Alexandria Engineering Journal (2014) **53**, 169–184

Alexandria University

Alexandria Engineering Journal

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ORIGINAL ARTICLE

Reliability of core test – Critical assessment and proposed new approach

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Received 14 November 2013; revised 21 December 2013; accepted 21 December 2013
Available online 22 January 2014

KEYWORDS

Strength;
Drilled cores;
Interpretation;
Codes;
Regression analysis;
Model

Abstract Core test is commonly required in the area of concrete industry to evaluate the concrete strength and sometimes it becomes the unique tool for safety assessment of existing concrete structures. Core test is therefore introduced in most codes. An extensive literature survey on different international codes' provisions; including the Egyptian, British, European and ACI Codes, for core analysis is presented. All studied codes' provisions seem to be unreliable for predicting the in-situ concrete cube strength from the results of core tests. A comprehensive experimental study was undertaken to examine the factors affecting the interpretation of core test results. The program involves four concrete mixes, three concrete grades (18, 30 and 48 MPa), five core diameters (1.5, 2, 3, 4 and 6 in.), five core aspect ratios (between 1 and 2), two types of coarse aggregates (pink lime stone and gravel), two coring directions, three moisture conditions and 18 different steel arrangements. Prototypes for concrete slabs and columns were constructed. More than 500 cores were prepared and tested in addition to tremendous number of concrete cubes and cylinders. Results indicate that the core strength reduces with the increase in aspect ratio, the reduction in core diameter, the presence of reinforcing steel, the incorporation of gravel in concrete, the increase in core moisture content, the drilling perpendicular to casting direction, and the reduction in concrete strength. The Egyptian code provision for core interpretation is critically examined. Based on the experimental evidences throughout this study, statistical analysis has been performed to determine reliable strength correction factors that account for the studied variables. A simple weighted regression analysis of a model without an intercept was carried out using the "SAS Software" package as well as "Data Fit" software. A new model for interpretation of core test results is proposed considering all factors affecting core strength. The model when calibrated against large number of test data shows good agreement. The proposed model can effectively estimate the in-situ concrete cube strength from core test results.

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

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http://dx.doi.org/10.1016/j.aej.2013.12.005

1. Introduction

The compressive strength of concrete is a direct requisite of all concrete structures that need to resist applied forces of whatever nature. Actually, the concrete compressive strength is a good index of most other properties of practical significance. To ensure concrete quality, standard test specimens are examined during construction. These specimens, which give the potential strength of concrete, are prepared, cured and tested according to relevant standard specifications and codes. On the other hand, determination of the actual strength of concrete in a structure is not easy because it is dependent on the history of curing and the adequacy of compaction of concrete. Therefore, one question that designers frequently ask is whether or not the standard test specimens can represent in situ-strength of concrete. The answer to this question becomes even more important when the strengths of standard test specimens are found to be lower than the specified value. In this case, either the strength of concrete in the actual structure is low or the specimens are not actually representing the concrete in the structure. The problem is generally solved by drilling and testing core specimens from the suspected structural member. Furthermore, it may not be possible to find and test standard specimens at a later age and it may be necessary to assess the current strength of a structure to determine whether the strength and durability are adequate for its future use when the concrete is doubted or the structure is intended to be used for higher stress conditions. For these special situations, the core test is the most useful and reliable way to assess the properties of the concrete in the structure [1]. For these reasons, the common way of determining in-situ strength of concrete is to drill and test cores [1–10]. Although the method consists of expensive and time consuming operations, cores give reliable and useful results since they are mechanically tested to destruction [2]. However, the test results should be carefully interpreted because core strengths are affected by a number of factors such as diameter, l/d ratio and moisture condition of the core specimen, the direction of drilling, the presence of reinforcement steel bars in the specimen and even the strength level of the concrete [11–24].

2. Impact of core test

The determination of cube strength is the most common and simple approach for evaluating the concrete strength during the construction of new buildings; however, the absence of cube results or the doubt on the results may raise a critical situations. Furthermore, during the rehabilitation of existing structures, another approach for evaluating the concrete strength is of great importance. From this point, testing of concrete elements in existing structures comes into picture. From that point, core test is commonly required in the area of concrete industry and hence is included in most international codes' provisions. In fact, core test becomes a must in many critical circumstances and sometimes becomes the unique tool for concrete quality assessment. From general prospective, core test is ultimately needed to assess one or a combination of the following:

1. The quality of the concrete provided to a construction (potential strength).
2. The quality of the concrete in the construction (in-situ strength), known as actual strength.
3. The ultimate capacity of the structure to carry the imposed loads; actual loads, design loads, and new additional loads.
4. The deterioration in a structure due to overloading, fatigue (bridge structures, machine base, etc.), chemical reaction (ASR or chemical spillage, etc.), fire or explosion, and weathering.

3. Codes provisions for core analysis; state-of-the-art

To determine in-situ cube strength, core test is available but most codes give different results depended on the factors used. It is generally agreed that the compressive strength of extracted core can be obtained by dividing the ultimate load by the cross-sectional area of the core, calculated from the average diameter; however, the critical problem is actually to translate this result to cube/cylinder strength as mentioned earlier. In fact, the core test results must be carefully interpreted since core strength is affected by a number of factors such as diameter, aspect ratio (l/d), moisture condition of the core specimen, direction of drilling, the presence of reinforcement steel bars in the core, type and size aggregate and even the strength level of the concrete. Factors considered in codes provisions for core interpretation are different. Table 1 summarizes the factors considered in Egyptian code, American code, European code, British code and Concrete society to interpret core strength to in site concrete strength. The table clearly implies that for a specific core strength, the obtained in-situ strength is different based on the considered code. The approaches adopted in some of the listed codes/for core interpretation are summarized below. More details about other codes approaches for core analysis may be seen elsewhere [14].

3.1. Current Egyptian Code (2008)/standard and British Code (2003)

According to these codes, the estimated in-situ concrete cube strength (f_{cu}) may be calculated from the measured compressive strength of core (f_{core}) according to the following expression:

$$f_{\mathrm{cu}} = (F_{l/d}) \cdot (F_{\mathrm{Reinf.}}) f_{\mathrm{core}} \tag{1}$$

where the factors ($F_{l/d}$) and ($F_{\mathrm{Reinf.}}$) account for the effect of l/d and the presence of reinforcing steel, respectively. These factors are given in the codes as follows:

$$F_{1/d} = \frac{D}{1.5 + 1/\lambda} \tag{2}$$

$$F_{\mathrm{Reinf.}} = 1 + 1.5 \frac{\Phi_r * d}{\Phi_c * \ell} \tag{3}$$

where D is the equal to 2.5 for core drilled horizontally (perpendicular to casting direction); or 2.3 for cores drilled vertically (parallel to casting direction), λ is length to diameter ratio (l/d) after ends' preparation, Φ_r is diameter of the reinforcing bar, Φ_c is core diameter, d is distance of axis of bar from the nearest core end, and ℓ is the core length after end preparation.

Table 1 Factors involved in interpretation of core results by different codes.

List	Code/standard	Edition	Factors Considered					
			Aspect ratio	Diameter	Reinforcing	Moisture	Damage	Direction
1	Egyptian Code/Standard Specification	2008	√		√			√
2	British Code/Standard Specification	2003	√		√			√
3	American Concrete Institute ACI	1998	√					
		2012	√	√		√	√	
4	European Standard Specification	1998	√	√	√		√	
		2009	√		√			
5	Japanese Standard	1998	√					
6	Concrete Society	1987	√		√		√	√

In addition, for core specimen containing two bars no further apart than the diameter of the larger bar, only the bar corresponding to the higher value of ($\Phi_r * d$) is considered. If the bars are further apart, their combined effect should be assessed by replacing the term ($\Phi_r * d$) by the term ($\sum \Phi_r * d$).

It should be pointed out that above equations used to interpret the core concrete strength to the in-situ concrete cube strength have been developed based on a set of assumptions and through many converting process. It is also of interest to note that the damage effect is considered in the development of the formulas in indirect way. The subject derivation and detailed formulas may be seen elsewhere [14].

3.2. American Concrete Institute (ACI)

3.2.1. Former ACI Code (2002) & Current ASTM (2009)

The methodology of core interpretation given in the former ACI code was remained without changes for decades and up to Year (2003). The in-place strength of concrete cylinder at the location from which a core test specimen was extracted can be computed using the equation:

$$f_{cy} = F_{l/d} \cdot f_{core} \tag{4}$$

where f_{cy} is the equivalent in-place concrete cylinder strength, f_{core} is concrete core strength, and $F_{l/d}$ is the strength correction factor for aspect ratio.

