Gazi University Journal of Science
GU J Sci
25(3): 737-750(2012)

ORIGINAL ARTICLE

Assessing the Relationship between the Compressive Strength of Concrete Cores and Molded Specimens

Ali ERGÜN[1,♠], Gökhan KÜRKLÜ[1]

[1]*Afyon Kocatepe University, Technical Education Faculty, Construction Department, Afyonkarahisar 03200, Turkey*

Received:28.11.2011 Resubmitted: 03.02.2012 Accepted: 19.03.2012

ABSTRACT

There is no universal relation between the compressive strength of cores drilled from concrete elements and molded cylinder and cube concrete specimens. The strength of concrete cores depends on several parameters. The strength correction factors account for these parameters. In this study, the effects of diameters, length to core diameter ratio (λ=L/D), test age, and coring orientation on the compressive strength of cores were analyzed with respect to the molded cylinder and cube concrete specimens. According to the test results; the compressive strength changes in 100 and 75 mm diameter cores were found to be more significant and reliable compared to those of 50 mm diameter cores. The strength decreased by 10% and 6% in 100 and 75 mm diameter cores drilled perpendicular and parallel to the direction of casting due to drilling damage. The compressive strength of cores with λ=1.0 was equivalent to 92% of that of cores with λ=2.0. Furthermore, it was found that the cores drilled perpendicular to the direction of casting and having a λ=2.0 ratio was 83% and 71% of that of 28-day standard cylinder and cube, respectively. The correction factors between cores and standard cylinder and cube specimens were determined to assess the in-site compressive concrete strength.

Keywords: Compressive strength; concrete cores; molded specimens; evaluation; correction factors.

1. INTRODUCTION

For the evaluation of the structural safety of existing Reinforced Concrete (RC) buildings, the in-situ compressive strength of concrete is required. The in-situ compressive concrete strength is generally determined by taking standard cores from different structural members and testing them in the laboratory environment. The compressive strength of core concrete is affected by many parameters. These parameters are; the magnitude of core compressive strength itself, core diameter, core diameter over length ratio, coring orientation, core moisture condition at the time of testing and presence of reinforcement within the concrete core [1-7]. For a realistic prediction of the compressive strength of core concrete, the effect of all the above mentioned parameters should be taken into consideration. This is achieved by using correction factors present in several standards such as ASTM C 42/C 42M-04 [8], BS 1881 [9] and Concrete Society [10]. The concrete compressive strength obtained from core testing is multiplied by these correction factors to obtain the compressive strength of a standard cylindrical cored specimen with a diameter of 100 mm and length of 200 mm.

The Turkish Standard, TS-EN 13791 [11] related to concrete coring, recommends a cylindrical core diameter of 100-150 mm and a length to core diameter ratio (λ=L/D) of 1.0-2.0. The standard also assumes that the compressive strength of a concrete core with a diameter of 100 mm and λ=1.0 is equal to that of a standard 150 mm cube and a diameter of 100-150 mm and λ=2.0 is equal to that of a standard 150 mm cylindrical concrete specimen. In addition, the Turkish-European standard TS-EN 12504-1 [12] recommends that the compressive strength of core concrete should be compared with that of the standard cube specimen when λ=1.0 and with that of the standard cylindrical specimen when λ=2.0. However, there is no mention of the strength correction factors

♠Corresponding author, e-mail: aergun@aku.edu.tr

regarding the parameters affecting the compressive strength of core concrete in the same standard.

The experimental research conducted by Bartlett and MacGregor (1994 d) on concrete cores has produced important findings on the effect of core diameter on the core compressive strength. It was found that concrete cores with smaller diameters have smaller compressive strength. The test results indicated that the average compressive strength of concrete cores with 50 mm diameter is equal to 94 percent and 92 percent of that of the cores with a 100 mm and 150 mm diameter respectively.

Similarly, Tuncan et al (2008) has tested cylindrical concrete cores with 46 and 69 mm diameters and λ values changing between 0.75 and 2.0. These cores were obtained from concrete blocks produced in the laboratory environment using aggregates with different types and sizes. They observed that the compressive strength of concrete decreases as the maximum aggregate size increases. For instance, for two cylindrical concrete specimens with 46 mm diameter and λ=2.0, it was determined that the relative strengths of 46 mm diameter cores with respect to standard cylinder specimen were 85 % and 72 % for cores drilled from natural aggregate-bearing concretes produced by 10 and 30 mm maximum sizes of aggregates respectively.

Bartlett and MacGregor (1994 b) were determined strength correction factors for converting the strength of a core with a λ between 1.0 and 2.0 to the strength of an equivalent standard specimen with a λ of 2.0. They found that the correction factors were 0.91 and 0.87 for air-dried cores and soaked cores respectively. These factors were closer to 1 for the high strength concretes.

Bartlett and MacGregor (1994 c) investigated the effect of moisture condition on the strength of mature cores obtained from well-cured elements. They found that the strength of air-dried cores has an average 14 % larger than the strength of soaked cores. For the effect of the moisture condition of the cores, the correction factors were taken as 1.09 and 0.96 for soaked and air dried cores respectively [7].

The relationship between the flexural capacity of the beams and the strength of the cores obtained from the beams was investigated by Bartlett and MacGregor (1994 a). According to their test results, they determined that the compressive strength of a concrete core with a diameter 100 mm and λ=2.0 was equal to in-situ compressive concrete strength by multiplying 1.06 for damage sustained during drilling of the core.

The in-situ compressive concrete strength of cores having different dimensions was modeled as;

$$f_{c,ip} = F_{L/D} F_{dia} F_r F_{mc} F_d \, f_{c,NS}$$

where $f_{c,ip}$ is the in-situ concrete strength, $f_{c,NS}$ is the strength of the non-standard specimens differing from standard test specimens which are 100 mm in diameter by 200 mm long. The correction factors $F_{L/D}$, F_{dia} ,F_r , F_{mc} and F_d account for the effect of length to diameter ratio, the diameter, the presence of reinforcing bar pieces, the moisture condition and damage caused by the drilling operation respectively [13-7].

Özer (1987) were tested the compressive strength of standard test specimens and concrete core specimens which are extracted from the blocks with three different W/C ratios and two different curing conditions at the end of 28 days. Ultrasonic pulse velocity method and concrete hammer method were conducted as well on the same concrete blocks. The analysis of test results indicated that the strength value of concrete cores taken from air cured blocks are compatible with those obtained from the standard test specimens [14].

In the present codes and regulations, the strength tests of cores taken from the structural elements are used for checking strength compliance of concrete in a structure under construction or determining an equivalent specified strength to assess the capacity of an existing structure. For example, the strength compliance of concrete in a new construction can be investigated in accordance with the provisions of ACI 318 [15]. The suspected concrete is considered structurally adequate if the average strength of the three cores, corrected for L/D in accordance with ASTM C 42/C 42M, exceeds 0.85 fc' , and no individual strength is less than 0.75 fc' [13].

Up to now, in the previous studies about the cores with diameter of 100-150 mm and a length to diameter ratio of λ= 2.0 taken from the structural elements have been compared to a standard cylinder and cube concrete specimen. The main objective of this research is to clarify the relationship between the compressive strength of concrete cores and molded specimens with different dimensions. In this research, the results of total 1488 different specimens compressive tests were presented with the aim of contributing to the experimental database and to better understand how the effect of length to diameter ratio, the diameter, the curing conditions and damage caused by the drilling operation affect the relationship between the compressive strength of concrete cores and molded specimens different from the previous studies. In this study, the cores with different diameters (D=50, 75 and 100 mm), length to diameter ratios (λ=1.0, 1.5 and 2.0), curing conditions and directions taken from the produced slab and beam concrete blocks was compared to either a standard 150/300 mm cylinder and 150 mm cube concrete specimens or reference specimens which is molded into cylinder form with the same diameter, length to diameter ratio and field curing of cores. Moreover, the compressive strengths of cores were compared to those of standard cylinder and cube specimens either cured at 28-day water or having field curing at same age with the cores. After the evaluation of experimental study, the correction coefficients were determined to assess the concrete in a new structure or to evaluate the actual in-situ concrete strength. These coefficients were compared to the correction factors in the present codes and regulations.

