Experimental Study of Confined Low-, Medium- and High-Strength Concrete Subjected to Concentric Compression

Antonius[1] & Iswandi Imran[2]

[1]Department of Civil Engineering, Universitas Islam Sultan Agung,
Jl. Raya Kaligawe Km. 4, Semarang 50112, Indonesia
[2]Structural Engineering Research Group, Civil Engineering Department,
Institut Teknologi Bandung, Jl. Ganesa No.10, Bandung 40132, Indonesia
Email: antoni67a@yahoo.com

Abstract. An experimental study of 23 low-, medium- and high-strength concrete columns is presented in this paper. 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 30 MPa and 70 MPa. The test parameters in the study are concrete compressive strengths and confining steel properties, i.e. spacing, volumetric ratios and configurations. The effects of these parameters on the strength and ductility of square-confined concrete were evaluated. Of the specimens tested in this study, the columns made with higher-strength concrete produced less strength enhancement and ductility than those with lower-strength concrete. The steel configurations were found to have an important role in governing the strength and ductility of the confined high-strength concrete. Moreover, several models of strength enhancement for confined concrete available in the literature turned out to be quite accurate in predicting the experimental results.

Keywords: *confinement; ductility; high-strength concrete; strength.*

1 Introduction

1.1 Background

High-strength concrete (HSC) is gaining popularity in the last decade. This material has been used in many types of constructions, such as high-rise buildings, bridges, marine structures, offshore platforms etc. One of the advantageous characteristics of high-strength concrete is the high strength-to-weight ratio. This enables the use of reinforced concrete columns with smaller cross-sectional dimensions for high-rise buildings.

The development of concrete technology and practice has led to a changing perception of the definition of high-strength concrete [1-3]. CEB-FIP [4] and

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Nishiyama [5] define HSC as a concrete having a minimum 28-day compressive strength of 60 MPa. In North America, HSC is usually considered to be a concrete with a 28-day compressive strength of at least 41 MPa. In this paper, concrete with a strength up to 41 MPa is defined as low-strength concrete, concrete with a strength from 41 to 55 MPa as medium-strength concrete, and concrete with a strength above 55 MPa as high-strength concrete.

Although high-strength concrete offers many advantages in terms of performance, and also costs, its brittle behavior remains a major drawback in the case of seismic applications. Because of their brittleness, high-strength concrete columns commonly exhibit premature cover spalling under high compression [6].

Many researchers have reported the lack of ductility and deformation capacity of HSC columns [7-10]. 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 [5,10].

Current design provisions in the Indonesian National Standard for reinforced-concrete design of buildings (SNI-03-2847-2002) [11], which is similar to ACI 318 [12], are not applicable to the design of HSC columns. Strength and ductility aspects of HSC columns are one area where design provisions are still limited.

Early research on confined concrete, leading to the formulation of empirical stress-strain relationships, was generally carried out on small- and large-scale, concentrically loaded specimens. Many research reports on confined concrete ($f'c \leq 38$ MPa) are available in the literature [13-15]. The same can be said about confined high-strength concrete [7,9,10,16-19]. However, very limited test data are available from experimental investigations covering low-, medium- and high-strength concrete column specimens. The common approach in the literature is to study cases with different concrete strength classifications separately. Many design variables have been considered in each of these researches. The amount of confining steel receives the most attention in many researches. Other test parameters considered include the compressive strength of concrete, the yield strength of rebar, the distribution of longitudinal steel, tie spacing, and cross-section dimensions. It is the purpose of the research presented in this paper to complement the available confined concrete database with the compressive strength of confined concrete ranging from low to high. The results of this study will provide much needed general design information for normal- and high-strength concrete columns.

1.2 Research Significance

Research on confined concrete, especially with a wide range of compressive strengths (i.e. covering normal- and high-strength concrete), still needs to be conducted. The design equations in the present concrete code are only applicable for normal-strength concrete columns ($f'_c \leq 55$ MPa) [11,12]. Research focusing on confined concrete columns with a compressive strength ranging from normal to high will provide a significant contribution to the understanding of the general behavior of confined concrete.

2 Experimental Programs

2.1 Materials and Ranges of Concrete Strengths

Three different mixes were used to attain the cylindrical strength targets of low-, medium- and high-strength concrete, denoted as L, M and H (see Table 2). For this research, the sand and coarse aggregate used were taken from a local quarry. The size of the coarse aggregate was in the range between 8 and 14 mm. A superplasticizer (SP) from the brand named Sikament NN was used to improve the workability of the high-strength concrete mixes. In addition, for the high-strength mixes fifteen percent by weight of the Portland cement was replaced with Fly Ash.