The former ACI code does not include any equation to calculate the correction factor ($F_{l/d}$); however, the code gives different values for this term that is associated with different aspect ratios (l/d) as given in Table 2. It should also be noted that the approach of current ASTM is similar to that mentioned above. The only considered variable is the aspect ratio (l/d). It should be noted that identical approach to that mentioned above is still effective in ASTM C42/C42M-03 [10].

3.2.2. Current ACI Code (2012) [15]

Starting from Year 2003, significant changes have been made to the relevant ACI Code provisions regarding the interpretation of core strength test results. New factors have been considered. These include core diameter, moisture content of core sample, core damage associated with drilling, in addition to the effect of aspect ratio that was previously considered in the former ACI edition (1998). According to the ACI 214.4R-03, the in-place concrete strength can be computed using the equation:

Table 2 Mean values for factor $F_{l/d}$ according to ACI Code (1998) and ASTM.

	Specimen length-to-diameter ratio, l/d			
	1.00	1.25	1.50	1.75
$F_{l/d}$	0.87	0.93	0.96	0.98

$$f_c = F_{l/d} \cdot F_{dia} \cdot F_{mc} \cdot F_D \cdot f_{core} \tag{5}$$

where f_c is the equivalent in-place concrete cylinder strength, f_{core} is concrete core strength, $F_{l/d}$ is strength correction factor for aspect ratio, F_{dia} is strength correction factors for diameter, F_{mc} is strength correction factor for moisture condition of core sample, and F_D is the strength correction factor that accounts for effect of damage sustained during core drilling including micro-cracking and undulations at the drilled surface and cutting through coarse-aggregate particles that may subsequently pop out during testing.

The ACI committee considered the correction factors presented in Table 3 for converting core strengths into equivalent in-place strengths based on the work reported by Bartlett and MacGregor [6]. It should be noted that the magnitude of

Table 3 Strength correction factors according to ACI 214.4R-03.

List	Factors	Mean values
(1)[b]	$F_{l/d}$:l/d ratio	
	As-received	$1 - \{0.130 - \alpha f_{core}\}\left(2 - \frac{l}{d}\right)^2$
	Soaked 48 h	$1 - \{0.117 - \alpha f_{core}\}\left(2 - \frac{l}{d}\right)^2$
	Air dried[a]	$1 - \{0.144 - \alpha f_{core}\}\left(2 - \frac{l}{d}\right)^2$
(2)	F_{dia}: core diameter	
	50 mm	1.06
	100 mm	1.00
	150 mm	0.98
(3)	F_{mc}: core moisture content	
	As-received	1.00
	Soaked 48 h	1.09
	Air dried[a]	0.96
(4)	F_D: damage due to drilling	1.06

[a] Standard treatment specified in ASTM C 42/C 42M.

[b] Constant α equals $4.3(10^{-4})$ 1/MPa for f_{core} in MPa.

damage factor suggested in the table is based on data for normal weight concrete with strengths between 14 and 92 MPa.

3.3. European Code (CEN)

3.3.1. Former CEN Code (1998)

The main factors considered in the former European code are the size and geometry of the core, coring direction, the presence of reinforcing bars or other inclusions and the effect of drilling damage. This approach was originally taken from the German Standards by that time. The proposed relationship to convert the strength of a core specimen f_{core} into the equivalent in-situ concrete value f_c as recommended by the code and reported elsewhere [16] is as follows:

$$f_c = C_{H/D} \cdot C_{\text{dia}} \cdot C_a \cdot C_d \cdot f_{\text{core}} \tag{6}$$

where f_c is the equivalent in-place concrete strength, f_{core} is concrete core strength, $C_{H/D}$ is correction factor for aspect ratio and is calculated according to the following formula where H and D are, respectively, the core height and diameter:

$$C_{H/D} = \frac{2}{1.5 + D/H} \tag{7}$$

$C_{\text{dia.}}$ is the correction factors for core diameter, that is equal to 1.06, 1.00 and 0.98 for core diameter, respectively, equal to 50, 100 and 150 mm. C_a is correction factors for the presence of reinforcing steel, equal to 1 for no bars, and varying between 1.03 for small diameter bars ($\Phi = 10$ mm) and 1.13 for large diameter bars ($\Phi = 20$ mm) and C_d is the correction factors for damage due to drilling,

The factor C_d is proposed to be 1.10 providing that the core extraction is carefully carried out by experienced operators. However, taking into account that the lower the concrete quality the larger the drilling damage, it appears more suitable to put $C_d = 1.20$ for $f_{\text{core}} < 20$ MPa, and $C_d = 1.10$ for $f_{\text{core}} > 20$ MPa, as suggested by Dolce et al. [16].

3.3.2. Current CEN Code (2009)

The approach proposed by current European Code for interpreting the core strength to in-situ concrete cube strength (f_{cu}) is similar to that suggested previously by the former British Code that presented earlier. The damage and diameter factors considered in the former CEN Code were eliminated in the more recent edition. Factors considered are only aspect ratio and the presence of reinforcing steel as given in Eqs. (2) and (3). The main difference in core interpreting between recent CEN Code and British Code seems to be in the magnitude of the Term '*D*' in Eq. (3). The CEN Code considers $D = 2.5$ for cube strength and 2.0 for cylinder strength instead of the values of 2.3 and 2.5 that is mentioned in the British Code. In addition, the aspect ratio should be limited between 1.0 and 1.2

3.4. Concrete Society (CS)

The approach proposed by Concrete Society CS [23] is similar to that suggested by the former British Standard presented earlier. However, the Concrete Society estimates the so-called Potential concrete strength that is different than the in-situ concrete cube strength. According to Concrete Society, the estimated potential concrete strength (f_{pot}) can be calculated from the measured compressive strength of core (f_{core}) according to the following expression:

$$f_{\text{pot}} = (F_{l/d}) \cdot (F_{\text{Reinf.}}) f_{\text{core}} \tag{8}$$

where the factors ($F_{l/d}$) and ($\mathrm{F}_{\text{Reinf.}}$) account for the effects of l/d and the presence of reinforcing steel, respectively, and they can be determined using Eqs. (2) and (3) presented earlier.

Again, the difference seems to be in the magnitude of the term '*D*' that is considered 2.3 or 2.5; depending on the drilling direction; in the current Egyptian Code, but it is proposed to be 2.0 in the current European Code. However; according to Concrete Society, the term '*D*' is equal to 3.25 for cores drilled horizontally (perpendicular to casting direction); or 3.0 for cores drilled vertically (parallel to casting direction). The derivation of these numbers may be seen elsewhere [14].

From general prospective, it has been shown that the potential strength is approximately 1.5 times the strength of a core providing that the core length/diameter ratio = 2, the drilling direction is vertical, the core is free of reinforcement, and concrete is well compacted and does not include the weaker material near the top of a lift. Actually, the formulae for converting core strength to cube strength indicate that, if the concrete in the structure is fully compacted and normally cured, the actual concrete strength is about 77% of the potential strength.

4. Research significance

Core tests are generally performed to assess whether suspect concrete in a new structure complies with strength-based acceptance criteria or not. In addition, it is critically used to determine in-place concrete strengths in an existing structure for the evaluation of structural capacity. It is generally agreed among engineers, contractors, consultants and researchers that the results of core tests are very reliable to assess the strength of concrete elements. Unfortunately, this statement may not be totally true and may lead to a misleading in the assessment of structural safety. Actually, the available test information on cores is full of contradictions and confusions. The conflict between different codes regarding the interpretation and conversion of the core results to the in site concrete strength raises a critical debate. It seems that the core test itself may be reliable but the core analysis is questionable. This comprehensive and costly program; which includes drilling about 500 cores, is undertaken to reconsider and focus on this critical aspect.

