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Codes applicability of estimating the FRC compressive strength by the core-drilling method

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ABSTRACT

The core-drilling method is a reliable and confident method to evaluate the in-situ compressive strength. Codes and standard relations are developed to evaluate the compressive strength of the traditional concrete. The fiber reinforced concrete (FRC) is different in its behavior and mode of failure when compared to traditional concrete. This paper presents an experimental study on the applicability of these features of FRC. 168 drilled specimens were extracted from 10 different concrete mixes then tested. The investigated parameters were: the fiber type (polypropylene, glass, steel); fiber volume fraction (0.25%, 0.50%, 0.75%); cutting direction (horizontal, vertical); core diameter (100 mm, 150 mm). Standard cubes and cylinders were taken from each mix to evaluate the compressive strength. The results of the drilled cores were verified to more than predicted by code. The results revealed that the existing relationships underestimate the core compressive strength for FRC. A new modification factor was proposed depending on the fiber type and fiber volume fraction to estimate accurately the in-situ core compressive strength.

1. Introduction

In some special cases, assessing the in-situ concrete compressive strength using a non-destructive method is a concern. Core-drilling method is considered one of the most accurate and confident methods used. It is sometimes considered a non-destructive [1–4] or semi-destructive method [5]. The actual compressive strength (mother strength) is one of the most important outputs of this method [1–4,6–11]. Thus, researchers and standards aimed to investigate the circumstances and factors affecting the obtained results. The common studied factors were the aspect ratio, core diameter, direction of cutting, existence of reinforcing bars, damage and moisture content. On the other hand, various studies were performed to cover additional non-traditional factors. Researchers [12,13] examined the effect of testing small diameter cores and found that the obtained strength was directly related to the coarse aggregate size. Even the type of coarse aggregate and the alkali-silica reaction on the compressive strength were investigated by [14,15], respectively. [16] presented an experimental study to evaluate the 3-days cored specimens age on the compressive strength. The results widely varied when compared to another non-destructive test. Fire damage of concrete [17,18], presence and orientation of steel reinforcement [5,14] and even the position of the cored sample [9,19] were all checked experimentally. The results confirmed that all the aforementioned factors should be taken into consideration. Due to the great reliability of the core-drilling method results, it is appropriate to use it as a comparison against other non-destructive tests [9,19–22]. In addition to the finite element analysis or the neuro-fuzzy techniques, it is used as a reliable source of data [22,23].

Today it is well known that incorporating chopped yarn fiber for producing high performance fiber reinforced cementitious composites [24] or high performance fiber reinforced concretes [25] are widely used for repairing, strengthening, and new construction purposes. Using fiber directly affects the compressive strength and mode of failure of concrete. To the best knowledge of the authors, the assessment of FRC compressive strength by the core test has not been introduced or verified by any standard before. Thus, the main aim of this study was to investigate the validity of the related standards to assess the calculated compressive strength of fiber reinforced concrete. The main investigated parameters were the incorporated fiber type (polypropylene, glass, and steel), fiber volume fraction (0.25 %, 0.5%, and 0.75 %), the cutting direction (horizontal and vertical), and the core diameter (100 and 150 mm). Reference standard samples were prepared to compare the obtained results. The results were verified by more than one standard, including the ACI Code (1998) [26], ASTM (2009) [27], current ACI

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

List	Code / Standards	Factors considered					
		Aspect ratio	Diameter	Direction	Reinforcing	Damage	Moisture
1	American Concrete Institute ACI (2012)	●	●			●	●
2	European Code (2009)	●	●		●	●	
3	ASTM (2009)	●					
4	Egyptian Code (2008)	●		●	●		
5	American Concrete Institute ACI (1998)	●					
6	European Code (1998)	●	●		●	●	
7	Concrete Society (1987)	●		●	●	●	
8	British Standard Specification (1983)	●		●	●		

Table 2
$F_{l/d}$ values according to ACI Code (1998) and ASTM (2009).

Slenderness ratio (l/d)	1.00	1.25	1.50	1.75
$F_{l/d}$ value	0.87	0.93	0.96	0.98

Code (2012) [28], former CEN code (1998) [29], current CEN code (2009) [30], Egyptian Code (2008) [31], British Standard (1983) [32] and Concrete society (1987) [33]. A new modification factor was suggested to be introduced in some equations to accurately estimate the compressive strength.

2. Codes and standards provisions

Although core testing is the most direct and reliable method to estimate concrete strength in a structure, it must be considered that there are many differences between the strength measured on core specimens and the actual in-situ strength. To determine in-situ cube strength, core testing is a possibility but most codes give different results depending on the factors used. It is generally agreed that the compressive strength of the 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 issue is to translate this result into cube strength. In fact, the compressive strength of the concrete cores is affected by a number of factors such as slenderness ratio of sample (ratio between sample length and sample diameter, $\lambda = l/d$), the direction of drilling (parallel or perpendicular to casting direction), diameter value (50 mm, 100 mm, or 150 mm), presence of reinforcement steel bars in the specimen, moisture condition of the core specimen and the effect of drilling damage to the sample [34–39]. Table 1 summarizes the factors considered in American code, European code, Egyptian code, British standards and Concrete society to interpret core strength to in-situ concrete strength. The approaches adopted in some of the listed codes / standards for core interpretation are summarized below.

2.1. *Former ACI code (1998) [26] and ASTM (2009) [27]*

The methodology of core interpretation given in the ACI code (1998) [26] and ASTM (2009) [27] has remained unchanged for decades. The in-situ strength of a given concrete cylinder at the location from which a core test specimen was extracted can be computed using the equation:

$$f_c = F_{l/d} \times f_{core} \tag{1}$$

where f_c is the equivalent in-situ concrete cylinder strength, f_{core} is concrete core strength (obtained by dividing the maximum crushing compressive load by the actual cross-sectional area of the tested core sample without any correction factors), and $F_{l/d}$ is the strength correction factor as given in Table 2.

2.2. *Current ACI code (2012) [28]*

Since 2002, significant changes have been made to the relevant ACI Code provisions regarding the interpretation of core strength test results. New factors have been considered such as core diameter, moisture content of core samples and core damage associated to drilling. According to the ACI Code (2012) [28], the in-situ concrete strength can be computed using the equation:

$$f_c = F_{l/d} \times F_{dia.} \times F_{mc} \times F_D \times f_{core} \tag{2}$$

where f_c is the equivalent in-situ concrete cylinder strength.

$F_{l/d}$ is the strength correction factor for aspect ratio.

F_{dia} is the correction factor equal to 1.06, 1.00 or 0.98 for core diameters of 50, 100 and 150 mm, respectively.

F_{mc} is the strength correction factor for the moisture condition of the core sample (As-received = 1.00, Soaked 48 h = 1.09, Air dried = 0.96).

F_D is the strength correction factor that accounts for the damaging effect of core drilling, including micro-cracking and undulations at the drilled surface, and may be considered equal to 1.06.

2.3. *Former CEN code (1998) [29]*

The proposed equation to convert the strength of a core specimen into the equivalent in-situ concrete strength according to former European code [29] is as follows:

$$f_c = C_{H/D} \times C_{dia.} \times C_a \times C_d \times f_{core} \tag{3}$$

where f_c is the equivalent in-place concrete strength.

C_{dia}. is the correction factor equal to 1.06, 1.00 or 0.98 for core diameters equal to 50, 100 and 150 mm, respectively.

C_a is the correction factor for the presence of reinforcing steel (1.00 for no bars and varying between 1.03 for small diameter bars ($\varphi = 10$ mm) and 1.13 for large diameter bars ($\varphi = 20$ mm)).

C_d is the correction factor for damage due to drilling, proposed to be 1.20 for $f_{core} < 20$ MPa and 1.10 for f_{core} greater than 20 MPa.

