International Journal on Engineering Applications (I.R.E.A.), Vol. 11, N. 2
ISSN 2281-2881 March 2023

Effect of Longitudinal Bars on Shear Strength Prediction of High-Strength No-Coarse Aggregate Concrete

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Abstract – *High-Strength Concrete (HSC) offers a higher strength-to-volume ratio than that of normal-strength concrete, which has become increasingly popular in recent decades. However, its design provision is not explicitly served in most building codes. This study focuses on the shear strength of HSC and the longitudinal reinforcement ratio, which influences the shear strength. The ratio has been analyzed and compared with 12 reinforced HSC beams without coarse aggregate. Concretes with cylinder compressive strengths from 58 to 110 MPa have been used. The concrete mixes have been made without coarse aggregate and a maximum fine aggregate size of #30 sieve. The specimens have been reinforced with various longitudinal reinforcement ratios and tested until failure by using a four-point bending test setup. The tests have shown that the degree of influence of longitudinal reinforcement has been in agreement with the ACI 318 formula, but it has overestimated the concrete's shear strength. Based on the results, a modification has been proposed to the existing formula to improve its accuracy for HSC. The proposed formula shows significant improvement in terms of accuracy in predicting concrete shear strength compared to those from the ACI 318M-19 as well as the formulas proposed by other researchers for the range of specimens used in this research.* ***Copyright © 2023 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: ACI 318, Coarse Aggregate, Concrete Shear Strength, High-Strength Concrete, Longitudinal Reinforcement*

Nomenclature

a	Shear span, distance from a point load to support [mm]
b_w	Beam width [mm]
CoV	Coefficient of Variation
d	Beam effective depth [mm]
d_a	Maximum aggregate diameter [mm]
f'_c	Concrete compressive strength [MPa]
N_u	Axial force [kN]
P	Point load [kN]
r	Exponent factor for ρ_w
R^2	Coefficient of determination
V_c	Concrete shear strength [kN]
V_{form}	Concrete shear strength from formula [MPa]
V_{test}	Concrete shear strength from test result [MPa]
w/c	Water-to-cement ratio
α	Exponent factor for f'_c
λ	Lightweight concrete modification factor
λ_s	Size effect modification factor
κ	Concrete shear strength coefficient
ρ, ρ_w	Longitudinal reinforcement ratio

I. Introduction

Concrete is one of the most used construction materials, with its first usage dating back to around the 2nd century BCE. In recent years, various research has been done to improve the properties of conventional concrete. Improvement could be done on its strength, resistance, or modification for specific usage and environmental conditions [1]-[5]. This modified and improved concrete is called special concretes. Special concretes are formulated to tackle specific conditions, such as resistance to chemical attacks. High-strength concrete is also a type of special concretes, designed for structures that require withstanding high compressive loads with minimum volume. According to ACI 363R, high-strength concrete is defined as concrete with a specified compressive strength of 55 MPa or higher. This definition is also used in ACI 318M-19. High-strength concrete is not well defined in other building codes, but it is generally accepted that concrete with a cylindrical compressive strength of around 60 MPa or higher is considered high-strength concrete. High-strength concrete has superior compressive strength compared to conventional concrete and is commonly used for the construction of high-rise buildings. Compressive members made with high-strength concrete can withstand a higher load and can be proportioned more efficiently than normal-strength concrete [6]-[8]. Properties of high-strength concrete that are actively researched include its behavior when subjected to various actions (axial, shear), water absorption, etc. [9]-[16], and also the proportioning of its mixtures [17]-[19]. High-strength concrete is usually designed with low w/c, in the range of 0.40 or

https://doi.org/10.15866/irea.v11i2.22596

lower. In order to make concrete with low *w/c* and with acceptable workability, various additives, and admixtures such as superplasticizers and pozzolan are required [20].

As with conventional normal-strength concrete, flexural moment and shear occur similarly in beams made with high-strength concrete when subjected to transverse loads.

