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Influence of Core with Different Dimensions and Conditions on Compressive Strength of Concrete

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ABSTRACT: The core test is essential in the concrete industry for estimating concrete strength and sometimes serves as the sole method for evaluating the safety of existing concrete structures. An extensive experimental study was conducted to assess the factors that influence the interpretation of core test results.

The study included five different concrete mixes and five concrete strength classes (20, 30, 40, 50, and 60 MPa), two core diameters (150 and 100 mm), four core aspect ratios (ranging from 1 to 2), two sizes of coarse aggregates (maximum sizes of 10 and 20 mm), and two coring directions (vertical and horizontal). Concrete prototypes were constructed, and more than 225 cores were prepared and tested to produce a substantial number of concrete cylinders (nine cylindrical specimens for each concrete mix design), with sizes of 150x300 mm and 100x200 mm used.

The results indicated that core strength decreases with an increase in aspect ratio, a decrease in core diameter, drilling perpendicular to the casting direction, and a decrease in concrete strength. Statistical analysis was performed to identify reliable strength correction factors that account for the variables studied. A simple weighted regression analysis model was developed using the "Data Fit" software. The new model for interpreting core test results incorporates all the identified factors affecting core strength. When calibrated against a large set of test data, the model demonstrated good agreement. The proposed model can effectively estimate the in-situ concrete cylinder strength based on core test results.

Keywords: Core, Cylindrical specimens, Compressive strength

1.1. Introduction

The main feature of hardened concrete is its concrete compressive strength, which is usually determined by crushing concrete samples in the laboratory through a test known as the "compressive strength test". This test is most frequently performed on concrete due to its simplicity and cost-effectiveness. Nevertheless, a range of factors, such as the size and shape of the specimen, the casting mold, curing conditions, and the rate of load application, can influence the results of the experiment. [1].

The standard size and shape of test specimens for assessing concrete compressive strength vary across different countries, as different standards prescribe distinct geometries. For example, cylinder specimens are commonly used in the United States, Canada, and Australia, while cube specimens are standard in the United Kingdom, Germany, and most other European countries. In some countries, such as Libya, both standard-sized cylinders and cubes are utilized, although their popularity may differ.

The most widely used standard dimensions for test specimens are 150x150x150 mm for cubes and 150x300 mm for cylinders. In certain situations, non-standard smaller sizes are more practical, such as when assessing the strength of existing structures using core specimens of 100 mm diameter and 100 mm height [2]. There is a growing shift towards using smaller sizes due to their ease of handling, material savings, and the reduced requirement for high-capacity testing machines [3].

The effect of specimen shape on compression strength has been extensively studied to aid in predicting the equivalent standard specimen strength when testing non-standard sizes. Many investigations have overlooked the relationship between the nucleation and propagation of fracture processes and the specimen's failure. Experimental observations indicate that a localized micro-cracked area forms at peak stress or just before peak stress. Therefore, compressive failure is best analyzed using Fracture Mechanics [4].

The distinction between normal-strength and high-strength concrete is not clearly defined, as it varies depending on the time period and geographic location [5]. The American Concrete Institute (ACI) has classified high-strength concrete, since 1981, as having a compressive strength exceeding 41 MPa, although this definition this definition lacks clarity and strictness.

Drilled cores are usually stronger when they are drilled vertically (in the direction of placement and compaction) as opposed to horizontally (perpendicular to the placement direction). According to ACI 214.4R-03, the variation is attributed to bleeding in new concrete, forming pockets of weak paste below coarse aggregate particles, leading to a weak bond between paste and coarse aggregate. indicates that, regardless of the aspect ratio of the specimen, the average ratio between vertically drilled cores and horizontally drilled cores falls between 1.075 and 1.08. Consequently, it can be reasonably assumed that the correction factor (Fdir) for coring direction is constant and can be considered equal to 1.0 for horizontal coring and 1.075 for vertical coring.

1.2. Problem Formulation

1 How does the use of non-standard specimens affect the compressive strength for different concrete grades?

2 What is the compressive strength conversion factor between standard and non-standard specimens when different concrete strengths are used?