2. EXPERIMENTAL STUDY

A test procedure was developed to analyze the relationship between the compressive strength of cylinders with varying diameters and lengths and concrete specimens that were cast in 150 mm cubic

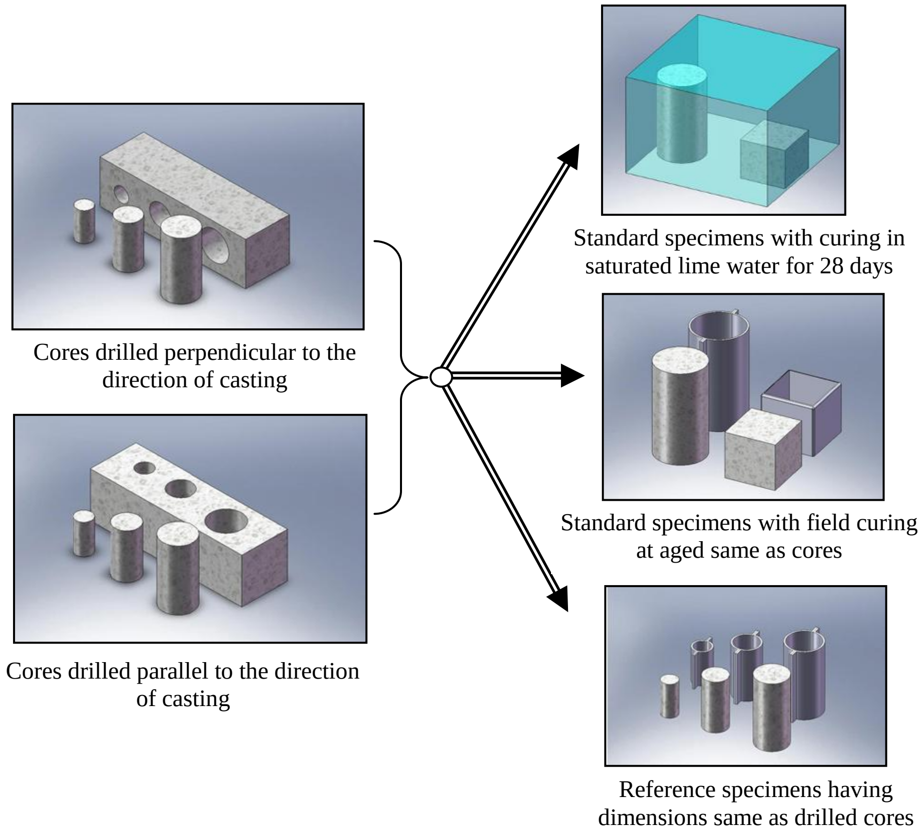


Fig.1. Schematically test procedure

molds, and also core specimens taken with different diameters and directions from slab and beam blocks produced from the same concrete. The test procedure is given in a schematic diagram in Fig.1. Eight different series made of ready-mixed concrete and having a compressive strength between 15 MPa-25 MPa were used in the experimental study. Ready-mixed concrete was preferred in order to maintain homogeneity throughout the experimental program. Ready-mixed concrete mixture consists of the ordinary Portland cement and crushed limestone aggregates with maximum grain size 22 mm. Water/cement ratio and aggregate grain size was changed to obtain different strength values. Each series is composed of slab and beam blocks to be drilled, core and reference as well as standard specimens to be used for comparison purposes. Each group covers 6 specimens.

Slab blocks were chosen for cores taking from parallel to the direction of casting, and beam blocks were chosen for cores taking from perpendicular to the direction of casting. 50, 75, 100, 112.5, 150, 200 mm thick slab and beam blocks were produced so as not to perform another cutting operation after drilling cores for the desired length. Reference specimens are concrete specimens cast in specially-designed fiberglass cylinder molds with 50 mm diameter and 50, 75, 100 mm length; 75 mm diameter and 75, 112.5, 150 mm length; and 100 mm diameter and 100, 150, 200 mm length. Standard specimens were cast in a cylinder mold with 150 mm diameter and 300 mm length, and standard cube molds with 150 mm length. The properties and notations of groups in each series and the designations of series are shown in Table 1, and specimens are given in Fig.2

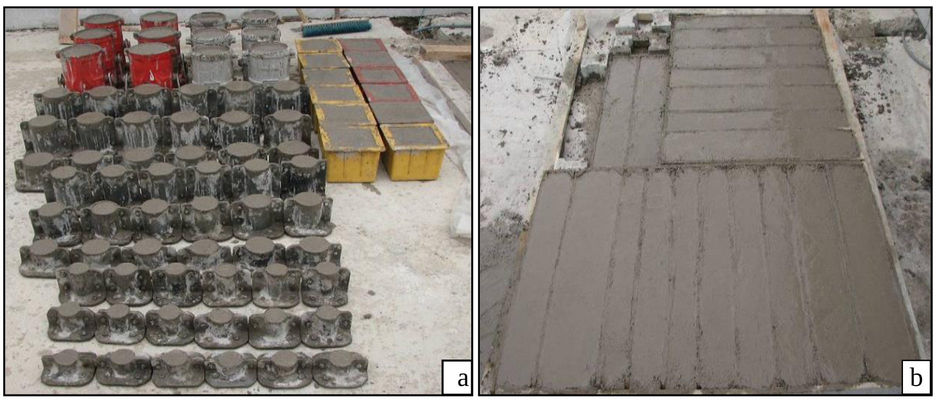


Fig.2. Casting concrete into formworks of specimens (a) and blocks (b) for any series

Table 1. The properties and notations of groups, the designations of series

						Series							
						N1	N2	N3	N4	N5	N6	N7	N8
			Concrete Class			C16	C18	C22	C20	C20	C25	C14	C20
Specimen type			Notation	Specimen Size (mm)		Day							
Specimen Age (day)	Standard curing	Cube	$f_{co,cube}$	150		28	28	28	28	28	28	28	28
		Cylinder	$f_{co,cylin}$	D=150 L=300		28	28	28	28	28	28	28	28
	Field curing	Cube	$f_{c,cube}$	150		28	28	28	56	56	56	90	90
		Cylinder	$f_{c,cylin}$	D=150 L=300		28	28	28	56	56	56	90	90
	Reference specimen	Cylinder	$f_{c,R}$	D	L								
				100	100	28	28	28	56	56	56	90	90
					150	28	28	28	56	56	56	90	90
					200	28	28	28	56	56	56	90	90
				75	75	28	28	28	56	56	56	90	90
					112.5	28	28	28	56	56	56	90	90
					150	28	28	28	56	56	56	90	90
				50	50	28	28	28	56	56	56	90	90
					75	28	28	28	56	56	56	90	90
					100	28	28	28	56	56	56	90	90
	Cores	Cores drilled parallel to the direction of casting	$f_{c,NS,II}$	D	L								
				100	100	28	28	28	56	56	56	90	90
					150	28	28	28	56	56	56	90	90
					200	28	28	28	56	56	56	90	90
				75	75	28	28	28	56	56	56	90	90
					112.5	28	28	28	56	56	56	90	90
					150	28	28	28	56	56	56	90	90
				50	50	28	28	28	56	56	56	90	90
					75	28	28	28	56	56	56	90	90
					100	28	28	28	56	56	56	90	90
	Cores	Cores drilled perpendicular to the direction of casting	$f_{c,NS,\perp}$	D	L								
				100	100	28	28	28	56	56	56	90	90
					150	28	28	28	56	56	56	90	90
					200	28	28	28	56	56	56	90	90
				75	75	28	28	28	56	56	56	90	90
					112.5	28	28	28	56	56	56	90	90
					150	28	28	28	56	56	56	90	90
				50	50	28	28	28	56	56	56	90	90
					75	28	28	28	56	56	56	90	90
					100	28	28	28	56	56	56	90	90