$C_{H/D}$ is the correction factor for aspect ratio and is calculated according to Eq. (4). H and D are the core height and diameter, respectively.

$$C_{H/D} = \frac{2}{1.5 + \frac{D}{H}} \tag{4}$$

2.4. *Current CEN code (2009) [30]*

The damage and diameter factors considered in the former CEN code [29] were eliminated in the more recent edition. The factors currently considered are aspect ratio and the presence of reinforcing steel. According to this code, the estimated in-situ concrete strength (f) may be calculated from the measured compressive strength of core (f_{core}) according to the following expressions:

$$f = F_{l/d} \times F_{Reinf.} \times f_{core} \tag{5}$$

Table 3
Mix proportions per meter cubic of RC and FRC-materials (kg).

Mixture Code	Cement	Fine aggregates	Coarse aggregates	Water	Admixture	Short fibers properties Type	Weight	V_f (%)
Mix (1)	350	680	1117	195	—	—	—	—
Mix (2)	350	680	1117	195	3.65	Polypropylene	6.5	0.25%
Mix (3)	350	680	1117	195	3.65		13.1	0.50%
Mix (4)	350	680	1117	195	5.77		19.5	0.75%
Mix (5)	350	680	1117	195	3.65	Glass	8.7	0.25%
Mix (6)	350	680	1117	195	3.65		16.8	0.50%
Mix (7)	350	680	1117	195	5.77		25.2	0.75%
Mix (8)	350	680	1117	195	3.65	Steel	19.6	0.25%
Mix (9)	350	680	1117	195	3.65		39.3	0.50%
Mix (10)	350	680	1117	195	5.77		58.9	0.75%

$$F_{l/d} = \frac{D}{1.5 + \frac{1}{\lambda}} \tag{6}$$

$$F_{Reinf.} = 1 + 1.5\frac{\varphi_r \times d}{\varphi_c \times l} \tag{7}$$

where the factors $F_{l/d}$ and $F_{Reinf.}$ account for the effect of l/d and the presence of reinforcing steel, respectively. D equals 2.5 for cube strength and 2.0 for cylinder strength. λ is the length to diameter ratio (l/d) after ends' preparation. φ_r is the diameter of the reinforcing bar. φ_c is the core diameter.

2.5. *Egyptian code (2008) [31] and British standard (1983) [32]*

The approach proposed by the Current Egyptian Code (2008) [31] and British Standard (1983) [32] to predict the core strength of in-situ concrete cube strength (f_{cu}) is similar to the method suggested previously by CEN Code (2009) presented earlier. The main difference between the guidelines in the recent Egyptian Code and the CEN Code seems to be in the magnitude of the Term 'D' in Eq. (6). The Egyptian Code considers D to be equal to 2.5 for cores drilled horizontally (perpendicular to casting direction); or 2.3 for cores drilled vertically (parallel to casting direction) that is mentioned in the CEN Code (2009).

2.6. *Concrete Society (1987) [33]*

The approach proposed by the Concrete Society (1987) [33] is similar to that suggested by the Egyptian Code and British Standard presented earlier. However, the Concrete Society estimates the so-called potential concrete strength to be different than the in-situ concrete cube strength. According to the 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:

$$f_{pot} = F_{l/d} \times F_{Reinf.} \times f_{core} \tag{8}$$

where the factors $F_{l/d}$ and $F_{Reinf.}$ account for the effects of l/d and the presence of reinforcing steel, respectively, and they can be determined using Eqs. (6) and (7) presented earlier. The main difference seems to be in the magnitude of the term 'D', considered equal to 2.3 or 2.5, depending on the drilling direction. In the Egyptian Code, it is proposed to be 3.25 for cores drilled horizontally (perpendicular to casting direction) or 3.0 for cores drilled vertically (parallel to casting direction). From general perspective, 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 is equal to 2, the drilling direction is vertical, the core is free of reinforcement, concrete is well compacted and does not include the weaker material near the top of a lift. In fact, the formula for converting core strength into cube strength indicates that, if the concrete in the structure is fully compacted and normally cured, the actual concrete strength is about 77% of the potential strength.

3. Experimental program

This paper presents an experimental study of a set of parameters affecting the measured compressive strength of the cored FRC elements. The tested parameters were 1) direction of drilling (horizontal and vertical), 2) fiber type (polypropylene, glass and steel), 3) fiber volume fraction (0.25%, 0.5% and 0.75%), and 4) drilling diameter (100 and 150 mm). Ten different concrete mixes were prepared to achieve the experimental program as listed in Table 3. Portland cement CEM-I 42.5 N that satisfies the requirements of EN-196–1 [40], with initial and final setting times of 120 and 230 min, was used. Crushed limestone with a



(a) Core drilling (b) Concrete blocks after specimens extraction

Fig. 1. Process of specimen's extraction.

Table 4
Compressive strengths of standard specimens*.

Mixture code	Fiber type	V_f (%)	Compressive strengths (MPa) Cylinder specimen (150 × 300 mm)						Cube specimen (150 mm)					
			7 days			28 days			7 days			28 days		
			Average (μ)	Standard deviation (σ)	Coef. of variation (V)	Average (μ)	Standard deviation (σ)	Coef. of variation (V)	Average (μ)	Standard deviation (σ)	Coef. of variation (V)	Average (μ)	Standard deviation (σ)	Coef. of variation (V)
Mix (1)	—	—	20.77	1.325	0.064	26.98	2.226	0.083	25.62	1.625	0.063	34.15	2.441	0.071
Mix (2)	PP	0.25%	23.99	1.596	0.067	31.56	1.639	0.052	30.00	1.935	0.065	38.96	1.545	0.040
Mix (3)		0.50%	24.10	1.325	0.055	31.71	1.489	0.047	30.54	1.472	0.048	39.15	1.534	0.039
Mix (4)		0.75%	25.56	1.796	0.070	34.08	1.925	0.056	34.19	1.965	0.057	43.14	1.820	0.042
Mix (5)	G	0.25%	25.41	2.634	0.104	33.00	2.013	0.061	32.58	1.497	0.046	40.73	1.523	0.037
Mix (6)		0.50%	26.54	2.053	0.077	34.47	2.536	0.074	33.61	2.119	0.063	42.55	2.460	0.058
Mix (7)		0.75%	24.22	1.869	0.077	31.05	1.900	0.061	29.48	1.902	0.065	39.31	1.925	0.049
Mix (8)	S	0.25%	23.45	0.936	0.040	30.46	0.978	0.032	28.56	0.965	0.034	38.08	0.837	0.022
Mix (9)		0.50%	24.41	0.667	0.027	32.55	0.589	0.018	31.72	0.998	0.031	41.20	0.676	0.016
Mix (10)		0.75%	29.14	1.558	0.053	38.34	1.602	0.042	37.39	1.509	0.040	47.33	1.676	0.035

* The values quoted are a mean of six specimens, PP indicates to Polypropylene fiber, G indicates to Glass fiber, and S indicates to steel fiber.

maximum nominal size of 20 mm was used as a coarse aggregate. Different physical and mechanical properties were determined for the coarse aggregate (bulk density = 1657 kg/m^3, specific gravity = 2.56, water absorption = 0.9 % and crushing value = 15.5 %).

Siliceous sand with a fineness modulus of 2.2 and free from organic impurities (complying with ASTM C87/C87M [41]) was used as a fine aggregate. Tap water (pH = 7.3) was used for both mixing and curing of all the tested mixes and cored specimens. To overcome the negative effect of adding fiber to the concrete flowability, a type F (ASTM-C494 [42]) superplasticizer was used. All mixes recorded slump values ranging between 60 and 100 mm. Three different types of fiber were incorporated (polypropylene, glass and steel). The polypropylene fiber has a nominal length of 18 mm and modulus of elasticity (E) equal to 33 GPa. The used glass fiber was 120 mm in length and had E = 70 GPa. Additionally, corrugated steel fiber of 50 mm length, 1 mm diameter (aspect ratio of 50) was used. Its tensile strength and E modulus were 510 MPa and 210 GPa, respectively. Concrete mix proportions are listed in Table 3.