In beams without shear reinforcement, cracks are formed on inclined planes due to shear stresses, especially near the beam's supports. These stresses are resisted in two ways, i.e. beam and arch mechanisms.

Beam failure occurs when shear stresses can be no longer transferred to the supports through those mechanisms [21]. In the ACI 318M-19 [21], the concrete shear strength equation for which the shear reinforcement provided is less than the minimum shear reinforcement (where concrete without shear reinforcement satisfies this criterion) is given by (1). By assuming normal weight concrete ($\lambda = 1$) and no axial force ($N_u = 0$), the concrete shear strength V_c can be expressed as:

$$V_c = 0{,}66\lambda_s(\rho_w)^{1/3}\sqrt{f'_c}b_w d \tag{1}$$

where λ_s is the size effect modification factor and ρ_w is the longitudinal reinforcement ratio. The size modification factor λ_s is provided in (2):

$$\lambda_s = \sqrt{\frac{2}{1 + 0{,}004d}} \leq 1 \tag{2}$$

The formulas used for comparison are taken from various sources and are listed in Table I. Some formulas are converted from ultimate shear stress to ultimate shear strength by multiplying them with the cross-section area.

Previous works on this topic suggest that shear strength and transfer of reinforced concrete beams without shear reinforcement are affected by many factors, such as the surface of the shear interface, and the size of the aggregate, which contributes through a mechanism called "aggregate interlock" [22]-[25], and reinforcement ratio and strength, which contributes through dowel action [26], [27]. Longitudinal reinforcement contributes to shear strength in various ways, but it serves mainly to restrain the width of the cracks and transfer shear force through dowel action.

TABLE I

FORMULAS BY OTHER RESEARCHERS

Source	Formula	
Zsutty [28]	$V_c = 2.2(\rho f'_c d/a)^{1/3} b_w d$ where $a/d \geq 2.5$	(3)
Bazant and Sun [29]	$V_c = 0.54\rho^{1/3}\left(f'^{\,1/2}_c + 249\sqrt{\rho/(a/d)^5}\right)\left(\frac{1 + \sqrt{5.08/d_a}}{\sqrt{1 + d/(25d_a)}}\right)b_w d$	(4)
Kim and Park [30]	$V_c = 3.5f'^{\,\alpha/3}_c\rho^{3/8}\left(1/\sqrt{1 + 0.008d} + 0.18\right)(0.4 + d/a)b_w d$ where $\alpha = \begin{cases} 2 - 3a/d & \text{for } 1.0 \leq a/d < 3.0 \\ 1 & \text{for } a/d \geq 3.0 \end{cases}$	(5)
Cavagnis [31]	$V_c = \kappa(100\rho f'_c d_a/a)^{1/3} b_w d$ where $\kappa = 0.87$ (average value)	(6)

With the increasing longitudinal reinforcement ratio ρ, its capability to restrain the crack width and inhibit the propagation of flexural cracks further increases the shear capacity [19]. Shear strength is also influenced by the bond between concrete and steel reinforcement. Due to the low *w/c* ratio in high-strength concrete, the bond strength between mortar and steel is equivalent to the coarse aggregate's strength [23]. Thus, coarse aggregate is frequently not used to prevent premature failure due to the splitting of coarse aggregate. As shown by Christianto et al. [32], the shear strength of high-strength no-coarse aggregate concrete increases with an increasing longitudinal reinforcement ratio. The addition of steel fiber to the concrete mix increases the shear strength even higher [33],[34]. By using the Eurocode 2 formula, the longitudinal reinforcement ratio has a lower effect on the shear strength of this high-strength concrete compared to normal concrete [35], [36]. The high-strength no-coarse aggregate concrete also exhibits size effect behavior like normal concrete [37]. The size effect behavior of this type of concrete can be expressed in a form similar to (2) [38]. The contribution of each mechanism is unknown and difficult to be exactly determined. Hence, these mechanisms are often lumped and termed concrete shear strength. The influence of longitudinal reinforcement itself is also affected by various parameters, such as the size and the layout of the steel rebars. In order to simplify the calculation, building codes such as ACI 318 and Eurocode 2 only require the longitudinal reinforcement ratio ρ to be known, regardless of its size or layout. Concrete shear strength formulas are often expressed to be proportional to the longitudinal reinforcement ratio raised to a certain exponent. Different building codes also often have a different value for this exponent, but it is generally a value less than unity. For example, Eurocode 2 2004 assumes shear strength is proportional to $(100\rho)^{1/3}$, ACI 318M-19 assumes $\rho^{1/3}$, and other researchers, such as Kim and Park, assume $\rho^{3/8}$ [30]. As of ACI 318M-19, there is no equation explicitly applicable to high-strength concrete. The specified cylinder compressive strength is also limited up to 70 MPa for design purposes, which is normal for high-strength concrete to exceed this value.