The confining steel used was plain rebar with a diameter of 5.5 mm and a yield strength of 398 MPa. The yield strength was determined by tension tests of three sample bars (Figure 1).

Table 1 summarizes the dimensions, number of test specimens, concrete strengths and volumetric ratios of confining steel used in several experimental studies conducted on square-confined concrete columns under concentric loadings, from 1990 to 2007. Most of the studies shown in Table 1 were conducted either with low-, medium- or high-strength concrete columns. Only one study was conducted with a wider range of concrete strengths, i.e. from low- to high-strength concrete [16].

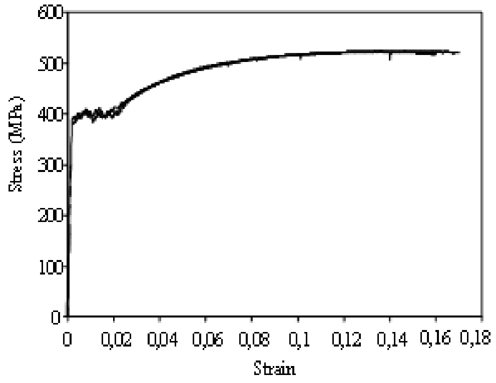


Figure 1 Stress-strain relationship of confining steel used in this test program.

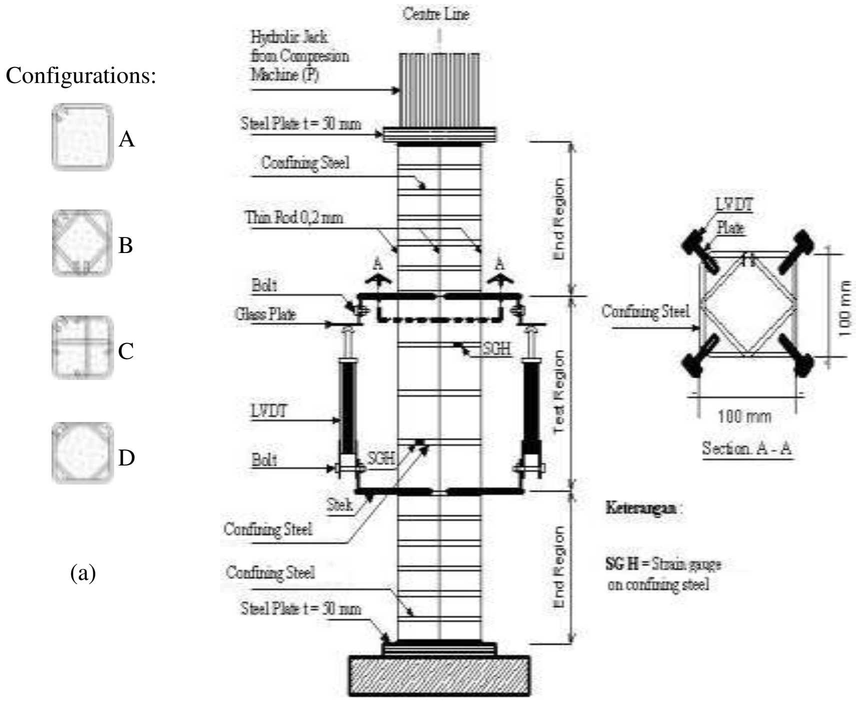
In this study, the range of concrete strengths used for the test specimens varied from 30 to 70 MPa. This range was selected to complement the database of columns tested under concentric loading as shown in Table 1.

Table 1 Columns with a square section tested under concentric loading (1990-2007).

Researchers	Amount of specimens	Dimensions (mm)	f'_c (MPa)	ρ_s (%)	f_y (MPa)
Nagashima, *et al.*, 1992, [18]	26	225x225	61-120	1.6-4	823-1414
Cusson & Paultre, 1994, [17]	30	235x235	52-123	1.4-5	392-770
Sun, *et al.*, 1994, [19]	14	200x200	52-55	1.7-4.5	889-1046
Saatcioglu &Razvi, 1998, [10]	24	250x250	60-124	0.9-4.6	400-1000
Li, *et al.*, 2000, [16]	27	240x240	41-97	0.8-5.0	445-1318
Ming Chung, *et al.*, 2006, [13]	17	200x200	17-34	0.2-2.3	-
Husem & Pul, 2007, [20]	36	150x150	~ 64	0.5-3.1	-

2.2 Specimen Details and Instrumentation

For this research, 23 confined and unconfined concrete columns (dimensions 100 x 100 x 500 mm) were designed. Figure 2 shows the columns' cross-sections and instrumentation. The specimens were designed without longitudinal reinforcement or concrete cover in order to study purely the behavior of the confining steel. For the purpose of the test, the total height of each column was divided into 3 regions, comprising of two 150 mm regions at each end of the column, and a 200 mm region in the middle. The specimens were categorized into four configurations as shown in Table 2 (i.e. configurations A, B, C and D), representing different arrangements of confining steel. FLA-5 type strain gauges were used to monitor the strains in the confining steel, and displacement transducers (LVDT) were used to measure axial deformations in the tested columns.



