THESIS

EFFECT OF SPECIMEN SHAPE AND SIZE ON COMPRESSIVE STRENGTH OF HIGH-STRENGTH CONCRETE

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GRADUATE SCHOOL, KASETSART UNIVERSITY
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THESIS APPROVAL

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THESIS

EFFECT OF SPECIMEN SHAPE AND SIZE ON COMPRESSIVE STRENGTH OF HIGH-STRENGTH CONCRETE

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the Requirements for the Degree of
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High-strength concrete is currently a common construction material and its compressive strength is the most basic and important material property in structural design. However, it needs to be consistent in using this value because the control specimen sizes and shapes may be different and the conversion factors for concrete having compressive strength higher than 500 kg/cm^2 are not available in the current standard of practice published by the Engineering Institute of Thailand. In this study, the influences of specimen size and shape on compressive strength of high-strength concrete are investigated using four different specimen types i.e. cube 100 mm, cube 150 mm, cylinder Ø100x200 mm and cylinder Ø150x300 mm. A total of 288 specimens were cast from four different concrete mixes having design compressive strength (standard cylindrical strength) of 550, 700, 850 and 1000 kg/cm^2.

After testing of specimens at 7 and 28 days, the results show that the cube specimen is generally stronger than the cylinder specimen and this effect will be gradually decreased when the concrete strength increased. The ratio of the compressive strength at 28 days of Ø150x300 mm cylinder to the 150 mm cube is varied from 0.78 to 0.86 for the designed cylinder compressive strength of 550 to 1,000 kg/cm^2. For the effect of specimen size, the results show that compressive strength increases as the specimen size decreases. From the 28-days test results, the ratio of 150 mm to 100 mm cube strength and Ø150x300 mm to Ø100x200 mm cylinder strength are 0.96 and 0.97, respectively. This size effect might be ignored as the relationships showed that the effect is relatively small compared to specimen shape effect.

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Satja Muangnok

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LIST OF SYMBOLS AND ABBREVIATIONS

ACI	=	American Concrete Institute
ASTM	=	American Society of Testing and Materials
BS	=	British Standard
CF	=	Conversion factor for effect of specimen type
cm	=	Centimeter
d	=	Diameter or width of specimen
EIT	=	Engineering Institute of Thailand
ESD	=	Extreme standardize deviation
$f_c^{'}$	=	Compressive strength of concrete (N/mm^2 or kg/cm^2)
$f_{cy}^{'}$	=	Compressive strength of concrete cylinder (N/mm^2 or kg/cm^2)
$f_{cu}^{'}$	=	Compressive strength of concrete cube (N/mm^2 or kg/cm^2)
HPC	=	High-performance concrete
HSC	=	High-strength concrete
kg	=	Kilogram
ksc	=	Kilogram per square centimeter
l	=	Length or height of specimen
LSM	=	Least square method
l/d	=	Aspect ratio
mm	=	Millimeter
MPa	=	Mega Pascal or Newton per square millimeter
MSEL	=	Modified size effect law
n	=	Number of samples
N	=	Newton
NSC	=	Normal-strength concrete
OPC	=	Ordinary Portland cement
psi	=	Pound per square inch
r	=	Correlation coefficient

LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

s	=	Standard deviation
$\bar{s}$	=	Median of absolute deviations from the median
SEL	=	Size effect law
TIS	=	Thai Industrial Standard
V	=	Coefficient of variation
w	=	width of specimen
w/b	=	Water to binder ratio
w/c	=	Water to cement ratio
X_i	=	Data value
$\overline{X}$	=	Sample mean value
$\overline{X}_m$	=	Sample median value
Z_i	=	Coefficient for detecting of outlier data
Ø	=	Diameter of cylinder specimen

EFFECT OF SPECIMEN SHAPE AND SIZE ON COMPRESSIVE STRENGTH OF HIGH-STRENGTH CONCRETE

INTRODUCTION

As the use of high-strength concrete (HSC) has become a common practice in various applications for many decades, especially for high-rise buildings, long span bridges and repair and rehabilitation works, it is important to have confidence in the suitable and applicability of current testing practices. The 28-days compressive strength of concrete determined by a standard uniaxial compression test is accepted universally as a general index of concrete strength. Among several parameters, size and shape of test specimens are two of the most important parameters that influence the result of concrete compressive strength due to its fracture characteristics. There are basically two shapes of test specimen, cube and cylinder, used in the determination of the compressive strength of concrete. In the British approach, 150 mm cube is employed as standard specimen while Ø150x300 mm cylinder is commonly used in the American approach.

Thailand is one of several countries that uses both cylinder and cube as standard test specimens to establish the characteristic compressive strength. Because of the differences in the shape, aspect ratio, and the associated end restraint provided by the machine platen, cube and cylinder strengths obtained from the same batch of concrete are different, the higher strength being given by the cubes (Mansur and Islam, 2002). Investigations conducted at various research centers around the globe have indicated that the factor that relates cube strength to cylinder strength does not remain constant for all grades of concrete. Moreover, when concrete strength increases and testing laboratories do not have the capabilities to break standard cubes or cylinders, it results in many reports of concrete strength being based on smaller specimens, e.g. 100 mm cubes or Ø100x200 mm cylinders. Therefore, introducing of size parameters for the test specimens in order to translate the test data to the strength of standard control specimens is also necessary for HSC.

OBJECTIVES

The main objectives of this present research study are:

1. To experimentally investigate the characteristics of compressive strength from different size and shape of specimens.

2. To compare the compressive strengths obtained from the same concrete mix with varying size and shape of specimen.

3. To suggest the size and shape factors to convert the compressive strength of concrete determined from various types of specimen to standard Ø150x300 cylinder strength.

Scope of Research

This research study will be performed with the scope listed below:

1. This study only deals with axial compressive strength from test specimens at 7 and 28 days with limited variables to the specimen type and strength level of concrete.

2. Test specimens in this study are cylinders (Ø100x200 mm and Ø150x300 mm) and cubes (100 mm and 150 mm). The concrete compressive strengths are expected to be 550, 700, 850 and 1000 kg/cm^2 (standard cylindrical strength at 28 days). The specimens shall be tested by uniaxial load until ultimate load capacity is reached.

LITERATURE REVIEW

With the increasing use of High-Strength Concrete (HSC), it is important to have confidence in the suitable and applicability of current testing practices. Refinement and verification may be needed for the factors that may have an effect on compression test results. For normal strength concrete (NSC), the influence of the foregoing factors has been studied and reported. For HSC, however, very few investigations have been reported concerning these aspects. As the uniaxial test is used to monitor the compressive strength of concrete for quality control or acceptance purpose, the parameters that are used to establish the characteristic compressive strength need to be carefully controlled.

Imam *et al.* (1995) investigated the important factors, i.e. specimen size, specimen shape and mould material, which may have an effect on compressive testing results of high-strength concrete. Compressive tests were performed on 6 different specimen types with a total of 360 specimens cast from 18 different high-strength concrete mixtures (f_c' = 82-117 MPa). From the results, they have concluded that the compressive strength decreases about 5% for each 50 mm increase of the cube size and the concrete compressive strength of 150 mm cube specimen is about 5.8% greater than that of Ø150x300 mm cylinder specimen. Also conversion factors were given, as shown in Table 1.

Table 1 Conversion factors between different specimen types

Conversion to	from	Cast iron moulds				Plastic moulds	
		Cylinder 150x300 mm	Cube 100 mm	Cube 150 mm	Cube 200 mm	Cube 100 mm	Cube 150 mm
Cast iron moulds	Cylinder 150x300 mm	1.000	0.897	0.945	0.989	0.968	1.050
	Cube 100 mm	1.115	1.000	1.053	1.103	1.079	1.170
	Cube 150 mm	1.058	0.950	1.000	1.046	1.025	1.110
	Cube 120 mm	1.011	0.907	0.956	1.000	0.979	1.061
Plastic moulds	Cube 100 mm	1.033	0.927	0.976	1.021	1.000	1.084
	Cube 150 mm	0.953	0.855	0.901	0.942	0.922	1.000

Source: Imam *et al.* (1995)

Tokyay and Özdemir (1997) investigated the specimen size and shape effects on the compressive strength of high-strength concrete. The experimental study was performed on different sizes of cylinder and cube specimens cast from three concrete mixtures having compressive strength levels of 40, 60 and 75 MPa. The results show that strength values of 75 mm diameter cylinder and 75 and 100 mm cube specimens were lower than those of the larger specimens used.

Mansur and Islam (2002) performed an experimental study on the effects of different concrete specimen types on the compressive strength and established the inter-relationships between their strengths. Each of a total eleven test data sets generated in this study consists of five strength values for the five different types of test specimens. Each strength value was calculated by averaging the strength of at least three identical specimens. A total of 210 specimens were tested in this program. In the analysis, the 150 mm cube compressive strength was taken as the reference, and strength values determined for each type of specimen were converted to the corresponding standard cube strength by using suitable expressions obtained from linear regression analyses.

For the four sets of test data involving 150 mm cube strength as the reference, the linear regression analyses carried out yielded the following relationships between standard cube strength and the strengths determined by four other types of test specimens:

• For Ø150x300 mm cylinder:

$$(f_c')_{cu150} = 1.01(f_c')_{cy150x300} + 9.94 \qquad (1)$$

• For Ø100x200 mm cylinder:

$$(f_c')_{cu150} = (f_c')_{cy100x200} + 6.41 \qquad (2)$$

• For Ø100x100 mm cylinder:

$$(f_c')_{cu150} = 0.92(f_c')_{cy100x100} + 5.14 \quad (3)$$

• For 100 mm cube:

$$(f_c')_{cu150} = 0.91(f_c')_{cu100} + 3.62 \quad (4)$$

in which $(f_c')_{cu}$ and $(f_c')_{cy}$ are cube and cylinder strengths in MPa, respectively; and the subscripts denote the size of the specimens in mm. The correlation coefficients, *r*, for the above four regression analyses are close to unity, the minimum being 0.978. The correction factors were also presented as shown in Table 2 and 3.

Table 2 Correction factors to convert concrete strength to equivalent 150 mm standard cube strength

Compressive strength of concrete (MPa)	Correction factors for concrete strength determined by			
	150x300 mm Cylinder	100x200 mm Cylinder	100x100 mm Cylinder	100 mm Cube
20	1.510	1.316	1.176	1.093
30	1.344	1.210	1.090	1.033
40	1.261	1.156	1.047	1.003
50	1.212	1.124	1.022	0.984
60	1.179	1.103	1.005	0.972
70	1.155	1.088	0.992	0.964
80	1.137	1.076	0.983	0.957
90	1.123	1.067	0.976	0.952
100	1.112	1.060	0.970	0.948

Source: Mansur and Islam (2002)

Table 3 Correction factors to convert concrete strength to equivalent Ø150x300 mm standard cylinder strength

Compressive strength of concrete (MPa)	Correction factors for concrete strength determined by			
	150 mm Cube	100 mm Cube	100x200 mm Cylinder	100x100 mm Cylinder
20	0.497	0.594	0.809	0.670
30	0.660	0.689	0.867	0.749
40	0.742	0.744	0.896	0.788
50	0.791	0.775	0.913	0.812
60	0.824	0.796	0.925	0.828
70	0.847	0.811	0.933	0.839
80	0.865	0.822	0.939	0.848
90	0.878	0.831	0.944	0.854
100	0.889	0.838	0.948	0.860

Source: Mansur and Islam (2002)

From the result of experimental study, it has been found that the ratio of cube to cylinder compressive strengths decreases with an increase in the level of concrete strength. Also, a decrease in either the size or the aspect ratio of specimens leads to a decrease in the cube/cylinder strength ratio.