To avoid the balling effect of the fiber during concrete mixing, the fibers were wet mixed then the mixture was poured in wooden molds of 1200 mm length, 1200 mm width and 200 mm height for the vertical cutting block (core drilling parallel to the cast direction). Molds of 1200 mm length, 200 mm width and 600 mm height were prepared for samples in the horizontal cutting block. To prevent and control moisture evaporation from concrete blocks, once it gets hardened wet covering of damp hessian protected by polythene sheets were used. This curing process lasted for 28 days. It is worth mentioning that the core drill is vertically installed during the cutting process of all specimens as shown in Fig. 1(a). Therefore, the horizontal cutting blocks had to be rotated 90° during the cutting process. The details of core drilling and the extraction process are shown in Fig. 1.

For each concrete mix, 6 standard cubes (150x150x150 mm) and other 6 standard cylindrical molds (150 mm diameter × 300 mm height) were prepared to evaluate the actual compressive strength at the ages of 7 and 28 days. After 24 h, all specimens were demolded and moist cured adjacent to the concrete blocks. The standard cubes and cylinders were tested using a compressive testing machine of 2000 kN capacity. The values that deviated 25% from the mean value were eliminated and a new average was calculated. It worth mentioned that due to the highly quality control in laboratory during execution the experimental work only the result of one standard cube at the age of 28 days for Mix 4 (polypropylene fiber) deviated by 25% from the mean value. Then this result was removed and the new average was calculated as listed in Table 4. The measured compressive strength for cubes as well as cylinders is listed in Table 4. After 28 days of hardening, cores were extracted with core drill bits with diameters of 100 and 150 mm. For each tested parameter, six specimens were extracted to accurately evaluate the actual compressive strength.

All samples were labeled by identification code as shown in Table 5 and Fig. 2(a). The specimens were classified into 7 groups. Group I represents the control specimens, Groups II, III and IV represent the horizontal cutting specimens prepared by polypropylene, glass and steel fiber, respectively. Finally groups V, VI and VII study the effect of drilling direction specimens prepared by polypropylene, glass and steel fiber, respectively.

Samples were trimmed by saw cutting (see Fig. 2(b)) to obtain an overall aspect ratio (length/diameter) of about ≈1. Specimens were moist cured and a special set up was made to measure the accurate diameter as shown in Fig. 2(c) and (d). The trimmed specimens were capped to reduce their horizontal surface prior to the test. A compressive testing machine of 2000 kN capacity was used to test the cored specimens with a loading rate of 0.25 MPa/s. All specimens were tested under saturated surface dry conditions. The research program consisted of a total number of 168 drilled specimens (28 investigated parameters each one consists of 6 drilled cores as listed in Table 5) and 240 standard specimens as given in Table 4.

Table 5
Test matrix.

Group	Specimen code	Short fibers properties		Core diameter Nominal diameter		Drilling direction		Averagecompressive strength (f_{core}) (MPa)	Standard deviation (б) (MPa)	Coef. of variation (V)	Investigated parameters
		Type	V_f (%)	100 mm	150 mm	Horizontal	Vertical				
I	C-0%-H-100 mm	–	–	✓		✓		37.40	0.637	0.017	Control specimens
	C-0%-H-150 mm	–	–		✓	✓		37.37	1.754	0.047	
	C-0%-V-100 mm	–	–	✓			✓	36.47	0.339	0.009	
	C-0%-V-150 mm	–	–		✓		✓	36.39	0.850	0.023	
II	C-0%-H-100 mm*	–	–	✓		✓		37.40	0.637	0.017	Study the effect of fiber volume fraction (V%) for polypropylene fibers
	C-0%-H-150 mm*	–	–		✓	✓		37.37	1.754	0.047	
	P-0.25%-H-100 mm	Polypropylene	0.25%	✓		✓		37.40	0.362	0.010	
	P-0.25%-H-150 mm		0.25%		✓	✓		37.37	1.931	0.050	
	P-0.50%-H-100 mm		0.50%	✓		✓		36.47	0.578	0.016	
	P-0.50%-H-150 mm		0.50%		✓	✓		37.30	1.837	0.049	
	P-0.75%-H-100 mm		0.75%	✓		✓		32.76	0.584	0.018	
	P-0.75%-H-150 mm		0.75%		✓	✓		31.32	0.510	0.016	
III	C-0%-H-100 mm*	–	–	✓		✓		37.40	0.637	0.017	Study the effect of fiber volume fraction (V%) for glass fibers
	C-0%-H-150 mm*	–	–		✓	✓		37.37	1.754	0.047	
	G-0.25%-H-100 mm	Glass	0.25%	✓		✓		36.79	0.979	0.027	
	G-0.25%-H-150 mm		0.25%		✓	✓		38.99	1.734	0.044	
	G-0.50%-H-100 mm		0.50%	✓		✓		36.40	1.267	0.035	
	G-0.50%-H-150 mm		0.50%		✓	✓		38.58	0.226	0.006	
	G-0.75%-H-100 mm		0.75%	✓		✓		29.87	0.565	0.019	
	G-0.75%-H-150 mm		0.75%		✓	✓		35.11	1.492	0.042	
IV	C-0%-H-100 mm*	–	–	✓		✓		37.40	0.637	0.017	Study the effect of fiber volume fraction (V%) for steel fibers
	C-0%-H-150 mm*	–	–		✓	✓		37.37	1.754	0.047	
	S-0.25%-H-100 mm	Steel	0.25%	✓		✓		37.61	2.202	0.056	
	S-0.25%-H-150 mm		0.25%		✓	✓		38.84	1.706	0.044	
	S-0.50%-H-100 mm		0.50%	✓		✓		38.89	2.073	0.053	
	S-0.50%-H-150 mm		0.50%		✓	✓		37.59	2.212	0.059	
	S-0.75%-H-100 mm		0.75%	✓		✓		41.43	1.385	0.033	
	S-0.75%-H-150 mm		0.75%		✓	✓		39.17	0.591	0.015	
V	C-0%-H-100 mm*	–	–	✓		✓		37.40	0.637	0.017	Study the effect of drilling direction for polypropylene fibers
	C-0%-H-150 mm*	–	–		✓	✓		37.37	1.754	0.047	
	C-0%-V-100 mm*	–	–	✓			✓	36.47	0.339	0.009	
	C-0%-V-150 mm*	–	–		✓		✓	36.39	0.850	0.023	
	P-0.50%-H-100 mm*	Polypropylene	0.50%	✓		✓		36.47	0.578	0.016	
	P-0.50%-H-150 mm*		0.50%		✓	✓		37.30	1.837	0.049	
	P-0.50%-V-100 mm		0.50%	✓			✓	34.29	1.360	0.040	

(*continued on next page*)

Table 5 (*continued*)