(a)

(b)

Figure 2 Instrumentation of specimens.

Axial deformations were measured within each of the 3 regions along the column height. The overall head movement of the test machine was also measured. All instrumentations were connected to a computer-based data acquisition system. Figure 3 shows the reinforcement cages.

2.3 Test Procedure

All columns were tested under concentric compression produced by a Dartec Universal Testing Machine (UTM) with a capacity of 1200 kN. The tests were done under displacement control. The test setup is shown in Figure 4. The load was given in regular increments, and sets of deformation readings were taken at every load stage.

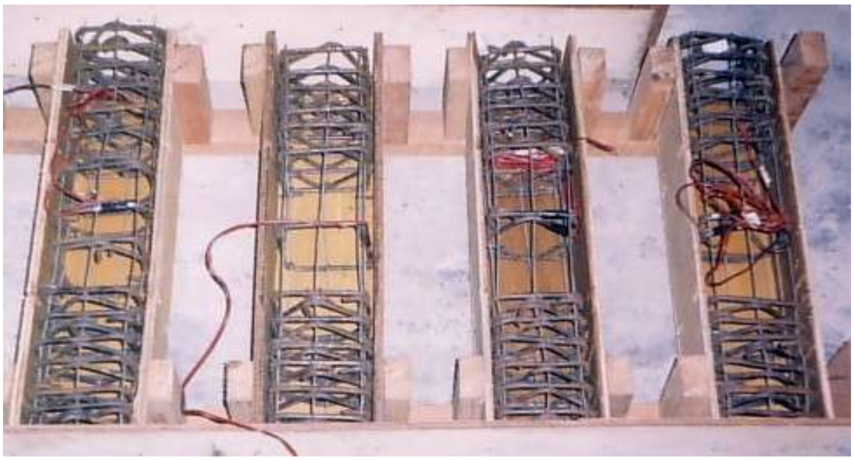


Figure 3 Typical reinforcement cages for confined concrete.

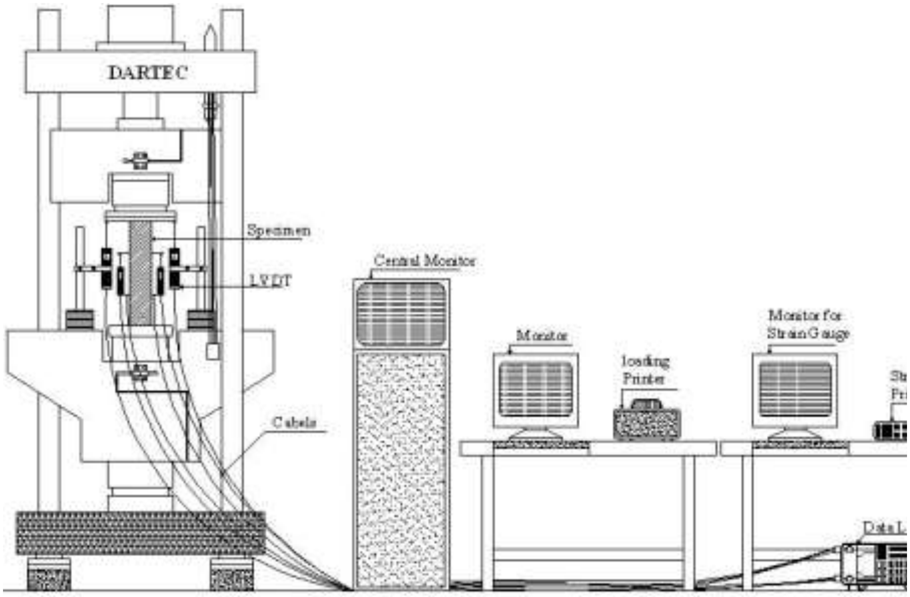


Figure 4 Test set-up.

2.4 Strength and Ductility Computation

Strength enhancement due to confinement is expressed as the ratio of confined to unconfined concrete strength in the member (i.e. $K=f'_{cc}/f'_{co}$). The confined concrete area was measured from center to center of the steel perimeter. 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.

