9
		0.009	784	197	586.7	628	26.4	34.8	0.011	865.8	197.3	668.47	628	30.1	38.5	0.0124	953.97	197.3	756.7	628	34.1	42.4
		0.0103	739.1	197	541.8	628	24.4	32.8	0.0122	836.6	197.3	639.27	628	28.8	37.2	0.0132	940.43	197.3	743.1	628	33.5	41.8
		0.0115	711	197	513.7	628	23.2	31.6	0.0134	804.9	197.3	607.61	628	27.4	35.8	0.0139	922.73	197.3	725.4	628	32.7	41

		0.0127	687.9	197	490.6	628	22.1	30.6	0.0145	774.5	197.3	577.24	628	26	34.4	0.0147	904.1	197.3	706.8	628	31.9	40.2
		0.0139	663.1	197	465.8	628	21	29.5	0.0157	745.6	197.3	548.27	628	24.7	33.1	0.0155	885.83	197.3	688.5	628	31	39.4
		0.0152	641.2	197	443.9	628	20	28.5	0.0169	719.1	197.3	521.77	628	23.5	32	0.0164	867.9	197.3	670.6	628	30.2	38.6
		0.0164	609.7	197	412.4	628	18.6	27.1	0.018	692.8	197.3	495.51	628	22.3	30.8	0.0176	847.97	197.3	650.7	628	29.3	37.7
									0.0192	672.6	197.3	475.31	628	21.4	29.9	0.0189	823.9	197.3	626.6	628	28.2	36.6
									0.0204	652.8	197.3	455.54	628	20.5	29	0.0202	801.8	197.3	604.5	628	27.2	35.6
									0.0215	602.2	197.3	404.91	628	18.3	26.8	0.0215	782.2	197.3	584.9	628	26.4	34.8
									0.0226	580.2	197.3	382.91	628	17.3	25.8	0.0241	761.5	197.3	564.2	628	25.4	33.8
									0.0234	558.1	197.3	360.84	628	16.3	24.8	0.0269	737.1	197.3	539.8	628	24.3	32.8
																0.0287	712.13	197.3	514.8	628	23.2	31.7
																0.0303	689.67	197.3	492.4	628	22.2	30.7
																0.0318	663.53	197.3	466.2	628	21	29.5
																0.0336	643	197.3	445.7	628	20.1	28.6
																0.0352	611.07	197.3	413.8	628	18.7	27.2
																0.0371	600.67	197.3	403.4	628	18.2	26.7
																0.0389	573	197.3	375.7	628	16.9	25.5
																0.0404	554.5	197.3	357.2	628	16.1	24.6
																0.0419	536.83	197.3	339.5	628	15.3	23.9

Test data for normal-strength concrete column specimen confined with yield strength of transverse reinforcement equals 503MPa