Group	Specimen code	Short fibers properties		Core diameter Nominal diameter		Drilling direction		Averagecompressive strength (f_{core}) (MPa)	Standard deviation (б) (MPa)	Coef. of variation (V)	Investigated parameters
		Type	V_f (%)	100 mm	150 mm	Horizontal	Vertical				
	P-0.50%-V-150 mm		0.50%		✓		✓	33.85	1.124	0.033	
VI	C-0%-H-100 mm*	–	–	✓		✓		37.40	0.637	0.017	Study the effect of drilling direction for glass fibers
	C-0%-H-150 mm*	–	–		✓	✓		37.37	1.754	0.047	
	C-0%-V-100 mm*	–	–	✓			✓	36.47	0.339	0.009	
	C-0%-V-150 mm*	–	–		✓		✓	36.39	0.850	0.023	
	G-0.50%-H-100 mm*	Glass	0.50%	✓		✓		36.40	1.267	0.035	
	G-0.50%-H-150 mm*		0.50%		✓	✓		38.58	0.226	0.006	
	G-0.50%-V-100 mm		0.50%	✓			✓	42.71	1.556	0.036	
	G-0.50%-V-150 mm		0.50%		✓		✓	37.50	0.853	0.023	
VII	C-0%-H-100 mm*	–	–	✓		✓		37.40	0.637	0.017	Study the effect of drilling direction for steel fibers
	C-0%-H-150 mm*	–	–		✓	✓		37.37	1.754	0.047	
	C-0%-V-100 mm*	–	–	✓			✓	36.47	0.339	0.009	
	C-0%-V-150 mm*	–	–		✓		✓	36.39	0.850	0.023	
	S-0.50%-H-100 mm*	Steel	0.50%	✓		✓		38.89	2.073	0.053	
	S-0.50%-H-150 mm*		0.50%		✓	✓		37.59	2.212	0.059	
	S-0.50%-V-100 mm		0.50%	✓			✓	40.47	1.927	0.048	
	S-0.50%-V-150 mm		0.50%		✓		✓	39.21	1.012	0.026	

* Indicates to repeated specimens between groups.

4. Test results and analysis

Ten concrete mixes were investigated in this study: a control mix and nine fibrous concrete mixtures. Three different fiber types including polypropylene, glass and steel fibers were studied. For each type of fiber, three fiber volume fractions as 0.25, 0.50 and 0.75% were conducted. Standard specimens made of each concrete mixture were prepared according to their corresponding specifications (i.e. cube or cylinder) as reference and control specimens. Along with the prepared control samples, concrete blocks from each mixture were prepared and cured according to the referenced standard. After 28 days, core samples were cut, prepared and tested considering the corresponding specifications. The following sections present the test results and the analysis.

4.1. Efficiency of the different codes in compressive strength determinations of the control mix

For this section, the ratios between the predicted core compressive strength to the corresponding standard compressive strength are calculated and presented in Fig. 3. Where the predicted core compressive strength (f_{pre}) represents the predicted compressive strength of the core sample and obtained by substitution in the code equation with the correction factors according to every code. The corresponding standard compressive strength (f_{act}) represents the compressive strength of the standard cubes or cylinders according to the used code. The calculated ratios for 100 mm diameter cores cut horizontally are 1.39, 1.08, 1.21, 1.08, 1.21, 1.21, 1.08 and 1.08 for ACI-2.12(A), CEN-2009(B), ASTM-2009(C), ECP-2008(D), ACI-1998(E), CEN-1998(F), C-1987(G) and BS-1983(H), respectively. On the other hand, for 150 mm core diameter cut horizontally, the calculated ratios are 1.36, 1.08, 1.20, 1.08, 1.20, 1.18, 1.08 and 1.08 in the same order, respectively. However, when the core samples were cut vertically, the relative strength values seemed to be slightly lower. Moreover, increasing the core diameter was not operative, as shown in Fig. 3 for B, D, G and H codes. Whereas, codes A, C, E and F give slightly higher ratios for compressive strength for 100 mm core diameter compared with 150 mm ones.

To define the most accurate code method, an analysis process was conducted and the results are listed in Table 6. For each code, the calculated value will be divided by the standard compressive strength, making the result dimensionless. Each code will have four dimensionless values. The selection of the most accurate code will be determined through calculating the following:

The average.

$$\mu = \frac{\sum x_i}{n} \tag{9}$$

Where n is the sample size.

Standard deviation.

$$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{n-1}} \tag{10}$$

Coefficient of variation.

$$V = \frac{\sigma}{\mu} \tag{11}$$

Characteristic Property (CP) with confidence level of 95%.

$$CP = \mu - 1.64\sigma \tag{12}$$



Fig. 2. Preparation of specimens.

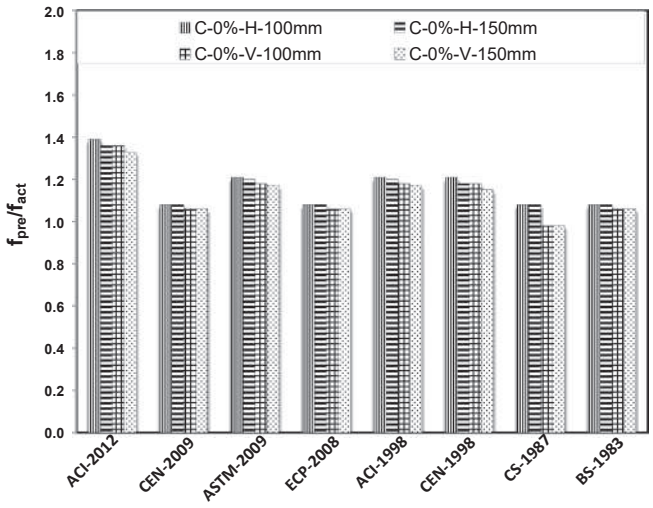


Fig. 3. Validation of codes formula with the experimental results (GI).

By sorting the calculated results and ranking the most accurate method for each property, summing the sorting numbers for the average, standard deviation, coefficient of variation and the characteristic property and considering the minimum sum, it is clear that the methods B, D and H give the most accurate results when compared to the other methods for estimating the in-situ compressive strength for concrete mixtures free from fibers. Generally, method B, D and H come in the rank (I) followed by method F in the rank (II) followed by method G which comes in the rank (III) then method E in the rank (IV), method C comes in the rank (V) and finally method A in the rank (VI).

4.2. Efficiency of the existing codes in predicting the core compressive strength for mixtures containing pp fibers

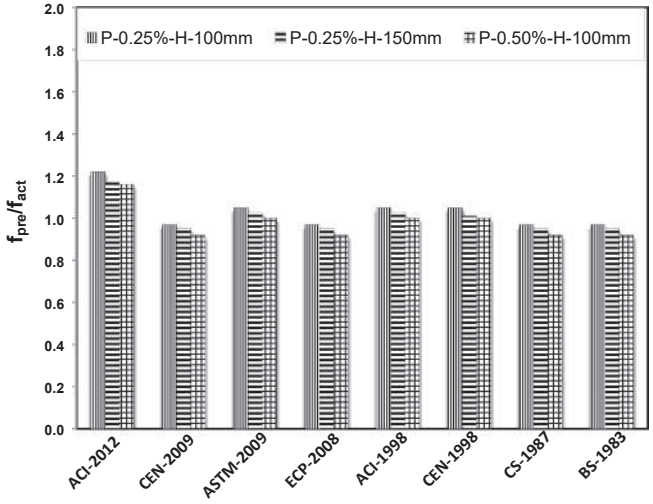
In this group, three mixtures were prepared and tested to evaluate the effectiveness of existing codes in predicting the in-situ compressive strength using the core method. Three different polypropylene fibers were used. For each mix, core samples with 100 mm and 150 mm diameter were cut horizontally. The compressive ratios (the predicted core compressive strength divided by the corresponding compressive strength according to the used code) were calculated and plotted in Fig. 4. The ratios approaching unity indicate the most accurate method. For the mixture containing 0.25% PP, the strength ratios for 100 mm cores are 1.22, 0.97, 1.05, 0.97, 1.05, 1.05, 0.97 and 0.97 for code methods A, B, C, D, E, F, G and H, respectively. From these results, it is clear that method A overestimates the in-situ compressive strength. Whereas, the other methods give values ranging from 0.97 to 1.05. Moreover, similar results were noticed for 150 mm diameter core specimens. On the other hand, the results obtained for the mixtures containing 0.5% and 0.75% PP show relatively low values.