5. Experimental program

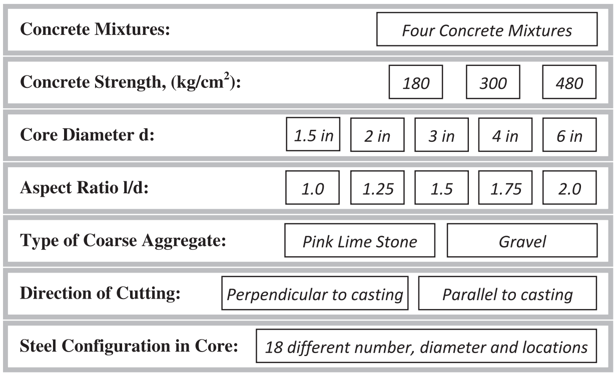
A special testing program on cores was constructed to investigate the influence of different variables that may affect the interpreting of core test results into in-situ cube strength. Variables considered are as follows; 1 – core length-to-diameter ratio (L/d), 2 – core diameter (d), 3 – direction of drilling, 4 – the presence of reinforcing steel, 5 – moisture content of core specimen, and 6 – damage due to drilling. Four different concrete mixtures were considered throughout the program using two types of aggregate; crushed aggregate (pink lime stone) and natural aggregate (gravel). Ordinary Portland cement CEM I-42.5N (ASTM Type I) was used. Three levels of concrete grades were considered; 18, 30, and 48 MPa. Concrete mix proportions are given in Table 4.

Table 4 Concrete mixes used throughout the program.

Mix.	Mix proportion (kg/m^3)					Some properties	
	Coarse agg.	Fine agg.	Cement	Total water	Admixture (L)	w/c	Aggregate type
Mix 1	1080	760	300	170	5	0.57	Pink lime stone
Mix 2	1070	705	400	175	4	0.44	
Mix 3	1080	760	450	160	6	0.36	
Mix 4	1200	690	400	142	5	0.36	Gravel

The program comprises prototypes of slabs and columns. Actually, the examined structural elements were 1.20 × 2.20 m-concrete slabs with different thicknesses; 10, 12, 15, 17.5, 20, and 30 cm. Slabs were made of the three concrete grades mentioned above with and without reinforcing steel. Also, concrete columns having cross-section of 20 × 80 cm and 1.2 m height were constructed using high-strength concrete (480 kg/cm^2). Special wooden forms were designed and fabricated. Slabs and columns were cast and cured in the laboratory condition simultaneously with corresponding 15 cm-standard cubes and 15 × 30 cm – standards cylinders.

After hardening, cores with different diameters (1.5, 2, 3, 4 and 6 in.) were extracted from slabs and columns using a diamond-tipped core drilling machine then trimmed to give overall aspect ratios (l/d) between 1.0 and 2.0. The aspect ratios of capped core specimens were 1.0, 1.25, 1.5, 1.75 and 2.0. In addition, non-standard cylinders comparable to extracted cores with respect to diameter, aspect ratio, concrete grade and reinforcement were introduced to evaluate the damage effect due to drilling. The compressive strengths of cores and associated standard specimens were determined at comparable ages using a compression testing machine with a fully automatic press. The rate of load application for all specimens was 0.25 MPa/s as recommended by most codes. Each strength value is the average of at least three core specimens. Layout of the current research plan is presented in Fig. 1 while some stages of the experimental work are shown in the photographs given in Figs. 2–8.



Concrete Mixtures:	Four Concrete Mixtures
Concrete Strength, (kg/cm^2):	180 300 480
Core Diameter d:	1.5 in 2 in 3 in 4 in 6 in
Aspect Ratio l/d:	1.0 1.25 1.5 1.75 2.0
Type of Coarse Aggregate:	Pink Lime Stone Gravel
Direction of Cutting:	Perpendicular to casting Parallel to casting
Steel Configuration in Core:	18 different number, diameter and locations

Figure 1 General layout of the research program.

A total number of about 500 cores in addition to 300 standard molded cubes and cylinders were examined in the current research. In fact, this work was very exhausting, costly and time consuming.

6. Results and discussions

Results of about 500 cores were examined to evaluate the effects of studied variables on the relations between core strength and strength of corresponding standard molded cubes and cylinders. Some results are to be presented; however, comprehensive obtained data may be seen elsewhere [14]. The compressive strength of standard specimens is listed in Table 5.

6.1. Effect of studied variables on core strength

6.1.1. Effect of length/diameter ratio (l/d)

The length to diameter ratio (l/d) of core specimens has long been recognized as a prime factor that influences the failure load. This effect depends on various conditions such as strength of concrete, elastic modulus and certainly on (l/d) ratio. Strength correction factors for (l/d) ratio ($F_{l/d}$) are determined herein by converting the strength of a core with an (l/d) between 1 and 2 to the strength of an equivalent standard core with (l/d) equal 2. Standard cylinder having a length/diameter ratio of 2.0 is considered herein as a benchmarking. As the ratio increases, the measured strength decreases due to the effect

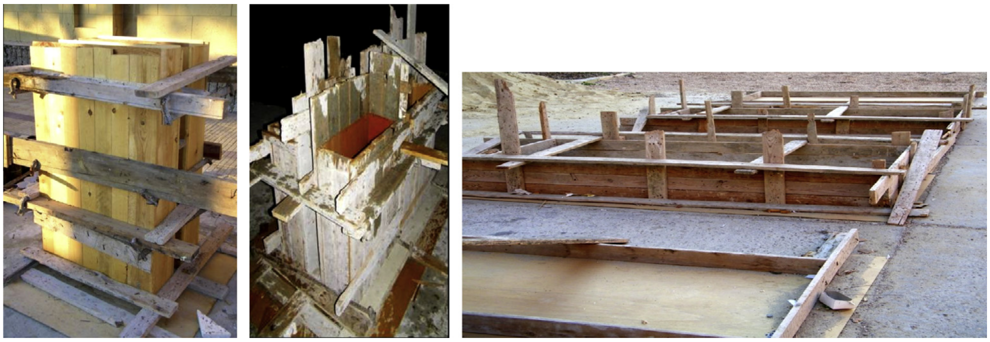


Figure 2 Fabrication of molds for columns and slabs.

Figure 3 Reinforced slabs with different configurations of reinforcement and depth.

Figure 4 Some molds for standard cubes and cylinders.

of specimen shape on stress distributions. The current study has revealed that the correction factor for (l/d) ratio depends on level of strength, diameter of specimen and moisture.

Fig. 9 illustrates the relation between the aspect ratio (l/d) and correction factor ($F_{l/d}$) according to level of strength and core diameter. The figure clearly demonstrates that the factor ($F_{l/d}$) is significantly reduced for high strength concrete. As the concrete strength increases, a correction factor becomes closer to 1.0. Fig. 10 presents comparison between the obtained data with two different recognized code and society (ACI [15] and Concrete society CS [23]). The current correction factor ($F_{l/d}$) given by ACI 214.4R-03 fits the data for high strength level (48 MPa); however, in low strength concrete (18 MPa), the (l/d) ratio becomes so effective that the ACI approach appears irrational. On the other hand, the ACI factor ($F_{l/d}$) has been found out to agree with Chung's equation (1989) for low strength concrete but does not coincide with that equation in high strength concrete. Disregarding the effect of concrete strength level on ($F_{l/d}$) seems to be responsible to large extent to this conflict.

On the basis of data obtained herein through testing large number of cores, statistical analysis has been performed to determine a reliable factor ($F_{l/d}$). A simple weighted regression analysis of a model without an intercept was carried out using the "SAS Software" package (SAS Institute, 2008) as well as "Data Fit" software. Figs. 11 and 12 show the multi-dimension relationship among the subject factor ($F_{l/d}$), aspect ratio, and concrete core strength derived from the advanced statistical analysis programs.

The advanced performed analysis with the results of large numbers of cores (about 150 data) gives that the correction factor that accounts for aspect ratio ($F_{l/d}$) can be given by the formula:

Figure 5 Non-standard molded reinforced cylinders comparable to extracted cores.

Figure 6 Some reinforced concrete slabs used throughout the program.

Figure 7 Core drilling at pre-specified locations and some extracted cores.

Figure 8 General view for columns and slabs.

$$F_{l/d} = \frac{1}{1 + \left[\left(\frac{75}{f_{\text{core}}^{1.15}}\right) \times \left(2 - \frac{l}{d}\right)^2\right]} \tag{9}$$

where f_{core} is the core strength in kg/cm^2; and l/d is length to diameter ratio for the same unit.

6.1.2. Effect of core diameter (D)

The core diameter plays an important role in affecting core strength results. It is generally agreed for molded concrete that the concrete strength is decreased as the specimen size increases. However, it is of great interest to explore that the inverse trend is evident in case of drilled cores. As the diameter decreases, the ratio of cut surface area to volume increases, and hence the possibility of strength reduction due to cutting damage increases. For core diameters above 100 mm this effect may not be significant be also it cannot be neglected as discussed later. Fig. 13 shows the mean ratio between strength of cores having different diameters and drilled at comparable locations in a specific structural element. From overall prospective, the figure shows that smaller cores have lesser strengths. In smaller cores the effect of core diameter on

Table 5 Compressive strength of standard specimen.