3 series were tested at the age of 28 days, another 3 series were of 56 days and the remaining 2 were at the age of 90 days. Six (6) of the produced blocks, reference and standard specimens were moist cured in the morning and evening for the first 7 days, and then kept under laboratory conditions until tested (Fig.3). The other 6 of the standard cylinder and cube specimens in the series were cured in lime-saturated water for 28 days and then tested. During the test, cores with different sizes were taken from the related blocks by drilling parallel and perpendicular to the direction of casting. The obtained cores were kept for 2 days in dry air conditions, then they were capped with sulfur-graphite and their compressive strength test results were found. The reference and standard cylinder specimens were capped the same day, and their compressive strength values were measured together with standard cubes. All the specimens were tested on a compressive setup as illustrated in Fig. 4. The experiments were performed on a closed-loop servo-hydraulic dynamic testing machine, with a capacity of 2000 kN. The loading plates are made of hardened steel and have polished surfaces. Specimens were tested in load control keeping constant the axial loading velocity throughout the experimental program. A total of 1488 different specimens were tested in this study.

Fig.3. Reference specimens and blocks that would be drilled core for any series

Fig.4. Testing setup for specimens

3. RESULTS AND DISCUSSION

In this experimental study, the cores with different diameters (50, 75 and 100 mm) and L/D ratios (λ=1.0, 1.5 and 2.0) were drilled parallel and perpendicular to the direction of casting from beam and slab blocks in each series. The relationship between the compressive strength of the drilled cores and the compressive strength of the reference specimens under the same size, age and curing conditions was studied in this research. Moreover, the compressive strengths of cores were compared to those of standard cylinder and cube specimens cured at 28-day water and standard specimens with field curing at the same age. Compressive strength test results of cores, reference and standard specimens are the average of 6 specimens from each series. The average compressive strength of cores, reference and standard specimens for the 8 series is given in Table 2.

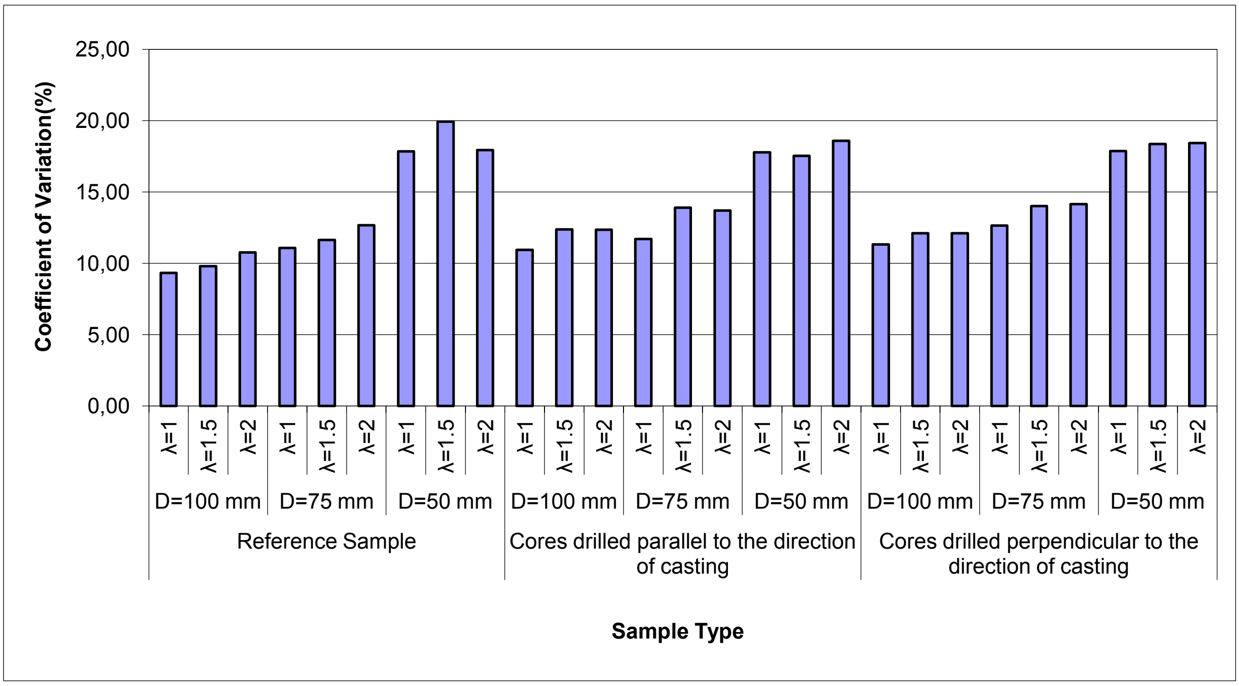
Table 2. Average compressive strength of different cores and molded concrete specimens (MPa)

Specimen type		Seri no								
			N1	N2	N3	N4	N5	N6	N7	N8
		Seri age(days)	28	28	28	56	56	56	90	90
Standard curing for 28 days	Cube ($f_{co,cube}$)		18.8	20.4	27.6	22.4	26.3	29.1	17.8	24.5
	Cylinder ($f_{co,cylin}$)		16.4	18.3	22.7	20.1	20.8	25.5	14.6	21.7
Field curing until the age of block	Cube ($f_{c,cube}$)		17.9	20.0	26.8	23.1	27.2	31.9	22.8	31.3
	Cylinder ($f_{c,cylin}$)		15.9	17.1	21.1	20.9	22.0	26.5	18.5	26.0
Reference specimen ($f_{c,R}$)	D=100 mm	λ=1.0	16.6	17.3	21.2	20.3	23.0	24.3	17.2	22.8
		λ=1.5	15.0	16.2	19.6	19.2	20.2	23.0	15.8	20.5
		λ=2.0	14.9	15.8	19.1	18.4	20.0	22.4	15.5	19.5
	D=75 mm	λ=1.0	15.7	16.9	20.7	20.4	23.1	21.9	16.3	22.6
		λ=1.5	14.9	14.9	19.8	19.2	21.9	20.5	15.5	21.4
		λ=2.0	14.4	14.5	19.2	18.8	20.8	20.3	15.2	20.4
	D=50 mm	λ=1.0	15.1	15.2	20.6	16.7	19.2	20.0	14.2	20.9
		λ=1.5	14.0	14.4	19.2	16.0	17.9	19.0	13.2	20.0
		λ=2.0	13.3	14.0	17.8	15.4	17.6	18.1	12.5	19.6
Cores drilled parallel to the direction of casting ($f_{c,NS,II}$)	D=100 mm	λ=1.0	15.5	16.1	19.5	19.5	20.6	22.8	16.0	19.9
		λ=1.5	14.5	14.7	18.3	18.4	18.9	21.5	15.3	18.8
		λ=2.0	14.4	14.5	18.1	17.4	18.7	21.0	14.9	18.3
	D=75 mm	λ=1.0	14.8	15.1	19.5	18.8	21.9	20.8	15.1	21.0
		λ=1.5	13.8	14.3	19.0	18.0	20.5	19.4	14.0	19.4
		λ=2.0	13.5	13.9	18.6	17.5	20.0	18.5	13.8	19.1
	D=50 mm	λ=1.0	13.9	14.4	18.0	15.2	18.2	19.0	13.4	19.4
		λ=1.5	13.0	13.8	17.3	15.1	17.3	18.0	12.9	19.3
		λ=2.0	12.7	13.7	17.1	14.8	17.1	17.8	12.4	19.1
Cores drilled perpendicular to the direction of casting ($f_{c,NS,\perp}$)	D=100 mm	λ=1.0	15.0	15.2	18.9	18.3	20.2	22.4	15.7	18.4
		λ=1.5	14.2	14.3	17.8	17.5	18.4	21.2	14.9	17.0
		λ=2.0	14.0	14.1	17.6	17.0	18.2	20.8	14.5	16.5
	D=75 mm	λ=1.0	14.4	14.4	18.8	18.5	21.2	20.0	14.5	20.4
		λ=1.5	13.4	13.8	17.6	17.8	19.9	18.6	13.8	19.0
		λ=2.0	13.2	13.5	17.2	17.0	19.2	18.2	13.5	18.6
	D=50 mm	λ=1.0	13.2	13.7	17.6	14.6	17.4	18.2	12.5	18.2
		λ=1.5	11.8	13.1	16.5	14.2	16.8	17.4	12.2	17.4
		λ=2.0	11.4	12.9	16.3	13.9	16.5	16.9	12.0	16.8