Specimen Lable																						
PN (unconfined)		2N1(confined)							2N2 (confined)							2N3 (confined)						
			Average Load(KN)			Average Stress (MPa)				Average Load(KN)			Average Stress (MPa)				Average Load(KN)			Average Stress (MPa		
Strain	Ave. Str. (MPa)	Strain	Colu. Spec.	Long. Rein.	Conc.	Long. Rein.	Conc.	Colu. spec.	Strain	Colu. spec.	Long. Rein.	Conc.	Longi. Rein.	Conc.	Colu. spec.	Strain	Colu. spec.	Long. Rein.	Conc.	Long. Rein.	Conc.	Colu. spec.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.3	0	0.3	0	0.01	0.013	0	0.2	0	0.2	0	0.009	0.009	0	0.1	0	0.1	0	0	0.004
0	0.197	0	7.4	0	7.4	0	0.33	0.329	0	2.5333	0	2.5333	0	0.114	0.113	0	0.1	0	0.1	0	0	0.004
0	0.439	0	11.9	0	11.9	0	0.54	0.529	0	10.367	0	10.367	0	0.467	0.461	0	3.033	0	3.0333	0	0.14	0.135
6E-05	1.031	3E-05	28.9	1.9635	26.937	6.25	1.21	1.284	2E-05	22	1.309	20.691	4.167	0.933	0.978	2E-05	8.533	1.309	7.2243	4.1667	0.33	0.379
0.0002	2.476	9E-05	53.15	5.8905	47.26	18.75	2.13	2.362	6E-05	45.2	3.927	41.273	12.5	1.86	2.009	4E-05	16.03	2.618	13.415	8.3333	0.6	0.713
0.0003	4.616	0.0003	89.35	15.708	73.642	50	3.32	3.971	0.0003	74.833	17.017	57.816	54.17	2.606	3.326	0.0002	37.67	11.78	25.886	37.5	1.17	1.674
0.0004	6.721	0.0003	116.3	19.635	96.665	62.5	4.36	5.169	0.0004	115.33	24.871	90.462	79.17	4.077	5.126	0.0005	70.47	31.42	39.051	100	1.76	3.132
0.0005	8.185	0.0004	141	23.562	117.44	75	5.29	6.267	0.0005	145.5	28.798	116.7	91.67	5.26	6.467	0.0007	118.4	41.89	76.512	133.33	3.45	5.262
0.0006	9.67	0.0004	167.35	27.489	139.86	87.5	6.3	7.438	0.0006	173.77	37.961	135.81	120.8	6.121	7.723	0.0008	160.6	51.05	109.52	162.5	4.94	7.136
0.0006	11.15	0.0005	200.35	31.416	168.93	100	7.61	8.904	0.0007	199.53	41.888	157.65	133.3	7.106	8.868	0.001	197.2	60.21	137.02	191.67	6.18	8.766
0.0007	12.62	0.0006	233.1	37.306	195.79	118.8	8.83	10.36	0.0008	233.67	47.124	186.54	150	8.408	10.39	0.0011	231.3	71.99	159.34	229.17	7.18	10.28
0.0008	14.1	0.0007	265.5	41.233	224.27	131.3	10.1	11.8	0.0009	267.83	54.978	212.86	175	9.594	11.9	0.0013	265	83.78	181.19	266.67	8.17	11.78
0.0009	15.56	0.0008	297.85	47.124	250.73	150	11.3	13.24	0.001	301.57	60.214	241.35	191.7	10.88	13.4	0.0016	298.4	98.17	200.19	312.5	9.02	13.26
0.001	17.03	0.0008	330.3	51.051	279.25	162.5	12.6	14.68	0.001	335.33	65.45	269.88	208.3	12.16	14.9	0.0018	331.7	110	221.78	350	10	14.74
0.001	18.49	0.0009	362.65	54.978	307.67	175	13.9	16.12	0.0011	368.87	71.995	296.87	229.2	13.38	16.39	0.002	365	123	241.99	391.67	10.9	16.22
0.0012	19.95	0.001	395.05	60.868	334.18	193.8	15.1	17.56	0.0013	402.47	78.54	323.93	250	14.6	17.89	0.0021	398.3	133.5	264.75	425	11.9	17.7