This research aims to analyze and compare the degree of contribution of longitudinal reinforcement on the shear strength of high-strength concrete using the existing ACI 318 formula. Based on the results, a modification is proposed to the existing ACI 318 formula for predicting the shear strength of high-strength concrete more accurately. In this research, the contribution of longitudinal reinforcement on the shear strength of high-strength no-coarse aggregate concrete is investigated.

The paper begins with a review of concrete shear strength, its mechanism, and various formulas to predict its value. The details of the test methods and results are explained in the next section. The results are analyzed and compared to other formulas considered in this research. The paper concludes with a proposed modification to the influence of the longitudinal reinforcement ratio in the ACI 318-19 formula for predicting the shear strength of high-strength concrete.

II. Methods

The specimen data used in this research have been taken from research conducted by Christianto, et al. [32]-[35], [37], [38]. The experimental methods are described briefly in the following sections. The specimens consist of twelve ø10 cm × 20 cm cylinders to measure the compressive strength and twelve 7 × 12.5 × 110 cm^3 beams for the four-point bending test. The materials and proportioning of the concrete mix are summarized in Table II. Silica fume is used as pozzolanic material and serves to fill the space between mortar and aggregate due to its fine particle size [39]. Twelve specimens of 7 × 12,5 × 110 cm^3 concrete beams have been cast for testing. Each beam has been provided with two bars of steel reinforcement of various sizes, which are ø6, ø8, ø10, ø12, ø16, and ø19. Twelve ø10 cm × 20 cm cylinders have been also cast to measure the cylinder strength. The concrete mix has been mixed in a mixer and then cast into their respective molds. The molds have been disassembled 48 hours after casting, and then the specimens have been cured in the water bath for 58 days.

After 58 days, the specimens have been removed from the water bath and steam cured for 8 hours. After the specimens have been cured, the cylinder specimens have been tested for the compressive test and the beam specimens have been tested for the four-point bending test. The model of the beam specimen can be seen in Fig. 1 and the photograph of both flexural and shear failure can be seen in Figs. 2. The details of each beam specimen are provided in Table III.

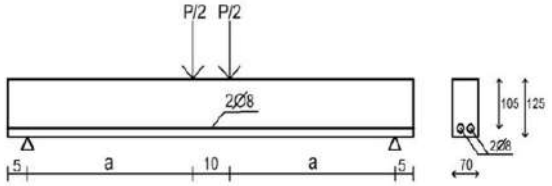
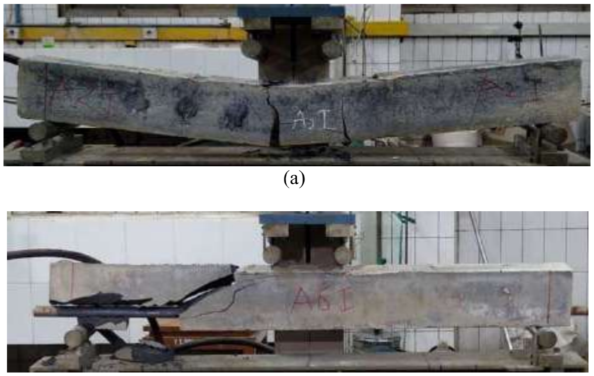