The standard deviation of the compressive strength of reference specimens and cores was calculated and the coefficient of variation (COV) values that were the ratio of the average of compressive strength to standard deviation was found. Fig. 5 indicates the average coefficient of variation (COV) values of specimen strengths respective to specimen type. As can be seen in the figure, the COV values increase as the specimen diameter decreases. It is interesting that the COV values for 50 mm specimen diameters are the highest. This relationship reveals that the changes in the compressive strength of 100 mm and 75 mm diameter cores at λ=1.0, 1.5 and 2.0 ratios are more significant and reliable compared to those of 50 mm diameter cores. Tuncan et al

(2007) found that the COV values of 69 mm and 46 mm diameter cores were ranged between 8 and 18 % regardless of aggregate type, maximum aggregate size and the age of concrete. The preferred minimum core diameter is three times the nominal maximum size of the coarse aggregate, but it should be at least two times the nominal maximum size of the coarse aggregate [8]. The main reason of high COV values obtained from 50 mm diameter cores could be the nominal maximum size of the coarse aggregate which was 22 mm used in concrete mixture.

Fig 5. Average coefficient of variations (COV) values of specimen strengths respective to specimen type



The standard deviation of the compressive strength of reference specimens and cores was calculated and the coefficient of variation (COV) values that were the ratio of the average of compressive strength to standard deviation was found. Fig. 5 indicates the average coefficient of variation (COV) values of specimen strengths respective to specimen type. As can be seen in the figure, the COV values increase as the specimen diameter decreases. It is interesting that the COV values for 50 mm specimen diameters are the highest. This relationship reveals that the changes in the compressive strength of 100 mm and 75 mm diameter cores at λ=1.0, 1.5 and 2.0 ratios are more significant and reliable compared to those of 50 mm diameter cores. Tuncan et al (2007) found that the COV values of 69 mm and 46 mm diameter cores were ranged between 8 and 18 % regardless of aggregate type, maximum aggregate size and the age of concrete. The preferred minimum core diameter is three times the nominal maximum size of the coarse aggregate, but it should be at least two times the nominal maximum size of the coarse aggregate [8]. The main reason of high COV values obtained from 50 mm diameter cores could be the nominal maximum size of the coarse aggregate which was 22 mm used in concrete mixture.

Effect of damage caused by the drilling operation on core strengths

The compressive strengths of cores drilled parallel and perpendicular to the direction of casting with varying diameters and λ=L/D ratios were compared to those of the reference specimens with same properties in order to determine the effect of damage caused by the drilling operation. The effect of drilling damage on specimens with different diameters, λ ratios and directions of drilling are given in Fig.6. It was found that the reference specimens had higher compressive strength compared to the core specimens with the same size. The effect upon 100 and 75 mm diameter core specimens are more significant compared to 50 mm core specimens. It was concluded that the direction of core drilling significantly affects compressive strength. When we take the average of test results excluding the 50 mm diameter cores, cores drilled perpendicular to the direction of casting show a 10% decrease in strength, and those drilled parallel to the direction of casting show 6% decrease in strength due to drilling damage. Fig.6 indicates that the decrease in strength caused by drilling operation is not associated with core surface area. Correction factor regarding drilling damage is shown below:

$$F_{d,\parallel} = 1.06 \quad (3.1)$$
$$F_{d,\perp} = 1.10 \quad (3.2)$$

The average difference between the compressive strengths of cores drilled parallel to the direction of casting and the ones drilled perpendicular to the direction of casting is 4%. Previous studies indicated this difference as between 8% - 12%, yet Bartlett and MacGregor (1994a) reported that there was no significant change related to the direction of drilling. The difference has been attributed to moisture forming under aggregate particles, which increases stress when loaded in the transverse direction [6,16].

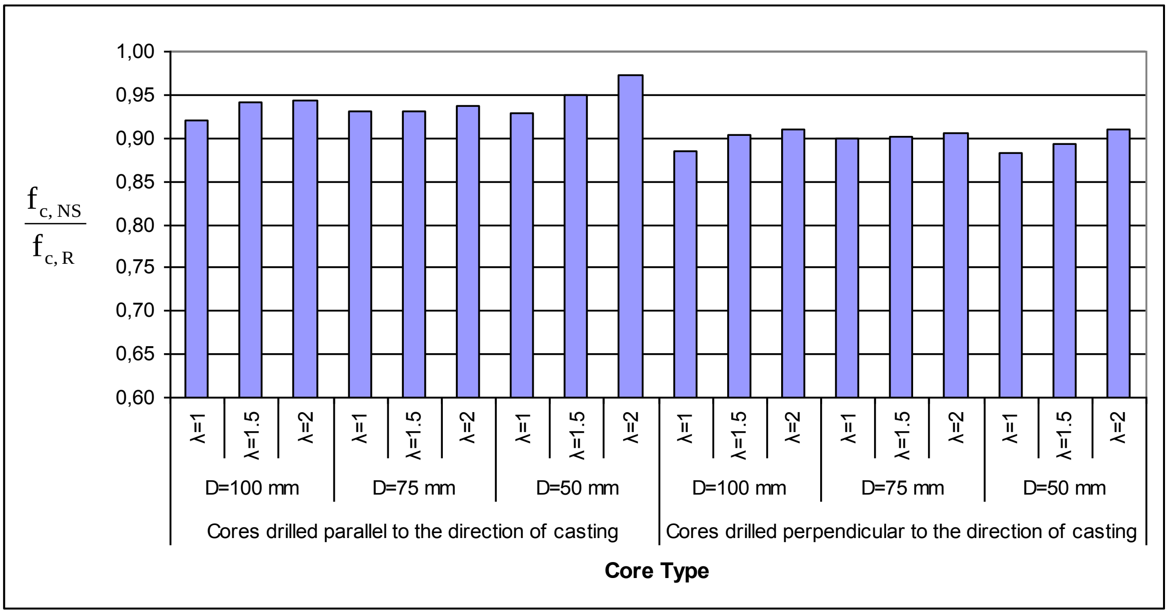


Fig 6. The strength relationship between cores and reference specimens which molded into cylinder form for same diameter, length to diameter ratio and field curing