Mixture	Compressive strength (MPa)			
	Cylinder specimen (150 × 300 mm)		Cube specimen (150 mm)	
	7 days	28 days	7 days	28 days
Mix 1	10.5	13.4	13.1	19.3
Mix 2	19.3	24.1	23.5	29.8
Mix 3	18.8	39.6	39.1	49.1
Mix 4	18.8	23.8	23.2	29.6

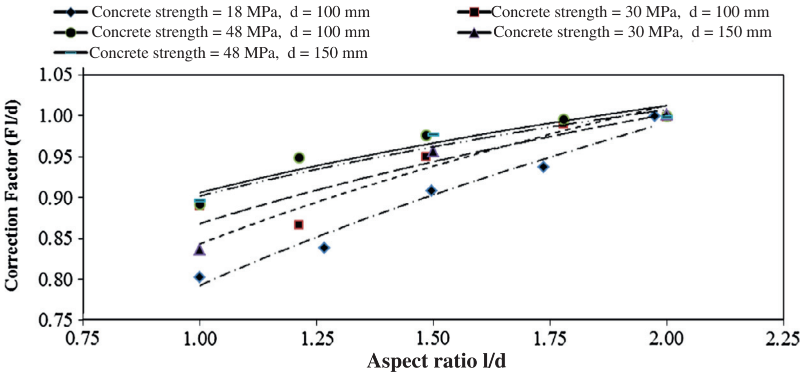


Figure 9 Relation between core aspect ratio and correction factor $F_{l/d}$.

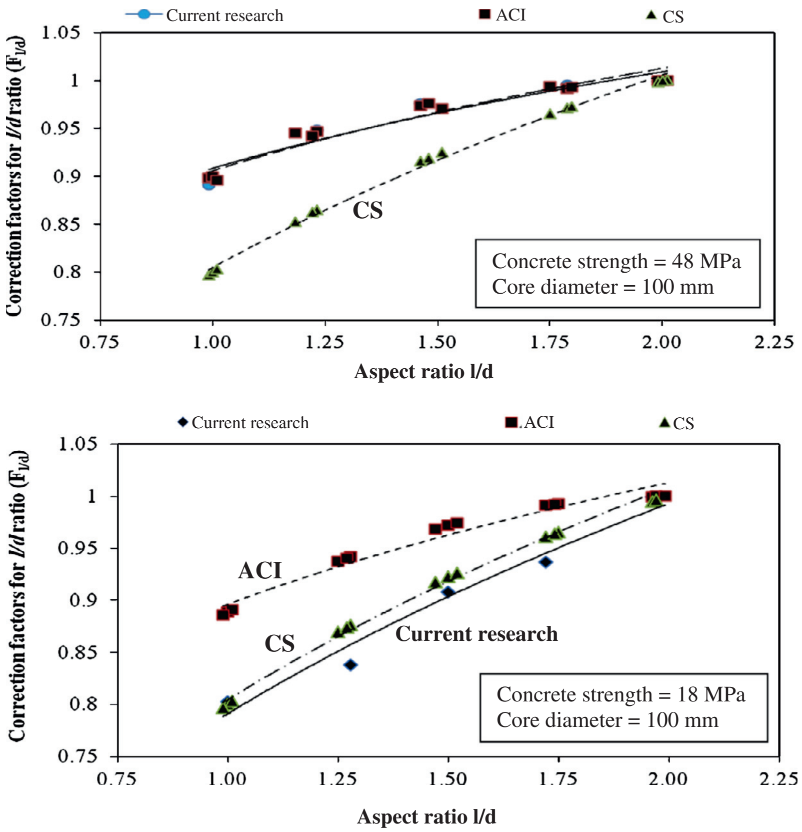


Figure 10 Relation between correction factor $F_{l/d}$ and aspect ratio as compared with ACI Code and CS.

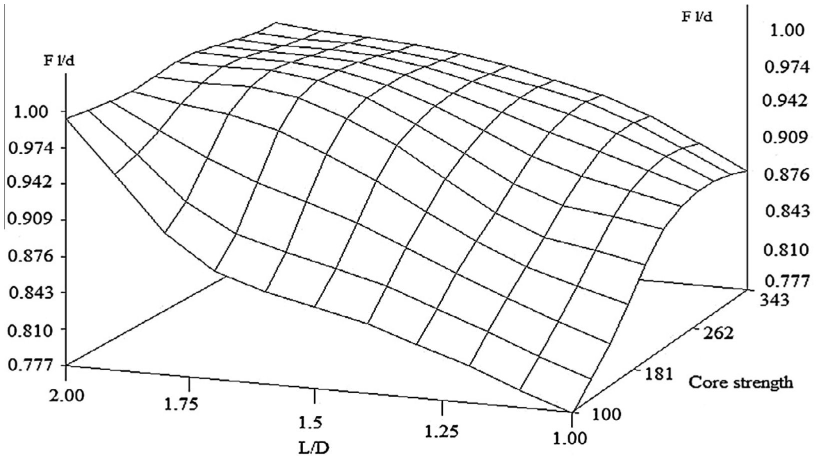


Figure 11 Advanced statistical analysis for prediction of ($F_{l/d}$) using "SAS Program" (SAS Institute, 2008).

reduction in core strength becomes significant. Fig. 14 indicates that the factor (F_d) required to compensate strength reduction varies from 1.05 to 1.08 in averages for core diameter, 75 and 50 mm, and it goes as high as 1.13–1.17 in smaller core with diameter 38 mm and also depends on degree of compaction and potential defects in the concrete.

The coefficient of variation in the compressive strength decreases for larger core diameter as shown in Fig. 15. It is depend mostly on the variance of the thickness of the damaged region. It is imperative that a large number of cores to be drilled in case of core diameter less than 100 mm to maintain comparable within-test variation as for large diameter cores. It should be pointed out that Both Egyptian and British Codes allow the use of cores with diameters either 100 or 150 mm without suggesting any correction factor for this study; however, the ACI Code allows the use of smaller cores down to 50 mm diameter and under some precautions 38 mm-diameter core may be used according to ACI Code [14].

The statistical analysis has been performed to determine a reliable factor (F_d) accounting for core diameter. Again, the

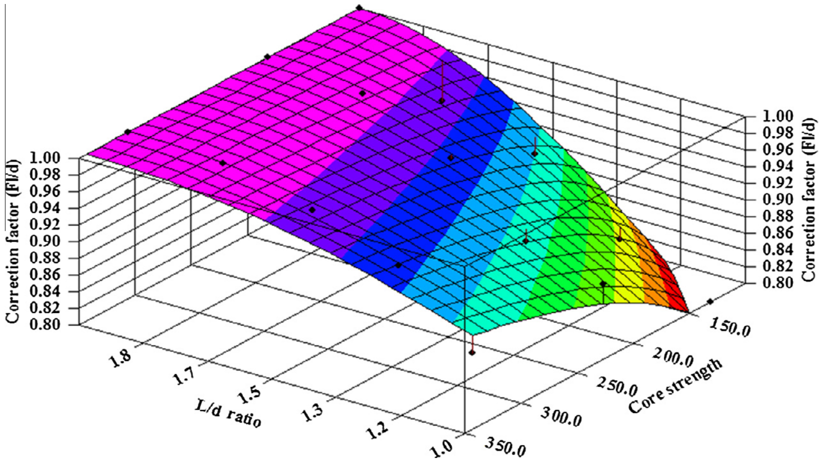


Figure 12 Advanced statistical analysis for prediction of ($F_{l/d}$) using "Data Fit" software.

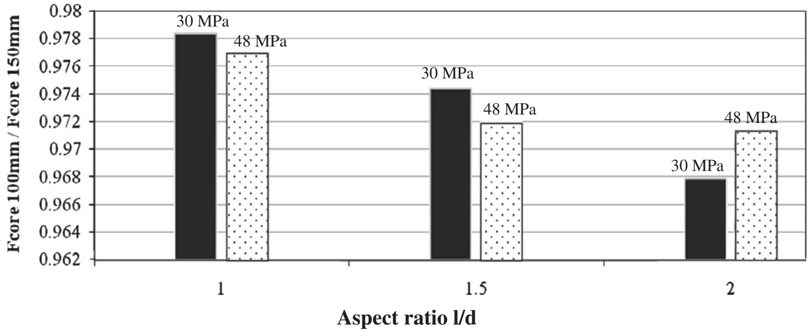


Figure 13 Mean Ratio between 100 mm- and 150 mm-core strengths for different aspect ratios (l/d) and concrete strength.