0.0013	21.41	0.001	426.95	64.795	362.15	206.3	16.3	18.98	0.0014	435.87	86.394	349.47	275	15.75	19.37	0.0024	431.4	149.2	282.14	475	12.7	19.17
0.0015	22.45	0.0011	459	70.686	388.31	225	17.5	20.4	0.0015	469.4	92.939	376.46	295.8	16.97	20.86	0.0026	464.2	163.6	300.54	520.83	13.5	20.63
0.0018	24.08	0.0012	490.75	76.576	414.17	243.8	18.7	21.81	0.0016	502.73	99.484	403.25	316.7	18.18	22.34	0.0028	497.4	175.4	321.99	558.33	14.5	22.11
0.0019	25.54	0.0013	521.5	80.503	441	256.3	19.9	23.18	0.0017	536	107.34	428.66	341.7	19.32	23.82	0.0031	530.1	192.4	337.71	612.5	15.2	23.56
0.0021	26.99	0.0013	550.6	82.467	468.13	262.5	21.1	24.47	0.0018	569.23	113.88	455.35	362.5	20.52	25.3	0.0033	563.1	197.3	365.77	628	16.5	25.03
0.0023	28.43	0.0013	581.65	82.467	499.18	262.5	22.5	25.85	0.0019	602.63	117.81	484.82	375	21.85	26.78	0.0036	595.9	197.3	398.57	628	18	26.48
0.0025	29.72	0.0013	615.05	84.43	530.62	268.8	23.9	27.34	0.002	635.7	128.28	507.42	408.3	22.87	28.25	0.0039	628.6	197.3	431.31	628	19.4	27.94
0.0028	31.26	0.0014	646.05	88.357	557.69	281.3	25.1	28.71	0.0021	668.57	133.52	535.05	425	24.12	29.71	0.0043	661.1	197.3	463.81	628	20.9	29.38
0.0032	31.04	0.0015	677.15	92.284	584.87	293.8	26.4	30.1	0.0023	701.47	142.68	558.79	454.2	25.19	31.18	0.0046	693.4	197.3	496.14	628	22.4	30.82
0.004	30.42	0.0015	708.45	96.211	612.24	306.3	27.6	31.49	0.0024	734.27	151.84	582.42	483.3	26.25	32.63	0.005	725.4	197.3	528.07	628	23.8	32.24
0.0047	29.6	0.0016	738.6	100.14	638.46	318.8	28.8	32.83	0.0026	766.4	161.01	605.39	512.5	27.29	34.06	0.0054	757.8	197.3	560.51	628	25.3	33.68
0.0051	28.24	0.0017	767.35	107.99	659.36	343.8	29.7	34.1	0.0028	799.17	172.79	626.38	550	28.23	35.52	0.0059	789.7	197.3	592.44	628	26.7	35.1
		0.0018	800.1	113.88	686.22	362.5	30.9	35.56	0.0029	831.37	181.95	649.42	579.2	29.27	36.95	0.0065	818.1	197.3	620.77	628	28	36.36
		0.0019	826.65	119.77	706.88	381.3	31.9	36.74	0.0031	861.3	195.04	666.26	620.8	30.03	38.28	0.0074	844	197.3	646.71	628	29.1	37.51
		0.002	854.4	125.66	728.74	400	32.8	37.97	0.0036	890.13	197.29	692.84	628	31.23	39.56	0.0081	872.1	197.3	674.84	628	30.4	38.76
		0.0022	874.25	139.41	734.84	443.8	33.1	38.86	0.0041	903.67	197.29	706.37	628	31.84	40.16	0.0087	893.1	197.3	695.81	628	31.4	39.69
		0.0025	899.9	155.12	744.78	493.8	33.6	40	0.0047	911.2	197.29	713.91	628	32.18	40.5	0.0093	909.3	197.3	711.97	628	32.1	40.41
		0.0027	902	170.82	731.18	543.8	33	40.09	0.0051	913.63	197.29	716.34	628	32.29	40.61	0.01	917.6	197.3	720.34	628	32.5	40.78
		0.003	869.35	186.53	682.82	593.8	30.8	38.64	0.0057	907.43	197.29	710.14	628	32.01	40.33	0.0118	916.1	197.3	718.81	628	32.4	40.72
		0.0032	813.85	197.29	616.56	628	27.8	36.17	0.0062	894.23	197.29	696.94	628	31.41	39.74	0.0138	902.4	197.3	705.07	628	31.8	40.11
		0.0035	742.3	197.29	545.01	628	24.6	32.99	0.0067	881.83	197.29	684.54	628	30.85	39.19	0.0158	872.4	197.3	675.14	628	30.4	38.77
		0.0037	690.95	197.29	493.66	628	22.3	30.71	0.0072	866.37	197.29	669.07	628	30.16	38.51	0.0179	842.5	197.3	645.21	628	29.1	37.44
		0.004	648.8	197.29	451.51	628	20.4	28.84	0.0079	841.87	197.29	644.57	628	29.05	37.42	0.0193	796.5	197.3	599.21	628	27	35.4
		0.0042	601.9	197.29	404.61	628	18.2	26.75	0.0084	810.47	197.29	613.17	628	27.64	36.02	0.0192	761.1	197.3	563.77	628	25.4	33.83
		0.0045	566.6	197.29	369.31	628	16.6	25.18	0.009	780.8	197.29	583.51	628	26.3	34.7	0.019	728.4	197.3	531.07	628	23.9	32.37
		0.0047	527.45	197.29	330.16	628	14.9	23.44	0.0095	752.3	197.29	555.01	628	25.02	33.44	0.0195	696	197.3	498.71	628	22.5	30.93

									0.0101	726.57	197.29	529.27	628	23.86	32.29	0.0205	660.3	197.3	462.97	628	20.9	29.35
									0.0107	700.9	197.29	503.61	628	22.7	31.15	0.0221	634.1	197.3	436.81	628	19.7	28.18
									0.0112	670.6	197.29	473.31	628	21.33	29.8	0.0238	611.7	197.3	414.44	628	18.7	27.19
									0.0118	639.2	197.29	441.91	628	19.92	28.41	0.0253	595.2	197.3	397.87	628	17.9	26.45
									0.0124	607.1	197.29	409.81	628	18.47	26.98	0.0265	578.6	197.3	381.31	628	17.2	25.72
									0.0129	582.47	197.29	385.17	628	17.36	25.89	0.028	562.2	197.3	364.91	628	16.4	24.99
									0.0135	558.4	197.29	361.11	628	16.28	24.82	0.0291	548	197.3	350.67	628	15.8	24.35
									0.014	533.83	197.29	336.54	628	15.17	23.73	0.0307	536.1	197.3	338.77	628	15.3	23.83
																0.0321	524.6	197.3	327.34	628	14.8	23.32
																0.0338	512	197.3	314.71	628	14.2	22.76
																0.0348	500.3	197.3	303.04	628	13.7	22.24
																0.0355	489.5	197.3	292.17	628	13.2	21.75
																0.0363	476.1	197.3	278.84	628	12.6	21.16
																0.037	462.4	197.3	265.11	628	11.9	20.55
																0.0377	446.7	197.3	249.44	628	11.2	19.85
																0.0384	429.2	197.3	231.94	628	10.5	19.08
																0.0392	416.9	197.3	219.64	628	9.9	18.53
																0.0399	405.9	197.3	208.57	628	9.4	18.04