Effect of core length to diameter ratio (λ=L/D) on core strengths

The compressive strengths of cores with the same diameters vary according to their length/diameter (λ=L/D) ratios. According to most of the international standards, the preferred length of cores is 2.0 times the diameter and λ=2.0 is accepted for standard core specimens. For converting the compressive strength of a core with λ=1.0 to the compressive strength of an equivalent standard core with λ=2.0, the strength correction factor is required [4,8]. If the ratio of length to diameter (L/D) of the core is less than 2.0, the obtained compressive strength is corrected by multiplying by the appropriate correction factor [8]. In this section, the difference between the compressive strengths of cores with a ratio of λ=2.0 and the compressive strengths of cores with ratios of λ=1.0, λ=1.5 and λ=2.0, same diameters and orientations was analyzed to determine length/diameter effect. Fig.7 shows the strength ratio of cores having λ=2.0 to cores having λ=1.0, λ=1.5 and λ=2.0 with same diameter and orientation. According to this point, the strength correction factor is 0.92 for λ=1.0 and 0.98 for λ=1.5. This ratio is same value for both the cores drilled parallel to the direction of casting, and those drilled perpendicularly. The strength correction factor used to convert the strength of cores with different λ=L/D value to those of cores with λ=2.0 ratio are given in the following equation:

$$F_{\lambda=L/D} = -0.075x(\lambda)^2 + 0.309x(\lambda) + 0.68 \quad (3.3)$$

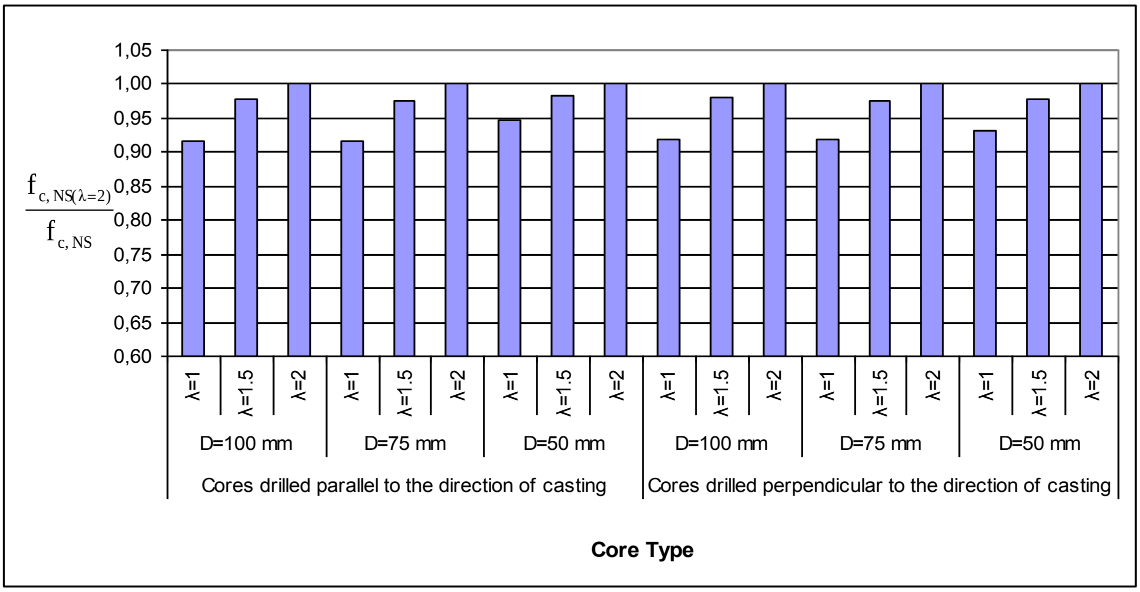


Fig 7. The strength ratio of cores having λ=2.0 to cores having λ=1.0, λ=1.5 and λ=2.0 for same diameter and orientation

The strength correction factor ($F_{\lambda=L/D}$) required to convert λ=1.0 core specimen to λ=2.0 equivalent standard core specimen is reported as 0.87 by ASTM C 42/C 42M-04 [8], 0.92 by BS 1881 [9], and 0.8 by Concrete Society [10]. In addition, Bartlett and MacGregor (1994 b) suggested that the correction factors were 0.91 and 0.87 for air-dried cores and soaked cores respectively and they were closer to 1 for the high strength concretes.

The relationship between the strength of core and the strength of standard cylinder and cube at same curing and age of drilled blocks

The compressive strength of cores drilled from the structural elements is used to evaluate the structural capacity of an existing structure based on the actual in-situ concrete strength. In practice, the strengths of cores should be converted to in-situ standard cylinder and cube specimen strengths. Correction factors are necessary for such conversions. In this study, the cores drilled from structural elements were tested together with 150/300 mm cylinder and 150 mm cube specimens under the same age and curing conditions. The comparison of the compressive strength of cores with the strength of

150/300 mm cylinder specimens are given in Fig.8, and the comparison of the compressive strength of cores with the strength of 150 mm cube specimens are shown in Fig.9.

The ratio of core compressive strength to standard cylinder and cube specimen strength declined as the diameter of cores became smaller. Moreover, as the L/D ratio of cores increased, the related strength ratio decreased. The following graphics show that the relationship between 100 and 75 mm diameter cores is similar compared to 50 mm diameter cores. The average ratio between the compressive strength of 100 and 75 mm diameter core drilled parallel and perpendicular to the direction of casting and the compressive strength of standard cylinder and cube specimens is given in Fig.10. For λ=1.0, $f_{c,NS,II}/f_{c,cylin}$ =0.89, $f_{c,NS,\perp}/f_{c,cylin}$ =0.86, $f_{c,NS,II}/f_{c,cube}$ =0.75, and $f_{c,NS,\perp}/f_{c,cube}$ =0.72. Herein, the difference between the strength of standard cube specimens to that of cylinder specimens is 19%.

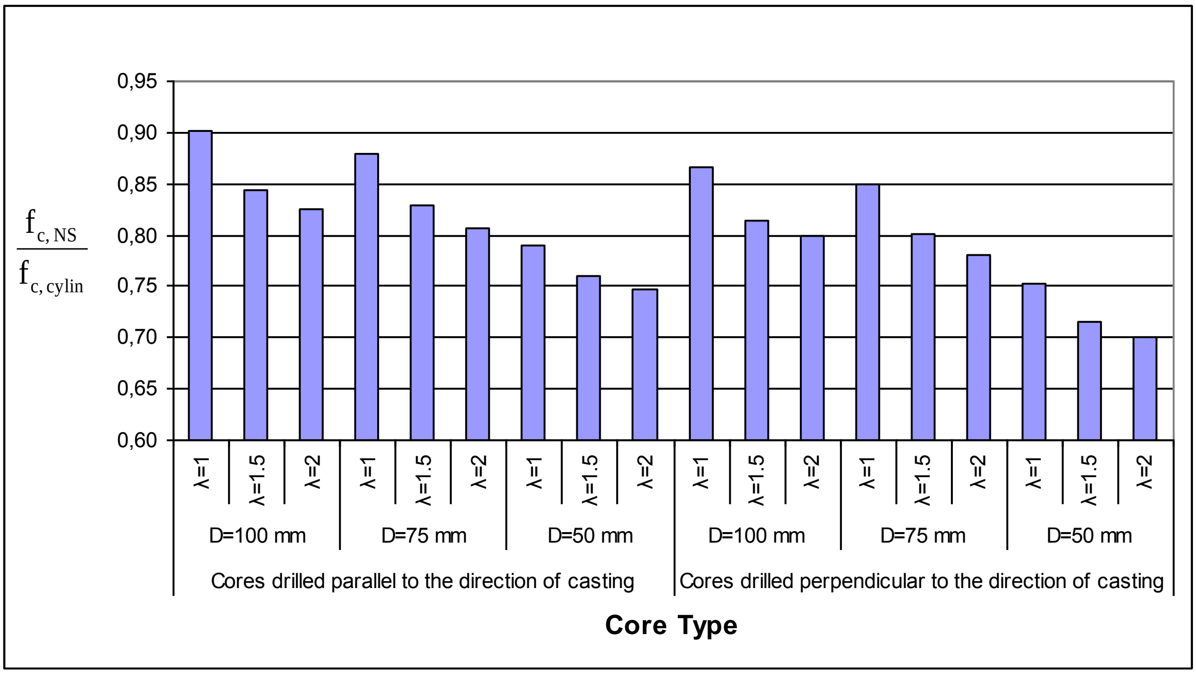


Fig 8. Comparisons of the strength of concrete cores against 150/300 mm cylinders at same curing and age of drilled blocks