For this research, the energy method was used to measure ductility. With this method the ductility is calculated based on the area under concrete stress (f_{cc}) versus the axial strain (ε) curve (see Figure 5). The ductility indices are denoted as μ_E, that is the area OACDE divided by the area OAB, where B corresponds to the yield strain ε_y, and E corresponds to the point of first fracture of the confining steel. The $0.85f'_{cc}$ rule is used to define the yield strain.

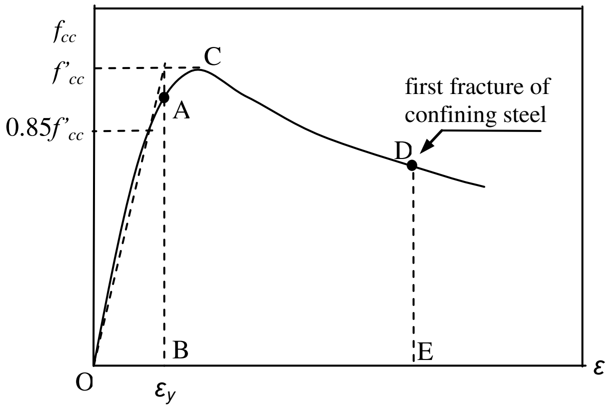


Figure 5 Ductility measurement.

3 Experimental Results and Discussion

The results of the experimental work on the test specimens are provided in Table 2 and Figure 6 shows examples of failure in the test specimens.

Figure 7 shows the measured stress-strain results of the tested columns. The ascending branches of measured stress-strain relationships in all test columns are almost linear. In addition, the descending branches of the columns with a higher-strength concrete are steeper than those with a lower-strength concrete. The unconfined concrete columns, i.e. SCL, SCM and SCH, failed in a sudden and explosive manner at peak load. The measured compressive strength of unconfined concrete for low-, medium- and high-strength concrete were respectively 0.86, 0.85 and 0.82 of the compressive strength of the concrete cylinder.

Table 2 Detail of confining steel and test results.

Specimen	f'_c (MPa)	Confining steel				P_{max} (kN)	f'_{cc} (MPa)	K	μ_E
		Conf.	Ø-spacing	ρ_s (%)	At peak response				
SCL	34	-	-	-	-	-	-	-	-
SCM	45	-	-	-	-	-	-	-	-
SCH	67	-	-	-	-	-	-	-	-
AL5	34	 A	5.5 – 50	2.01	Yield	301.84	33.80	1.16	5.7
AM5	45		5.5 – 50	2.01	Yield	381.77	42.75	1.12	5.7
AM10			5.5 – 100	1.005	Yield	341.22	38.21	1	2.8
AH5	67		5.5 – 50	2.01	Yield	533.23	59.71	1.10	3.7
AH10			5.5 – 100	1.005	Yield	489.47	54.81	1	1.8
BL5	34	 B	5.5 – 50	3.43	Yield	300.86	33.69	1.37	10.7
BM5	45		5.5 – 50	3.43	Yield	453.39	50.77	1.33	7.3
BM10			5.5 – 100	1.72	Yield	341.14	38.20	1	2.3
BH5	67		5.5 – 50	3.43	No yield	631.64	70.73	1.29	7.5
BH10			5.5 – 100	1.72	Yield	499.92	55.98	1.02	1.8
CL5	34	 C	5.5 – 50	3.02	Yield	329.26	36.87	1.27	9.5
CM5	45		5.5 – 50	3.02	Yield	375.25	42.02	1.24	6.6
CM10			5.5 – 100	1.51	Yield	341.40	38.23	1	2.6
CH5	67		5.5 – 50	3.02	Yield	606.63	67.93	1.10	11.3
CH10			5.5 - 100	1.51	Yield	496.97	55.65	1.02	2.1
DL5	34	 D	5.5 – 50	3.63	Yield	390.88	43.77	1.50	7.4
DM5	45		5.5 – 50	3.63	No yield	444.01	49.72	1.30	3.6
DM10			5.5 – 100	1.82	Yield	341.05	38.19	1	2.8
DH5	67		5.5 – 50	3.63	No Yield	558.41	62.53	1.16	4
DH10			5.5 – 100	1.82	Yield	509.02	57.00	1.04	2.1

(a) (b)

Figure 6 Failure of specimens: (a) tie spacing 50 mm, (b) tie spacing 100 mm.

Experimental studies of high-strength concrete columns conducted by many researchers indicate that confining steel does not yield at peak response [1,10,21]. Similar behavior can also be seen in the specimens made of medium- and high-strength concrete tested in this study, especially those with a high volumetric ratio of confining steel (i.e. specimens BH5, DM5 and DH5).

