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EFFECT OF SHAPE AND SIZE ON COMPRESSIVE STRENGTH PROPERTIES OF HIGH PERFORMANCE CONCRETE

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ABSTRACT: An experimental work conducted to study the effect of specimen shape and size on the compressive strength of high-performance concrete is reported in this paper. Cubes and cylinder specimens of different sizes were used for this purpose and concrete strength was varied from 40MPa to 100MPa. Throughout the investigation the parameters, such as concrete making and testing conditions for all the specimens were closely controlled to reduce the scatter of results. The test results obtained in the study reveal that strength obtained with smaller specimens is higher in average than the standard specimens. Based on the test data, simple models were proposed to relate the effect of shape and size. The proposed model has been compared with the models present in the literature. An investigation was also made regarding the crack pattern of both types of specimens. In Cubes the cracking process was provoked by a stress concentration near the corners and as load increases, crushing leads to vertical cracks and column like fragments, where as in cylinders a main inclined crack was nucleated and finally it broke by diagonal fracture plane.

Keywords: Compressive strength, High-performance concrete, Size effect, Specimen shape

1. Introduction

Concrete structures much larger than the specimens tested in the laboratories are being built in ever increasing numbers. However, the experimental data base collected to establish design code specifications consists of mostly small-size laboratory specimens. In the last few decades concrete technology has made it easier to reach higher strengths and so called High Performance Concrete (HPC) has appeared as a new construction material. HPC can that be strong that usual specimens 150mmX150mmX150mm (Cubes) and 150mmX300mm (Cylinders) may surpass the loading capacities of the standard laboratory equipments. To overcome this drawback HPC mixture properties are evaluated by smaller specimens.

Previous tests and theoretical investigations showed that structural concrete behavior is largely influenced by the specimen size. The size effect was studied by behavioral comparisons of geometrically similar test specimens. Initially, these observations were based only on test data. The sizes and shapes of compressive strength test specimens of concrete vary from one country to another. Cylinders are used in United States, Canada, France, Australia, etc., whereas, cubes are the standard shapes in the India, United Kingdom, Germany, and many other European countries. There are several countries where tests are made on both cubes and cylinders. However, the advantages such as easy handling, necessitating lower capacity test machines, using less concrete etc., offered by smaller specimens have caused them to be used more frequently.

In the last few years, many researchers (Hillerborg 1988, Bazant 1989; Vonk 1992; Van Mier 1992; Bazant 1993; Neville 1996) have started to realize that, the strain localization also occurs for concrete specimens loaded in compression. Unlike failure caused by pure tension loading which usually takes place in a relatively narrow localized zone, compressive loading failure occurs within a larger damage zone. The compressive failure shows a similar failure mechanism as tensile failure. In both cases, the failure is caused by the distributed splitting cracks in the direction of member length as the lateral deformation increases during the failure progression. However, the compressive failure mechanism is more complex than tensile failure mechanism. Size effect of compressive failure is not as distinct as in tensile failure, because the formation of micro-cracks in compressive failure is distributed in a wider region than in tensile failure. J.R. del Viso et al., (2008), have studied the effect of size and shape on the compressive strength properties of High-strength concrete (HSC).

Presently, most design codes for concrete structures do not consider the effect of size. Since quasibrittle materials fail by formation of cracks, size effect has to be implemented. In compressive failure of quasibrittle materials, the size effect is quite apparent. Though the behavior of compressive failure has been studied extensively, the failure mechanism and its size effect have been insufficiently studied when compared to tensile failure mechanism. Experimental data for proper analyses of size effect is currently lacking. However, from the few available experimental data, it is apparent that compressive strength decreases as specimen sizes increase.

The focus of this study is to further develop and clarify compressive size effect in HPC (up to 100MPa). By far the most common test carried out on concrete is the compressive strength test. The main reason to understand this fact is that this kind of test is easy and relatively inexpensive to carry out. The experimental results and simple analysis of size and shape effects are presented in this paper.

2. Experimental Program

2.1 Test Specimens

From the four concrete mixes different size cubes (50X50X50, 67X67X67, 100X100X100 and 150X150X150 mm) and cylinders (50X100, 75X150, 100X200 and 150X300 mm) with length to depth ratio as two were cast. All the specimens were compacted with equivalent compaction effort depending on their sizes and continuously cured in water and tested at 28 days and 56 days. A total of 182 Cubes and 182 Cylinders were cast and tested in such a way that minimum of six specimens were tested for a given size and strength of concrete.