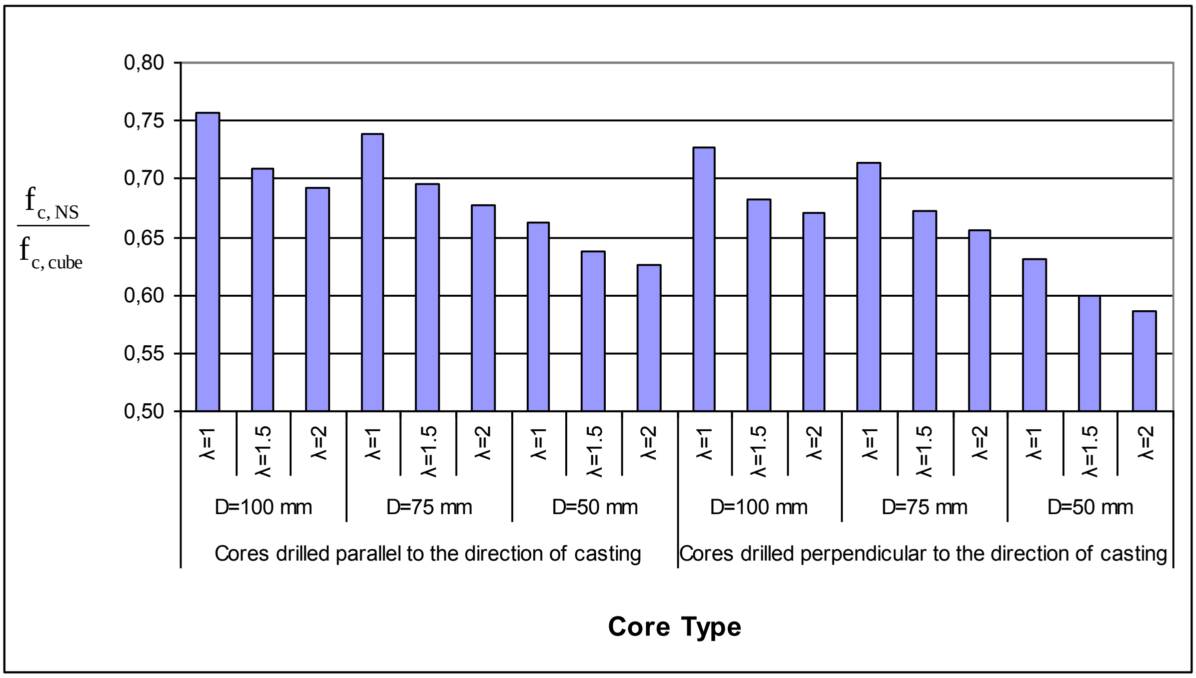


Fig 9. Comparisons of the strength of concrete cores against 150 mm cube specimens at same curing and age of drilled blocks

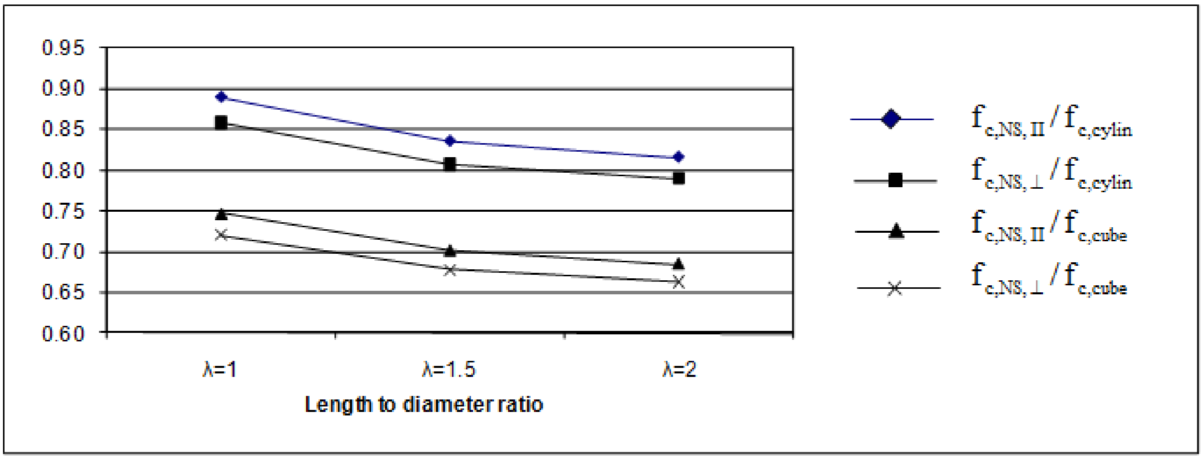


Fig. 10. Variation in the strength ratio of cores to standard cylinder and cube specimens having same aged and curing with cores

Evaluations regarding this comparison can be seen in BS 1881 [9] and Concrete Society [10]. BS 1881 [9] suggests that λ=2.0 core strength should be multiplied by 1.25 while converting it to equivalent cube strength. According to this, the $f_{c,NS}/f_{c,cube}$ ratio is 0.8 for λ=2.0 and is 0.87 for λ=1.0. Besides, the fact that the direction of drilling is not taken into consideration in this conversion raises doubts regarding a realistic estimation. However, Concrete Society [10] suggests a more detailed correlation. Drilling damage and direction of drilling is taken into account in the formula. In-situ equivalent cube strength is calculated by means of $\left(f_{c,cube} = \frac{2.5}{1.5+\frac{1}{\lambda}} \times f_{c,NS}\right)$ expression for core drilled perpendicular to the direction of casting. Accordingly, $f_{c,NS}/f_{c,cube}$ ratio is 1 for λ=1.0, and $f_{c,NS}/f_{c,cube}$ is 0.8 for λ=2.0. This is quite a rough ratio. Moreover, while the study suggests a 19% difference between the cube strength and cylinder strength, Concrete Society [10] accepts this value as 25%. TS-EN 13791 [11]

reports $f_{c,NS}/f_{c,cube}$ ratio for λ=1.0 as 1.0 and $f_{c,NS}/f_{c,cylin}$ ratio for λ=2.0 as 1.0.

The relationship between the strength of cores and the strength of standard cylinders and cubes at 28 days

For quality control of the concrete, the standard cylinder and cube specimens cured in lime-saturated water for 28 days are used. Moreover, for this purpose, the relationship between the strength of cores drilled from hardened concrete and that of 28-day standard cylinder and cube specimens is significant. In this study, the compressive strength of standard cylinder and cube cured in lime-saturated water for 28 days and that of cores drilled from the blocks having same concrete properties of the standard cylinder and cube were compared. The comparison between the strength of cores with different ages to that of 28-day standard cylinder specimens is given in Fig.11, and the difference between the strength of cores and that of cube specimens is shown in Fig.12.