Fig. 1. Model of the beam specimen [32]


(a)

(b)

Figs. 2. (a) Flexural failure, (b) shear failure [32]

TABLE II
CONCRETE MIX [32]

Materials	Notes
Ordinary Portland Cement (OPC)	-
Silica sand (sieve no. 30 and no. 50)	110% of cement mass
Silica fume	20% of cement mass
Marble powder (sieve no. 200)	10% of cement mass
Superplasticizer	2.5% of cement mass
Accelerator	5 liters/m^3 of concrete mix

TABLE III
SPECIMEN DATA [32]

Beam	Rebar	ρ	Cylinder compressive strength, f'_c (MPa)	Type of failure
A11	2ø8	1.37%	77.56	Flexure
A12	2ø8	1.37%	74.56	Flexure
A21	2ø6	0.77%	50.30	Flexure + shear
A22	2ø6	0.77%	65.79	Flexure + shear
A31	2ø10	2.14%	107.60	Flexure + shear
A32	2ø10	2.14%	110.40	Flexure + shear
A41	2ø12	3.08%	71.23	Shear
A42	2ø12	3.08%	62.37	Shear
A51	2ø16	5.47%	79.54	Shear
A52	2ø16	5.47%	56.49	Shear
A61	2ø19	7.72%	76.71	Shear
A62	2ø19	7.72%	75.45	Shear

III. Results and Discussions

In order to measure the longitudinal reinforcement ratio contribution in the ACI 318M-19 formula, the non-dimensional ratio $V_c/b_wd(f'_c)^{1/2}$, where V_c is the concrete's shear strength, is plotted against the cube root of longitudinal reinforcement ratio, $\rho^{1/3}$. Non-dimensional ratio $V_c/b_wd(f'_c)^{1/2}$ is used to normalize the shear strength due to the variability of concrete compressive strength.

The plot between the non-dimensional ratio $V_c/b_wd(f'_c)^{1/2}$ against $\rho^{1/3}$ is shown in Fig. 3. Trendlines are added to each plot in order to identify the overall trend of the graph. Fig. 3 shows plots of the cube root of longitudinal reinforcement ratio, $\rho^{1/3}$, versus non-dimensional ratio $V_c/b_wd(f'_c)^{1/2}$. Values in the "ACI 318M-19 Formula" plot are calculated using the ACI 318M-19 formula and values in the "Test" plot are obtained from laboratory testing. The use of the cube root of the longitudinal reinforcement ratio is intended to linearize the graph, which makes it easier to identify the fitness of the formula prediction against the test results.

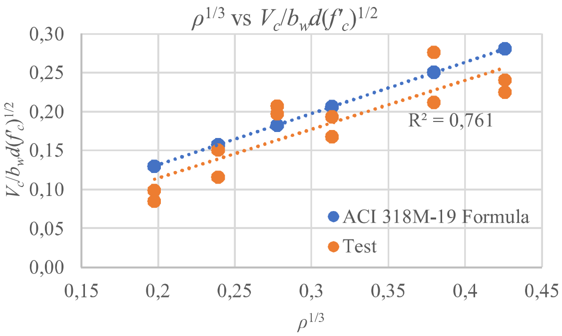


Fig. 3. Influence of longitudinal reinforcement ratio to non-dimensional ratio $V_c/b_wd(f'_c)^{1/2}$

A linear plot with a similar gradient to actual shear strength means more fitness against the test results. The coefficient of determination (R^2) is also computed for the actual shear strength plot to determine the proportionality between $\rho^{1/3}$ and shear strength. By inspection, it can be identified that the ACI 318M-19 formula has a similar trend to the experimental result. Then the coefficient of determination (R^2) for the "Test" plot is computed to quantify the linearity of the plot. An R^2 value that is close to unity indicates that the plot has good linearity. The "Test" plot has an R^2 value of 0.761, which indicates good linearity between $\rho^{1/3}$ and concrete shear strength.