Felekoglu and Turkel (2005) investigated the compressive strength values of cube and cylinder specimens at two strength levels with different sizes and proposed transformation coefficients. Concrete mix designs at two different strength grades (NSC and HSC) were prepared. A total of 144 specimens of 4 different types (150 mm and 200 mm cubes, Ø100x200 and Ø150x300 cylinders) from both NSC and HSC mixes used in groups of nine in compressive strength tests at 7 and 28 days were prepared. Standard curing was applied to these specimens until the time of test.

Test results showed that, the compressive strength values increase with the increase in size of the specimen. This behavior which is the opposite of literature was thought to be caused by the “wall effect”. The maximum aggregate size of concrete mixtures is 25 mm, which caused the wall effect and low compactness, particularly for Ø100x200 mm cylinder specimens. At the same time, this situation puts forward the importance of the selection of the mold type which is proposed by the standards for a given maximum aggregate size.

Experimental study verified that cylindrical specimens always gave lower strength values when compared with cubic specimens. In order to convert the strength of different types of samples to standard cylinder (Ø150x300 mm) and standard cube (150 mm) strengths, coefficients were proposed and presented in Table 4.

Table 4 Transition coefficients of different specimens to standard specimens

Transition Coefficient	NSC Cube 150 mm	HSC Cube 150 mm	NSC Cylinder 100x200 mm	HSC Cylinder 100x200 mm	NSC Cube 200 mm	HSC Cube 200 mm	NSC Cylinder 150x300 mm	HSC Cylinder 150x300 mm
Standard Cylinder	0.75	0.90	1.02	1.16	0.75	0.85	1.00	1.00
Standard Cube	1.00	1.00	1.36	1.29	1.01	0.94	1.34	1.10

Source: Felekoglu and Turkel (2005)

Yi *et al.* (2006) experimentally investigated the effect of specimen sizes, specimen shapes, and placement directions on compressive strength of concrete specimens based on fracture mechanics. Experiments for the Mode I failure were carried out using cylinder, cube, and prism specimens. Based on the modified size effect law (MSEL), the test results are curve-fitted using least square method (LSM) to obtain the new parameters for the MSEL. The equations for size effect of cylinders and cubes were proposed as shown in Eq. (5) and (6), respectively.

• Size effect for cylinders:

$$f_{cy}(d)=\frac{0.49\,f_c'}{\sqrt{1+d/0.26}}+0.81\,f_c' \tag{5}$$

• Size effect for cubes:

$$f_{cu}(d)=\frac{1.17\,f_c'}{\sqrt{1+d/0.26}}+0.62\,f_c' \tag{6}$$

where compressive strength of general cylinder $f_{cy}(d)$, cubes $f_{cu}(d)$ and compressive strength of standard cylinder f_c' are in MPa and diameter d is in cm. The term “general” represents the cylinders with arbitrary chosen dimensions.

Table 5 Conversion factors with sizes and shapes of the specimen for normal-strength concrete

Cylinder specimen's size and CF	d (mm)	cy	cu	pr	cu,p	pr,p
cy (100), CF =1	50	1.05	1.34	1.14	1.47	1.13
	100	1.00	1.18	1.01	1.27	1.00
	150	0.97	1.10	0.94	1.16	0.93
	200	0.96	1.05	0.90	1.09	0.88
cy (150), CF =1	50	1.07	1.38	1.17	1.51	1.16
	100	1.03	1.22	1.04	1.30	1.02
	150	1.00	1.13	0.97	1.19	0.95
	200	0.98	1.07	0.92	1.12	0.90

Source: Yi *et al.* (2006)

Table 6 Conversion factors with sizes and shapes of the specimen for high-strength concrete

Cylinder specimen's size and CF	d (mm)	cy	cu	pr	cu,p	pr,p
cy (100), CF =1	50	1.08	1.16	1.01	1.28	1.06
	100	1.00	1.04	0.88	1.11	0.95
	150	0.96	0.98	0.81	1.02	0.90
	200	0.93	0.94	0.77	0.96	0.86
cy (150), CF =1	50	1.13	1.21	1.06	1.34	1.10
	100	1.04	1.09	0.92	1.16	0.99
	150	1.00	1.02	0.85	1.06	0.94
	200	0.97	0.98	0.80	1.00	0.90

Source: Yi *et al.* (2006)

Table 5 and 6 show the conversion factors (CF) for normal and high-strength concrete, respectively, to transfer the compressive strength of several sizes, shapes and placement directions of specimen to the strength of basic sizes Ø100x200 and Ø150x300 cylinders.

Yazıcı and Sezer (2007) investigated the influence of size and capping type of cylindrical specimens on compressive strength of concrete. For this purpose, three hundred and eighty-four cylindrical specimens having dimensions of Ø150x300mm and Ø100x200mm were cast from eight concrete mixtures. Linear and nonlinear regression analyses were employed between compressive strength of Ø100x200mm cylinder ($f_c'_{100x200}$) and Ø150x300mm cylinder ($f_c'_{150x300}$). The results showed that the average compressive strength of Ø100x200mm cylinders is generally higher than Ø150x300mm cylinder specimens for the average compressive strength of concretes varies between 14 and 47 MPa. Reasons for this phenomenon were expressed as:

1. In the uniaxial compression test, smaller contact area between the specimen surface and steel platen of test machine resulting in lower friction-based shear forces in small specimens.

2. By means of statistical approach, the number of microcracks and defects in smaller specimens are fewer than bigger specimens, resulting in a rise in density.

The results of the experimental study revealed that a certain conversion factor cannot be proposed and the suitable average conversion factor (the ratio of compressive strength of Ø100x200mm cylinder to Ø150x300mm cylinder, $f_c'_{100x200}/f_c'_{150x300}$) can be taken as 103%.

Theoretical Background

Development of High-Strength Concrete

High-strength concrete (HSC) is defined by ACI Committee 363 as concretes having specified compressive strengths for design of 6000 psi (41 MPa) or greater. As the given definition, the primary difference between high-strength concrete and normal-strength concrete relates to the compressive strength that refers to the maximum resistance of a concrete sample to applied pressure. HSC is generally made by lowering the water-cement ratio (w/c) which may be 0.35 or even lower. Cementitious materials other than Portland cement, consisting mainly of fly ash, ground blast furnace slag, or silica fume (microsilica), are considered in the production of high-strength concrete because of the required high cementitious materials content and low w/c. These materials can help control the temperature rise in concrete at early ages and may reduce the water demand for a given workability. However, low amount of water causes loss of workability of fresh concrete, which cannot be compacted properly and leads to dropping of hardened concrete strength. Therefore, high-range water reducing agents or superplasticizers are added to maintain the workability of fresh concrete while using low w/c. The function of superplasticizer is to disperse the cement particle which allows even small amount of water to flow and react with cement particles easily. Additionally, aggregates must be selected carefully for high-strength mixes, as weaker aggregates may not be strong enough to resist the loads imposed on the concrete and cause failure to start in the aggregate rather than in the matrix or at a void, as normally occurs in regular concrete.

In addition to higher strength in compression, most other engineering properties of modern concrete are improved leading to the alternative term “high-performance concrete” (HPC). Given this well accepted view of HPC, we can ascertain that the definition of HSC is a narrower one than is HPC. The definition of HSC fits within the overall scope of HPC, with strength representing a parameter of performance. The exact point at which normal strength concrete ends and high strength begins is debatable and varies from one global region to another. It has become commonplace to associate HPC with durability. This is widely accepted probably on the basis that durability is of prime importance in assessing overall concrete performance. Although concrete that is designed to have high durability performance may also exhibit high strength performance, it is not always safe to assume that the reverse is necessarily true that all high strength concrete will be necessarily durable concrete.

Compressive Testing of High-Strength Concrete

The term “concrete strength” is generally taken to refer to the uniaxial compressive strength as measured by a compressive test of standard test cylinder, cube or prism depending on customary standard practice of each country. In American approach, cylindrical specimens are used in practical testing for acceptance or quality control purposes. Cylindrical specimens are made and cured in accordance with ASTM C31 “Standard Practice for Making and Curing Concrete Test Specimens in the Field”. Specimens are tested in accordance with ASTM C39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens”, whilethe UK and other countries in Europe use 150 mm cube as customary concrete test specimen. The cube shall be made and tested in accordance with BS EN 12390-2:2000 “Testing hardened concrete-Part 2: Making and curing specimens for strength tests” and BS EN 12390-3:2000 “Testing hardened concrete-Part 3: Compressive strength of test specimens”, respectively.

The practical standards for compressive testing of NSC for both American and British approaches are still valid for HSC. However, the quality control and testing of HSC are more critical than NSC. Minor deviations from specified requirements or procedures may go unnoticed with the latter, but can become major deficiencies with HSC. Therefore, ACI 363.2-98 “Guide to Quality Control and Testing of High-Strength Concrete” is published by The American Concrete Institute (ACI Committee 363) to correct quality control and testing of HSC through facilitating the proper evaluation of the results. The guide applies to concrete with a specified compressive strength of 6,000 psi (41 Mpa) or greater. It covers planning, trial mixtures, preconstruction meetings, batching, placing, curing and testing.

Specimen Shape and Size Effect on Compressive Strength

Research in the field of fracture mechanics has indicated that the failure type of concrete specimens under compression depends, among other parameters, on specimen size, specimen shape, mould material, curing method, capping method, preparation of specimen ends, rate of loading, and bearing block dimension of the testing machine (M. Imam et al. 1995).

ASTM C31 specifies the standard specimen as a cylinder with a diameter of 152 mm (6 in.) and a height of 305 mm (12 in.). This specimen size has evolved over the years from practical considerations, and the design and construction team is familiar with the empirical values obtained. This specimen size may lead to practical problems when testing high-strength concrete because the crushing loads may exceed the capacities of available testing machines. The use of the smaller test cylinders is acceptable provided strength, without any reduction factors, determined in accordance with ASTM C39. Regardless of specimen size, the size used to evaluate trial mixture proportions should be consistent with the size specified for acceptance testing. If necessary, the relationship between the compressive strengths of the two specimen sizes can be determined at the laboratory or field trial stage using the testing machine that will be used for the project (ACI 363.2, 1998).

With consideration on shape effect of specimen, it is necessary to refer to its aspect ratio (in terms of height to diameter or width). Theoretically, the test of concrete in compression assumes that specimen is loaded under a pure state of uniaxial loading. However, this is not the case when there are friction forces between the load plates and the specimen surfaces exist at the top and bottom surfaces of a concrete specimen. The forces are to restrain the specimen from expanding at both ends. As a result, confining stresses are generated around the two ends of the specimen. Note that in a test of cylinder with aspect ratio equal to 2.0, the cracks propagate vertically in the middle of the specimen. When they get close to the ends, due to the confining stresses, they propagate in an inclined direction, leading to the formation of two cones at the ends. It can be seen that the confining effect is not too significant at the middle of the specimen (where failure occurs). For the specimen which has low aspect ratio, such as a cube (aspect ratio = 1.0), the confining stresses will increase the apparent strength of the concrete. The strength obtained from a cylinder is hence lower than cube strength and closer to the actual uniaxial strength of concrete.

CEB-FIP (1990) Model Code, which is mostly applied in European countries, contains a table of equivalence for strength of the two types of specimens for high-strength concrete. The table indicates that the ratio of the cube to cylinder strength decreases progressively from 1.25 for a cylinder strength of 40 MPa to 1.12 when the cylinder compressive strength reaches a value of 80 MPa.

In Thailand, the conversion factor from 150mm cube strength to standard Ø150x300mm cylinder compressive strength can be obtained from the relationship shown in Fig. 1. There is also the standard of ready-mixed concrete which showed the concrete strength of cube and cylinder test specimen specified for each concrete strength grade, as shown in Table 7. However, the range of concrete strength is still limited to normal-strength level (less than 500 kg/cm^2). While the effect of nonstandard specimen size to compressive strength is not presented.