Test data for high-strength concrete column specimen confined with yield strength of transverse reinforcement equals 580MPa

Specimen Lable																						
PN (unconfined)		1H1(confined)							1H2 (confined)							1H3 (confined)						
			Average Load(KN)			Average Stress (MPa)				Average Load(KN)			Average Stress (MPa)				Average Load(KN)			Average Stress (MPa)		
Strain	Ave. Str. (MPa)	Strain	Colu. spec.	Long. Rein.	Conc.	Long. Rein.	Conc.	Colu. spec.	Strain	Colu. spec.	Long. Rein.	Conc.	Long. Rein.	Conc.	Colu. spec.	Strain	Colu. Spec.	Long. Rein.	Conc.	Long. Rein.	Conc.	Colu. spec.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.009	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0	0.6	0	0.03	0.027
0	0.116	0	4.7667	0	4.7667	0	0.215	0.21	0	2.5	0	2.5	0	0.113	0.111	0	7.9333	0	7.9333	0	0.36	0.353
0	0.585	0	12.867	0	12.867	0	0.58	0.57	0	6.7667	0	6.7667	0	0.305	0.301	2E-05	19.1	1.309	17.791	4.167	0.8	0.849
4E-05	1.241	0	24.767	0	24.767	0	1.116	1.1	4E-05	14.933	2.618	12.315	8.333	0.555	0.664	6E-05	41.267	3.927	37.34	12.5	1.68	1.834
0.0001	2.31	6E-05	60.967	3.927	57.04	12.5	2.571	2.71	0.0001	33.533	9.163	24.37	29.17	1.098	1.49	0.0002	85.033	10.47	74.561	33.33	3.36	3.779
0.0003	4.018	0.0001	121.37	9.163	112.2	29.17	5.057	5.39	0.0002	60.167	13.09	47.077	41.67	2.122	2.674	0.0003	136.8	19.63	117.17	62.5	5.28	6.08
0.0005	6.502	0.0003	177.3	17.017	160.28	54.17	7.225	7.88	0.0004	94.8	23.562	71.238	75	3.211	4.213	0.0005	179.83	28.8	151.04	91.67	6.81	7.993
0.0006	9.206	0.0004	230.4	22.253	208.15	70.83	9.382	10.2	0.0005	133.57	34.034	99.533	108.3	4.486	5.936	0.0006	220.33	40.58	179.75	129.2	8.1	9.793
0.0007	11.34	0.0005	275.73	28.798	246.94	91.67	11.13	12.3	0.0007	166.73	43.197	123.54	137.5	5.568	7.41	0.0008	260	47.12	212.88	150	9.6	11.56
0.0008	13.16	0.0006	322.7	35.343	287.36	112.5	12.95	14.3	0.0008	204.63	49.742	154.89	158.3	6.982	9.095	0.0008	295.13	52.36	242.77	166.7	10.9	13.12
0.0009	14.83	0.0006	365.2	39.27	325.93	125	14.69	16.2	0.0009	244.83	58.905	185.93	187.5	8.381	10.88	0.0009	328.8	58.9	269.9	187.5	12.2	14.61
0.001	16.29	0.0007	408.3	44.506	363.79	141.7	16.4	18.1	0.001	278.53	65.45	213.08	208.3	9.604	12.38	0.0011	362.3	68.07	294.23	216.7	13.3	16.1
0.0011	17.76	0.0008	452.8	51.051	401.75	162.5	18.11	20.1	0.0012	311.7	73.304	238.4	233.3	10.75	13.85	0.0012	395.67	74.61	321.05	237.5	14.5	17.59
0.0012	19.23	0.0009	497.3	58.905	438.4	187.5	19.76	22.1	0.0013	344.8	81.158	263.64	258.3	11.88	15.32	0.0013	428.93	82.47	346.47	262.5	15.6	19.06
0.0014	20.66	0.001	530.1	64.141	465.96	204.2	21	23.6	0.0014	377.83	87.703	290.13	279.2	13.08	16.79	0.0014	461.73	89.01	372.72	283.3	16.8	20.52
0.0015	21.8	0.0011	562.93	69.377	493.56	220.8	22.25	25	0.0015	410.33	96.866	313.47	308.3	14.13	18.24	0.0015	495.23	96.87	398.37	308.3	18	22.01
0.0016	23.6	0.0013	595.67	79.849	515.82	254.2	23.25	26.5	0.0016	443.33	103.41	339.92	329.2	15.32	19.7	0.0016	528.3	102.1	426.2	325	19.2	23.48
0.0018	25.04	0.0013	628.47	83.776	544.69	266.7	24.55	27.9	0.0018	476.27	109.96	366.31	350	16.51	21.17	0.0018	561.33	110	451.38	350	20.3	24.95