When considering code method A, a noticeable reduction in the relative compressive strength can be noticed with increasing the use of

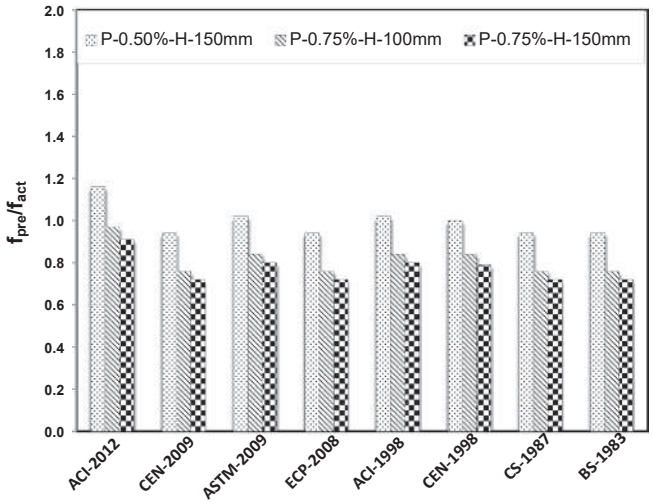
Table 6
Sorting values for the evaluated codes according to the measurements.

Code	Code value/ C-0%-H-100	Code value/ C-0%-H-150	Code value/ C-0%-V-100	Code value/ C-0%-V-150	Average (μ)		Standard deviation (б)		Coefficient of variation (V)		Characteristic Property (CP)		General rank	
					Value	Rank	Value	Rank	Value	Rank	Value	Rank	Sum	Rank
A	1.39	1.36	1.36	1.33	1.36	5	0.024	3	0.018	3	1.320	5	16	5
B	1.08	1.08	1.06	1.06	1.07	2	0.012	1	0.011	1	1.051	2	6	1
C	1.21	1.20	1.18	1.17	1.19	4	0.018	2	0.015	2	1.160	4	12	3
D	1.08	1.08	1.06	1.06	1.07	2	0.012	1	0.011	1	1.051	2	6	1
E	1.21	1.20	1.18	1.17	1.19	4	0.018	2	0.015	2	1.160	4	12	3
F	1.21	1.18	1.18	1.15	1.18	3	0.024	3	0.021	4	1.140	3	13	4
G	1.08	1.08	0.98	0.98	1.03	1	0.058	4	0.056	5	0.935	1	11	2
H	1.08	1.08	1.06	1.06	1.07	2	0.012	1	0.011	1	1.051	2	6	1

A(ACI-2.12), B(CEN-2009), C(ASTM-2009), D(ECP-2008), E(ACI-1998), F(CEN-1998), G(C-1987) and H(BS-1983).

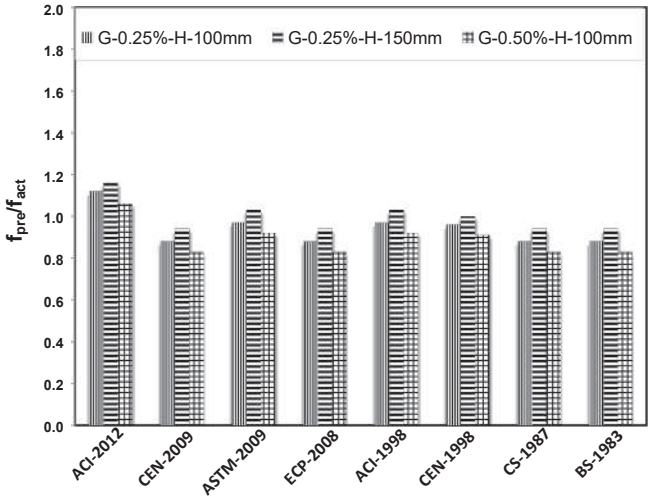


(a) Core diameter 100mm

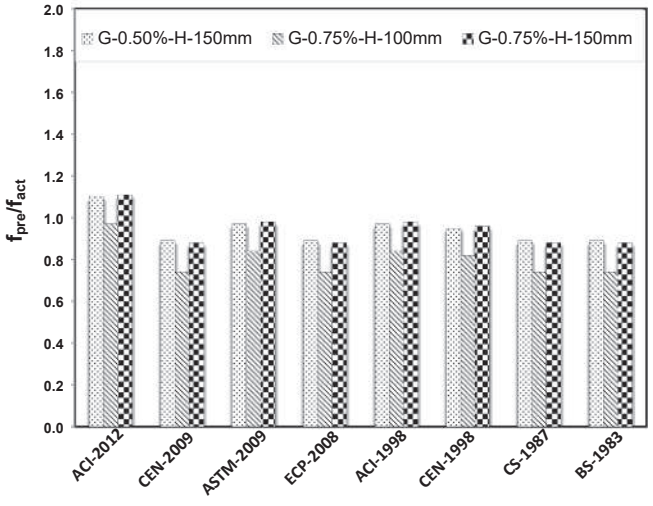


(b) Core diameter 150mm

Fig. 4. Validation of codes formula with the experimental results (GII).



(a) Core diameter 100mm



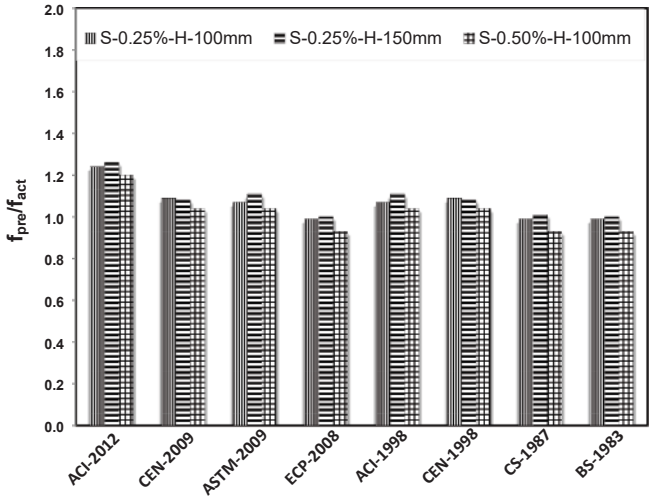
(b) Core diameter 150mm

Fig. 5. Validation of codes formula with the experimental results (GIII).

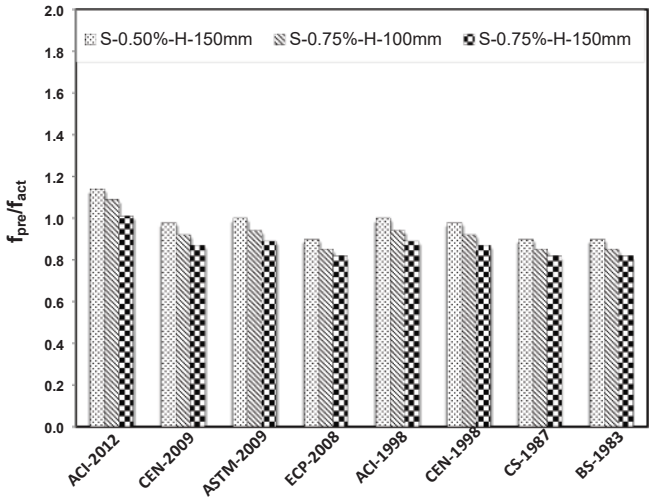
PP fiber volume fraction. For 100 mm diameter cores the relative compressive strength values are 1.22, 1.16 and 0.97 for 0.25%, 0.5% and 0.75% PP, respectively. Moreover, the same trend can be noticed for all the code methods investigated. Remarkable reductions can be noticed in the values of the relative compressive strengths with the increase of the dosage of pp used. The reduction reached 0.72 for 150 mm diameter core made with the mix containing 0.75% PP according to code methods B, D, G and H. This suggests that the investigated code methods cannot effectively predict the in-situ compressive strength for concrete mixes containing PP fibers.