The actual exponent value may differ but it can be inferred that the actual value is not significantly different from 1/3. The accuracy of shear strength prediction could also be seen in Fig. 3. The ACI 318M-19 formula slightly overestimates the actual shear strength for all specimens. This result is expected since the absence of coarse aggregate reduces the contribution of the aggregate interlock mechanism, which resists slippage between concrete in the crack interface. The bond strength between the reinforcement surface and concrete is also lower due to the smoother bond interface. With the shear strength known to be proportionally close to $\rho^{1/3}$, calculations are made to obtain the actual value of the exponent. The exponent value of 1/3 in the ACI 318M-19 formula is replaced by parameter r. The value of r is determined by calculation. By replacing the exponent value of 1/3 with parameter r, the ACI 318M-19 formula for concrete shear strength can be written as:

$$V_c = 0.66\lambda_s(\rho_w)^r\sqrt{f'_c}b_w d \tag{7}$$

where shear strength is assumed to be proportional to $(\rho_w)^r$. By using a logarithm, (7) can be rearranged to isolate parameter r as provided in (8):

$$r = \log_\rho \frac{V_c}{0.66{f'_c}^{1/2}b_w d} \tag{8}$$

The calculated value of r, its average, and the Coefficient of Variation (CoV) are presented in Table IV. CoV is included to measure the scatter of the calculated value, where lower numbers indicate a more narrowly scattered, value that is more consistent. Based on the values presented in Table IV, the average value of r of 0.3685 is not too far off from the original value of 1/3 = 0.3333 on the original formula. Interestingly, this exponent value of 0.3685 is very close to the value obtained by Kim and Park [30] which is 3/8 (0.375). The calculated values are also consistent, indicated by the CoV value of 0.1221 or 12%. The value of r can also be used to deduce the relative influence of longitudinal reinforcement on shear strength in high-strength concrete in comparison to normal-strength concrete. Since the value of the reinforcement ratio is always smaller than unity, a larger exponential value results in a smaller degree of influence. The average value obtained of 0.3685 is larger than the original value of 1/3 (0.3333).

TABLE IV

Exponential Value For Longitudinal Reinforcement Ratio

Beam	ρ	Shear Strength (kN)	*r*
A21	0.77%	5.1655	0.3896
A22	0.77%	5.0755	0.4208
A11	1.37%	7.1205	0.4055
A12	1.37%	9.2855	0.3437
A31	2.14%	12.1655	0.3133
A32	2.14%	12.7705	0.3007
A41	3.08%	10.3205	0.3934
A42	3.08%	11.2555	0.3519
A51	5.47%	17.0255	0.2990
A52	5.47%	11.7255	0.3904
A61	7.72%	14.8055	0.3936
A62	7.72%	13.8455	0.4198
		Average	0.3685
		CoV	0.1221

This indicates that the longitudinal reinforcement's influence is smaller in high-strength concrete in contrast to normal-strength concrete, particularly for no-coarse aggregate concrete. For usage in standard building codes, it is desirable to choose a single value for practicality.

The value chosen should yield a representative, conservative yet sufficiently accurate prediction and also preferably easy to remember. The average value of 0.3685 is considered representative of these test results, which is then rounded up to 0.4 for inherent conservatism and easy-to-remember value. Thus, the modified ACI 318M-19 formula to predict shear strength for high-strength concrete is:

$$V_c = 0.66\lambda_s(\rho_w)^{0.4}\sqrt{f'_c}b_w d \tag{9}$$

However, this result should not be generalized due to the limited number of specimens in this research. The shear strength of each beam specimen is calculated by using the proposed formula given by (9) and then compared to the results obtained using various formulas proposed by other researchers.