Table 7 Ready-mixed concrete strength grade with specified compressive strength

Concrete Strength Grade	Compressive Strength at 28 days MPa (kg/cm^2)	
	Cube 150 mm	Cylinder 150x300 mm
C 10/8	10 (100)	8 (80)
C 12.5/10	12.5 (125)	10 (100)
C 15/12	15 (150)	12 (120)
C 20/15	20 (200)	15 (150)
C 25/20	25 (250)	20 (200)
C 30/25	30 (300)	35 (350)
C 35/30	35 (350)	30 (300)
C 40/35	40 (400)	35 (350)
C 45/40	45 (450)	40 (400)

Source: TIS 213 (1977)

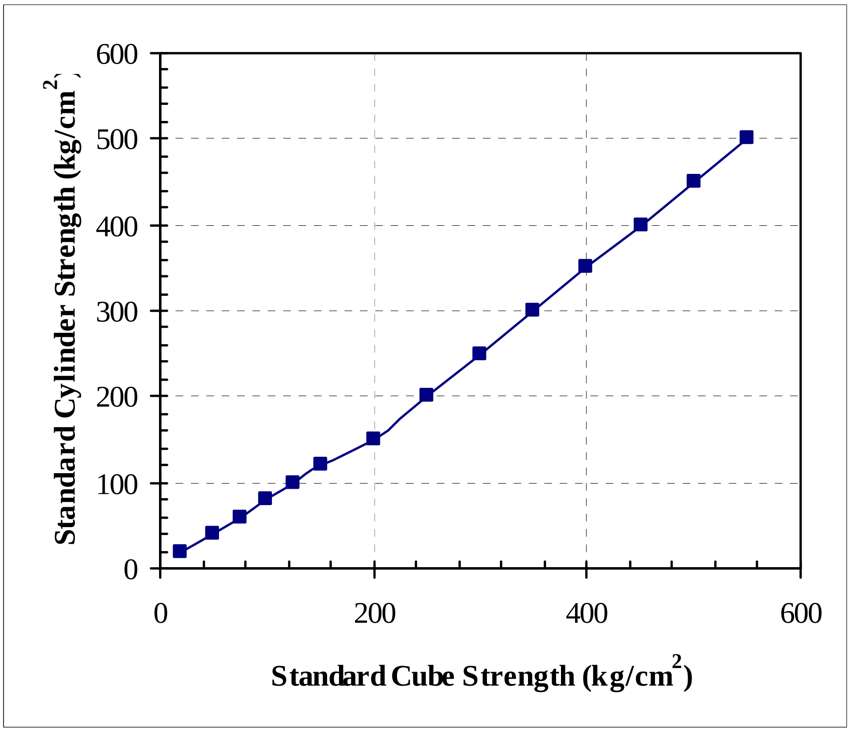

Figure 1 Correlation between standard cylinder and cube strength

Source: EIT Standard 1014 (2003)

Statistical Analysis of Experimental Data

Concrete is a mixture of aggregate, cement, water, air and other admixtures. Variations in the properties or proportions of these constitutions, as well as variations in placing and compaction of the concrete, lead to variations in strength of the hardened concrete. In addition, discrepancies in the test will lead to apparent differences in strength. The statistical methods provide valuable tools for assessing the results of strength tests leading to the conclusion.

General statistical terms

The strength test result is generally defined as the average strength, of all specimens, which is statistically termed as the "sample mean" ($\overline{X}$) in the set of testing. This is the arithmetic mean of the data values obtained by taking their sum and dividing by the number of data (*n*).

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{6}$$

where $\sum X_i$ is the sum of all strength test results and *n* is the number of test in the record.

The dispersion of the data can be measured by the "sample standard deviation" (*s*) which is the root-mean-square deviation of the strengths from their mean value.

$$s = \sqrt{\frac{\sum_{i=1}^{n} X_i^2 - n\overline{X}^2}{n-1}} \tag{7}$$

The standard deviation divided by the mean value is called the "coefficient of variation" (*V*) which is simply the standard deviation expressed as a percentage of the average value.

$$V = \frac{s}{\overline{X}} x100\% \tag{8}$$

Outliers and acceptance of results

An outlier is generally defined as a value that appears to be uniquely different from the rest of the data set. There is a real chance that a set of data may contain a few points that are much larger or smaller than the rest. These values might indicate that something went wrong with the data collection process or reflect the fact of population. In the former reason, statistics derived from data sets that include outliers will often be misleading. However, the engineer cannot just throw out those points that do not fit with expectations – there must then be some consistent basis for elimination (Holman, 1989).

Grubbs' test, or Extreme Standardize Deviation (ESD), is a method that is particularly easy to understand for assessing outliers. The method quantifies how far each data point (X_i) is from the mean value ($\overline{X}$) and standardizes this value by dividing by the standard deviation (*s*).

$$Z_i = \frac{\left| X_i - \overline{X} \right|}{s} \qquad (9)$$

The Z_i value will then be compared with the critical value (Z_{crit}) which come from the assumption of normally distributed data. However, the method is flawed if the data contain outliers since both $\overline{X}$ and *s* are very sensitive to outliers and the method sometime does not find outliers even when they are there. To fix this problem, $\overline{X}_m$ and $\bar{s}$ shall be used, in Eq. 9, instead of $\overline{X}$ and *s*, respectively (Gatti, 2005). The value $\overline{X}_m$ is the sample median and $\bar{s}$ is the median of absolute deviations from the median, as following expression.

$$\bar{s} = 1.483 \underset{j=1,\ldots,n}{median} \left| X_j - \overline{X}_m \right| \qquad (10)$$

Note that 1.483 is a correction factor for consistency with the usual spread parameter of normal distribution. The Eq. 9 can be rewritten as

$$\overline{Z_i} = \frac{\left| X_i - \overline{X}_m \right|}{\overline{s}} \tag{11}$$

and identify as outliers those X_i such that $\overline{Z}_i \geq 2.5$ or $\overline{Z}_i \geq 3.0$.

Linear regression analysis

Regression analysis is a technique in statistics that examines the relation of a dependent variable (response variable) to specified independent variables (explanatory variables). Regression can be used for testing of hypothesis, prediction, inference and modeling of causal relationships of a statistical model when paired with assumption. These uses of regression rely heavily on the model assumptions being satisfied. Regression analysis has been criticized as being misused for these purposes in many cases where the appropriate assumptions cannot be verified to hold. One factor contributing to the misuse of regression is that it can take considerably more skill to critique a model than to fit a model. The key relationship in a regression is the regression equation. A regression equation contains regression parameters whose values are estimated using data. The estimated parameters measure the relationship between the dependent variable and each of the independent variables. When a regression model is used, the dependent variable is modeled as a random variable because of either uncertainty as to its value or inherent variability. The data are assumed to be a sample from a probability distribution, which is usually assumed to be a normal distribution.

In the linear regression model, the dependent variable is assumed to be a linear function of one or more independent variables plus an error introduced to account for all other factors. The general form of a simple linear regression is

$$y = mx + b \tag{12}$$

The equation algebraically describes a straight line for a set of data with one independent variable where x is the independent variable, y is the dependent variable, m represents the slope of the line, and b represents the y-intercept. The x_i and y_i are the data quantities from the sample or population in question, and m and b are the unknown parameters (constants) that are to be estimated from the data. Estimates for the values of m and b can be derived by the method of ordinary least squares. The method is called “least squares” because estimates of m and b minimize the sum of squared error estimates for the given data set.

MATERIALS AND METHODS

Materials and Equipment

Concrete

In this experimental study, four different high-strength concrete mixtures were used. The expected cylinder compressive strengths of concrete mixes are 550, 700, 850 and 1000 kg/cm^2. Concrete mixes were designed, treated, and controlled under the same conditions. The cement used in all mixes is Portland cement type I, when natural river sand and crushed limestone are used as fine and coarse aggregates, respectively. The silica fume is used as mineral admixture. To achieve workable mixes with the desired quality and strength, a superplasticizer in the form of an aqueous solution is also used.

Five trial mixtures of high strength concrete were performed, based on the same materials with four different water-binder ratios (w/b), in order to get enough information in designing the final mix proportions. The design of trial mixes are expected to produce a range of strengths that encompass the target strengths. Three test cylinders per trial mixture are made and tested at 7 days. From trial mix test results, the high strength concrete mix proportions are adjusted with the assumption of compressive strength at 7 days is 80% of the strength at 28 days. The w/b, water and superplasticizer contents of each mix are adjusted to make compressive strength close to the expected strength and also to improve workability of fresh concrete. The slump values for all mixes in this study are expected to be more than 20 cm to facilitate the compaction of concrete. Table 8 shows the final mix proportions of high-strength concrete in this study.

Table 8 High-strength concrete mix proportions

	Mix 1	Mix 2	Mix 3	Mix 4
Expected fc’ at 28 days (ksc)	550	700	850	1,000
Ordinary Portland cement (kg/m^3)	350	412	464	500
Silica fume (kg/m^3)	21	37	56	75
Water (kg/m^3)	140	140	130	120
Superplasticizer (kg/m^3)	7.42	8.98	15.60	17.25
Coarse aggregate (kg/m^3)	1,161	1,107	1,080	1,080
Fine aggregate (kg/m^3)	801	775	734	688
w/b	0.38	0.31	0.25	0.21

Note: - Maximum size of coarse aggregate is 19 mm with cleaned and saturated-surface dry condition.

- Fineness Modulus of fine aggregate (sand) is approximately equal to 3.0 with oven dry status.
- For ordinary Portland cement, Elephant brand cement (type I Portland cement TIS 15, 1989) is used.
- For Polycarboxylic base superplasticizer, Sika Viscocrete – 10 is used.
- For silica fume, Sikacrete PP1 is used.

Equipment

1. Standard Moulds
    - Cube 100 mm
    - Cube 150 mm
    - Cylinder Ø100x200mm
    - Cylinder Ø150x300mm
2. Concrete Mixing Machine
3. Weighing Scales
4. Concrete Vibrator
5. Compression Testing Machine (300 Tonnes Capacity)
6. Digital Camera

Experimental Methods

The uniaxial compression tests were performed on a total of 288 specimens cast from 4 different high strength concrete mixtures. In order to determine shape and size effects, 4 different specimen types with the dimensions shown in Fig. 2 are used. All specimens were tested at 2 ages, i.e. 7 and 28 days. The determination of the strength for each concrete mixture, specimen age and specimen type are based on the average of 9 specimens. List of specimens, with different mould types and concrete strengths, are shown in Table 9.

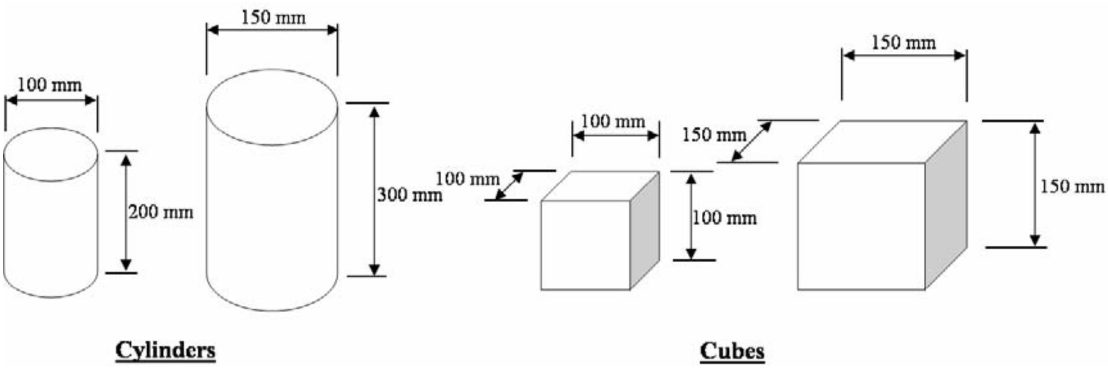

Figure 2 Dimension of specimens

Table 9 Number of specimen with different mould types and concrete mixes

Specimen Shape	Dimension (mm)	Number of Specimens			
		Mix 1	Mix 2	Mix 3	Mix 4
Cylinder	Ø 100×200	18	18	18	18
Cylinder	Ø 150×300	18	18	18	18
Cube	100×100×100	18	18	18	18
Cube	150×150×150	18	18	18	18
	Total	72	72	72	72
		288			

Specimen Preparation

Concrete mixing and casting for all batches were controlled under the same conditions as follow.