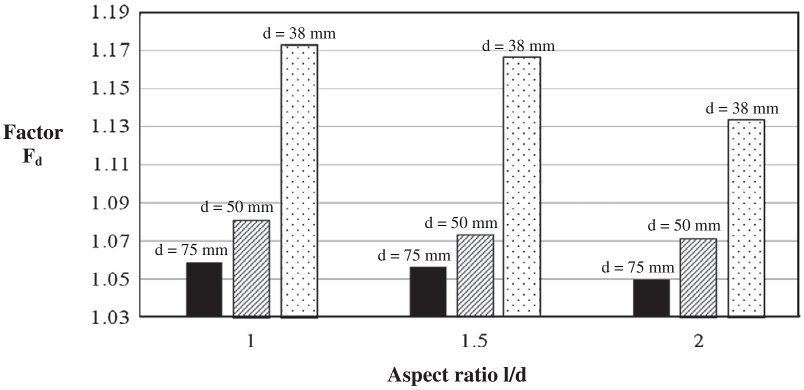


Figure 14 Effect of core diameter (d) on core strength for different aspect ratios (l/d) (d = 38, 50, 75 mm).

"SAS Software" package (SAS Institute, 2008) as well as "Data Fit" software yields the following expression for the correction due to diameter effect (F_d):

$$F_d = 1.507 - 0.11\ln(d) \tag{10}$$

where (d) is the core diameter in mm.

6.1.3. *Effect of damage due to drilling*

Non-standard cylinders comparable to extracted cores with respect to diameter, aspect ratio, concrete grade and reinforcement were prepared to evaluate the damage effect due to drilling. Samples were divided into groups and each consists of two identical samples but one was obtained by drilling and the other by concrete pouring. Results of laboratory tests reported herein and elsewhere [14] confirm that the damage occurred in core samples due to cutting process is directly related to concrete strength and type of aggregate. Results have also revealed that the concrete strength level has a pronounced effect on the damage factor (F_{dmg}) and is considered to be a main factor. In addition, aspect ratio (l/d), core diameter, and the cutting surface area of core specimen should also be given attention. Analysis of test result has shown that the effect of

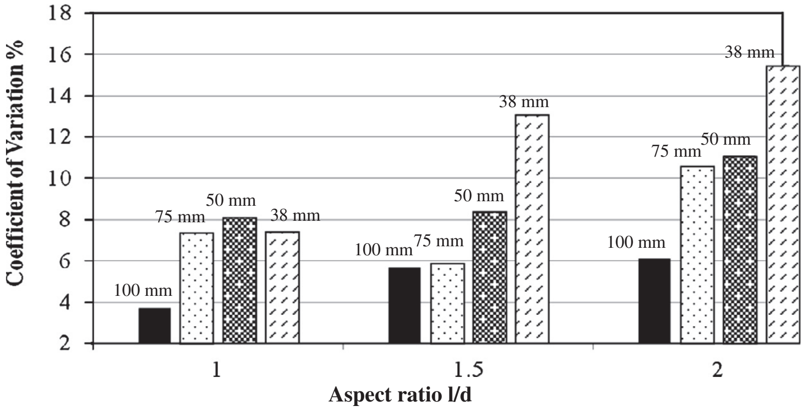


Figure 15 Effect of core diameter on the precision of core test results for different aspect ratios (l/d) (d = 38, 50, 75, 100 mm).

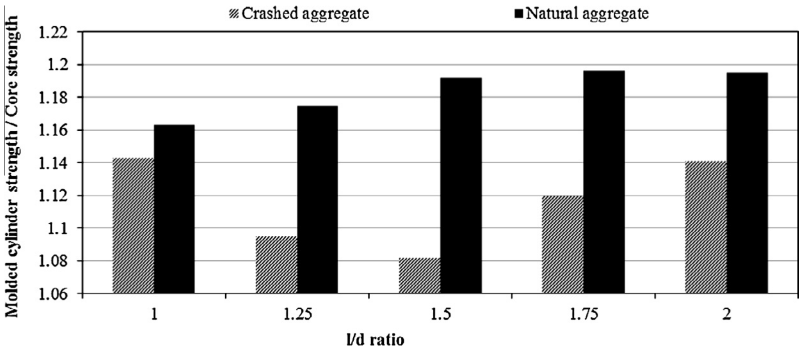


Figure 16 Effect of aggregate type on damage factor for different aspect ratios (l/d).

(l/d) ratio on core damage is minimal. It is evident from Fig. 16 that the presence of natural aggregate (gravel) has more harmful effect on the extracted core as compared to crushed aggregate (pink lime stone). Strength reduction up to 14–20% was noticeable in cores made with crushed and natural aggregates, respectively.

In fact, the drilling operation weakens the bonds between the aggregate and the surrounding matrix. In high strength concrete where the matrix-aggregate bond is higher and the transition zone is more cohesive, the damage in core specimen is low. Actually, during the coring operation pronounced shearing forces between the coring bit and the concrete surface are developed which would cause greater damage to low strength concrete as compared to higher strength concrete (Fig. 17) illustrates the relation between the damage factors according concrete strength level.

The statistical analysis has been performed using "SAS" and "Data Fit" software and a significant number of core test results as shown in Fig. 18. The formula for correction due to damage effect (F_{dmg}) is as follows:

$$F_{\text{dmg.}} = 2.4 \times \frac{(l/d)^{0.006}}{[(d)^{0.1} \times (f_{\text{core}})^{\alpha}]} \tag{11}$$

where f_{core} is the core strength in kg/cm^2; d is the core diameter in mm, l/d is the core aspect ratio, and α is a constant depending on type of aggregate that is equal to 0.06 in crushed pink lime stone.

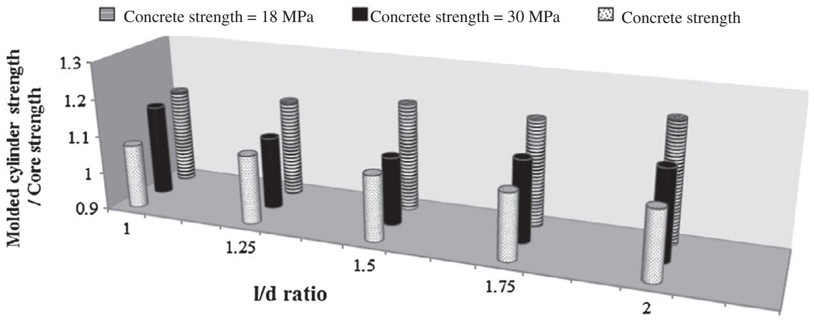


Figure 17 Effect of concrete strength on damage factor for different aspect ratios (l/d).

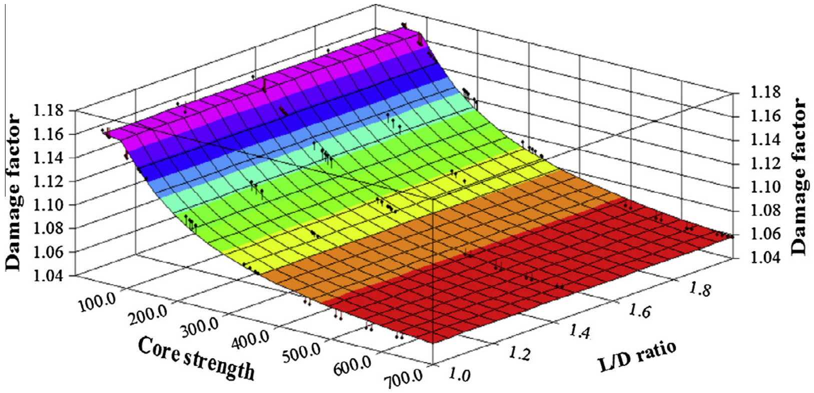


Figure 18 Advanced statistical analysis for formulating the damage factor (F_{dmg}) using "Data Fit" Software & 250 results of cores as affected by multiple variables (crushed agg.-concrete).