3.1 Effect of Compressive Strength

Concrete strength is one of the primary variables investigated extensively in this test. Columns with the same amount and arrangement of reinforcement but with distinctly different concrete strengths were tested to study the effects of this parameter.

Figure 7 shows the comparison of four columns with different concrete strengths. The results indicate a consistent decrease in strength enhancement and ductility as the concrete strength increases. However, when the volumetric ratio of confining steel is moderate, as in the case of column CH5, the column shows ductile behavior and the effect of the concrete strength becomes insignificant.

The relationship between the concrete strength and the strength enhancement of confined concrete (*K*) with different configuration variables can be seen in Figure 8. All of the specimens show a decrease of strength enhancement as the concrete strength increases. It can also be seen that the specimen with configuration D has the highest K value for low-strength concrete (f'_c=34 MPa). The specimen with configuration B has the highest K value for medium- and high-strength concrete.

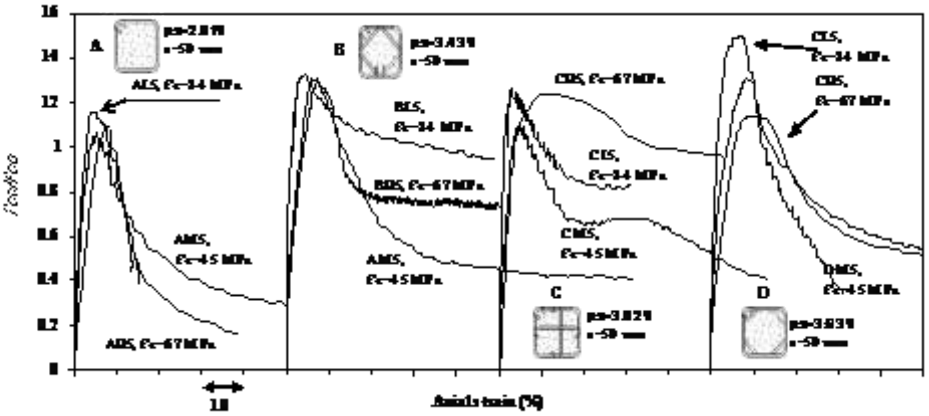


Figure 7 Curves of confined concrete with different concrete strengths.

Figure 8 also shows that when the volumetric ratio of confining steel is very high, as in the case of specimens with configuration D, the K value decreases quickly when used with medium- and high-strength concrete.