4.3. Efficiency of the existing codes in predicting the core compressive strength for mixtures containing glass fibers

This section presents and analyzes the test results of three mixtures



(a) Core diameter 100mm



(b) Core diameter 150mm

Fig. 6. Validation of codes formula with the experimental results (GIV).

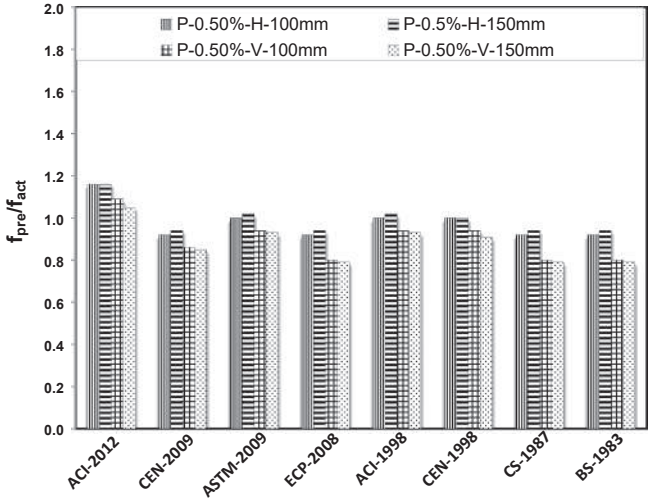


Fig. 7. Validation of codes formula with the experimental results (GV).

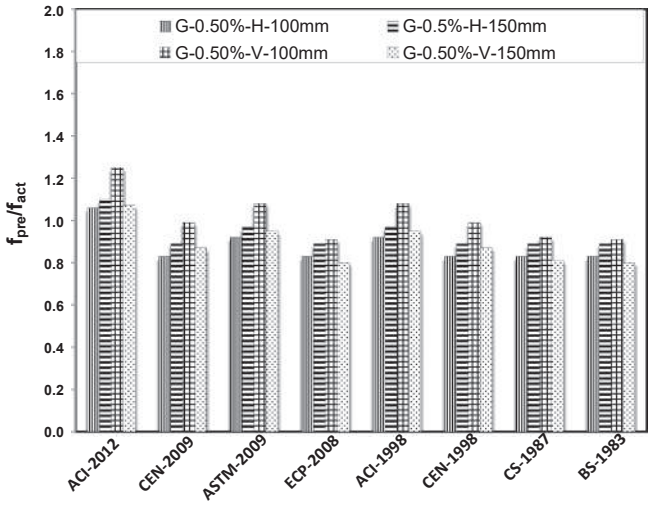


Fig. 8. Validation of codes formula with the experimental results (GVI).

containing three different glass fiber volume fractions: 0.25%, 0.5% and 0.75%. The relative compressive strength values for the conducted specimens are presented in Fig. 5. Code method A results in relative strength values ranging between 0.97 and 1.12. Most of the results of this test method overestimate the compressive strength. Additionally, most results of the other code methods underestimate the compressive strength values, as shown in Fig. 5. Moreover, increasing the core diameter values from 100 mm to 150 mm resulted in a relatively slight decrease in the investigated values. Whereas, increasing the dosage of glass fibers reduced the relative compressive strength values as can be observed in Fig. 5.

4.4. Efficiency of existing codes in predicting the core compressive strength for mixtures containing steel fibers

Three mixtures containing different steel fiber volume fractions were investigated and the relative compressive strength values were evaluated using different code methods. The results are plotted in Fig. 6. It is possible to notice that method A overestimates the core compressive strength as the relative compressive strength values range between 1.01 and 1.24. Whereas, the other code methods give scattered values ranging from 0.82 (0.75% steel) to 1.11 (0.25% steel). Additionally, using cores of 100 mm diameter seems to result in relatively high strength compared to 150 mm diameter core specimens. For the investigated code test methods, increasing steel fiber volume fraction reduces the relative compressive strength values, which suggests the in-situ compressive strength is underestimated using the existing code methods. Finally, the existing code test methods did not accurately predict the in-situ compressive strength for mixtures containing steel fibers.

4.5. Efficiency of existing code methods in predicting the compressive strength of concrete as affected by cutting direction for fibrous concrete

Figs. 7-9 present the relative compressive strength test results for three mixtures containing 0.5% fiber volume fractions from PP, G and steel fibers, respectively. The relative compressive strength results for mixtures containing 0.5% PP are shown in Fig. 7. It is possible to observe that method A overestimates the in-situ compressive strength as the results ranged from 1.05 (P-0.5%-V-150 mm) to 1.16 (P-0.5%-H-150 mm), while the test results ranged between (0.79) and 1.02. Comparing results obtained from horizontally cut cores with those cut vertically, it can be concluded that horizontal cores result in slightly higher values. Moreover, the results presented in Fig. 8 have a trend similar to the

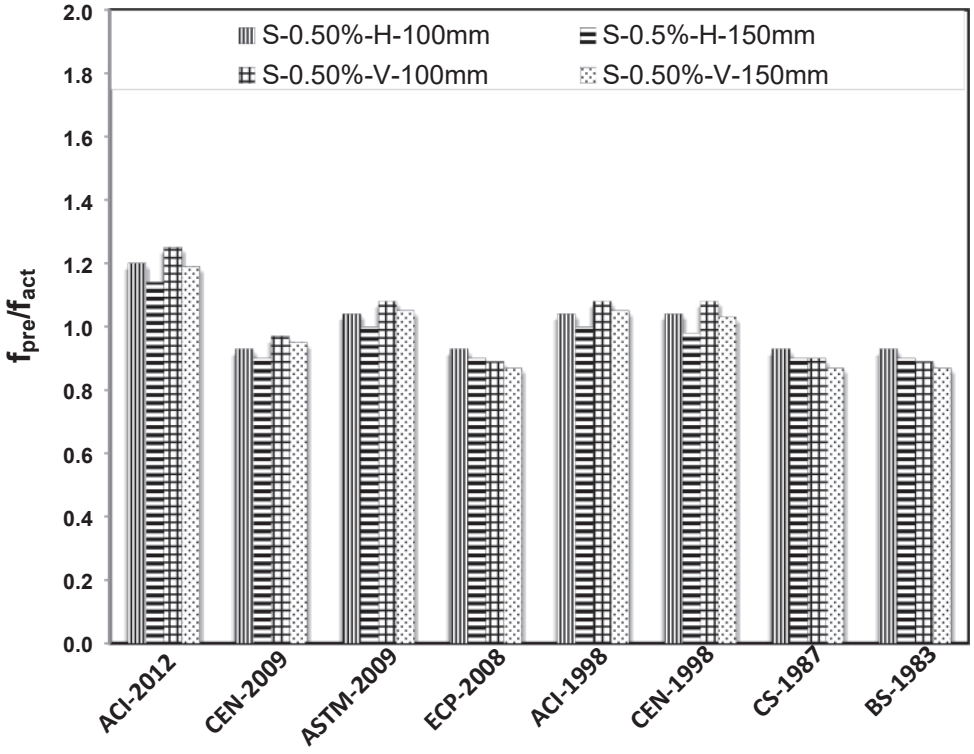


Fig. 9. Validation of codes formula with the experimental results (GVII).

previous given for polypropylene fibers, as existing glass fibers tend to reduce the estimated core strength values. The influence of cutting direction of core sampling is presented in Fig. 9. As mentioned previously, method A overestimated the core compressive strength compared to the other code test methods. Moreover, for both investigated core sizes, the inclusion of steel fibers reduced the estimated core strength. Therefore, the existing code methods did not effectively predict the in-situ compressive strength of concrete containing different fiber types as well as different fiber volume fractions.