6.1.4. Effect of coring direction

According to ACI 214.4R-03 [15], cores drilled vertically (in the direction of placement and compaction) can be stronger than cores drilled horizontally (perpendicular to the placement's direction. The difference in core strength due to drilling direction is generally attributed to bleeding in fresh concrete, which creates a weak paste pockets underneath coarse aggregate particles resulting in weak paste-to-coarse aggregate bond. Results indicate that the mean ratio between the strength of core drilled vertically to that of core drilled horizontally varies between 1.075 and 1.08 as shown in Fig. 19. The figure implies that the effect of coring direction is almost undependable on aspect ratio or concrete strength level.

On the basis of the argument mentioned above, it may be reasonable to assume that the correction factor (F_{dir}) that accounts for coring direction is constant and can be considered equal to 1.0 and 1.075 for horizontal and vertical coring, respectively.

6.1.5. Effect of reinforcing steel

It is strongly believed that a reduction in measured core strength occurs for a core containing reinforcing steel (other than along its axis) depending on concrete strength level. The extent of this reduction also depends upon many other variables, and may range from 0% to 20% (when large diameter or multiple bars are present and associated with low level of concrete strength). The correction factor to account for this reduction (F_{reinf}) depends on several variables including level of concrete strength, number and diameter of reinforcing bars, bars location with respect to core axis nearest end of core.

To get a reliable expression for the factor (F_{reinf}) was very complicated process. Results of about 230 cores were considered with 18 steel configurations that are different with respect to steel bar's diameter, number of bars, bars' locations with respect to vertical and horizontal axis, and others. In conducting these comparisons, it was attempted to keep other parameters comparable to evaluate only one variable at a time. A number of different comparisons are shown in Table 6. For example, the main variable between Specimens A1 and A8 is the diameter of steel. Results are presented in full details elsewhere [1]; however, some points are outlined herein. Results of this research confirm that the presence of steel in drilled cores reduces core strength. Large diameter-bar adversely affects core strength. The reduction is more significant for low strength concrete (18 MPa). The presence of one 16 mm-bar in core samples with $l/d = 1$ reduces the core strength by about 9%. Strength reduction on the order of 25% is associated with the presence of one 22 mm-bar. The core strength is affected by the horizontal location of the bar. A 25 mm-deviation of 10 mm-bar from the vertical axis of the core causes additional strength reduction; up to 20%, as compared to comparable core specimen but without bar's deviation providing other variables are comparable. The noticeable strength reduction is due to the damage through cutting operation and the developed stress concentration around steel bars.

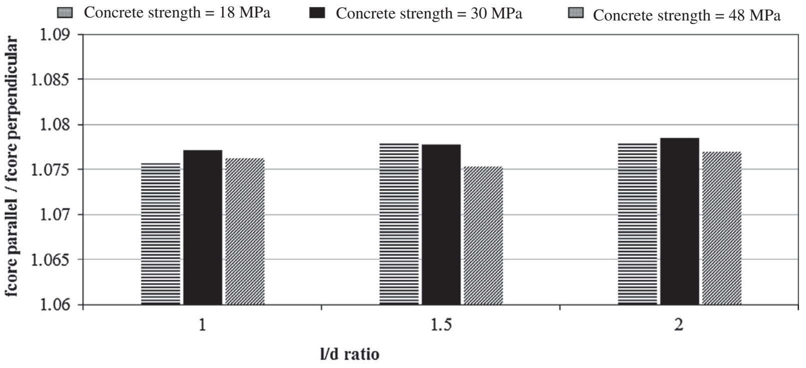


Figure 19 Effect of coring direction on core strength for different aspect ratios (l/d).

Table 6 List of comparisons between tested cores to determine.

	A18	A17	A16	A15	A14	A13	A12	A11	A10	A9	A8	A7	A6	A5	A4	A3	A2	A1
A1	♦●	●	♦●	■●	■●		●				●			▲	▲	■	▲	
A2																		
A3						■●				■●								
A4																		
A5																		
A6								■▲●	■▲●			■▲						
A7								■▲●	■▲●									
A8		●	♦	●	●													
A9																		
A10								■▲●										
A11																		
A12		●		●	●													
A13																		
A14		●		●														
A15		●																
A16	●♦																	
A17	♦																	
A18																		

● Diameter of steel bar.
▲ Distance of steel bar from nearly end of core.
■ Number of steel bars and spacing between bars.
♦ Distance of steel bar from vertical axis of specimen.

This brief review indicated that the various proposed relationships for correction factors are all nonlinear. It should be noted that the equations given by the Egyptian Code takes into account most variables that may affect the interpretation of the results; however, the code ignores the deterioration of steel–concrete bond that may occur and also the position of the reinforcement from vertical axis of core specimens.

Weighted nonlinear regression analysis has been performed to determine the factor (F_{reinf}) with the use of the software "SAS" package and "Data Fit." This shows that the correction factor for reinforcement (F_{reinf}) is given by the following expression:

- For cores containing a single bar:

$$F_{\text{reinf}} = \left[1 + 1.5\frac{[\Phi_r \times r + \Phi_r \times (S/10)]}{\Phi_c * L}\right] \times \frac{1.13}{f_{\text{core}}^{0.015}} \tag{12}$$

- For core specimen containing two bars no further apart than the diameter of the larger bar, only the bar corresponding to the higher value of ($\Phi_r * d$) is considered. If the bars are further apart, their combined effect is assessed by replacing the term ($\Phi_r * r$) by ($\sum \Phi_r * r$ as follows:

$$F_{\text{reinf}} = \left[1 + 1.5\frac{\sum[\Phi_r \times r + \Phi_r \times (S/10)]}{\Phi_c * L}\right] \times \frac{1.13}{f_{\text{core}}^{0.015}} \tag{13}$$

where F_{reinf} is the correction factor for reinforcement, Φ_r is the diameter of the reinforcement, Φ_c is the diameter of the concrete specimen, r is the distance of axis of bar from nearer end of specimen, S is the distance of axis of bar from axis of core specimen, L is the length of the specimen after end preparation by grinding or capping, and f_{core} is the concrete core strength (kg/cm^2).

6.1.6. Effect of moisture condition of core

Results of about 100 cores indicate that the strength of cores left to dry in air for 7 days is on average 13% greater than that of cores soaked at least 40 h before testing. The strength of cores with negligible moisture gradient and tested after cutting is found to be 7–9% larger than that of soaked cores as shown in Fig. 20. The authors strongly recommend to use a correction factor accounting for moisture condition (F_m) equals to 1.09 and 0.96, respectively, for cores tested after 48 h soaked in water and for those tested after 7 days dry in air.

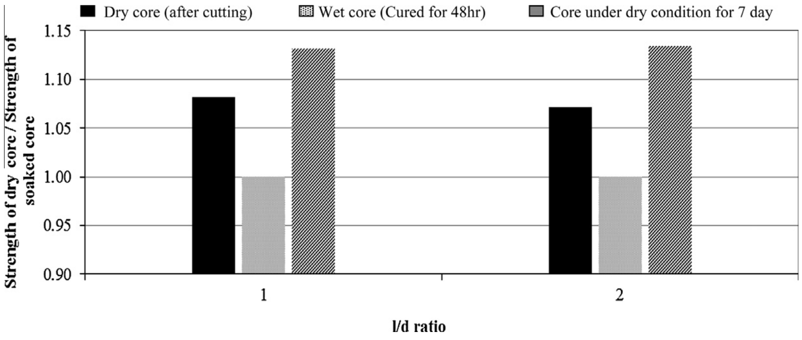


Figure 20 Effect of core moisture condition on core strength for different aspect ratios (l/d).

Table 7 Effect of strength level on the compressive strength of drilled cores.

Strength level of cast specimens (Standard cube), MPa	Strength reduction (%)
18	12–16
30	7–12.5
48	6–7

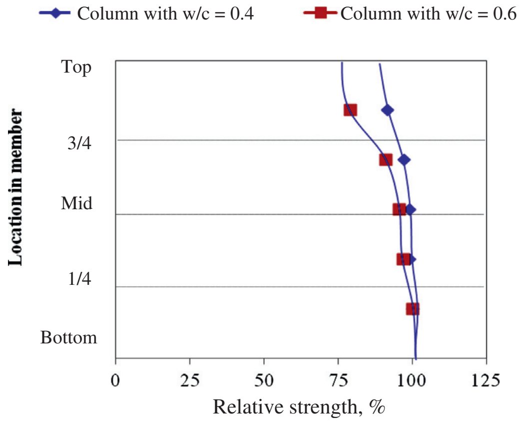


Figure 21 Strength variation through column's height.