3 What is the effect of size and shape on the compressive strength tests of normal and high-strength concrete?

4 What is the effect of drilling cores with the casting side for normal and high-strength concrete?

5 How does the mix cutting core impact compressive strength under varying dimensions and conditions?

1.3. Experimental Study

Strength will be evaluated at 28 days from casting. Casted cylinders will be examined with dimensions (Ø 150 x 300 mm). Core samples to be examined include various dimensions such as Ø150 x 300 mm, Ø150 x 200 mm, Ø150 x 100 mm, Ø100 x 200 mm, Ø100 x 150 mm and Ø100 x 100 mm.

Concrete compressive strength levels will be 20, 30, 40, 50, and 60 MPa for standard cylinder specimens. All specimens will be tested under uniaxial load to determine their ultimate load capacity. Variables include specimen shape, size, drilling direction, and concrete grade.

2. Literature review and basic theory

2.1. Specimen shape and size in various standards

The ASTM, AASHTO, and Canadian Standards Association (CSA) include provisions for the use of 4 x 8 in. cylinders. According to CSA standards, if non-standard cylinders are used, their strengths must be correlated to those of 6 x 12 in. cylinders (Day 1994b). ASTM and AASHTO both state that "cylinders for such tests as compressive strength, Young's modulus of elasticity, creep, and splitting tensile strength can vary in size, with a minimum of 2-in. diameter by 4-in. length. When correlation or comparison with field-made cylinders is desired, the cylinders should be 6 x 12 in." [8][9].

There are some limitations on using 4 x 8 in. cylinders. According to AASHTO T 126-93 and ASTM C 192-00, the diameter of a cylindrical specimen or the minimum cross-sectional dimension of a rectangular section must be at least three times the nominal maximum size of the coarse aggregate in the concrete. This requirement restricts the nominal maximum size of coarse aggregate in a 4 x 8 in. cylinder to 1 inch, effectively limiting the maximum aggregate gradation to a No. 57 stone. The Libyan National Center for Standardization and Metrology (LNCSM) refers to the requirements in ISO 1920-3 for cubes and cylinder test specimens and ISO 1920-6 for core testing [10].

2.2. Effects of specimen size and shape

Research has demonstrated that the failure type of concrete specimens under compression is determined by the fracture mechanism, which is influenced by various factors including specimen size, specimen shape, mold material, curing method, capping method, preparation of specimen ends, loading rate, and the bearing block dimension of the testing machine [11].

One of the earliest studies on the size effect was conducted in 1925 by Gonnerman, who used standard cubes of 6" and 8" and various sizes of cylinders. By testing multiple specimens at different ages, it was found that the average cylinder/cube strength ratio ranged from 0.85 to 0.88 [12][13].

Two types of specimens commonly used for evaluating hardened concrete are cubes and cylinders. Cylindrical specimens with a diameter of 150 mm and a height of 300 mm are predominantly used in Australia, Canada, France, New Zealand, and the United States. Conversely, cube specimens, typically sized 150 mm or 100 mm, are more common in European countries, including the UK and Germany [13]. Each country has its own national or regional standards and codes that detail the methodology for conducting the tests.

Cylinder specimens require capping with sulfur mortar or cement paste to achieve plain loading surfaces. In contrast, cubes do not need capping as they are simply flipped onto their sides when loaded. However, cubes have higher compressive strength, necessitating larger capacity testing machines, whereas cylinders are tested in the direction of casting, which is considered an advantage [13].

The effect of size and shape on the compressive strength test results of concrete specimens has been extensively studied. Bažant and Planas demonstrated how changing the size of the concrete specimen can affect the nominal strength, even when maintaining a constant aspect ratio [14]. The same concept applies to shape effect, where the nominal strength of concrete depends on the shape and aspect ratio of the specimen.

For high-strength concrete, further investigations into the shape and size effect on compressive strength have been conducted using different conversion factors based on specimen size. These factors include 0.8 for 150x300 mm cylinders and 150 mm cubes, 0.93 for 100x200 mm cylinders and 150 mm cubes, and 0.866 for 150x300 mm cylinders and 200 mm cubes [15].