2.2 Materials and Mix proportion

Four Concrete mixes were prepared by using 43 Grade OPC and 53 Grade (for M100) cement, river sand as fine aggregate, crushed basalt as coarse aggregate, a ether based high range water reducer (HRWR) and mineral admixtures(Fly ash and Silica fume). The mix designs were made to obtain four series of concrete mixes having 40, 60, 80 and 100 MPa characteristic compressive strength (Table 1). Mixing of concrete is made in a 125 kg ribbon mixer. For Concretes having compressive strength of 60-100 MPa in which HRWR was used had the slump in the range of 70-100mm. The 40 MPa concrete which had no HRWR, had shown a slump of 25mm. For sufficient and uniform compaction a table vibrator was used in the laboratory.

2.3 Method of Testing

Compressive strength of concrete is the most significant property of hardened concrete because any other strengths of concrete such as tensile, flexural, shearing and bond strength are all related to the compressive strength. The specimens were tested in the compression testing machine of 3000KN capacity and throughout the program the other parameters such as concrete making and testing conditions for all the specimens were closely controlled to reduce the scatter of results. Concrete cylinders were loaded uni-axially after leveling its top by grinding machine.

3.0 Results and Discussions

3.1 Size effect

The compressive strength results and percentage increase with reference to standard size specimens for different size cubes and cylinders are presented in Table 2 and 3. The results indicate an average percentage increase in strength of 8 to 25% and 6 to 18% for cubes and cylinders respectively. This shows increase in strength with the decrease in the size of the specimen. Also, the normal strength concrete has indicated maximum increase of 43% for cubes and 35 % for cylinders, whereas for HPC the maximum increase is 27% for cubes and 17% for cylinders. Hence, percentage increase decreases as the strength of concrete increases. This reveals that cube strength is more sensitive to size effect than cylinder strength.

3.2 Relationship of size effect

The size effect was studied by behavioral comparisons of geometrically similar test specimens. It was shown in several studies that larger compression specimens had steeper softening paths and hence show low strengths. This phenomenon is termed as size effect. In the present study a relation was established for size effect based on the test results.

3.2.1 Relationship for cubes

A relation between cube strength and the size of cube specimen is proposed as given below;

$$\sigma_{cube} = A(L)^{-B} \tag{1}$$

where
A and B: empirical constants.
L: Length of cube edge

The constant is generalized for different strength of concrete at 28 and 56-days strength results as given below, whereas constant B is considered to be equal to 0.21 for all ranges of concrete strengths at 28 and 56-days.

$$A = (-0.028)(\sigma_N)^2 + 6.4\sigma_N - 78.25$$

For 28 days (2)

$$A = (-0.06)(\sigma_N)^2 + 11.3\sigma_N - 219.68$$

For 56 days (3)

The experiental results were compared with these models at 28-days and 56-days and are shown in Fig. 1 and Fig. 2 respectively.

3.2.2 Relationship for Cylinders

Cylindrical strengths results are related to the height of the cylinder specimen as given below;

$$\sigma_{cube} = A(D)^{-B} \quad (4)$$

where
A and B: empirical constants.
D: height of cylinder
The constant is generalized for different strength of concrete at 28 and 56-days strength results as given below, whereas constant B is considered to be equal to 0.15 for all ranges of concrete strengths at 28 and 56-days.

$$A = (-0.0269)(\sigma_N)^2 + 5.9\sigma_N - 94.45$$

For 28 days (5)

$$A = (-0.0375)(\sigma_N)^2 + 7.6\sigma_N - 134.5$$

For 56 days (6)

The experimental results were compared with these models at 28-days and 56-days and are shown in Fig. 3 and Fig. 4 respectively.