0.0019	26.51	0.0014	661.13	90.321	570.81	287.5	25.73	29.4	0.0018	511.53	115.19	396.34	366.7	17.86	22.73	0.0019	594.4	116.5	477.9	370.8	21.5	26.42
0.002	27.99	0.0016	694.07	98.175	595.89	312.5	26.86	30.8	0.002	543.9	123.05	420.85	391.7	18.97	24.17	0.002	627.3	125.7	501.64	400	22.6	27.88
0.0023	29.02	0.0018	726.8	109.96	616.84	350	27.8	32.3	0.0021	576.83	129.59	447.24	412.5	20.16	25.64	0.0022	660.07	136.1	523.93	433.3	23.6	29.34
0.0025	30.74	0.0019	759.53	120.43	639.11	383.3	28.81	33.8	0.0022	609.6	136.14	473.46	433.3	21.34	27.09	0.0023	693.03	145.3	547.73	462.5	24.7	30.8
0.0026	32.16	0.0021	792.3	129.59	662.71	412.5	29.87	35.2	0.0023	642.37	146.61	495.76	466.7	22.35	28.55	0.0025	725.8	157.1	568.72	500	25.6	32.26
0.0028	33.64	0.0022	824.87	136.14	688.73	433.3	31.04	36.7	0.0025	675.03	154.46	520.57	491.7	23.46	30	0.0026	758.2	166.2	591.96	529.2	26.7	33.7
0.003	35.1	0.0023	857.93	146.61	711.33	466.7	32.06	38.1	0.0026	707.7	164.93	542.77	525	24.46	31.45	0.0028	790.23	176.7	613.52	562.5	27.7	35.12
0.0032	36.52	0.0025	890.5	155.77	734.73	495.8	33.12	39.6	0.003	739.9	191.11	548.79	608.3	24.74	32.88	0.003	822.93	187.2	635.75	595.8	28.7	36.57
0.0036	36.68	0.0026	923.23	166.24	756.99	529.2	34.12	41	0.0034	772.07	197.29	574.77	628	25.91	34.31	0.0032	856.07	197.3	658.77	628	29.7	38.05
0.0036	34.8	0.0028	955.57	178.02	777.54	566.7	35.05	42.5	0.0035	806.33	197.29	609.04	628	27.45	35.84	0.0034	887.57	197.3	690.27	628	31.1	39.45
0.004	32.56	0.003	987.1	188.5	798.6	600	36	43.9	0.0036	839.23	197.29	641.94	628	28.93	37.3	0.0037	919.53	197.3	722.24	628	32.6	40.87
0.0044	29.63	0.0032	1017	197.29	819.74	628	36.95	45.2	0.0038	872.1	197.29	674.81	628	30.42	38.76	0.004	951.77	197.3	754.47	628	34	42.3
0.0049	29.85	0.0034	1044.8	197.29	847.47	628	38.2	46.4	0.0039	904.63	197.29	707.34	628	31.88	40.21	0.0042	982.03	197.3	784.74	628	35.4	43.65
0.0055	28.75	0.0036	1061.9	197.29	864.57	628	38.97	47.2	0.0042	936.73	197.29	739.44	628	33.33	41.63	0.0047	1012.2	197.3	814.94	628	36.7	44.99
		0.0039	1081.5	197.29	884.24	628	39.86	48.1	0.0044	969.73	197.29	772.44	628	34.82	43.1	0.0054	1044.9	197.3	847.64	628	38.2	46.44
		0.0041	1089.2	197.29	891.94	628	40.2	48.4	0.0047	1000.8	197.29	803.54	628	36.22	44.48	0.006	1073.8	197.3	876.54	628	39.5	47.73
		0.0045	1050.8	197.29	853.47	628	38.47	46.7	0.0049	1032.4	197.29	835.07	628	37.64	45.88	0.0066	1103.6	197.3	906.31	628	40.9	49.05
		0.0048	993.03	197.29	795.74	628	35.87	44.1	0.0052	1062.7	197.29	865.37	628	39.01	47.23	0.0073	1130.5	197.3	933.17	628	42.1	50.24
		0.0052	908.3	197.29	711.01	628	32.05	40.4	0.0056	1092.5	197.29	895.17	628	40.35	48.55	0.0081	1154.1	197.3	956.81	628	43.1	51.29
		0.0055	840.8	197.29	643.51	628	29.01	37.4	0.0059	1116.9	197.29	919.57	628	41.45	49.64	0.0089	1163.7	197.3	966.41	628	43.6	51.72
		0.0059	729.33	197.29	532.04	628	23.98	32.4	0.0064	1134.7	197.29	937.41	628	42.25	50.43	0.0099	1157.2	197.3	959.91	628	43.3	51.43