Mix design parameters have also been shown to impact the strength ratio of cylinder to cube specimens [15]. One such parameter is aggregate grading, which leads to the "wall effect," where the amount of mortar filling the space between aggregates and the mold's wall is greater than that between the concrete's aggregates, as illustrated in Figure 2.1 [1]. This results in a significant increase in the compressive strength of specimens with a high surface-to-volume ratio and causes variations in the cylinder/cube conversion factor [3][13].

The wall effect has been extensively studied in the literature. One study simulated aggregate density in concrete specimens using a proposed three-dimensional model. The model's corresponding graph shows that aggregate density initially increases from the sides to the inner zone of a concrete specimen, peaks near the surface section, and then, after a slight decrease, reaches a constant level. Additionally, the peak point of the graphs rises with an increased fraction of aggregates [15].

To eliminate the impact of the wall effect in their research, some studies extracted concrete specimens from cast molds. The size effect was more noticeable in concrete samples with higher compressive strength due to their very brittle nature. Similarly, the maximum aggregate size significantly influenced the size effect for both medium and high compressive strengths [16] [17].

Several studies have proposed equations for converting the compressive strength of different specimens. Various theories have been suggested to explain the size effect. The weakest link theory posits that larger specimens are more likely to contain more defects and anomalies, resulting in lower bearing stress capacity [17]. In contrast, the summation theory proposed by Tuckers suggests that the strength of a specimen is equivalent to the combined strength of its individual components [17]. In summary, the results of various-sized concrete specimens in different situations are influenced by several factors, including the strength of different particles and internal defects.

Regarding the shape effect, another factor arises from the difference in fracture patterns between cubes and cylinders. In cylinders, the primary fracture surface nucleates internally, while in cubes, the lateral sides crack, leading to collapse due to crushing. This can also be observed in stress-strain curves [4].

2.3. Effects of core drilling.

The values for the shape correction factor of core length divided by diameter (Fl/d) provided by ACI 214.4R-03 were derived based on high-strength concrete (48 MPa core specimens). However, for low-strength concrete (18 MPa or less), the variation of the correction factor as a function of the (1/d) ratio seems overly exaggerated. In contrast, the ACI factor (Fl/d) corresponds with Chung's equation (1989) for low-strength concrete but diverges from the equation for high-strength concrete. This discrepancy is a significant source of conflict [18] [19].

A study by Khoury et al. (2016) indicated that the compressive strength of core specimens increases as the core aspect ratio (l/d) decreases, particularly for normal-strength concrete. The impact of the cylindrical specimen diameter on its strength can vary notably depending on the type of specimen [6].

For drilled cores, smaller diameters are more likely to experience a reduction in strength due to a higher ratio of cut surface to volume, which results in greater cutting damage and weakens the bond between the aggregate and the surrounding matrix. This strength reduction can be as much as 17% for cores with a diameter of less than 100 mm, while it is less significant but still considerable for larger diameters. This effect is particularly significant for low-strength concrete (18 MPa or less) and can be negligible for high-strength concrete [6] [19].

According to ACI 214.4R-03, a core drilled vertically (in the direction of placement and compaction) can be stronger than a core drilled horizontally (perpendicular to the placement's direction). This difference in core strength due to drilling orientation is generally attributed to bleeding in fresh concrete, which created weak paste pockets beneath coarse aggregate particles, resulting in a weak paste-to-coarse aggregate bond. Results show that the mean ratio of vertically drilled cores to horizontally drilled cores is approximately 8% [6].

2.4. Effects of capping

Both AASHTO and ASTM recommend the use of neoprene pads as caps for cylindrical concrete specimens. However, while ASTM C 1231 (18) specify that for either 6x12 in and 4x8 in cylinders as long as the compressive strength is between 1,500 and 12,000 psi (change to MPa and mm), AASHTO T 22 (1992) consider neoprene pads as an acceptable substitute for sulfur-mortar caps only for the 6x12 in cylinders or otherwise the apparent strength may need to be corrected. The caps requirement for ASTM is that the tests must demonstrate at least 95% confidence level (a = 0.05) with the average strength produced with unbounded caps is not less than 98% of the average strength of companion cylinders capped or ground.