The failure stress of series of geometrically similar structures of different sizes can be expressed by an infinite series as given by Bazant. Z. P (1986) and Kim et al (2002). Also further the infinite series was truncated to the linear form by Bazant Z. P and Planas, Jaime (1998) and is discussed by Elfahal. M.M (2003), and is presented as below.

$$\sigma_{cyl} = \frac{Cf_t}{\sqrt{1+\frac{D}{D_o}}} \quad (7)$$

where
C: constant
D/Do: relative structural size ratio
ft: tensile strength of concrete
Using equation 8 the cylindrical strengths were determined for different relative size ratios and different strengths of concrete and were compared with the experimental results as presented in Fig. 5. The values of ft in equation 8 were calculated by the equation proposed by Said Irvani (1996) as shown below.

$$f_t = 0.57\sqrt{f_c}$$

50MPa < f_c < 100 MPa (8)

3.3 Reationship between Cylinder and Cube strength

When a cylindrical concrete specimen is subjected to uni-axial compression loads, it tends to expand in the lateral direction. However, there exists a frictional force between the machine platens and the specimen. The frictional force creates a lateral compressive force which is responsible for the formation of a cone at failure. When the lateral constraint is eliminated, the lateral compressive force disappears and splitting type rupture is obtained. However, it seems to be valid to assume that the lateral constraint is produced to some extent since it is very difficult to eliminate the frictional force in practice. In this section we analyze test results to get a relationship between cylinder and cube strength valid for cubes of any size. According to Bazant and Planas(1998) the maximum load Pc is a function of the specimen geometry (shape and size), boundary conditions and concrete properties. A correlation between compressive strength for cubes of any size, σcube, and standard tests, fc(cylinder) can be derived. For concrete with a characteristic length of 150 mm, like one used in this work, the expression as per J. R.del Viso et al.,(2008) is as given by the below equation .

$$f_c = \sigma_{cube}\sqrt{\frac{L}{L+L_o}} \quad (9)$$

where
L0 = constant = 20mm.
A relation is established against the ratio of cylinder to cube strength to the length of cube specimen as in figure 6 with constant L0 = 18mm and this has good representation with the experimental results.

3.4 Crack Pattern

For a heterogeneous material like concrete, cracking is a dominant factor for its behavior, and the development of micro-cracking is closely related to the characteristics of the interfacial transition zone. The mode of failure of high performance concrete specimens in uni-axial compression is different from that of normal strength concrete specimens because of improvement in the microstructure of concrete. The number and length of continuous crack pattern developed at failure decreases as the compressive strength increases. In-fact, the cracking of HPC is more localized and it approaches the behavior of a homogeneous material when compared with cracking in normal strength concrete (NSC). It is generally observed that the cracks develop between the interface of aggregate and the cement paste in NSC, on the other hand, in HPC, cracks propagate through the aggregate as well as paste and, consequently there is less resistance across crack surface due to reduced interlocking.

The mode of failure and cracking characteristics of both types of concrete specimens (Cubes and Cylinders) for different concrete strengths were observed during the test. To visualize the cracks at different stages of loading the rate of loading is made slow and the loading was stopped when a crack is observed. In the case of cubes the fracture process is provoked by a stress concentration near the cube corners. Inclined micro-cracks appear and come together near the corner (Fig.9). As the load increases, the crushing leads to vertical cracks and column-like fragments (Fig.10). It has been observed that for normal strength concrete the first crack is seen at low stress level that is around 50% of ultimate. In higher strength concrete the first crack was produced at around 65%, the number of cracks increases on opposite faces at around 80% (Fig.8) and ultimately the corners fail at around 95% stress level (Fig.9). In case of smaller specimens the cracking was same except that the first crack was produced at higher stress level, at around 75% leading to higher apparent strength of concrete.

A simple visual inspection evidences that the extent of cracking through out the specimen is denser in the cubes than in cylinders. A main inclined fracture surface (Fig.11) is nucleated in cylinders and cylinders finally broke in all cases by a diagonal fracture plane (Fig.13). In the experimental study it is observed that the first crack in HPC cylinders is formed at around 85 % of ultimate load and on further loading the same crack propagates and initiating the failure with ultimately fewer numbers of cracks (Fig.12).

4.0. Conclusions

In this experimental program, mechanical behavior of High Performance Concrete (M40-M100) in compression, with four different size cubes and cylinders were investigated. Here we were particularly interested in the influence of size and shape of the specimens on the compressive strength. The following conclusions can be drawn from the study:

1. Although the use of small specimens offer certain advantages, their use in the compressive strength testing of higher strength concrete may result in significantly higher apparent strengths when compared with the standard specimens.
2. The test results and the discussion made in the earlier sections have clearly revealed the size effect. It is observed that the cube strength is more affected by size effect than the cylinder strength.
3. The size effect in the cubes and cylinders were modeled in this paper by simple equations for any strength of concrete. A comparison of experimental results of cylinders was made with the model presented by Bazant et al and also discussed by Elfahal et al.
4. A relationship between standard cylinder strength and strength obtained from cubes of any size is derived. It may help to deduce relations between the compressive strength determined from cylinders and cubes inside a theoretical frame.
5. Cracking pattern of HPC shows clear behavioral difference with normal strength concrete. Also the pattern of cracking of cylinders and cubes are entirely different. The cracking pattern may also be one of the reasons for variation in the strengths of specimens of different shape and siz

Notations

A, B and C = dimensionless empirical constants
D = cylinder height
D/Do = relative structural size ratio
Ec = modulus of elasticity concrete
L = Length cube specimen edge
Lo = empirical constant
Pc = maximum load
ft = tensile strength of concrete
fc = standard compression strength
σcube = compressive strength obtained for cubes
σcyl = compressive strength obtained for cylinders
σN = characteristic strength concrete

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Table 1 Mixture proportion

Strength of Concrete in MPa	Quantity of Ingredients of concrete in Kg/m3						HRWR in %
	Cement	Fly ash	Silica Fume	Water	Fine aggregate	Coarse Aggregate	
40	350	-	-	175	794.73	1100	-
60	366	91	-	160	701.1	1100	0.3
80	400	100	-	150	691.22	1100	0.5
100	440	68.75	41.25	137.5	672.16	1100	0.8

Table 2 Cube compressive strength

Grade of Concrete	Size of the Cube Specimen in mm	Compressive Strength 28 Days in	% Increase in strength with reference to	Compressive Strength 56 Days in N/mm2	% Increase in strength with reference to

		N/mm2	standard size		standard size
40	50X50X50	59	22	70	43
	67X67X67	56	15	64.4	31
	100X100X100	52.29	8	53	8
	150X150X150	48.51	-	49	-
60	50X50X50	95	40	110	30
	67X67X67	83	22	98	16
	100X100X100	76	12	92	8
	150X150X150	68	-	84.83	-
80	50X50X50	115	23	130	26
	67X67X67	110	18	122	18
	100X100X100	99.29	7	114	11
	150X150X150	93.17	-	103	-
100	50X50X50	125	21	138	27
	67X67X67	115.04	12	130	20
	100X100X100	110	7	115.6	7
	150X150X150	103.17	-	108.4	-

Table 3 Cylinder compressive strength

Grade of Concrete	Size of the Cylinder Specimen in mm	Compressive Strength 28 Days in N/mm2	% Increase in strength with reference to standard size	Compressive Strength 56 Days in N/mm2	% Increase in strength with reference to standard size
40	50X100	49	11	58	35
	75X150	47.24	7	54.33	26
	100X200	45.75	4	47	9
	150X300	44.12	-	43	-
60	50X100	84	29	92	16
	75X150	74.58	15	87	10
	100X200	70	8	83	5
	150X300	65	-	79	-
80	50X100	107.4	21	115	15
	75X150	101	13	110	10
	100X200	93.2	5	106.3	6
	150X300	89	-	100	-
100	50X100	108	8	125	17
	75X150	106	6	120.4	13
	100X200	103	3	113	6
	150X300	100	-	107	-