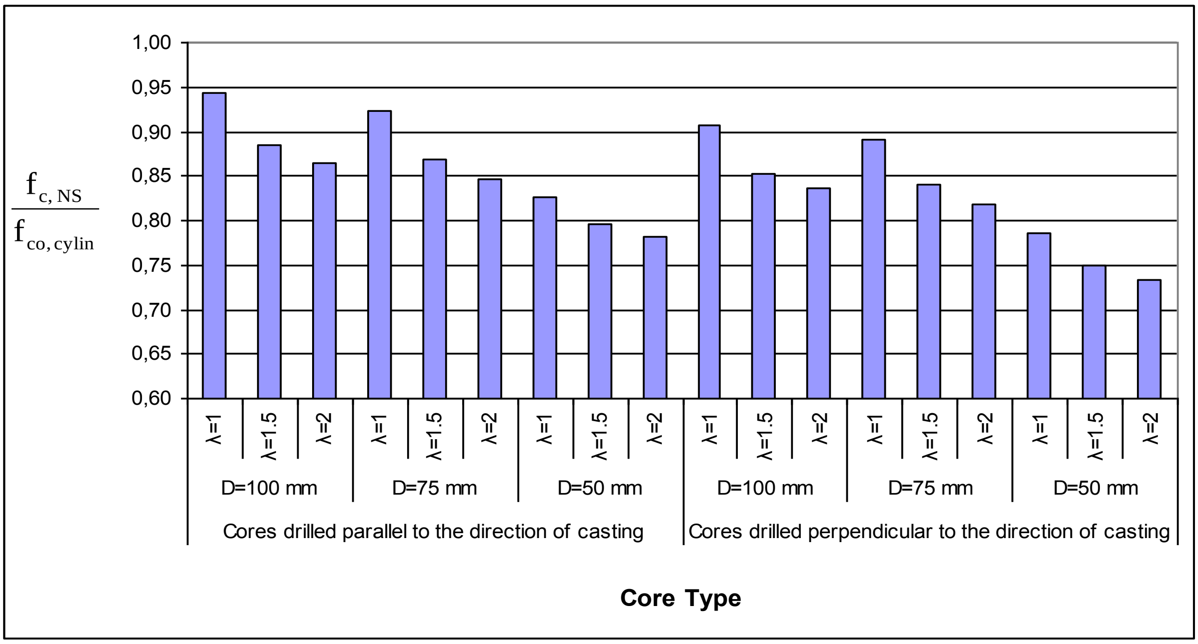


Fig. 11. Comparisons of concrete cores against standard cylinders at 28 days

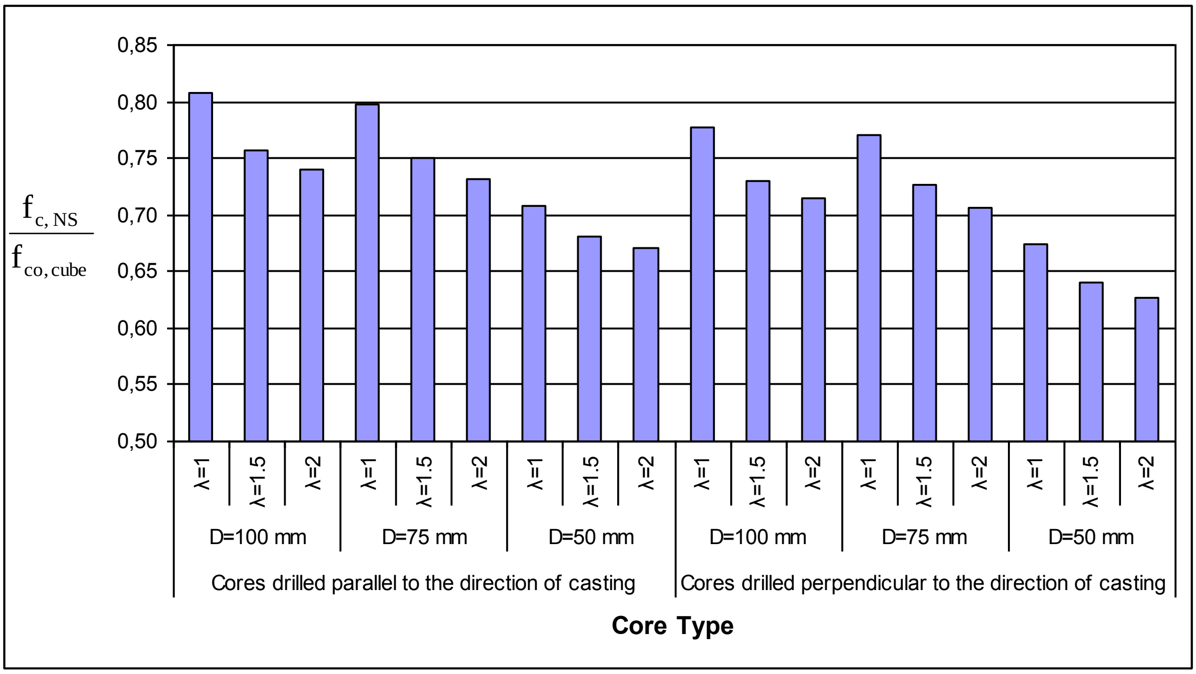


Fig. 12. Comparisons of concrete cores against standard cubes at 28 days

The relationship between the cores and standard cylinder and cube specimens cured for 28-day lime-saturated water is similar to the relationship between cylinder and cube specimens having the same age and curing conditions as the cores. Fig.13 shows the average strength ratio of 100 and 75 mm diameter cores drilled parallel and perpendicular to the direction of casting to that of standard cylinder and cube specimens having standard curing. For λ=1.0, $f_{c,NS,II} / f_{co,cylin}$ is 0.93, $f_{c,NS,\perp} / f_{co,cylin}$ is 0.90, $f_{c,NS,II} / f_{co,cube}$ is 0.80, and $f_{c,NS,\perp} / f_{co,cube}$ is 0.77. Herein, the difference between the strength of standard cube specimens to that of cylinder specimens is 16%.

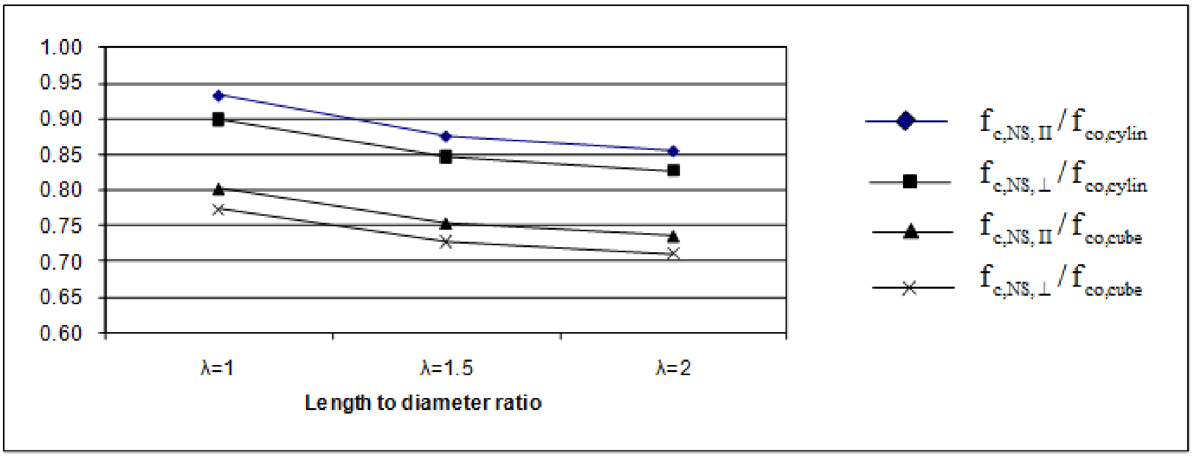


Fig. 13. Variation in the strength ratio of cores to standard cylinder and cube at 28 days

Concrete Society [10] defines 28-day cube strength as estimated potential cube strength. 28-day standard cube strength is calculated by making use of cores drilled perpendicular to the direction of casting and according to the ($f_{co,cube} = \dfrac{3.25}{1.5+\dfrac{1}{\lambda}} \times f_{c,NS}$) formula. Therefore, $f_{c,NS,\perp} / f_{co,cube}$ ratio is 0.77 for λ=1.0, and $f_{c,NS,\perp} / f_{co,cube}$ ratio is 0.62 for λ=2.0. This ratio is same as the test result for λ=1.0, but deviates by 15% for λ=2.0. And this difference results from the fact that; Concrete Society [10] takes the core strength of λ=1.0 to that of λ=2.0 as 0.8. ACI 318 M[15] requires that; concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores (λ=2.0) is equal to at least 85 percent of *fc′* (specified compressive strength of concrete). This rate complies with the $f_{c,NS,\perp} / f_{co,cylin}$ =0.83 value for λ=2.0 which is obtained from test results. Turkish Standards (TS) TS-EN 13791[11] and TS EN 12504-1[12] mention the use of cores with length to the diameter ratios λ=1.0 and 2.0, depending on the conversion of the compressive strength to a standard cube or standard cylinder specimen respectively. When we compare the test results with the criteria used in Turkish standards, approximately 20% difference is found in comparison with the standard cube, and about 15% difference is found in comparison with the standard cylinder. This approach yields a rough evaluation result.