5. Establishing a new method for predicting the fibrous concrete compressive strength by core test method

When comparing the experimental results in the previous sections to estimate the in- situ compressive strength by core test method using the existing codes equations, discrepancies were observed. Therefore, this section introduces a new method capable of correctly estimating the in-situ compressive strength for fibrous concrete. The proposed method adjusts the most accurate method among the investigated ones for mixtures free of fibers to consider the existence of different types of

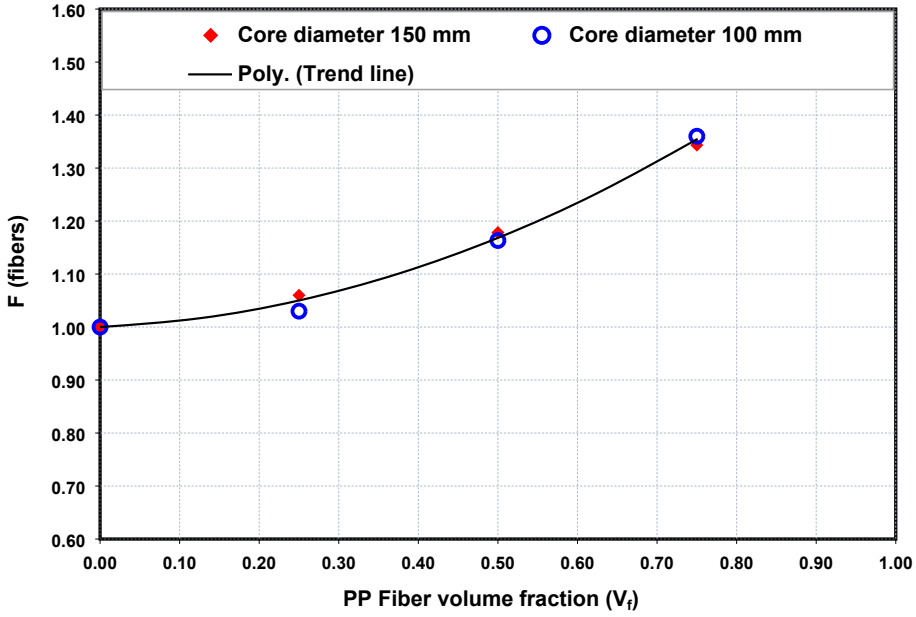


Fig. 10. Relationship between V_f and F_{fibers} for the used PP fibers.

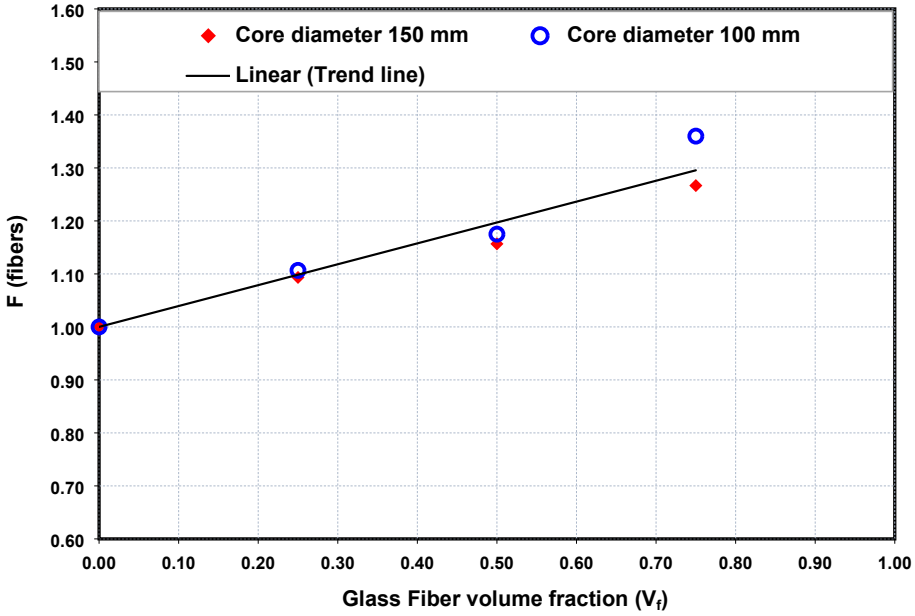


Fig. 11. Relationship between V_f and F_{fibers} for the used Glass fibers.

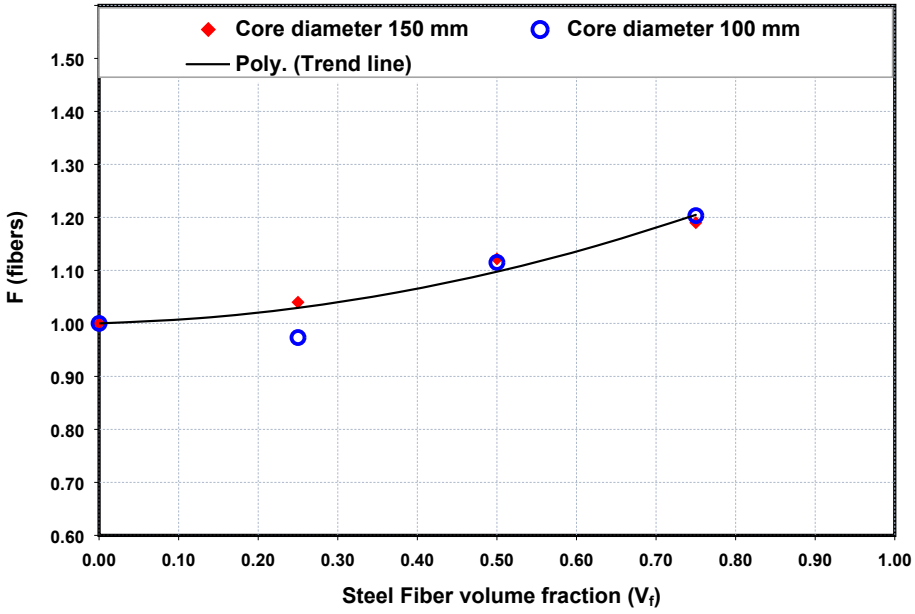


Fig. 12. Relationship between V_f and F_{fibers} for the used steel fibers.

fibers, as well as different volume fractions that may be used.

Considering method D (ECP-2008) which comes in the rank (I) as the British Standard (1983) [32], the compressive strength can be estimated as given in the following Equation:

$$F = F_{(l/d)} \times F_{(reinf.)} \times F_{(core)} \quad (13)$$

As previously shown, this testing method can accurately estimate the in-situ compressive strength for concrete mixtures free of fibers and underestimates the strength for fibrous concrete mixes. Therefore, a correction to account for the presence of fibers of different types, as well as different volume fractions, is proposed by introducing a new factor $F_{(Fibers)}$ and Eq.13 is modified as follows:

$$F = F_{(l/d)} \times F_{(reinf.)} \times F_{(core)} \times F_{(Fibers)} \quad (14)$$

Where

$$F_{(Fibers)} = 0.55\ (V_f)^2 + 0.06\ (V_f) + 1.00 \quad (15)$$

(for PP fibers).

$$F_{(Fibers)} = 0.39\ (V_f) + 1.00 \quad (16)$$

(for glass fibers).

$$F_{(Fibers)} = 0.32\ (V_f)^2 + 0.04\ (V_f) + 1.00 \quad (17)$$

(for steel fibers).