1. Concrete mixtures were batched using a pan mixer. Due to the limit of concrete mixer, each mixture is divided into four batches. Cement, silica fume and aggregates were mixed in the dry state for about 1 minute to ensure their uniformity. Mixing water and superplasticizer were added gradually and simultaneously during mixing. All contents are mechanically mixed for 2 min. The consistency of the fresh concrete is measured by the conventional slump test.

2. Seventy two specimens were cast from each concrete mixture. Concrete is consolidated by internal vibrator during placing of concrete to ensure full compaction.

3. All test specimens were demoulded after 24 hours and then exposed to continuous curing in water pond until the time of specimen preparation and testing.

Testing

After the specimens have been cured for 7 and 28 days, the uniaxial testing is performed with the test procedures described below.

1. The top end of cylindrical specimens is capped with sulfur pastes, in accordance with ASTM C 617, before setting up specimens on the Testing Machine.

2. The concrete specimens were tested for cylindrical compressive strength in accordance with ASTM C39 and cube compressive strength in accordance with BS EN 12390-3.

RESULTS AND DISCUSSION

Test Results and Data Analysis

The compressive strength values and statistical data determined from the experimental results are given in Table 10 through 13. Each strength value representing the data set was calculated by averaging the strength of nine specimens except the sets of data with symbol “*”, which means that the ultimate compressive strength of specimen is rejected due to the result being identified as outlier. The remaining results were then used for calculating the average strength value. To detect the outliers from the data set, Eq. 10 and 11 were used with the criteria that identify those data as outlier when $\overline{Z}_i \geq 3.0$. Refer to Appendix A for tables that show more statistical parameters.

With all specimen types, testing ages and strength levels the coefficient of variation were calculated by dividing the standard deviation to the average of compressive strength values. It was observed that the coefficients of variation of cube specimens are generally lower than cylinder specimens and standard deviations increase when the strength level increases.

Table 10 Compressive strength and statistical data of HSC mix 1

Specimen Type	Compressive Strength (kg/cm^2)							
	Cube 100		Cube 150		Cylinder 100		Cylinder 150	
Age (days)	7	28	7	28	7	28	7	28
1	596	684	*	709	360	595	506	615
2	689	727	618	711	431	578	507	473
3	663	733	651	715	515	617	540	555
4	719	737	647	752	482	614	488	625
5	647	736	643	689	500	659	468	509
6	691	802	645	751	497	636	518	619
7	699	690	664	766	454	638	502	481
8	656	774	616	797	506	625	517	657
9	647	790	657	769	425	620	512	647
Average	667	741	643	740	463	620	506	576
Standard Deviation	36.7	40.7	17.2	35.4	50.7	23.7	20.1	72.1
Coefficient of Variation (%)	5.5	5.5	2.7	4.8	10.9	3.8	4.0	12.5

Note: * means the rejected value which is identified as outlier data.

Table 11 Compressive strength and statistical data of HSC mix 2

Specimen Type	Compressive Strength (kg/cm^2)							
	Cube 100		Cube 150		Cylinder 100		Cylinder 150	
Age (days)	7	28	7	28	7	28	7	28
1	801	885	768	873	559	761	665	770
2	783	*	713	916	629	814	655	702
3	742	875	787	903	636	600	654	763
4	782	951	717	907	600	762	*	735
5	733	959	767	851	665	704	619	780
6	717	928	781	896	587	711	662	640
7	790	962	765	857	605	715	668	723
8	754	907	756	874	662	776	659	709
9	822	942	726	819	678	688	615	746
Average	769	926	753	877	625	726	650	730
Standard Deviation	34.6	33.7	27.9	31.5	39.9	62.0	20.7	43.1
Coefficient of Variation (%)	4.5	3.6	3.7	3.6	6.4	8.5	3.2	5.9

Note: * means the rejected value which is identified as outlier data.

Table 12 Compressive strength and statistical data of HSC mix 3

Specimen Type	Compressive Strength (kg/cm^2)							
	Cube 100		Cube 150		Cylinder 100		Cylinder 150	
Age (days)	7	28	7	28	7	28	7	28
1	956	*	864	1,040	785	862	766	893
2	890	998	888	984	853	826	823	879
3	959	940	853	1,009	879	787	797	856
4	988	1,055	876	1,008	859	813	829	872
5	1,007	1,102	925	1,045	882	931	741	*
6	1,038	1,104	909	1,039	760	938	813	922
7	945	1,116	878	975	861	923	838	809
8	1,006	1,078	944	1,009	791	919	766	865
9	913	1,116	893	988	829	**	860	*
Average	967	1,064	892	1,011	833	875	804	871
Standard Deviation	47.6	63.9	29.1	26.0	44.4	60.4	39.3	34.8
Coefficient of Variation (%)	4.9	6.0	3.3	2.6	5.3	6.9	4.9	4.0

Note: * means the rejected value which is identified as outlier data.
** means the ultimate strength of specimen cannot be obtained due to operating problem.

Table 13 Compressive strength and statistical data of HSC mix 4

Specimen Type	Compressive Strength (kg/cm^2)							
	Cube 100		Cube 150		Cylinder 100		Cylinder 150	
Age (days)	7	28	7	28	7	28	7	28
1	1,061	1,048	1,042	1,128	*	**	919	950
2	986	1,240	1,031	1,129	933	1,043	824	1,013
3	1,055	1,151	937	1,155	840	929	896	1,076
4	1,035	1,129	977	1,137	907	1,003	*	950
5	942	1,267	1,077	1,171	928	1,041	*	941
6	968	1,189	976	1,173	940	1,106	869	835
7	945	1,204	869	1,068	857	1,089	939	1,058
8	1,026	1,246	1,027	1,052	923	**	686	943
9	987	1,099	953	1,087	886	940	907	886
Average	1,001	1,175	988	1,122	902	1,021	863	961
Standard Deviation	45.5	73.9	63.6	43.9	37.4	68.4	86.3	77.4
Coefficient of Variation (%)	4.5	6.3	6.4	3.9	4.1	6.7	10.0	8.1

Note: * means the rejected value which is identified as outlier data.
** means the ultimate strength of specimen cannot be obtained due to operating problem.

Specimen Size Effect on Compressive Strength

Linear regression analysis is employed to find the relations between concrete strength values from different sizes of specimen. The relationships of average compressive strengths from Table 10 through 13 are plotted and shown in Fig. 3 through 6. The results show that the compressive strength of the bigger size specimen is generally lower when compared to the same shape of specimen obtained from the same concrete mix. This relationship agrees with the tendency pointed out in many literatures (Mansur and Islam, 2002; Yi *et al*., 2006; Yazici and Sezer, 2007). This is understandable when the probability of having large defects, such as voids and cracks, in the test specimen increases with its size. Thus smaller size specimen can give higher apparent strength and the test results for small size specimen may need to be modified. However, the results from some researchers (Tokyay and Ozdemir, 1997; Felekoglu and Turkel, 2005) show that the strength of smaller specimen is lower. The given reason for this effect is due to the limit of compact ability of concrete during preparation of specimens.

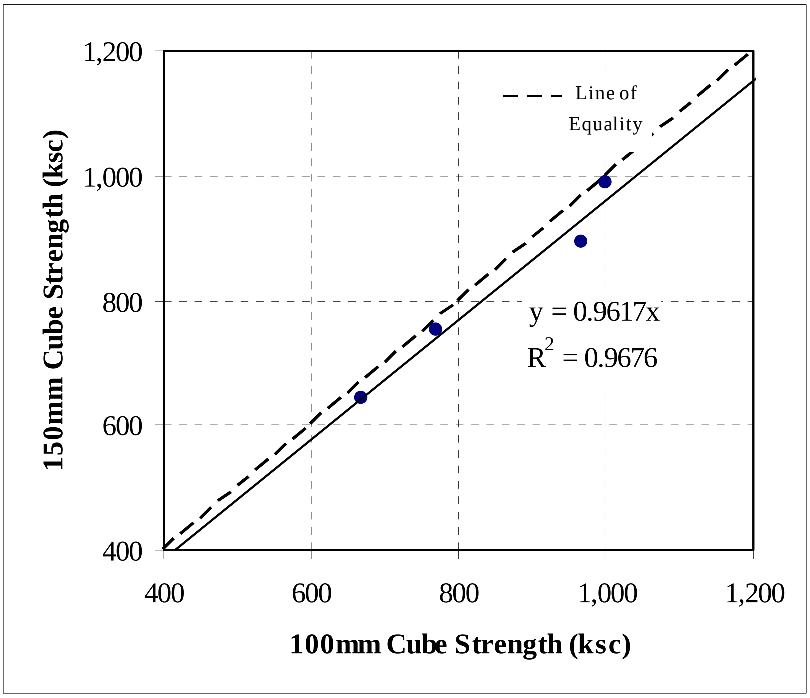

Figure 3 Relationships between compressive strength at 7 days of 100mm cube and 150mm cube

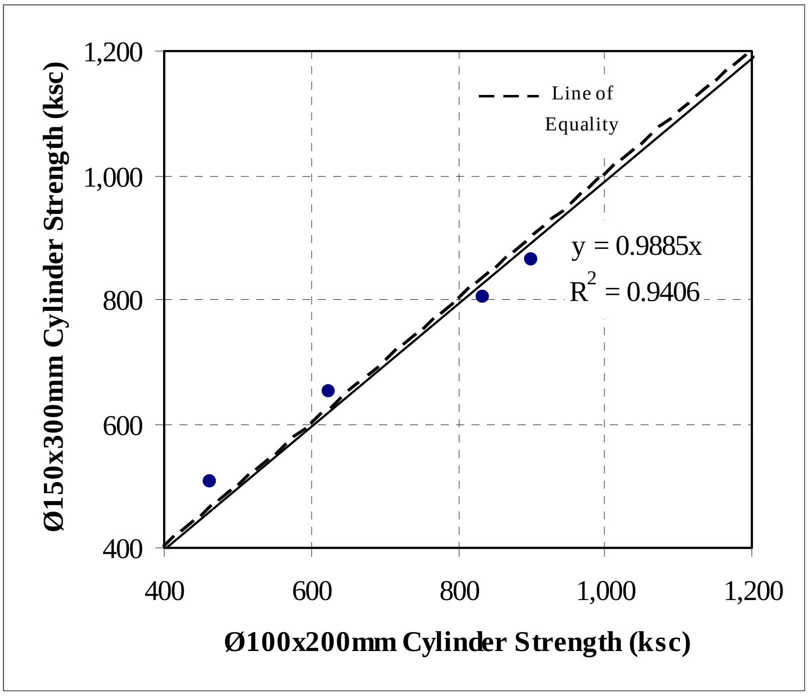

Figure 4 Relationships between compressive strength at 7 days of Ø100x200mm cylinder and Ø150x300mm cylinder