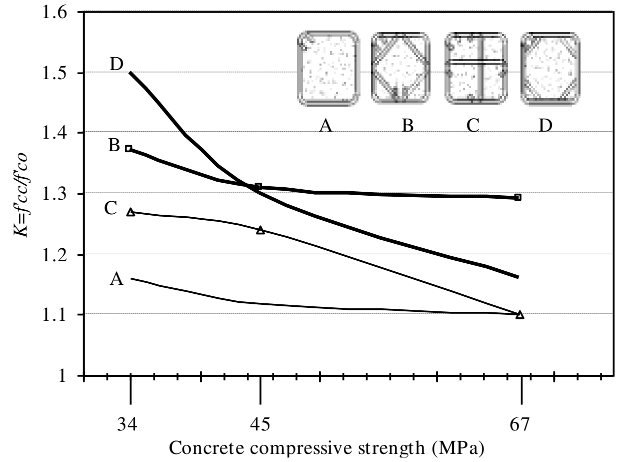


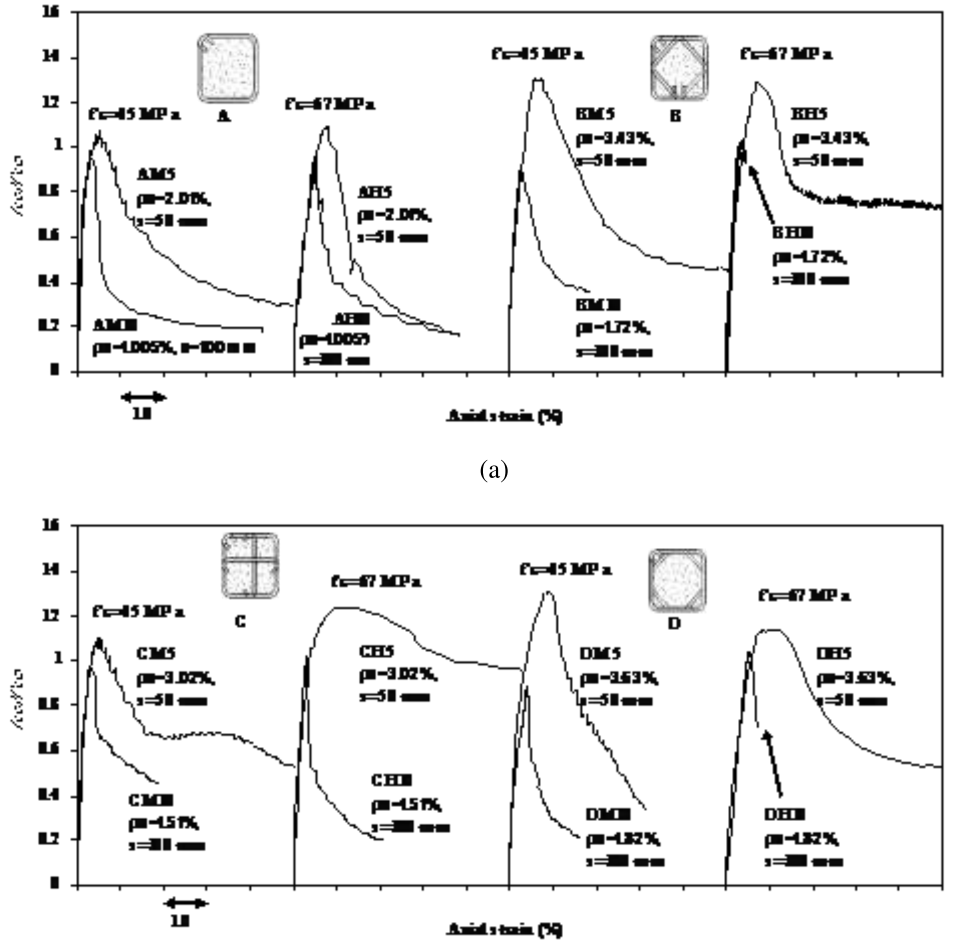
Figure 8 Influence of strength enhancement of confined concrete on concrete strength.

3.2 Effect of Tie Spacing

Experimental and theoretical evidence has shown that tie spacing plays a significant role in the mechanism of confined concrete [1,10,15]. The behavior of confined concrete with different tie spacings is shown in Figure 9. The columns have a different volumetric ratio of confining steel. The effectiveness of the confining steel diminishes quickly when the tie spacing increases. Specimens with a wide tie spacing may not develop any confinement. The medium- and high-strength concrete specimens tested in this study did not develop any confinement when the tie spacing was equal to the cross-section (see Figure 9 for specimens AM10, AH10, BM10, BH10, CM10, CH10, DM10 and DH10).

3.3 Effect of Volumetric Ratio and Steel Configuration

In general, both the strength and ductility of confined concrete increase as the volumetric ratio increases. An increase in the volumetric ratio of confining steel can also be expressed in terms of the confining configuration. This parameter affects the distribution of the confinement pressure and hence of its efficiency.



(a)

(b)

Figure 9 Curves of confined concrete with different tie spacings: (a) steel configurations A and B; (b) steel configurations C and D.

The significance of the volumetric ratio of confining steel is illustrated in Figure 10. The test data indicate that both the strength and the ductility of medium- and high-strength concrete increase as the volumetric ratio increases. Specimens with a low volumetric ratio (specimens with configuration A) exhibit brittle behavior, showing a high rate of strength decay immediately after peak response.

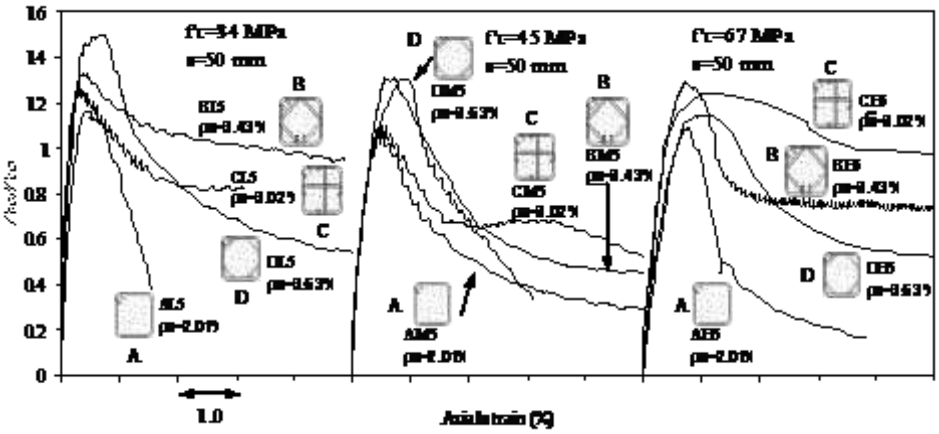


Figure 10 Curves of confined concrete with various of volumetric ratio configurations