Figs. 10-12 show the proposed methodology to estimate the fiber coefficients of the different types of the investigated fibers. In these figures, the relationship between the fiber volume fraction and the fiber factor (F fibers) that represents the inverse of the corresponding

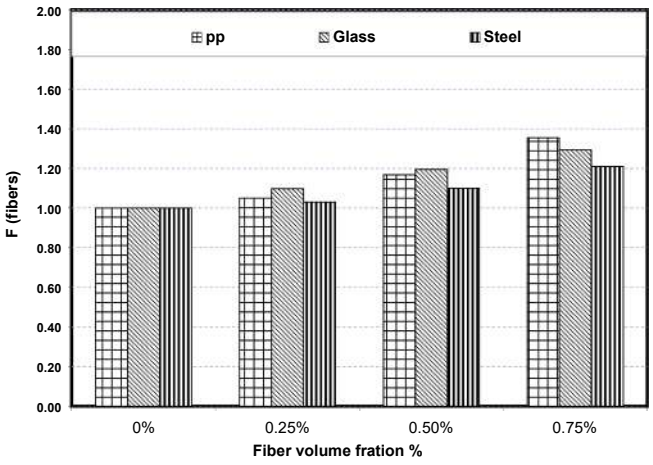


Fig. 13. Relationship between V_f and the estimated fiber coefficient for used fibers.

compressive strength ratio. Then, based on the best correlation curve, equations for estimating the fiber coefficient $F(_{Fibers})$ were proposed as shown previously. The fiber coefficient values were calculated and the results are presented in Fig. 13. It can be seen that, F (fibers) is a magnification factor (bigger than 1). The higher volume fraction the higher the F (fibers) value as shown in Fig. 13. This may be attributed to that in case of core-drilling process fibers were randomly cut and thus, lose a part of its confinement action. In addition to that for the fiber volume fractions of 0.25% and 0.5, the F (fibers) coefficient not differ more than 10% between the tested specimens. Using the estimated fiber coefficients, the relative core compressive strength values were re-estimated using the new proposed equations. It can be noted that big discrepancies were observed before implementing the fiber coefficient between the fiber volume fraction and the compressive strength ratio as shown in Fig. 14. On the other hand, significant improvements in the estimated core compressive strength can be noticed when comparing the estimated values using the proposed equations as plotted in Fig. 15. Relative strength values for cores ranged between 0.74 and 0.96 for PP, 0.81–1.0 for glass and 0.83–1.0 for steel fibers based on the old model as plotted in Fig. 14. On the other hand, with applying the F (fibers) coefficient, the relative core compressive strength values are 1.00–1.08 for PP, 1.02–1.05 for glass and 1.01–1.03 for steel fibers, which suggests the proposed method is highly efficient to estimate the core compressive strength for fibrous concrete mixtures cast with similar fibers.

6. Summary and conclusions

This study investigated ten concrete mixes, including a control mix and nine fibrous concrete mixtures. Three different fiber types including polypropylene, glass and steel fibers were studied. For each type of fiber, three fiber volume fractions as 0.25, 0.50 and 0.75% were used. The efficiency of the existing core test methods according to different codes was examined. Based on the results of the present testing program, as well as the analysis of results, it is possible to conclude that.

- The existing code methodologies underestimate the core compressive strength for fibrous concrete mixtures.
- Inclusion of fibers in concrete mixes reduces the estimated core compressive strength. Moreover, the reduction is dependent on both fiber type as well as the used fiber volume fraction.
- Inclusion of Polypropylene fibers significantly reduces the estimated core compressive strength values compared to glass and steel fibers.
- A new proposed model that can take into account the presence of fiber in concrete mixtures and estimate accurately the in-situ core compressive strength is introduced in this paper. The new model is based on introducing a new factor to consider both the fiber type as well as its volume fraction.
- The proposed fiber factor depends on both the fiber type and the fiber volume fraction. At a given fiber volume fraction, the fiber factor to account for the presence of fibers can be arranged in ascending order as steel, followed by glass and, lastly, polypropylene.

CRediT authorship contribution statement

Mohamed Taman: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Investigation, Software, Data curation, Resources. **Metwally Abd Elaty:** Methodology, Software, Data curation, Resources, Formal analysis, Writing – original draft. **Reda N. Behiry:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Investigation, Data curation, Resources, Software.

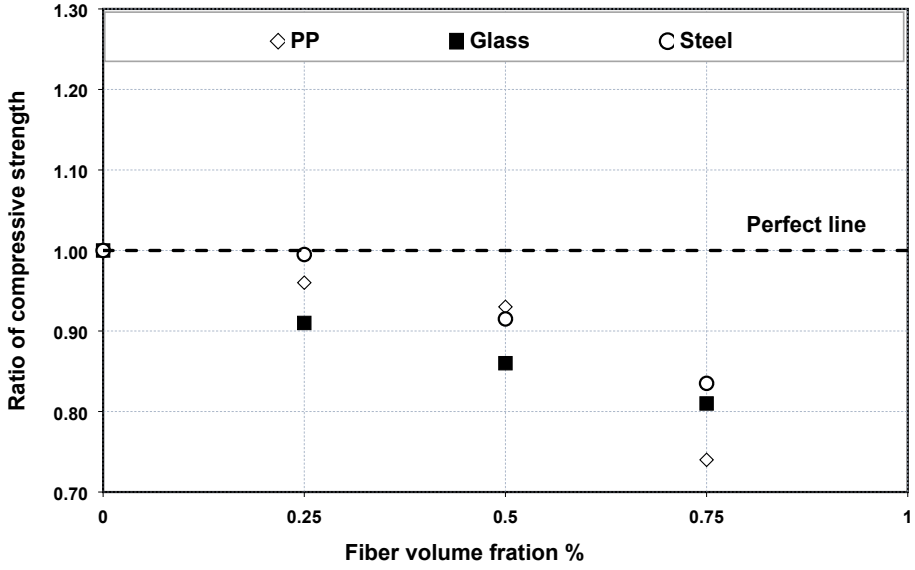


Fig. 14. Relationship between V_f and compressive strength ratio for used fibers before implementing fiber coefficient.

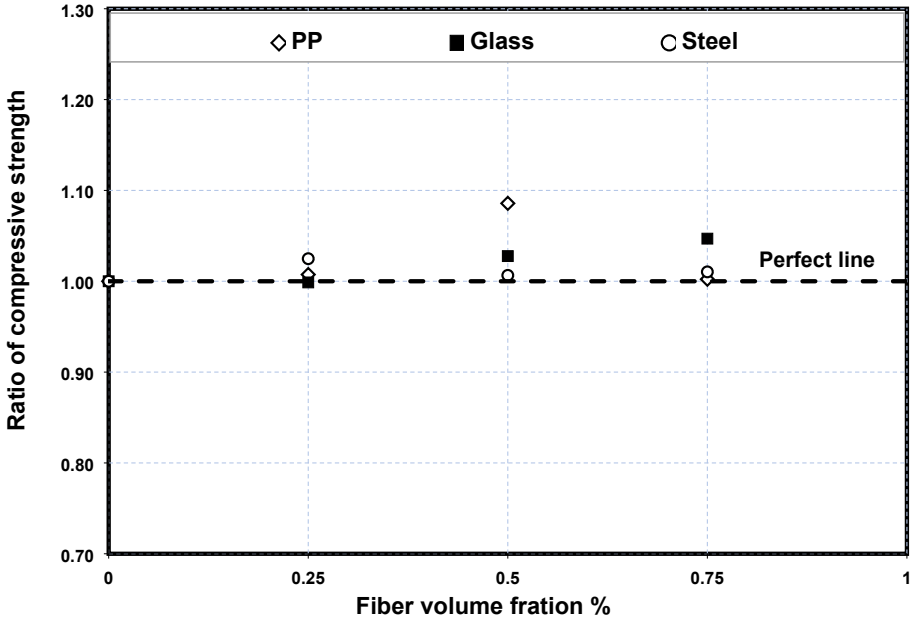


Fig. 15. Relationship between V_f and compressive strength ratio for used fibers after implementing fiber coefficient.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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