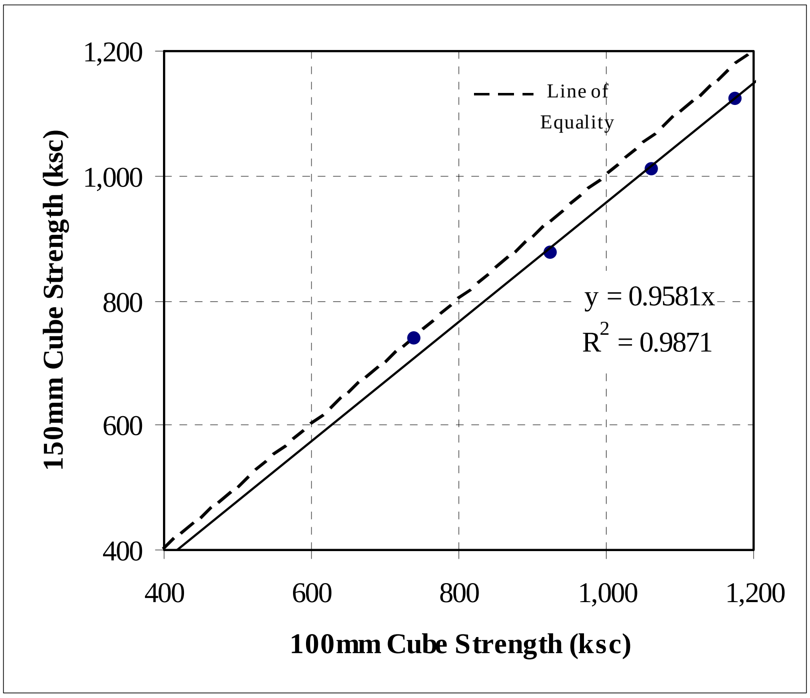

Figure 5 Relationships between compressive strength at 28 days of 100mm cube and 150mm cube

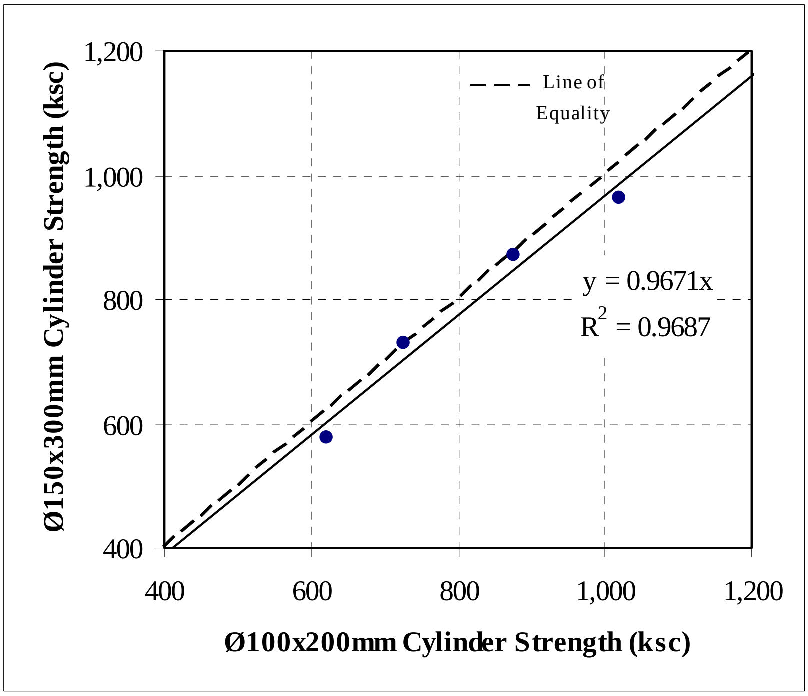

Figure 6 Relationships between compressive strength at 28 days of Ø100x200mm cylinder and Ø150x300mm cylinder

The proposed expressions, for specimen size effect, from previous research are summarized and shown in Table 14 and 15. In order to compare the results from present study with other research, the relations from Fig. 3 through 6 are also included in the tables. From the relationships, however, it seems to be valid to assume that the compressive strength obtained from cube 100 mm and cylinder Ø100x200 mm specimens can give the same results with standard cube 150 mm and cylinder Ø150x300 mm, respectively. Although the standard specimen for testing compressive strength is Ø150x300 cylinder as specified in ASTM, Ø100x200 cylinder has been used successfully in the United State without any transformation factors required. American Concrete Institute has also recommended that smaller test cylinders are acceptable provided the strength is determined in accordance with ASTM C 39 and the same size cylinder is used for both trial mixtures and acceptance testing (ACI 363.2-98).

Table 14 Relations between concrete strength values from different cylindrical specimen size

Researcher(s)	Proposed expression	Range of concrete strength (Mpa)
Mansur and Islam (2002)	$f_c'_{,cy150} = 0.98\ f_c'_{,cy100} - 3.49$	20 - 100
Felekoglu and Turkel (2005)	$f_c'_{,cy150} = 1.16\ f_c'_{,cy100}$	50 - 55
Yi *et al.* (2006)	$f_c'_{,cy150} = 0.968\ f_c'_{,cy100}$	20 - 80
Yazici and Sezer (2007)	$f_c'_{,cy150} = 0.97\ f_c'_{,cy100}$	14 - 47
Present study - for 7 days strength - for 28 days strength	 $f_c'_{,cy150} = 0.99\ f_c'_{,cy100}$ $f_c'_{,cy150} = 0.97\ f_c'_{,cy100}$	55 - 100

Note: $f_c'_{,cy150}$ = Ø150x300 cylindrical compressive strength (MPa),
$f_c'_{,cy100}$ = Ø100x200 cylindrical compressive strength (MPa)

Table 15 Relations between concrete strength values from different cube specimen size

Researcher(s)	Proposed expression	Range of concrete strength (MPa)
Mansur and Islam (2002)	$f_c'{}_{,cu150} = 0.91\ f_c'{}_{,cu100} + 3.62$	20 - 100
Yi *et al.* (2006)	$f_c'{}_{,cu150} = 0.929\ f_c'{}_{,cu100}$	20 - 80
Present study		
- for 7 days strength	$f_c'{}_{,cu150} = 0.97\ f_c'{}_{,cu100}$	55 - 100
- for 28 days strength	$f_c'{}_{,cu150} = 0.96\ f_c'{}_{,cu100}$	

Note: $f_c'{}_{,cu150}$ = 150 cube compressive strength (MPa),
$f_c'{}_{,cu100}$ = 100 cube compressive strength (MPa)

Specimen Shape Effect on Compressive Strength

It can be seen from the results shown in Table 10 through 13 that the cube strengths are consistently higher than the corresponding cylinder strength for the range of concrete strength considered in this study. The ratio of the compressive strength at 28 days of Ø150x300 mm cylinder to the 150 mm cube is varied from 0.78 to 0.86 for the designed cylinder strength of 550 to 1,000 kg/cm^2. The transformation factor proposed in CEB-FIP (1990) Model Code, in terms of the ratio of cylinder to cube strength, is 0.80 for cylinder strength of 40 MPa and the factor increases progressively to 0.89 when the cylinder compressive strength reaches a value of 80 MPa.

Fig. 7 to 10 show plots of cube against cylinder compressive strengths. The lines of relations shown on the figures indicate the best-fit lines obtained from the linear regression analysis with test data points. The relations are also shown in Table 16 in order to compare with the proposed expressions from previous research.

Table 16 Relations between concrete strength values from Ø150x300 mm cylinder to the 150 mm cube specimen

Researcher(s)	Proposed expression	Range of concrete strength (Mpa)
Mansur and Islam (2002)	$f_c'_{,cy150} = 0.99\ f_c'_{,cu150} - 9.84$	20 - 100
Felekoglu and Turkel (2005)	$f_c'_{,cy150} = 0.90\ f_c'_{,cu150}$	50 - 55
Yi *et al.* (2006)	$f_c'_{,cy150} = 1.16\ f_c'_{,cu150} - 11.02$	20 - 80
Present study - for 7 days strength - for 28 days strength	 $f_c'_{,cy150} = 1.05\ f_c'_{,cu150} - 14.96$ $f_c'_{,cy150} = 1.02\ f_c'_{,cu150} - 16.57$	 55 - 100

Note: $f_c'_{,cy150}$ = Ø150x300 cylindrical compressive strength (MPa),
$f_c'_{,cu150}$ = 150 cube compressive strength (MPa)

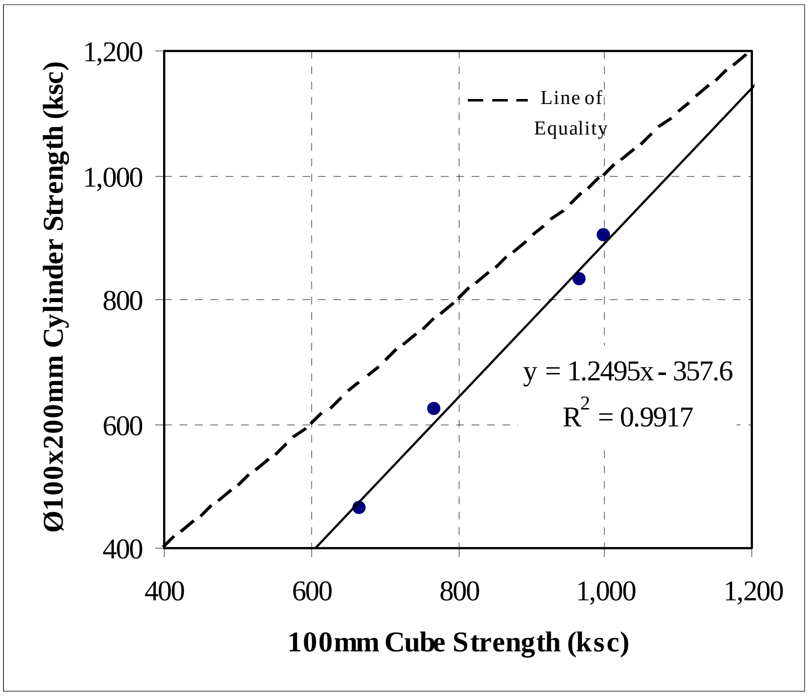

Figure 7 Relationships between compressive strength at 7 days of 100mm cube and Ø100x200mm cylinder

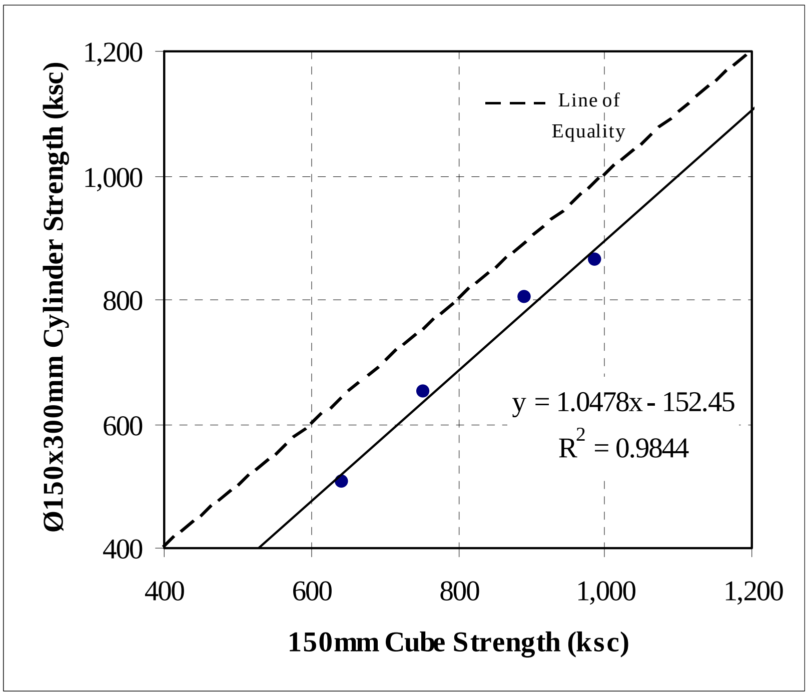

Figure 8 Relationships between compressive strength at 7 days of 150mm cube and Ø150x300mm cylinder