It is clear from Table 2 and Figure 10 that steel configuration B for confined low- and medium-strength concrete shows better ductility compared to the other configurations. Note that the specimens with configuration B have the highest volumetric ratio. Similar behavior was observed in confined high-strength concrete. The lateral pressure of the confining steel in specimen CH5 (ρ_s=3.02%) is more effective for improving the ductility of the confined concrete than in the specimens with a higher volumetric ratio (BH5, ρ_s=3.43% and DH5, ρ_s=3.63%). The confining steel of specimen CH5 yields at peak response, so that the maximum lateral pressure can be mobilized. However, in specimens BH5 and DH5 the confining steel does not yield at peak response. These results confirm that the configuration of confining steel has significant effects on the ductility of confined high-strength concrete.

3.4 Efficiency of Confinement

The confining-steel requirements in SNI-03-2847-2002 [11] and ACI 318 [12] are based on an arbitrary performance criterion that requires columns to maintain their concentric capacities beyond the spalling of the concrete cover. Therefore, the requirements for rectilinear reinforcement are obtained through an arbitrary extension of the requirements for circular spirals [5]. Hence, the configuration and the resulting efficiency of the confining steel are not recognized as design parameters.

The experimental results discussed above indicate that the test variables have a significant influence on confinement efficiency. Saatcioglu & Razvi [14] introduced the efficiency of confining steel through coefficient k_2:

$$k_2 = 0.15\sqrt{\left(\frac{b_c}{s}\right)\left(\frac{b_c}{s_1}\right)} \leq 1.0 \tag{1}$$

The variation of experimentally obtained strength enhancement values with the ratio $k_2\rho_s f_y/f'_c$ is displayed in Figure 11. This figure indicates that the strength enhancement increases approximately linearly with a ratio of $k_2\rho_s f_y/f'_c$. A similar phenomenon is occured in the investigation carried out by Saatcioglu and Razvi [10].

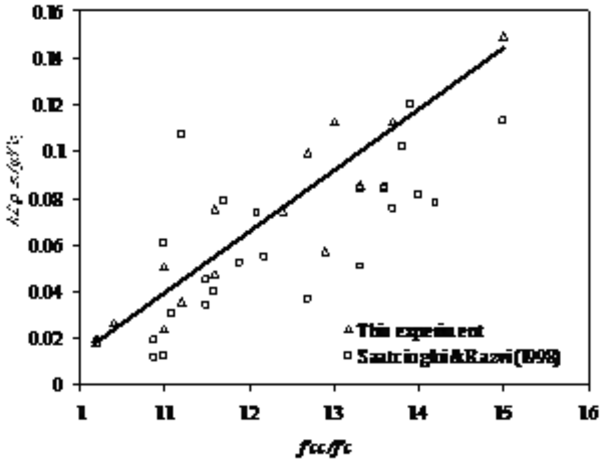


Figure 11 Relationship between strength enhancement and k2ρsfy/f'c ratio.

3.5 Comparison of Strength Enhancement of the Confined Concrete Equations

The strength enhancement of confined concrete (*K*) as discussed above plays an important role in governing the minimum requirements for confining steel in reinforced concrete columns. Figure 12 shows a comparison between the strength enhancement values of confined concrete (*K*) from this study and from equations proposed by Ansari & Li [22], CEB-FIP [23], Imran & Pantazopoulou [24], Muguruma, *et al.* [9] and Legeron & Paultre [3]. Strength enhancement equations for confined concrete are shown in Table 3, including a comparison of results between equations and experimental results, denoted by the Coefficient of Variation (COV) value.

The comparison shows that the COV value for the Ansari & Li equation is 23.3% and for the CEB-FIP equation is greater than 10%. Other equations provide a good prediction of the K value with a COV of less than 10% (see Table 3).

Table 3 *K* equations and COV value in relation to this experiment.