The comparisons are listed in Table V and are made by using the ratio between actual shear strength from the test to predicted shear strength from formulas, V_{test}/V_{form}.

Based on Table V, the modified ACI 318M-19 formula (8) gives the most accurate prediction of shear strength for high-strength concrete with an average of 90% of the test results.

TABLE V

Values Of V_{TEST}/V_{FORM} Ratio By Various Formulas

Beam	ρ	Equation 8	Equation 1 [28]	Equation 2 [29]	Equation 3 [30]	Equation 4 [31]
A21	0.77%	0.9505	1.4044	1.5859	1.7212	0.4609
A22	0.77%	1.1063	1.5631	1.8285	1.9157	0.5129
A11	1.37%	1.0239	1.4259	1.7402	1.7899	0.4679
A12	1.37%	0.7852	1.0791	1.3105	1.3546	0.3541
A31	2.14%	0.7164	1.0801	1.3989	1.3813	0.3544
A32	2.14%	0.6825	1.0378	1.3484	1.3272	0.3405
A41	3.08%	0.9771	1.2530	1.5759	1.6270	0.4112
A42	3.08%	0.8457	1.0992	1.3632	1.4272	0.3607
A51	5.47%	0.7456	0.9546	1.2612	1.2696	0.3133
A52	5.47%	0.9726	1.2367	1.5855	1.6447	0.4058
A61	7.72%	0.9838	1.2162	1.6462	1.6409	0.3991
A62	7.72%	1.0520	1.2934	1.7483	1.7450	0.4244
Average		0.9035	0.9035	1.2203	1.5327	1.5704
CoV		0.1575	0.1575	0.1480	0.1246	0.1340

Formulas by Zsutty [28], Bazant and Sun [29], and Kim and Park [30] overestimate the shear strength by 20% to 50%. On the other hand, the formula by Cavagnis [31] heavily underestimates the shear strength. This might be due to the formula that takes into account the effect of aggregate size, which is only fine-grain in the research. Most of the formulas give similar scatter with the CoV varying from 0.12 to 0.15.

IV. Conclusion

Based on the test results of high-strength no-coarse aggregate concrete, with f'_c varies from 58 to 110 MPa, the influence of longitudinal reinforcement on concrete shear strength of high-strength concrete has a similar trend to the shear strength equation in the ACI 318M-19 formula, which is formulated based on normal-strength concrete. From the test results, the calculated values of r are varying from 0.2990 to 0.4208, with an average of 0.3685. This value is similar to the value obtained by Kim and Park [30]. All of the calculated R-values are higher than the original formula, which indicates the degree of contribution of longitudinal reinforcement is less significant than the ACI 318M-19 formula's assumption. The average of R-values is rounded up for practicality and inherent conservatism, which yielded Equation (8), where the shear strength of high-strength concrete is proportional to $\rho^{0.4}$. For further research, the influence of longitudinal reinforcement's arrangement and diameter needs to be investigated. By considering the increase in longitudinal reinforcement grade, the effect of longitudinal reinforcement grade also needs to be investigated. More test results and finite element analysis of shear strength of high-strength no-coarse aggregate concrete are needed to confirm further the influence of longitudinal reinforcement ratio and the proposed formula presented in this research.

Acknowledgements

The authors would like to gratefully acknowledge all the contributions from those who have supported and provided assistance to make this research possible, especially for the technical guidance and support throughout the experimental work in the Laboratory of Construction Material Technology, Department of Civil Engineering, Universitas Tarumanagara, Jakarta. Special thanks are also due to all the sponsorships, particularly from PT. Indocement Tunggal Prakasa and PT. Master Builders Solutions Indonesia.

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