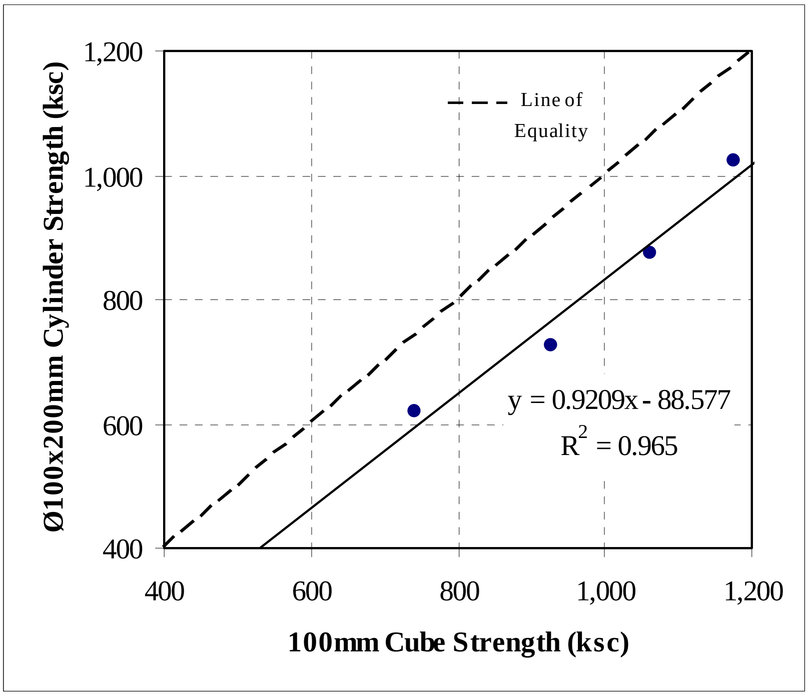

Figure 9 Relationships between compressive strength at 28 days of 100mm cube and Ø100x200mm cylinder

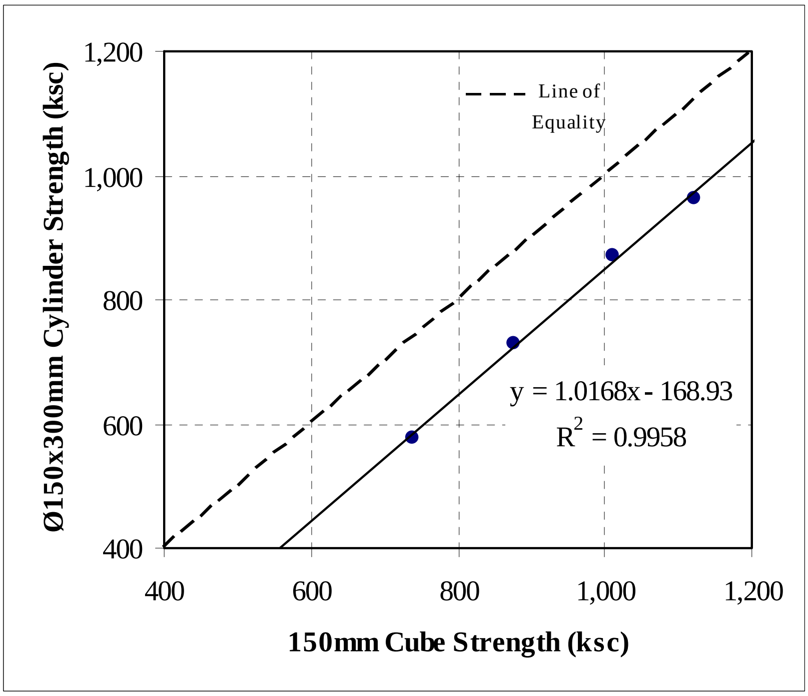

Figure 10 Relationships between compressive strength at 28 days of 150mm cube and Ø150x300mm cylinder

CONCLUSION AND RECOMMENDATION

Conclusion

Based on the results of the study, with particular test materials and test procedures employed, the following conclusions can be made.

1. The expressions for specimen size effect based on two different specimen sizes are presented. The results show that compressive strength increases as the specimen size decreases. From the 28-days test results, the ratio of 150 mm to 100 mm cube strength and Ø150x300 mm to Ø100x200 mm cylinder strength are 0.96 and 0.97, respectively. This effect might be ignored as the relationships show that the effect is relatively small compared to specimen shape effect.

2. The expressions for specimen shape effect based on the result from cube and cylinder specimens are presented. The compressive cube strength is generally higher than cylindrical strength and this effect trend to be decreased as the concrete strength increases. The ratio of the compressive strength at 28 days of Ø150x300 mm cylinder to the 150 mm cube is varied from 0.78 to 0.86 for the designed cylinder compressive strength of 550 to 1,000 kg/cm^2.

3. The current standard of practice in converting the 150 mm cube strength to standard Ø150x300 mm cylinder strength needs to be revised to include the conversion factors for concrete strength higher than 550 kg/cm^2. The suggested relations, obtained from Ø150x300 mm cylinder and 150 mm cube test results at 28 days, are shown on Fig. 11 and Table 17.

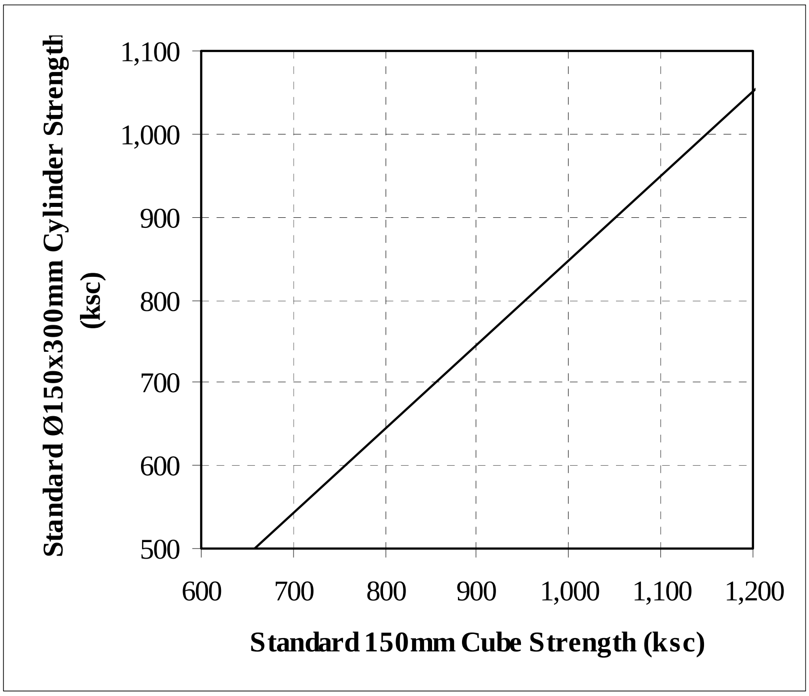

Figure 11 Relationships between compressive strength of standard 150mm cube and standard Ø150x300mm cylinder

Table 17 Relations between compressive strength of Ø150x300 mm cylinder and 150 mm cube specimen

Compressive Strength at 28 days (kg/cm^2)		Cylinder/Cube Strength Ratio
Cube 150 mm	Cylinder Ø150x300 mm	
650	492	0.757
700	543	0.775
750	594	0.792
800	645	0.806
850	695	0.818
900	746	0.829
950	797	0.839
1000	848	0.848
1050	899	0.856
1100	950	0.863
1150	1000	0.870

Validity Limit and Recommendation

Since this experimental study was performed following the specified procedures and concrete compositions, the conclusions and expressions are only for this specific condition. Further studies in this field, with wider range of concrete strength and greater number of test specimens, are still needed to obtain more accurate relations and statistical significance among various parameters. One batch mixing for a concrete mixture is also recommended to avoid high deviation in a set of compressive strength test result.

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APPENDICES

Appendix A

Test Results and Statistical Analysis

Appendix Table A1 Test results and statistical data of HSC mix 1 at 7 days

Sample Type	Sample Dimension (cm)			Ult. Load (kg)	Ult. Stress (ksc)	Statistical Parameter			
	W/D	L	H			$\overline{X}_m$	$\lvert X_j - \overline{X}_m \rvert$	$\overline{s}$	$\overline{Z}_i$
Cu100	10.0	10.0	10.0	59,640	596	663	66.5	38.5	1.73
	10.0	10.0	10.0	68,880	689		25.9		0.67
	10.0	10.1	10.0	66,950	663		0.0		0.00
	10.0	9.5	10.0	68,300	719		56.1		1.46
	10.0	10.1	10.0	65,330	647		16.0		0.42
	10.0	10.1	10.0	69,820	691		28.4		0.74
	10.0	10.1	9.5	70,610	699		36.2		0.94
	10.0	10.0	10.0	65,550	656		7.4		0.19
	10.0	10.1	10.0	65,300	647		16.3		0.42
Cu150	15.1	15.1	15.2	118,800	521	645	124.2	17.3	7.16*
	15.2	15.1	15.2	141,900	618		27.0		1.56
	15.2	15.1	15.1	149,500	651		6.1		0.35
	15.3	15.0	15.0	148,500	647		1.8		0.10
	15.0	15.1	15.1	145,700	643		2.0		0.11
	15.2	15.1	15.1	148,100	645		0.0		0.00
	15.0	15.1	15.1	150,300	664		18.3		1.06
	15.2	15.0	15.2	140,400	616		29.5		1.70
	15.0	15.1	15.1	148,800	657		11.7		0.67
Cy100	10.0		20.1	28,270	360	482	122.2	41.5	2.95
	10.0		20.1	33,860	431		51.1		1.23
	10.0		20.0	40,420	515		32.5		0.78
	10.0		20.0	37,870	482		0.0		0.00
	10.0		20.0	39,270	500		17.8		0.43
	10.0		20.1	39,040	497		14.9		0.36
	10.1		20.1	36,390	454		28.0		0.67
	10.0		20.0	39,730	506		23.7		0.57
	10.0		20.1	33,370	425		57.3		1.38
Cy150	15.0		30.1	89,440	506	507	0.5	15.7	0.03
	15.0		30.2	89,530	507		0.0		0.00
	15.0		30.1	95,370	540		33.0		2.11
	15.0		30.0	86,180	488		19.0		1.21
	15.0		30.2	82,660	468		38.9		2.48
	15.0		30.1	91,450	518		10.9		0.69
	15.0		30.2	88,740	502		4.5		0.28
	15.0		30.1	91,400	517		10.6		0.67
	15.0		29.9	90,470	512		5.3		0.34

Note: * means the $\overline{Z}_i$ value exceeds critical limit for normal data ($\overline{Z}_i \geq 3.0$).

Appendix Table A2 Test results and statistical data of HSC mix 2 at 7 days

Sample Type	Sample Dimension (cm)			Ult. Load (kg)	Ult. Stress (ksc)	Statistical Parameter			
	W/D	L	H			$\overline{X}_m$	$\lvert X_j - \overline{X}_m \rvert$	$\overline{s}$	$\overline{Z}_i$
Cu100	10.0	10.1	10.0	80,930	801	782	19.2	41.6	0.46
	10.0	10.0	10.0	78,270	783		0.6		0.02
	10.0	10.1	10.0	74,920	742		40.3		0.97
	10.2	10.0	10.0	79,770	782		0.0		0.00
	10.0	9.9	10.0	72,530	733		49.4		1.19
	10.0	10.0	10.0	71,710	717		65.0		1.56
	10.0	9.9	10.0	78,170	790		7.5		0.18
	10.0	10.0	10.0	75,400	754		28.1		0.67
	9.9	10.0	10.0	81,350	822		39.7		0.95
Cu150	15.1	15.0	15.0	173,900	768	765	2.9	24.1	0.12
	15.1	15.0	15.1	161,400	713		52.3		2.17
	15.1	15.0	15.2	178,300	787		22.3		0.92
	15.1	15.0	15.2	162,300	717		48.4		2.00
	15.0	15.3	15.3	176,100	767		2.4		0.10
	15.2	15.1	15.2	179,300	781		16.3		0.67
	15.2	15.0	15.2	174,400	765		0.0		0.00
	15.0	15.2	15.1	172,300	756		9.2		0.38
	15.1	15.1	15.2	165,500	726		39.1		1.62
Cy100	10.0		19.9	43,910	559	629	70.0	49.3	1.42
	10.0		19.9	49,410	629		0.0		0.00
	10.0		19.9	49,980	636		7.3		0.15
	10.0		19.9	47,150	600		28.8		0.58
	10.0		20.2	52,210	665		35.7		0.72
	10.1		20.0	47,000	587		42.5		0.86
	10.0		20.1	47,510	605		24.2		0.49
	10.0		20.1	52,020	662		33.2		0.67
	10.0		20.1	53,250	678		48.9		0.99
Cy150	15.1		29.9	119,100	665	655	9.8	14.5	0.67
	15.0		30.0	115,800	655		0.0		0.00
	15.0		30.0	115,600	654		1.1		0.08
	15.0		29.9	107,800	610		45.3		3.12*
	14.9		30.0	107,900	619		36.5		2.52
	15.0		30.0	117,000	662		6.8		0.47
	14.9		30.0	116,500	668		12.8		0.89
	15.0		30.0	116,400	659		3.4		0.23
	15.0		29.9	108,700	615		40.2		2.77

Note: * means the $\overline{Z}_i$ value exceeds critical limit for normal data ($\overline{Z}_i \geq 3.0$).