6.2. *Concrete characteristics*

6.2.1. *Level of concrete strength*

On the basis of the collected data, the effect of strength level on the compressive strength of drilled cores is presented in Table 7. It is evident from the table that the percentage of strength reduction in cores reduces with the increase in concrete strength level. It seems that in high strength concrete on the order of 50 MPa, the damage effect becomes negligible.

6.2.2. *Strength variation through column's height*

Concrete strength varies within the same element as a result of bleed water especially in vertical members. To explore this point, cores were drilled at different levels in columns. Fig. 21 shows the strength variation throughout the column length based on core tests. Results indicate that cores drilled at the top portion of column are found to be 10–20% weaker than cores extracted from the middle or lower portions, respectively, depending on water–cement ratio (w/c). The figure reveals a change in concrete strength with changing location, but the change seems to be not pronounced and can be neglected in the lower 75% of the column's height. It is therefore advisable not to drill cores in the upper quadrant of concrete column or walls to avoid incorrect judgment.

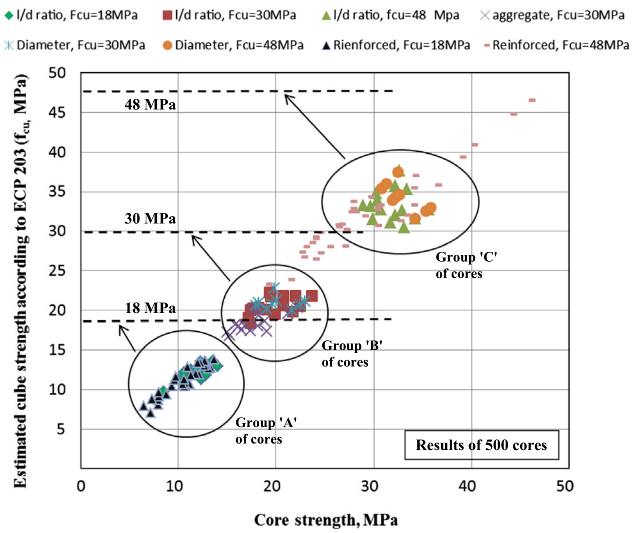


Figure 23 Reliability of approach included in the Egyptian Code for core analysis.

6.2.3. *Type of aggregate*

The relationship between compressive strength of drilled cores and comparable molded cylinders is shown in Fig. 22 for core specimen made with pink limestone and gravel. The cores were drilled from concrete blocks and were tested immediately after drilling. The blocks had been moist cured for 7 days and were then left to dry under lab condition for 28 days. The molded cylinders (4 × 8 in.) were also moist-cured. As expected, concrete made with pink limestone achieves strength higher than that obtained by concrete made with natural aggregate (gravel) although the w/c ratio of the gravel-concrete was

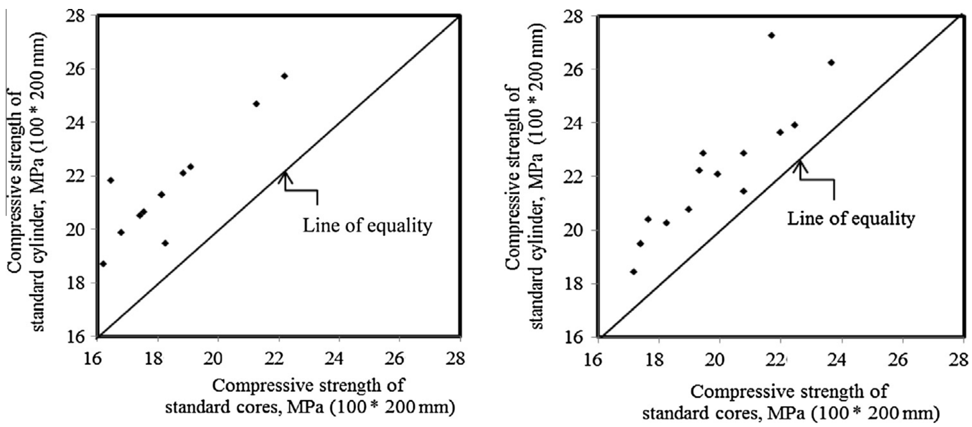


Figure 22 Effect of steel bars on the strength of poured and drilled cores.

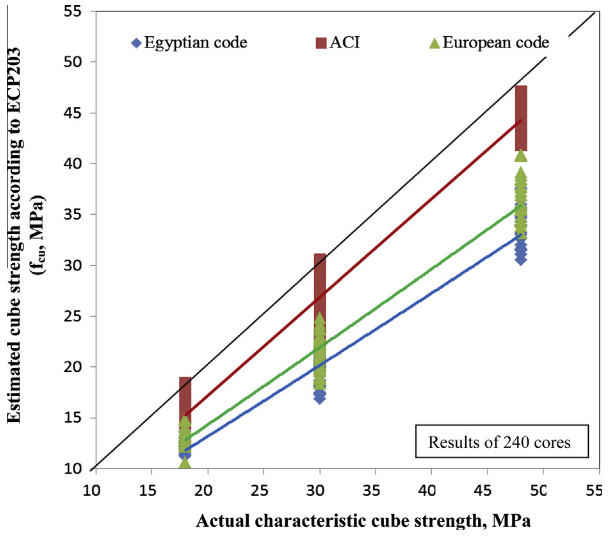


Figure 24 Reliability of approaches included in different codes for core analysis.

lower than that of limestone-concrete. This attributes to the weaker interfacial transition zone between the aggregate and the cement paste due to the smooth surface of the natural aggregate. It is clear from the figure that all drilled cores yield compressive strength less than that achieved by similar cylinders that have comparable aspect ratio, diameter, and identical number and location of steel bars. Again, the graph points out that the presence of steel in poured cylinders may slightly improve compressive strength while the presence of the same steel in drilled core has harmful effect on core strength due to damage effect.

7. Critical assessment

A total of 500 cores covering all studied variables are considered herein to critically asses the approach given by the Egyptian Code. Fig. 23 correlates between the measured core strength and the estimated in-situ cube strength using the code approach. Unfortunately, the Egyptian Code approach fails to predict actual concrete strength. The error varies from 5% to 65%. Fig. 24 confirms that none of the examined approaches (Egyptian Code, ACI Code, European Code) can give promising prediction. It should be noted that Fig. 24 was constructed using only 240 cores that do not contain steel bars. The ACI approach seems to be the closest one to the experimental data; however, if cores with reinforcement are to be introduced the ACI Code may give unsatisfactory prediction since it does not include any equations for to account for the presence of steel in cores. At his point, more dependable approach for core interpretation seems to be ultimately required.

Line of Equality

8. Proposed model for interpreting core test results

Based on experimental evidences and the use of two powerful softwares as mentioned earlier, the following model is proposed and may be considered as a modification to the current code provisions for core interpretation. According to the new

Table 8 Proposed strength correction factors for interpretation of core test results.

Factors	Proposed formula/magnitude
$F_{l/d}$: aspect ratio	$F_{l/d} = \frac{1}{1+\left[\left(\frac{75}{f_{core}^{1.15}}\right)\times\left(2-\frac{l}{d}\right)^2\right]}$
F_d: core diameter (50, 75, 100 and 150 mm)	$F_d = 1.507 - 0.11\ln(d)$
F_{dir}: *coring direction*	
– Parallel of casting	1.0
– Perpendicular of casting	1.075
F_{rienf}: *reinforcing steel*	
– Cores containing a single bar:	$F_{\mathrm{reinf}} = \left[1 + 1.5\frac{[\Phi_r\times r+\Phi_r\times(S/10)]}{\Phi_c * L}\right] \times \frac{1.13}{f_{\mathrm{core}}^{0.015}}$
– Cores containing two bars further apart than the diameter of the larger bar:	$F_{\mathrm{reinf}} = \left[1 + 1.5\frac{\sum[\Phi_r\times r+\Phi_r\times(S/10)]}{\Phi_c * L}\right] \times \frac{1.13}{f_{\mathrm{core}}^{0.015}}$
F_m: *core moisture condition*	
– After cutting	1.00
– Socked 48 h	1.09
– Air dried for 7 days	0.96
F_{dmg}: damage due to drilling	$F_{\mathrm{dmg.}} = 2.4 \times \frac{(l/d)^{0.006}}{[(d)^{0.1}\times(f_{\mathrm{core}})^{\alpha}]}$

Notations:
f_{core}: core strength (kg/cm^2).
d: core diameter (mm).
Φ_r: diameter of reinforcement (mm).
Φ_c: diameter of the concrete specimen (mm).
r: distance of axis of bar from nearer end of specimen (mm).
S: distance of axis of bar from axis of core specimen (mm).
L: length of the specimen after end preparation by grinding or capping (mm).
f_{core}: concrete core strength (kg/cm^2).
l/d: aspect ratio after capping.

procedure, the in-situ concrete cube strength ($f_{c,\mathrm{is}}$) can be predicted by converting the strength of non-standard cores ($f_{c,\mathrm{NS}}$) into equivalent strength of standard cores ($f_{c,S}$), and then by converting the last ($f_{c,S}$) into an equivalent in-situ concrete strength ($f_{c,\mathrm{is}}$). The core test result may be biased if the test specimen differs from a "standard" test specimen that is 4 in. (100 mm) in diameter by 8 in. (200 mm) long, does not contain any pieces of reinforcing bar, and the cutting direction is parallel to casting direction.