									0.007	1148.1	197.29	950.84	628	42.86	51.03	0.0111	1132	197.3	934.74	628	42.1	50.31
									0.0074	1127.4	197.29	930.14	628	41.92	50.11	0.0124	1105.4	197.3	908.14	628	40.9	49.13
									0.0081	1086.2	197.29	888.91	628	40.07	48.28	0.0133	1069.9	197.3	872.64	628	39.3	47.55
									0.0095	1003.2	197.29	805.94	628	36.33	44.59	0.0141	1023.9	197.3	826.61	628	37.3	45.51
									0.0101	922.53	197.29	725.24	628	32.69	41	0.015	963.6	197.3	766.31	628	34.5	42.83
									0.0107	859.67	197.29	662.37	628	29.86	38.21	0.0159	924.67	197.3	727.37	628	32.8	41.1
									0.0113	775.33	197.29	578.04	628	26.05	34.46	0.0167	893.87	197.3	696.57	628	31.4	39.73
									0.0119	719.03	197.29	521.74	628	23.52	31.96	0.0174	864.1	197.3	666.81	628	30.1	38.4
																0.0182	829.3	197.3	632.01	628	28.5	36.86
																0.0189	806.63	197.3	609.34	628	27.5	35.85
																0.0196	788.03	197.3	590.74	628	26.6	35.02
																0.0203	772.23	197.3	574.94	628	25.9	34.32
																0.021	757.8	197.3	560.51	628	25.3	33.68
																0.0217	742.77	197.3	545.47	628	24.6	33.01
																0.0224	726.2	197.3	528.91	628	23.8	32.28
																0.0231	709.13	197.3	511.84	628	23.1	31.52

Test data for high-strength concrete column specimen confined with yield strength of transverse reinforcement equals 503MPa