Appendix Table A3 Test results and statistical data of HSC mix 3 at 7 days

Sample Type	Sample Dimension (cm)			Ult. Load (kg)	Ult. Stress (ksc)	Statistical Parameter			
	W/D	L	H			$\overline{X}_m$	$\left\|X_j - \overline{X}_m\right\|$	$\overline{s}$	$\overline{Z}_i$
Cu100	10.0	10.1	10.0	96,570	956	959	2.4	68.2	0.03
	10.1	10.0	10.0	89,920	890		68.2		1.00
	10.0	10.0	10.0	95,850	959		0.0		0.00
	10.0	10.0	10.0	98,840	988		29.9		0.44
	10.0	10.0	10.0	100,700	1,007		48.5		0.71
	10.0	10.0	10.0	103,800	1,038		79.5		1.17
	10.0	9.9	10.0	93,590	945		13.1		0.19
	10.1	10.0	10.0	101,600	1,006		47.4		0.70
	10.0	10.0	10.0	91,250	913		46.0		0.67
Cu150	15.0	15.0	15.1	194,400	864	888	23.8	31.9	0.75
	14.8	15.0	14.9	197,100	888		0.0		0.00
	15.0	15.0	15.1	192,000	853		34.5		1.08
	15.1	15.2	15.3	201,000	876		12.1		0.38
	15.0	15.1	15.0	209,500	925		37.1		1.16
	15.1	14.9	14.9	204,600	909		21.5		0.67
	15.1	14.9	15.1	197,600	878		9.6		0.30
	15.2	14.9	15.2	213,700	944		55.7		1.75
	15.0	14.9	15.0	199,600	893		5.2		0.16
Cy100	10.0		19.9	61,650	785	853	68.4	37.4	1.83
	10.0		20.1	66,350	853		0.0		0.00
	10.0		20.0	69,000	879		25.2		0.67
	10.0		20.0	67,490	859		6.0		0.16
	10.0		20.0	69,270	882		28.7		0.77
	10.0		19.9	59,670	760		93.6		2.50
	10.0		20.0	67,630	861		7.8		0.21
	10.1		20.0	63,390	791		62.1		1.66
	10.0		19.9	65,130	829		24.0		0.64
Cy150	14.9		29.9	133,500	766	813	47.0	37.4	1.26
	14.9		29.9	143,500	823		10.3		0.28
	15.0		30.0	140,800	797		15.9		0.42
	15.0		30.0	146,500	829		16.4		0.44
	14.9		29.8	129,200	741		71.7		1.92
	14.9		30.0	141,700	813		0.0		0.00
	14.9		29.9	146,100	838		25.2		0.67
	15.0		29.9	135,300	766		47.0		1.26
	15.0		29.8	152,000	860		47.5		1.27

Appendix Table A4 Test results and statistical data of HSC mix 4 at 7 days

Sample Type	Sample Dimension (cm)			Ult. Load (kg)	Ult. Stress (ksc)	Statistical Parameter			
	W/D	L	H			$\overline{X}_m$	$\lvert X_j - \overline{X}_m \rvert$	$\overline{s}$	$\overline{Z}_i$
Cu100	10.0	10.1	10.0	107,200	1,061	987	74.9	61.5	1.22
	10.0	10.0	10.0	98,640	986		0.1		0.00
	10.1	10.0	10.0	106,600	1,055		68.9		1.12
	10.1	10.1	10.0	105,600	1,035		48.7		0.79
	10.0	10.1	10.0	95,150	942		44.5		0.72
	10.0	10.1	10.0	97,730	968		18.9		0.31
	10.0	10.1	9.9	95,450	945		41.5		0.67
	10.0	10.0	10.0	102,600	1,026		39.5		0.64
	10.0	10.1	10.0	99,640	987		0.0		0.00
Cu150	15.2	15.3	15.2	242,400	1,042	977	65.6	74.1	0.89
	15.3	15.1	15.1	238,100	1,031		53.9		0.73
	15.0	14.9	15.0	209,400	937		39.8		0.54
	15.1	15.1	15.1	222,700	977		0.0		0.00
	15.0	15.0	15.0	242,300	1,077		100.2		1.35
	15.1	15.2	15.2	224,100	976		0.3		0.00
	15.5	15.1	15.2	203,500	869		107.2		1.45
	15.0	15.0	15.0	231,000	1,027		50.0		0.67
	15.1	15.1	15.0	217,200	953		24.1		0.33
Cy100	10.0		20.1	59,840	762	907	145.4	38.3	3.79*
	10.0		20.0	73,290	933		25.8		0.67
	10.0		20.1	65,960	840		67.5		1.76
	10.0		20.1	71,260	907		0.0		0.00
	10.0		20.1	72,880	928		20.6		0.54
	10.0		20.1	73,860	940		33.1		0.86
	10.0		20.0	67,270	857		50.8		1.33
	10.0		20.0	72,480	923		15.5		0.41
	10.0		20.0	69,550	886		21.8		0.57
Cy150	15.0		30.2	162,400	919	869	49.8	73.9	0.67
	15.0		30.3	145,600	824		45.3		0.61
	14.9		30.0	156,200	896		26.6		0.36
	14.9		30.1	93,240	535		334.5		4.53*
	15.0		30.1	106,200	601		268.2		3.63*
	15.0		30.0	153,600	869		0.0		0.00
	15.0		30.0	165,900	939		69.6		0.94
	15.0		30.0	121,300	686		182.8		2.48
	15.0		30.1	160,300	907		37.9		0.51

Note: * means the $\overline{Z}_i$ value exceeds critical limit for normal data ($\overline{Z}_i \geq 3.0$).

Appendix Table A5 Test results and statistical data of HSC mix 1 at 28 days

Sample Type	Sample Dimension (cm)			Ult. Load (kg)	Ult. Stress (ksc)	Statistical Parameter			
	W/D	L	H			$\overline{X}_m$	$\lvert X_j - \overline{X}_m \rvert$	$\bar{s}$	$\overline{Z}_i$
Cu100	10.1	10.0	10.1	69,100	684	736	51.44	56.35	0.91
	10.0	10.0	10.1	72,710	727		8.50		0.15
	10.0	10.0	9.5	73,260	733		3.00		0.05
	10.0	10.0	10.0	73,730	737		1.70		0.03
	10.0	10.0	10.0	73,560	736		0.00		0.00
	10.0	10.0	10.1	80,170	802		66.10		1.17
	10.0	10.1	10.0	69,720	690		45.30		0.80
	10.0	10.0	10.0	77,360	774		38.00		0.67
	10.0	10.0	10.0	79,000	790		54.40		0.97
Cu150	15.2	15.0	15.2	161,700	709	751	42.22	53.39	0.79
	15.0	14.8	15.0	157,900	711		40.17		0.75
	15.0	14.9	15.1	159,900	715		36.00		0.67
	15.2	15.0	15.2	171,400	752		0.32		0.01
	15.2	15.2	15.3	159,100	689		62.81		1.18
	15.1	15.0	15.1	170,200	751		0.00		0.00
	15.1	14.9	15.3	172,400	766		14.82		0.28
	14.9	15.0	15.2	178,100	797		45.43		0.85
	15.0	15.0	15.2	173,000	769		17.45		0.33
Cy100	10.0		20.1	46,770	595	620	24.70	24.17	1.02
	10.1		19.8	46,330	578		41.93		1.73
	9.9		19.8	47,510	617		3.00		0.12
	10.0		20.0	48,220	614		6.24		0.26
	9.9		20.1	50,700	659		38.44		1.59
	10.0		19.9	49,990	636		16.30		0.67
	9.9		20.0	49,110	638		17.79		0.74
	10.0		20.0	49,060	625		4.46		0.18
	10.0		20.0	48,710	620		0.00		0.00
Cy150	15.0		30.0	108,600	615	615	0.00	63.30	0.00
	14.9		29.9	82,550	473		141.12		2.23
	14.9		30.1	96,830	555		59.22		0.94
	14.9		30.0	108,900	625		10.00		0.16
	14.9		30.0	88,820	509		105.16		1.66
	15.2		30.0	112,300	619		4.32		0.07
	15.0		30.0	85,080	481		133.10		2.10
	14.9		30.1	114,600	657		42.69		0.67
	14.9		30.0	112,800	647		32.36		0.51

Appendix Table A6 Test results and statistical data of HSC mix 2 at 28 days

Sample Type	Sample Dimension (cm)			Ult. Load (kg)	Ult. Stress (ksc)	Statistical Parameter			
	W/D	L	H			$\overline{X}_m$	$\lvert X_j - \overline{X}_m \rvert$	$\overline{s}$	$\overline{Z}_i$
Cu100	10.0	10.0	10.0	88,500	885	928	43.40	45.51	0.95
	10.1	10.1	9.9	79,100	775		152.99		3.36*
	10.0	10.0	10.0	87,470	875		53.70		1.18
	9.9	10.0	10.0	94,100	951		22.11		0.49
	9.9	10.0	10.0	94,950	959		30.69		0.67
	10.0	10.0	10.0	92,840	928		0.00		0.00
	10.0	9.9	9.9	95,280	962		34.02		0.75
	10.0	10.0	9.9	90,680	907		21.60		0.47
	10.0	10.0	9.9	94,210	942		13.70		0.30
Cu150	15.1	15.0	14.9	197,700	873	874	1.41	34.08	0.04
	15.1	15.0	15.0	207,400	916		41.41		1.22
	15.1	14.9	15.0	203,100	903		28.45		0.83
	15.0	15.0	15.0	204,000	907		32.41		0.95
	15.1	15.1	15.0	194,100	851		22.98		0.67
	15.1	14.9	15.1	201,600	896		21.78		0.64
	15.1	15.0	14.9	194,000	857		17.75		0.52
	15.1	14.9	15.1	196,700	874		0.00		0.00
	15.1	15.0	15.0	185,400	819		55.72		1.63
Cy100	10.1		20.1	61,000	761	715	46.07	68.32	0.67
	10.0		19.8	63,940	814		98.80		1.45
	10.1		20.1	48,100	600		114.95		1.68
	10.0		20.2	59,810	762		46.22		0.68
	10.0		20.1	55,300	704		11.20		0.16
	10.0		20.0	55,830	711		4.46		0.07
	10.0		20.1	56,180	715		0.00		0.00
	10.0		20.1	60,920	776		60.35		0.88
	10.0		20.0	54,040	688		27.25		0.40
Cy150	15.0		30.1	136,100	770	735	34.74	40.53	0.86
	15.0		30.2	124,000	702		33.73		0.83
	14.9		30.3	133,000	763		27.33		0.67
	15.1		30.2	131,700	735		0.00		0.00
	15.0		30.1	137,800	780		44.36		1.09
	15.0		30.2	113,100	640		95.42		2.35
	14.9		30.2	126,000	723		12.81		0.32
	15.0		30.1	125,300	709		26.38		0.65
	15.0		30.1	131,800	746		10.40		0.26

Note: * means the $\overline{Z}_i$ value exceeds critical limit for normal data ($\overline{Z}_i \geq 3.0$).