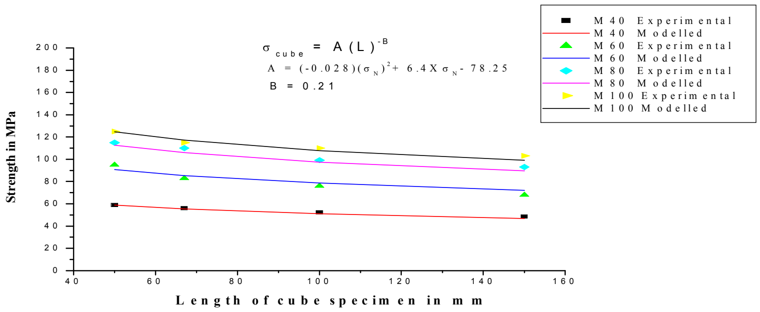

Fig. 1 Relationship between cube strength and length of cube edge at 28 Days

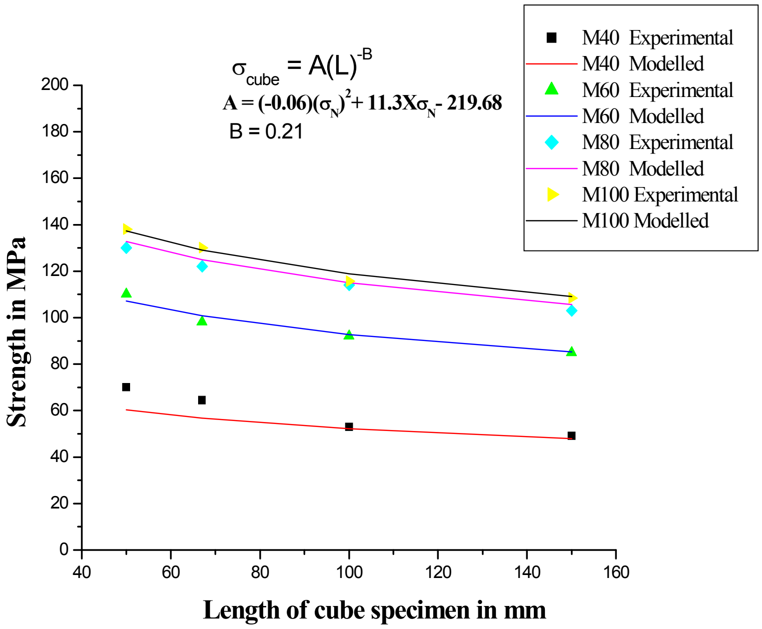

Fig. 2 Relationship between cube strength and length of cube edge at 56 Days

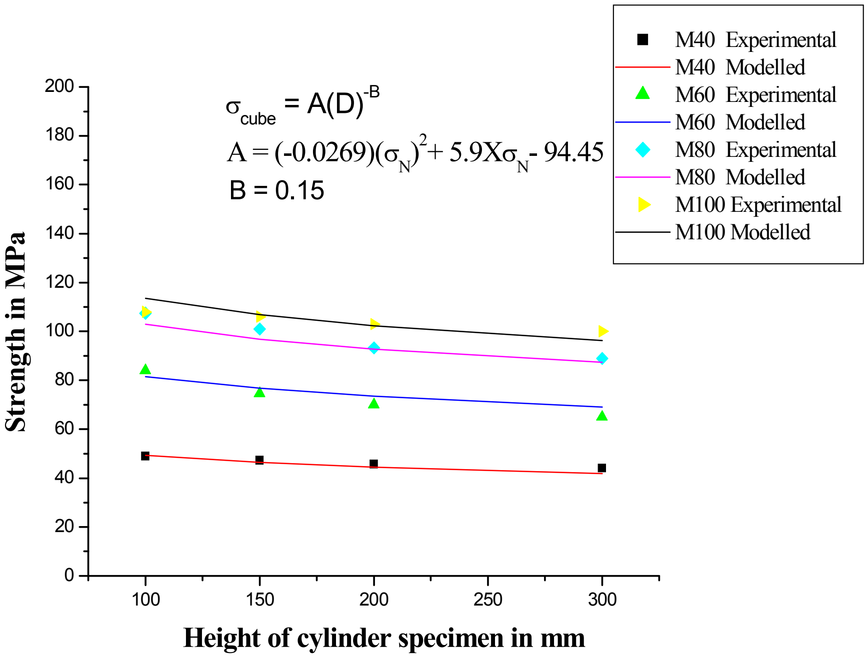

Fig. 3 Relationship between cylinder strength and height of cylinder at 28 Days

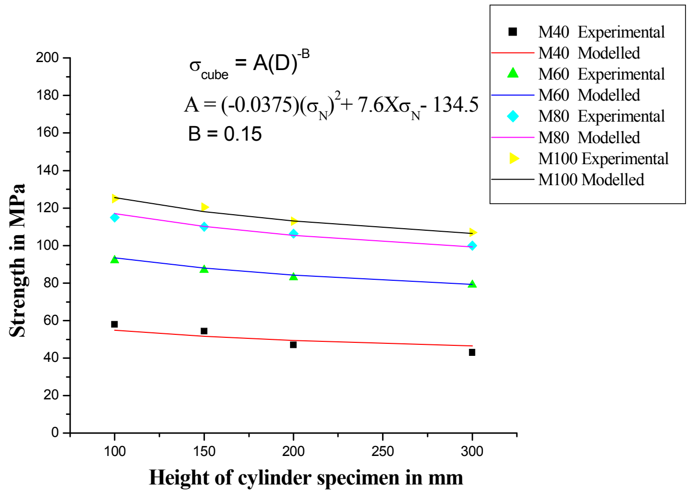

Fig. 4 Relationship between cylinder strength and height of cylinder at 56 Days

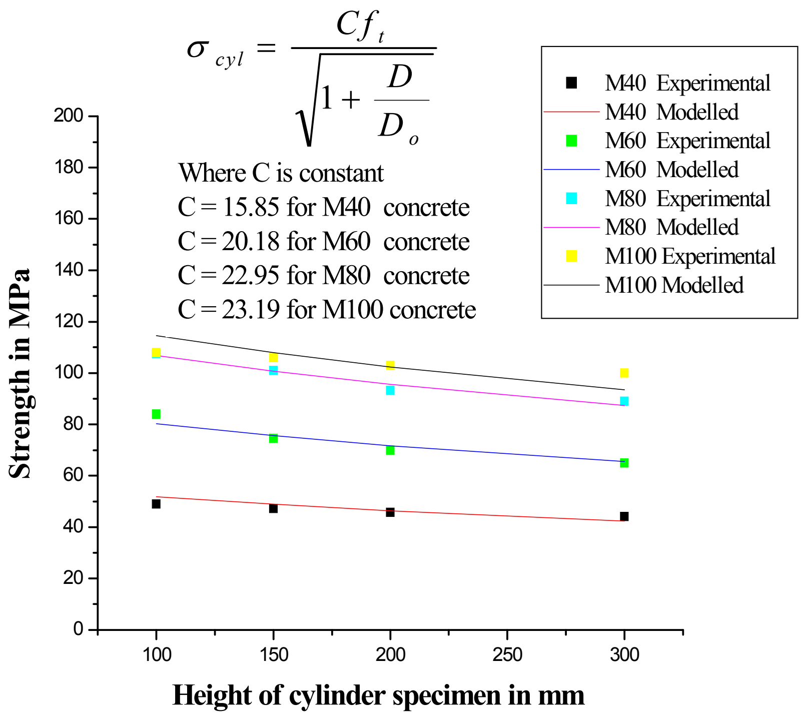