Researcher	Equations	Comments	COV
Muguruma, *et al.*, 1993 [9]	$K = \frac{f'_{cc}}{f'_c} = 1 + 49.f_2$ $f_2 = 0.313.\rho_w \frac{\sqrt{f_{yw}}}{f'_c}\left(1 - \frac{s}{d_{so}}\right)$	Equation derived from a test of confined concrete columns with square sections $(20<f'_c< 160$ Mpa	3%
Ansari & Li, 1998 [22]	$K = \frac{f'_{cc}}{f'_c} = 1 + 2.45.\left(\frac{\sigma_3}{f'_c}\right)^{0.703}$	The proposed equation utilizes active confinement tests and was derived using the Ottosen criteria.	23.3%
Imran & Pantazoupoulou, 2001 [24]	$K = \frac{f'_{cc}}{f'_c} = \left(\frac{f_2}{f'_c} - 0.021\right) +$ $\sqrt{1.043 + 10.571\frac{f_2}{f'_c}}$	Equation based on active confinement tests and Hsieh-Ting-Chen criteria.	9.7%
Legeron & Paultre, 2003 [3]	$K = \frac{f'_{cc}}{f'_c} = 1 + 2.4\left(I_e'\right)^{0.7}$	Proposed model based on experimental tests of normal- and high-strength concrete square columns.	7.9%
CEB-FIP, 2010 [23]	$K = \frac{f'_{cc}}{f'_c} = 1 + 5\frac{\sigma_2}{f'_c}$; $\sigma_2 \leq 0.05f'_c$ $K = \frac{f'_{cc}}{f'_c} = 1.125 + 2.5\frac{\sigma_2}{f'_c}$; $\sigma_2 > 0.05f'_c$	Proposed equation based on experimental research of normal-strength concrete square and circular columns	10.9%

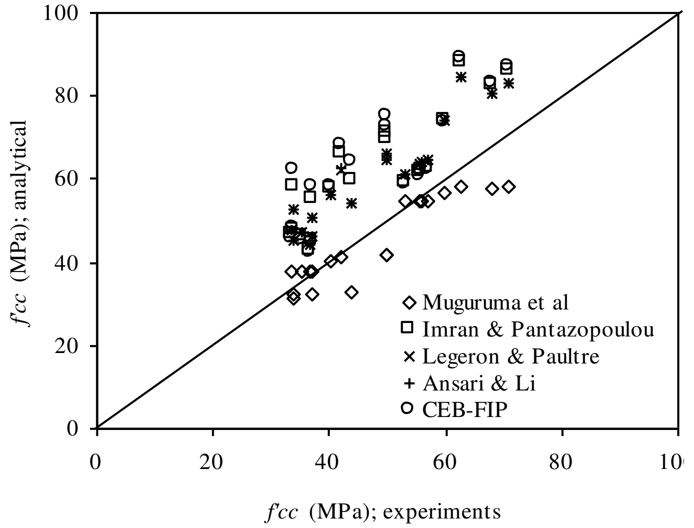


Figure 12 *K* values of models versus experimental values.

4 Conclusion

The behavior of confining steel at peak response of confined high-strength concrete indicates that yield is not always reached, although the yield strength of the confining steel used, i.e. 398 MPa, is still within the value recommended by the concrete code (i.e. <400 MPa). This fact is critical for the confinement modeling, especially to predict the amount of lateral stress developed in the confining steel. It is clear from the experimental results that the descending branch of confined low-, medium- and high-strength concrete varied significantly, depending on the design parameters (concrete strength, volumetric ratio and tie spacing of confining steel). The configuration of confining steel also has a significant influence on the ductility behavior of low- to high-strength confined concrete. This behavior has not been considered in the code philosophy of maintaining axial load capacity of a section after cover spalling.

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 confinement, 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.

Several equations proposed for estimating the strength enhancement of confined concrete (*K*) exhibit good agreement with the experimental results, namely the Muguruma, *et al*. model, the Imran & Pantazoupoulou model and the Legeron & Paultre model. This indicates that the models can be utilized to predict the *K* value of confined low-, medium- and high-strength concrete columns with square sections, as long as the effectively confined concrete core area is considered properly.

Acknowledgments

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Notations

A_c = core area measured from center to center of confining steel
A_g = gross area of concrete column
b_c = core dimension measured center to center of confining steel
$\O$ = diameter of reinforcement
f_2 = lateral stress of confining steel
f'_c = compressive strength of standard cylinder test at 28 days
f_{cc} = stress of confined concrete
f'_{cc} = peak stress of confined concrete
f'_{co} = peak stress of unconfined concrete
f_y = yield stress of confining steel
ε_y = strain corresponding to the 0.85 peak stress of confined concrete
I_e = confining stress index (Legeron & Paultre model)
K = strength enhancement of confined concrete
$= f'_{cc}/f'_{co}$
μ_E = ductility energy of confined concrete
P_{max} = maximum compressive load resisted by column
ρ_s & ρ_w = volumetric ratio of confining steel
s = spacing of confining steel measured center to center of the steel
s_l = spacing of longitudinal reinforcement
σ_2 = lateral stress of confined concrete (CEB-FIP model)