Specimen Lable																						
PN (unconfined)		2H1(confined)							2H2 (confined)							2H3 (confined)						
			Average Load(KN)			Average Stress (MPa)				Average Load(KN)			Average Stress (MPa)				Average Load(KN)			Average Stress (MPa)		
Strain	Ave. Str. (MPa)	Strain	Colu. spec.	Long. Rein.	Conc.	Long. Rein.	Conc.	Colu. spec.	Strain	Colu. Spec.	Long. Rein.	Conc.	Long. Rein.	Conc.	Colu. spec.	Strain	Colu. spec.	Long. Rein.	Conc.	Long. Rein.	Conc.	Colu. spec.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.009	0	0.9	0	0.9	0	0.041	0.04	0	0	0	0	0	0	0	0	0.65	0	0.65	0	0.029	0.029
0	0.116	0	27.4	0	27.4	0	1.235	1.218	0	0.25	0	0.25	0	0.011	0.011	3E-05	7.5	1.963	5.5365	6.25	0.25	0.333
0	0.585	0	57.9	0	57.9	0	2.61	2.573	0	3.9	0	3.9	0	0.176	0.173	6E-05	14.5	3.927	10.573	12.5	0.477	0.644
4E-05	1.241	0	94.4	0	94.4	0	4.255	4.196	3E-05	9.75	1.963	7.7865	6.25	0.351	0.433	0.0002	42.4	11.78	30.619	37.5	1.38	1.884
0.0001	2.31	6E-05	130.95	3.927	127.02	12.5	5.725	5.82	0.0002	19.5	9.817	9.6825	31.25	0.436	0.867	0.0003	95.8	19.63	76.165	62.5	3.433	4.258
0.0003	4.018	0.0002	171.65	9.817	161.83	31.25	7.294	7.629	0.0002	52.9	13.74	39.156	43.75	1.765	2.351	0.0004	140.55	27.49	113.06	87.5	5.096	6.247
0.0005	6.502	0.0002	209.6	13.74	195.86	43.75	8.828	9.316	0.0003	89.55	19.63	69.915	62.5	3.151	3.98	0.0005	176.8	33.38	143.42	106.3	6.465	7.858
0.0006	9.206	0.0003	243.2	19.63	223.57	62.5	10.08	10.81	0.0004	128.4	25.53	102.87	81.25	4.637	5.707	0.0007	211.1	41.23	169.87	131.3	7.657	9.382
0.0007	11.34	0.0004	275.85	23.56	252.29	75	11.37	12.26	0.0005	171.6	29.45	142.15	93.75	6.407	7.627	0.0008	245.1	47.12	197.98	150	8.924	10.89
0.0008	13.16	0.0004	308.5	27.49	281.01	87.5	12.67	13.71	0.0006	208.05	37.31	170.74	118.8	7.696	9.247	0.0009	278.75	54.98	223.77	175	10.09	12.39
0.0009	14.83	0.0005	341.15	33.38	307.77	106.3	13.87	15.16	0.0006	241.6	39.27	202.33	125	9.12	10.74	0.001	312.25	62.83	249.42	200	11.24	13.88
0.001	16.29	0.0006	373.55	39.27	334.28	125	15.07	16.6	0.0008	275.25	47.12	228.13	150	10.28	12.23	0.0011	345.6	66.76	278.84	212.5	12.57	15.36
0.0011	17.76	0.0007	405.8	41.23	364.57	131.3	16.43	18.04	0.0009	308.75	54.98	253.77	175	11.44	13.72	0.0012	378.9	74.61	304.29	237.5	13.72	16.84
0.0012	19.23	0.0008	438.2	49.09	389.11	156.3	17.54	19.48	0.001	342.5	62.83	279.67	200	12.61	15.22	0.0013	412.05	82.47	329.58	262.5	14.86	18.31
0.0014	20.66	0.0008	470.85	51.05	419.8	162.5	18.92	20.93	0.0011	375.9	68.72	307.18	218.8	13.85	16.71	0.0015	445.2	94.25	350.95	300	15.82	19.79
0.0015	21.8	0.0009	503.45	54.98	448.47	175	20.21	22.38	0.0013	409.4	78.54	330.86	250	14.91	18.2	0.0017	478.45	104.1	374.38	331.3	16.87	21.26
0.0016	23.6	0.001	535.85	62.83	473.02	200	21.32	23.82	0.0013	442.8	84.43	358.37	268.8	16.15	19.68	0.0018	511.25	111.9	399.33	356.3	18	22.72
0.0018	25.04	0.0011	568.5	66.76	501.74	212.5	22.62	25.27	0.0015	476.45	96.21	380.24	306.3	17.14	21.18	0.002	544.5	125.7	418.84	400	18.88	24.2
0.0019	26.51	0.0011	601.25	70.69	530.56	225	23.91	26.72	0.0016	510.6	102.1	408.5	325	18.41	22.69	0.0021	576.75	131.6	445.2	418.8	20.07	25.63