8.1. General form

The general form of the model may be written as follows:

$$f_{c,S} = (F_{l/d})(F_d)(F_{\mathrm{rienf}})(F_{\mathrm{dir}})f_{c,\mathrm{NS}} \qquad (14)$$

where $f_{c,S}$ and $f_{c,\mathrm{NS}}$ are the strengths of the "standard" and "Non-standard" core specimens respectively. The strength correction factors ($F_{l/d}$), (F_d), (F_{dir}) and (F_{rienf}) account for the effects of length to diameter ratio, core diameter, coring direction, and the presence of reinforcing bar pieces on the strength of non-standard core. These factors can be calculated using Equations from (9) to (13) presented earlier and is summarized in Table 8.

The in-situ concrete cube strength ($f_{c,\mathrm{is}}$) is modeled herein as follows:

$$f_{c,\mathrm{is}} = (F_m)(F_{\mathrm{dmg}})(f_{c,S}) \qquad (15)$$

where ($f_{c,\mathrm{is}}$) is the in-situ concrete cube strength and factors (F_m) and (F_{dmg}) account for the effects of the moisture condition of core and damage sustained during drilling, respectively, on the strength of the standard core specimen.

8.2. Calibration of proposed model

The proposed approach is calibrated against large number of experimental data in Fig. 25 where the estimated in-situ cube strength using the approach is plotted against actual cube strength. The figure shows good agreement indicating the validity of the proposed method. Also, Fig. 26 confirms that the proposed approach is more reliable for interpreting core results than other available methods (Fig. 24). In fact, the proposed model considers large number of variable and is based on comprehensive experimental program that included about 500 cores in addition to more than 300 specimens.

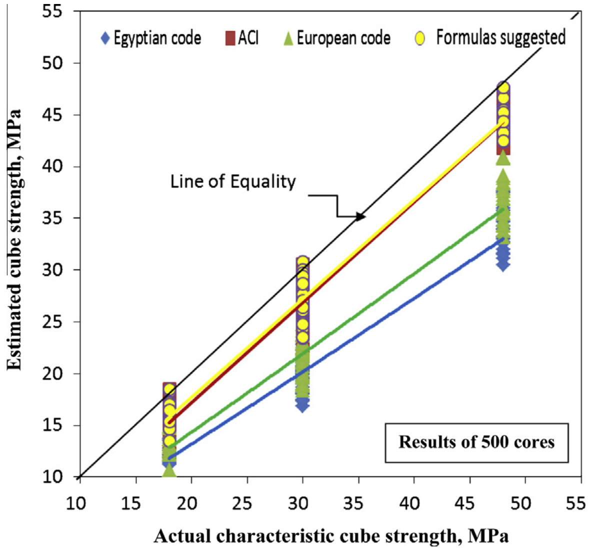


Figure 25 Comparison between the actual and estimated cube concrete strength.

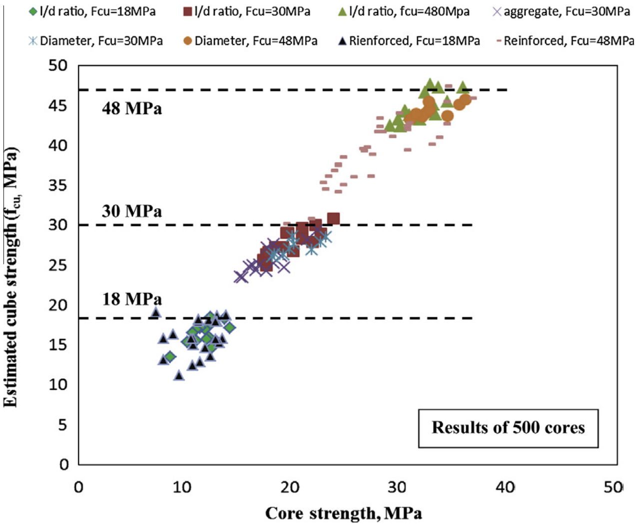


Figure 26 Calibration of proposed approach.

9. Conclusions

Based on the comprehensive experimental study reported herein the following conclusions can be drawn:

1. Core test is commonly required in the area of concrete industry for assessment of concrete quality. In fact, core test becomes a must in many critical circumstances and sometimes it is the unique tool for safety assessment in existing structure.
2. Core test is included in most international codes' provisions including 'Egyptian Code ECP203', ACI Code, British Code, European Code and others. Core test may be reliable; however the interpretation of the results to in-situ concrete strength is questionable. Actually, extensive literature survey indicates that different codes give different in-situ strength from one core test result.
3. A comprehensive study was undertaken in this research to examine the factors affecting the interpretation of core test results. More than 500 cores were prepared and tested as well as more than 300 concrete specimens. Actually, the program was very exhausted, costly and time consuming. Variables studied are core aspect ratio, core diameter, concrete strength level, the presence of reinforcing steel, coring direction, core damage due to drilling, type of coarse aggregate, core moisture condition, as well as the core location in vertical members with respect to height.
4. Results indicate that the core compressive strength increases with the decrease in the core aspect ratio (l/d); however, this effect becomes negligible for high strength concrete.
5. The effect of core diameter on core strength is completely different that in case of molded concrete cylinder. It is generally agreed for molded concrete that the

concrete strength is decreased as the specimen size increases. However, in case of drilled cores, as the diameter decreases, the ratio of cut surface area to volume increases, and hence the possibility of strength reduction due to cutting damage increases. Strength reduction up to 17% was recorded in cores with diameter less than 100 mm. On the other hand, for cores with larger diameter than 100 mm, this damage effect is minimal but should be considered.

6. The damage effect due to core drilling is significant for low strength concrete (18 MPa). In fact, the drilling operation weakens the bonds between the aggregate and the surrounding matrix. In addition, concrete made of gravel is subjected to damage during core drilling much more than concrete made with pink lime stone.
7. The measured strength of cores drilled vertically (parallel to casting direction) is greater than that for a horizontally drilled core (normal to casting direction) providing other variables are comparable. The difference is about 8%.
8. The presence of reinforcing steel in the core samples reduces the measured core strength. A strength reduction up to 25% was recorded for core contained 22 mm-bar. The noticeable strength reduction is due to the damage through cutting operation and the developed stress concentration around the existing steel bars.
9. The moisture condition of the core by the time of testing affects its strength. Contradictory, the strength of core specimen left in air for 7 days to dry achieved about 12% increase in the core strength.
10. Comparison between the actual concrete cube strength and the estimated values using different approaches recommended by many codes is unsatisfactory.
11. The ACI approach seems to be the closest one to the experimental data providing that steel bars do not exist in core samples. More dependable approach for core interpretation seems to be ultimately required.
12. On the basis of comprehensive collected data obtained in this research through testing large number of cores, statistical analysis has been performed to determine reliable strength correction factors that account for the studied variables. A simple weighted regression analysis of a model without an intercept was carried out using the "SAS Software" package (SAS Institute, 2008) as well as "Data Fit" software.
13. A performance-based model for interpretation of core test results is proposed in this research. The new approach considers all factors that may affect core strength. The model when calibrated against large number of test data shows good agreement.
14. Based on experimental evidences, it can be stated that the proposed model to estimate the in-situ concrete cube strength from the result of core test seems to be very promising.

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