Appendix Table A7 Test results and statistical data of HSC mix 3 at 28 days

Sample Type	Sample Dimension (cm)			Ult. Load (kg)	Ult. Stress (ksc)	Statistical Parameter			
	W/D	L	H			$\overline{X}_m$	$\lvert X_j - \overline{X}_m \rvert$	$\overline{s}$	$\overline{Z}_i$
	10.0	10.0	10.0	86,780	868		209.98		3.70*
	10.0	9.9	10.0	98,790	998		79.90		1.41
	10.0	10.0	10.0	93,960	940		138.18		2.44
	10.0	9.9	9.9	104,400	1,055		23.23		0.41
Cu100	10.0	10.0	9.9	110,200	1,102	1,078	24.22	56.68	0.43
	10.0	9.9	10.0	109,300	1,104		26.26		0.46
	10.0	9.9	10.0	110,500	1,116		38.38		0.68
	10.0	9.9	9.9	106,700	1,078		0.00		0.00
	10.0	10.0	9.9	111,600	1,116		38.22		0.67
	15.2	15.0	15.2	237,200	1,040		31.46		0.85
	15.1	14.9	14.9	221,400	984		24.85		0.67
	15.0	15.0	15.0	227,000	1,009		0.00		0.00
	15.5	14.9	15.0	232,700	1,008		1.31		0.04
Cu150	15.1	15.0	15.0	236,800	1,045	1,009	36.59	36.85	0.99
	15.0	14.9	15.2	232,300	1,039		30.48		0.83
	15.2	14.9	15.1	220,900	975		33.53		0.91
	15.4	15.0	15.0	233,100	1,009		0.20		0.01
	15.0	15.0	15.2	222,300	988		20.89		0.57
	10.0		19.8	67,740	862		28.44		0.44
	10.0		20.0	64,190	826		65.40		1.02
	10.0		20.0	61,820	787		103.81		1.62
	10.0		20.0	63,860	813		77.84		1.21
Cy100	10.0		19.8	73,110	931	891	39.94	64.23	0.62
	10.0		19.9	73,640	938		46.68		0.73
	10.0		19.9	72,530	923		32.55		0.51
	9.9		19.9	70,770	919		28.44		0.44
	10.0		19.9	-**	-**		-**		-**
	15.0		30.0	157,800	893		28.12		0.67
	14.9		30.0	153,300	879		14.34		0.34
	15.0		29.9	151,300	856		8.66		0.21
	14.9		29.9	152,100	872		7.46		0.18
Cy150	15.1		30.0	70,520	394	865	471.05	41.70	11.30*
	15.0		30.0	162,900	922		56.98		1.37
	14.9		30.0	141,000	809		56.20		1.35
	14.9		29.9	150,800	865		0.00		0.00
	15.0		30.0	112,500	637		228.23		5.47*

Note: * means the $\overline{Z}_i$ value exceeds critical limit for normal data ($\overline{Z}_i \geq 3.0$).
** means the ultimate strength of specimen cannot be obtained due to operating problem.

Appendix Table A8 Test results and statistical data of HSC mix 4 at 28 days

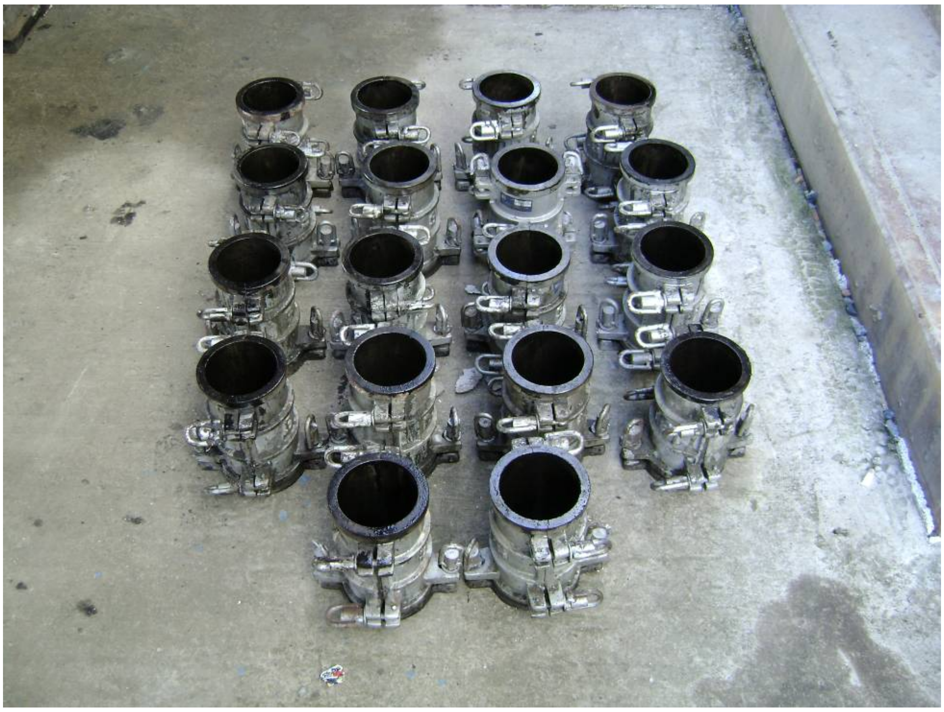
Sample Type	Sample Dimension (cm)			Ult. Load (kg)	Ult. Stress (ksc)	Statistical Parameter			
	W/D	L	H			$\overline{X}_m$	$\left\|X_j - \overline{X}_m\right\|$	$\overline{s}$	$\overline{Z}_i$
Cu100	10.0	10.1	10.0	105,800	1,048	1,189	141.58	85.06	1.66
	10.0	9.9	10.0	122,800	1,240		51.30		0.60
	10.0	10.0	10.0	115,100	1,151		38.11		0.45
	10.1	10.0	10.0	114,000	1,129		60.40		0.71
	10.0	10.0	10.0	126,700	1,267		77.89		0.92
	10.0	10.1	10.0	120,100	1,189		0.00		0.00
	10.0	10.0	10.0	120,400	1,204		14.89		0.18
	9.9	10.0	10.0	123,400	1,246		57.36		0.67
	10.0	9.9	10.1	108,800	1,099		90.12		1.06
Cu150	15.1	15.1	15.1	257,300	1,128	1,129	0.43	62.16	0.01
	15.0	15.0	15.2	254,000	1,129		0.00		0.00
	15.1	15.2	15.0	265,000	1,155		25.69		0.41
	15.2	15.0	15.2	259,200	1,137		7.95		0.13
	15.1	15.0	15.1	265,300	1,171		42.41		0.68
	15.0	15.1	14.9	265,700	1,173		44.18		0.71
	15.1	15.1	15.1	243,600	1,068		60.51		0.97
	15.1	15.2	15.0	241,500	1,052		76.69		1.23
	15.1	15.0	15.1	246,200	1,087		41.91		0.67
Cy100	10.0		19.8	-**	-**	1,041	-**	71.56	-**
	10.0		20.0	81,940	1,043		2.67		0.04
	10.0		20.1	72,960	929		111.66		1.56
	9.9		19.9	77,220	1,003		37.46		0.52
	10.0		19.9	81,730	1,041		0.00		0.00
	10.0		20.0	86,850	1,106		65.19		0.91
	10.0		19.9	85,520	1,089		48.26		0.67
	10.1		20.0	-**	-**		-**		-**
	10.0		19.8	73,790	940		101.10		1.41
Cy150	15.0		30.0	167,900	950	950	0.00	92.97	0.00
	14.9		29.8	176,600	1,013		62.69		0.67
	14.9		30.0	187,700	1,076		126.35		1.36
	14.9		30.1	165,700	950		0.18		0.00
	14.9		30.1	164,100	941		9.00		0.10
	15.0		30.0	147,500	835		115.44		1.24
	14.9		30.1	184,500	1,058		108.00		1.16
	15.0		30.0	166,700	943		6.79		0.07
	15.0		30.0	156,600	886		63.94		0.69

Note: ** means the ultimate strength of specimen cannot be obtained due to operating problem.

Appendix B

Materials and Equipment

Appendix Figure B1 Ø150x300 mm cylinder moulds



Appendix Figure B2 Ø100x200 mm cylinder moulds

Appendix Figure B3 150 mm cube moulds

Appendix Figure B4 100 mm cube moulds

Appendix Figure B5 Ordinary Portland cement (Elephant brand cement type I)

Appendix Figure B6 Fine aggregate (sand)

Appendix Figure B7 Coarse aggregate (crushed stone)

Appendix Figure B8 Silica fume (Sikacrete PP1)

Appendix Figure B9 Superplasticizer (Sika Viscocrete-10)

Appendix Figure B10 Weighing scales

Appendix Figure B11 Concrete mixing machine

Appendix Figure B12 Internal concrete vibrator

Appendix Figure B13 Compressive testing machine (model: ADR auto range 300 t)

Appendix C

Experimental Methods

Appendix Figure C1 Weighing of material

Appendix Figure C2 Materials ready for mixing

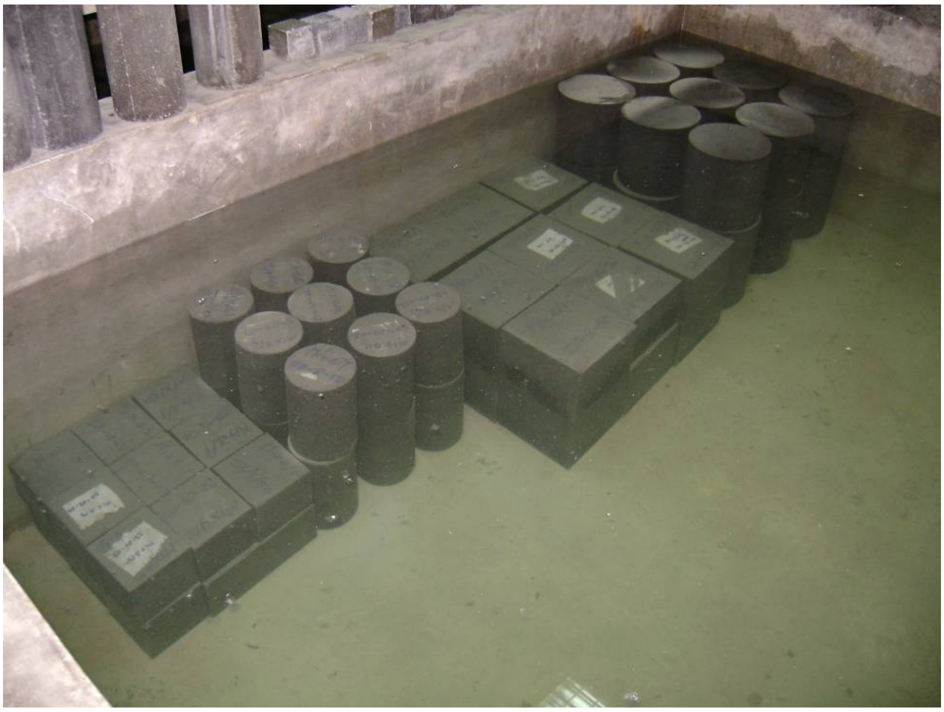
Appendix Figure C3 Dry mixing of concrete

Appendix Figure C4 Fresh concrete

Appendix Figure C5 Slump test

Appendix Figure C6 Compacting of concrete using internal vibrator

Appendix Figure C7 Concrete specimens after casting



Appendix Figure C8 Curing of specimens

Appendix Figure C9 Specimens ready for testing

Appendix Figure C10 Setting of specimen on compressive testing machine