3. Hypothesis of the research

The research hypothesis is formulated based on the review of literature:

3.1 Testing indicates that smaller concrete samples demonstrate increased compressive strength.

3.2 Concrete core specimens of 150 mm typically have lower compressive strength compared to 150 x 300 mm cylinders.

3.3 Core specimens drilled perpendicular to the casting direction typically exhibit higher compressive strength compared to core specimens drilled parallel to the casting direction.

4. Data Collection

Data was collected from experimental tests conducted at Misurata University's engineering laboratory.

5. Materials and Equipment Used

5.1 Cement:

Portland Cement Type I.

5.2 Aggregates:

Local coarse and fine aggregates tested for properties like sieve analysis, specific gravity, and moisture content as per ASTM.

5.3 Water:

Tap water used for casting all specimens according to BS5328: Part 1,2000.

5.4 Mix Design

Five concrete mixtures were designed using ACI 211. With same materials and that table 1 shows the concrete mix design details.

Table 1: Concrete Mix Design

Mix Design	w/c Ratio	Cement kg	Coarse Aggregate kg		Fine Aggregate kg		
			20 mm	10 mm	3.18 mm	Sand	
C20	0.590	320	510	510	248	577	185
C30	0.470	402	510	510	291	676	185
C40	0.420	453	510	510	213	496	185
C50	0.36	515	510	510	200	462	185
C60	0.300	620	510	510	169	398	185

6. Results and Discussions

6.1. Slump Test

Results show varying slump values for different mix designs, indicating changes in workability with varying cement content, slump was conducted as per ACI 211. The results are presented in the Tables 2.

Table 2: Slump test results

Mix design	C20	C30	C40	C50	C60
Slump test (cm)	6.70	4.90	4.10	3.80	3.20

6.2. Compressive Strength of cylindrical specimens

Compressive strength results of cylindrical specimens were obtained for all concrete mix designs as showing in Table 3. The relationship between nominal and actual compressive strength was analyzed.

Table 3: Compressive strength test results for cylindrical specimens

Mix Design	Cement content	w/c Ratio	Fcy. MPa 150x300 mm
C20	320	0.58	25.89
C30	402	0.46	33.99
C40	453	0.41	44.31
C50	515	0.36	53.15
C60	620	0.30	62.67

6.3 Compressive Strength of Core Specimens

6.3.1 Core specimens drilled vertically.

Results indicate that compressive strength is higher when cores are drilled perpendicular to the casting direction.

Table 4: Compressive strength test results for cylindrical and core specimens drilled vertically (parallel to casting direction) (foundations and slabs) .

Mix Design	Compressive Strength Test (MPa)						
	Cylinder 150*300 mm	Core D=150 mm			Core D=100 mm		
		300	200	150	200	150	75
C20	25.89	20.38	23.36	25.01	20.93	21.39	22.17
C30	33.99	29.59	30.81	31.96	31.18	32.14	34.25
C40	44.31	40.01	43.11	43.42	42.51	44.29	48.04
C50	53.15	49.19	52.01	53.88	50.62	52.13	53.27
C60	62.67	58.83	59.11	59.95	59.98	60.52	61.92

Figure

1: Compressive strength of all specimens for different mix design.

6.3.2 Core specimens drilled horizontally.

Table 5: Compressive strength test results for cylindrical and core specimens for core drilled horizontally (perpendicular to casting direction) (column and beams).

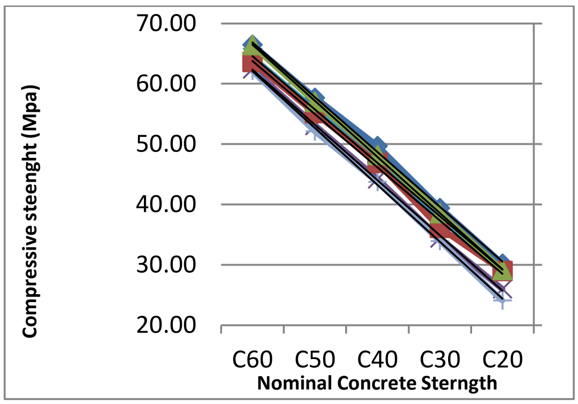

Figure 2: Compressive strength of cylindrical and core specimens for different mix design.