Fig. 5 Relationship between cylinder strength and height of cylinder as proposed in the literature

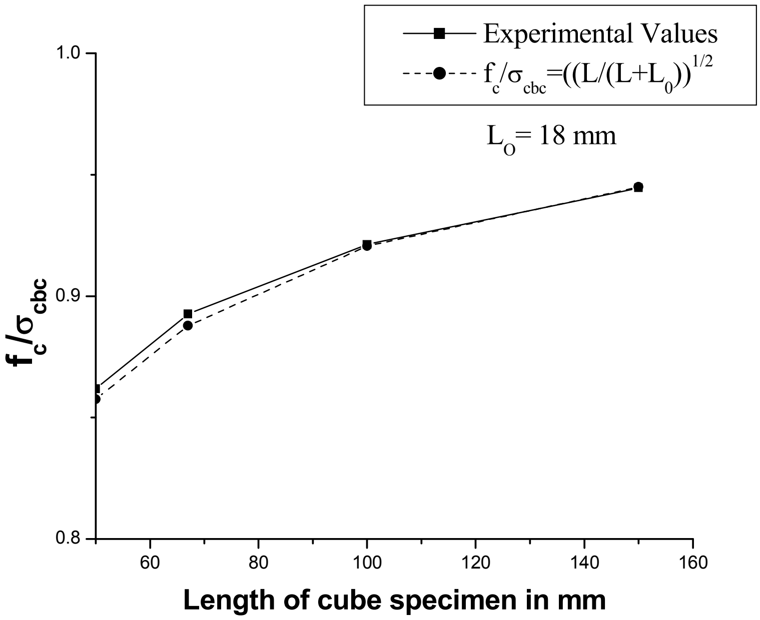

Fig. 6 Relationship between standard compressive strength and cube size

Fig. 7 Cubes and cylinders of different sizes and shapes

Fig. 8 Initiation of Crack and its propagation at higher stress levels

Fig.9 Coalescence of cracks near the corners

Fig.10 Vertical Cracks leading to Column fragments

Fig.11 Nucleation of inclined fracture surface and diagonal fracture zone

Fig.12 Ultimate Cracking pattern in cylinders