0.002	27.99	0.0012	633.9	72.65	561.25	231.3	25.3	28.17	0.0018	543.45	110	433.49	350	19.54	24.15	0.0022	609.45	137.4	472.01	437.5	21.28	27.09
0.0023	29.02	0.0013	666.65	80.5	586.15	256.3	26.42	29.63	0.0018	576.75	115.8	460.9	368.8	20.77	25.63	0.0023	642.15	145.3	496.85	462.5	22.39	28.54
0.0025	30.74	0.0014	703.15	86.39	616.76	275	27.8	31.25	0.002	610.65	127.6	483.02	406.3	21.77	27.14	0.0025	674.4	159	515.36	506.3	23.23	29.97
0.0026	32.16	0.0014	734.3	88.36	645.94	281.3	29.12	32.64	0.0022	644.15	139.4	504.74	443.8	22.75	28.63	0.0028	706.9	172.8	534.11	550	24.07	31.42
0.0028	33.64	0.0014	767.45	90.32	677.13	287.5	30.52	34.11	0.0024	677.5	151.2	526.31	481.3	23.72	30.11	0.003	739.3	188.5	550.8	600	24.83	32.86
0.003	35.1	0.0015	799.85	92.28	707.57	293.8	31.89	35.55	0.0025	711.75	155.1	556.63	493.8	25.09	31.63	0.0032	771.45	197.3	574.16	628	25.88	34.29
0.0032	36.52	0.0016	832.1	98.17	733.93	312.5	33.08	36.98	0.0027	744.8	166.9	577.9	531.3	26.05	33.1	0.0034	803.55	197.3	606.26	628	27.33	35.71
0.0036	36.68	0.0016	866.1	102.1	764	325	34.44	38.49	0.0028	777.7	176.7	600.99	562.5	27.09	34.56	0.0037	834.8	197.3	637.51	628	28.73	37.1
0.0036	34.8	0.0017	899.1	106	793.07	337.5	35.75	39.96	0.003	811.2	190.5	620.74	606.3	27.98	36.05	0.0039	867.45	197.3	670.16	628	30.21	38.55
0.004	32.56	0.0018	930.9	111.9	818.98	356.3	36.91	41.37	0.0033	845.8	197.3	648.51	628	29.23	37.59	0.0041	899	197.3	701.71	628	31.63	39.96
0.0044	29.63	0.0018	964.4	115.8	848.55	368.8	38.25	42.86	0.0035	879.45	197.3	682.16	628	30.75	39.09	0.0043	930.4	197.3	733.11	628	33.04	41.35
0.0049	29.85	0.002	997.25	123.7	873.55	393.8	39.37	44.32	0.0038	912.85	197.3	715.56	628	32.25	40.57	0.0045	962	197.3	764.71	628	34.47	42.76
0.0055	28.75	0.0021	1027.3	129.6	897.66	412.5	40.46	45.66	0.004	946.1	197.3	748.81	628	33.75	42.05	0.0046	993.35	197.3	796.06	628	35.88	44.15
		0.0022	1051.8	135.5	916.32	431.3	41.3	46.75	0.0043	979.25	197.3	781.96	628	35.25	43.52	0.0046	1023.6	197.3	826.26	628	37.24	45.49
		0.0023	1085.6	141.7	943.9	451	42.55	48.25	0.0048	1011.3	197.3	813.96	628	36.69	44.94	0.005	1054.6	197.3	857.26	628	38.64	46.87
		0.0023	1019.2	147.6	871.51	470	39.28	45.3	0.0051	1042.9	197.3	845.61	628	38.11	46.35	0.0055	1085.7	197.3	888.41	628	40.04	48.25
		0.0024	975.15	153.6	821.55	488.9	37.03	43.34	0.0056	1074.6	197.3	877.26	628	39.54	47.76	0.0067	1115.3	197.3	918.01	628	41.38	49.57
		0.0025	975.35	159.6	815.79	507.9	36.77	43.35	0.006	1103.8	197.3	906.51	628	40.86	49.06	0.0075	1143.3	197.3	945.96	628	42.64	50.81
		0.0026	975.5	163.6	811.92	520.7	36.6	43.36	0.0063	1130	197.3	932.66	628	42.04	50.22	0.0082	1166.9	197.3	969.56	628	43.7	51.86
		0.0027	971.55	169.6	801.98	539.8	36.15	43.18	0.0065	1151.9	197.3	954.56	628	43.03	51.19	0.0089	1192.4	197.3	995.06	628	44.85	52.99

									0.0066	1150.1	197.3	952.76	628	42.94	51.11	0.0098	1199.6	197.3	1002.3	628	45.18	53.32
									0.0069	1072.1	197.3	874.76	628	39.43	47.65	0.0108	1187.9	197.3	990.56	628	44.65	52.79
									0.0072	1034.2	197.3	836.86	628	37.72	45.96	0.0119	1130.7	197.3	933.41	628	42.07	50.25
									0.0076	1025.6	197.3	828.26	628	37.33	45.58	0.0131	1008.9	197.3	811.61	628	36.58	44.84
									0.0089	1021.1	197.3	823.76	628	37.13	45.38	0.0137	943.9	197.3	746.61	628	33.65	41.95
									0.0099	1016.8	197.3	819.51	628	36.94	45.19	0.0143	914.65	197.3	717.36	628	32.33	40.65
									0.0105	989.65	197.3	792.36	628	35.71	43.98	0.0149	903.65	197.3	706.36	628	31.84	40.16
									0.0106	874.45	197.3	677.16	628	30.52	38.86	0.0155	891.25	197.3	693.96	628	31.28	39.61
																0.0161	881.45	197.3	684.16	628	30.84	39.18
																0.0167	873.5	197.3	676.21	628	30.48	38.82
																0.0173	860.35	197.3	663.06	628	29.89	38.24
																0.0178	850.05	197.3	652.76	628	29.42	37.78
																0.0184	837.3	197.3	640.01	628	28.85	37.21
																0.019	825.95	197.3	628.66	628	28.34	36.71
																0.0196	814.95	197.3	617.66	628	27.84	36.22
																0.0202	801.95	197.3	604.66	628	27.25	35.64

Fig. Formwork provided for specimen



Fig. Casting column specimen



Fig. Specimen ready for test