4. CONCLUSIONS

In this study, the compressive strength of concrete specimens cast into cylinders with different diameters and lengths and 15 cm cube molds, and that of cores drilled with varying diameters and directions from slab and beam blocks obtained from the same concrete are tested. The following conclusions may be drawn from the test results:

1.) The COV values increased with the decrease in core diameters, and this effect was highly apparent in 50 mm diameter cores. The variation of the compressive strength of 100 mm and 75 mm diameter cores with the λ=1.0, 1.5 and 2.0 ratios were found to be more significant and reliable compared to those of 50 mm diameter cores. The strength ratios of 100 and 75 mm diameter cores were found to be close in the analysis of different parametric effects. Thus, 50 mm diameter cores should be cautiously used while determining the in situ concrete strength of the existing structure. From a more realistic perspective, it was found suitable to accept the core diameter as minimum 75 mm.

2.) The direction of drilling affects compressive strength of cores. Due to drilling damage, the strength decreased by 10% and 6% in 100 and 75 mm diameter cores drilled perpendicular, and parallel to the direction of casting respectively. The compressive strength of the cores drilled parallel to the direction of casting were found to be 4% higher compared to that of the cores drilled perpendicular to the direction of casting.

3.) The compressive strength of cores with the same diameter varies according to their L/D ratio. The compressive strength of cores with λ=1.0 was equivalent to 92% of the compressive strength of standard cores with λ=2.0. The strength correction factor is 0.98 for cores with λ=1.5.

4.) The compressive strength of cores was found to differ from that of standard cylinder and cube specimens with the same age and curing conditions. According to the test results, regarding 100 and 75 mm diameter cores drilled parallel and perpendicular to the direction of casting, $f_{c,NS,II}/f_{c,cylin}$ is 0.89, $f_{c,NS,\perp}/f_{c,cylin}$ is 0.86, $f_{c,NS,II}/f_{c,cube}$ is 0.75, $f_{c,NS,\perp}/f_{c,cube}$ is 0.72 for λ=1.0 ratio. In practice, $f_{c,cylin} = \frac{f_{c,NS,\perp}}{0.86}$ formula could be suggested when calculating the equivalent in-situ cylinder compressive strength by using the compressive strength of cores with λ=1.0 drilled perpendicular to the direction of casting in order to evaluate the structural capacity of an existing structure based on the actual in-situ concrete strength. While BS 1881 [9] and Concrete Society [10] accept a 25% difference between the strength of standard cube specimens and cylinder specimens, the result of this study showed a 19% difference.

5.) The relationship between the compressive strength of 28-day standard cylinder and cube specimens and that of the cores was found to be dependent on the age of the drilled structural block. According to test results, $f_{c,NS,II}/f_{co,cylin}$ is 0.93, $f_{c,NS,\perp}/f_{co,cylin}$ is 0.90, $f_{c,NS,II}/f_{co,cube}$ is 0.80, $f_{c,NS,\perp}/f_{co,cube}$ is 0.77 for 100 and 75 mm diameter cores drilled parallel and perpendicular to the direction of casting and having a λ=1.0 ratio. The strength of standard cube specimens showed a 16% difference to that of cylinder specimens. In practice, $f_{co,cylin} = \frac{f_{c,NS,\perp}}{0.90}$ formula could be suggested when calculating specified strength of standard cylinder specimens at 28 days by using the compressive strength of cores with λ=1.0 drilled perpendicular to the direction of casting in order to assess whether suspected concrete in a new structure complies with strength-based acceptance criteria.

6.) Considering the ratios of the compressive strength of cylinder and cube specimens with the same age and curing conditions as cores to that of 28-day standard cylinder and cube specimens, it was found that the compressive strength of cylinder and cube specimens with field curing was 4–5% higher than that of 28-day standard cylinder and cube specimens depending on the age of concrete.

7.) In Turkish standards commenting on the coring methods TS-EN 13791[11] and TS EN 12504-1[12], the equivalent strength of core in the structure by using the compressive strength of cores drilled from an existing structure was 15 – 20 % lower than the compressive strength of cores obtained from the experimental study. The evaluation of actual in-situ concrete strength according to Turkish standards will not yield to precision approach.

ACKNOWLEDGEMENT

The ready mixed concrete used in this investigating research was provided by KOLSAN Hazır Beton Company. The authors gratefully acknowledge the support of KOLSAN Hazır Beton Company.

REFERENCES

[1] Bartlett, F. M., and MacGregor, J. G. Effect of core diameter on concrete core strengths. ***ACI Materials Journal***, 91(5): 460-470, (1994d).

[2] Tuncan, M., Arioz Ö., Ramyar K. and Karasu B. Assessing concrete strength by means of small diameter cores. ***Construction and Building Materials***, 22: 981-988, (2008).

[3] Meininger, R.C., Wagner F.T., Hall, K.W. Concrete core strength-The effect of length to diameter ratio. Journal of Testing and Evaluation, ***JTEVA***, 5(3): 147-153, (1977).

[4] Bartlett, F. M., and MacGregor, J. G. Effect of core length-to-diameter ratio on concrete core strengths. ***ACI Materials Journal***, 91(4): 339-348, (1994b).

[5] Bartlett, F. M., and MacGregor, J. G. Effect of moisture condition on concrete core strengths. ***ACI Materials Journal***, 91(3): 227-236, (1994c).

[6] Bartlett, F. M., and MacGregor, J. G. Cores from high performance concrete beams. ***ACI Materials Journal***, 91(6): 567-576, (1994a).

[7] Bartlett, F. M. Precision of in-place concrete strengths predicted using core strength correction factors obtained by weighted regression analysis. ***Structural Safety***, 19(4): 397-410, (1997).

[8] ASTM C42/C 42M. Standard test method of obtaining and testing drilled cores and sawed beams of concrete. Annual Book of ASTM Standards, Vol. 04.02, USA (2004).

[9] BS 1881-120. Determination of compressive strengths of concrete cores. British Standards 1881 No: 120. British Standards Institution, UK (1983).

[10] Concrete Society Technical Report No:11. Concrete core testing for strength. The Concrete Society, London (1976).

[11] TS EN 13791. Basınç dayanımının yapılar ve öndökümlü beton bileşenlerde yerinde tayini (Assessment of in-situ compressive strength in structures and precast concrete components). Ankara, Turkey: Turkish Standard Institute; (2010) [in Turkish].

[12] TS EN 12504-1. Yapıda beton deneyleri, bölüm 1: karot numuneler–karot alma, muayene ve basınç dayanımının tayini (Testing concrete in structures - Part 1: Cored specimens-taking, examining and testing in compression). Ankara, Turkey: Turkish Standard Institute; (2002) [in Turkish].

[13] ACI Committee 214.4 R-03 M. Guide for obtaining cores and interpreting compressive strength results. (ACI 214.4 P-03), American Concrete Institute, Farmington Hills, MI, USA (2003).

[14] Özer, N.Ö. Evaluation of test results to determine the strength of concrete. MS Thesis, Middle East Technical University, Graduate School of Natural and Applied Sciences, Ankara, (1987).

[15] ACI Committee 318 M. Building code requirements for reinforced concrete. (ACI 318M-83), American Concrete Institute, Farmington Hills, MI, USA (2004).

[16] Johnston, C.D. Anisotropy of concrete and its practical implications. Highway Research Record, 423: 11-16, (1973).