Table 6: Compressive strength test results for core specimens which are taken from columns and footing /slab versus compacting direction.

The table 4.7 illustrated that the concrete compressive strength values of cores are drilled vertically to casting direction greater than those are drilled perpendicularly where the conversions factor values are between 0.99 to 1.30. In addition, these figures significantly decreased as well as concrete compressive strength increased.

6.3 Conversion Factors

Conversion factors for different specimen sizes and conditions calculated to standardize compressive strength results to equivalent 150x300 mm cylinder strengths.

Moreover, compressive strength test results of core drilled vertically and conversion factor (in between 1 to 2) according to standard cylinder 150*300 mm were drowned by using "Data fit" software as shown in figure 6.1 to get the relationship between compressive strength of standard cylindrical specimens to L/D ratio and compressive strength of all core specimens to gain equation (6.1) to estimate compressive strength depending on core test results.

Mix Design	Compressive Strength Test (MPa)			
	parallel to casting direction		perpendicular to casting direction	
	Core 150*300 mm	Core 100*200 mm	Core 150*300 mm	Core 100*200 mm
C20	20.38	20.93	17.25	17.83
C30	29.59	31.18	25.80	26.18
C40	40.01	42.51	37.79	37.78
C50	49.19	50.62	44.85	45.41
C60	58.83	59.98	56.24	57.48

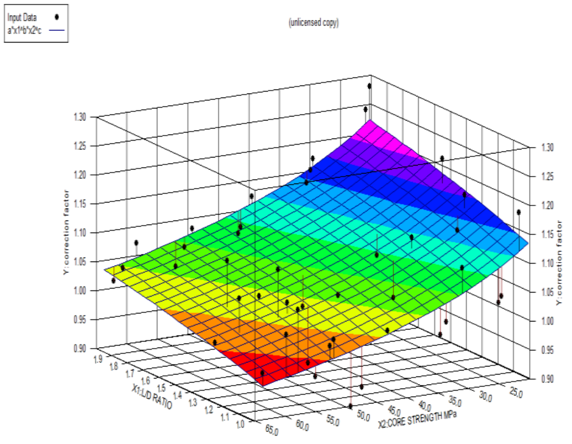

Figure 3: The relationship between compressive strength to compressive strength calculated from core test results and L/D respected.

From the "Data fit" software the equation 1 was created.

$F_{cy} = ax_1^b x_2^c$ equ. 1

this equation can be as bellow

Fc=1.845(l/d)^0.099. (fccore)^0.859

7. Conclusion

Based on the findings of this research, the following conclusions can be drawn for the specific test materials and methodologies used:

1. The results indicate that compressive strength increases as the specimen size decreases. Typically, conventional compressive cylindrical strength is higher than in-situ core strength, and this difference tends to diminish as concrete strength increases. This observation aligns with previous studies by Eltaweel (2018) ,Mansur and Islam (2002), Yi et al. (2006), and Yazici and Sezer (2007) [19].

2. The conversion factors for the compressive strength of cylinders with dimensions Ø100x200 mm and Ø75x150 mm to the standard cylinder size of Ø150x300 mm range from 0.76 to 0.88 for intended compressive strengths of 20 to 60 MPa. According to the CEB-FIP (1990) Model Code, the conversion factor for non-standard cylinder strength of 40 MPa is 0.80 and gradually increases to 0.89 as the cylinder compressive strength reaches 80 MPa. The IS-516-1979 standard indicates that the strength of a standard cylinder from a controlled concrete specimen will differ from core strength. Typically, core strength is considered to be 0.8 times the strength of the cylinder. However, the experimental results of this study suggest that there is no consistent relationship between cylinder and core strength across different concrete strength levels. This implies that the core strength of hardened concrete is not always 0.8 times the cylinder strength. Instead, the compressive strength is better predicted by the developed formula.

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