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A Proposed Formula for Predicting Size Effect on Shear Strength of Concrete Beams Without Coarse Aggregate

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Abstract – *In this research, the size effect on shear strength of concrete beams without coarse aggregate has been studied by evaluating the ACI 318-14, ACI 318-19, and Eurocode 2 formulas. The beam specimens had the width, length, a/d, and maximum aggregate size of 6 cm, 110 cm, 2.744, and 0.6 mm, respectively. The beam's depths had been set to have a range from 6 to 18 cm. The compressive strengths of the beam were in between 58.51 and 99.80 MPa. The beams had been tested under two concentrated loads. The longitudinal reinforcement consisted of two diameter 16 mm. The beams were designed without any stirrups. Based on the analysis, the ACI 318-19 approach provides the best prediction with the mean strength ratio and coefficient of variation of 1.5086 and 0.26, respectively. The ACI 318-19 also indicates insignificant downward trend on the strength ratio vs. effective depth. The test results show that the size effect is in good agreement with the Bažant's size effect law. In this paper, modifications to the existing formula are given to provide more accurate prediction.* **Copyright © 2022 Praise Worthy Prize S.r.l. - All rights reserved.**

***Keywords**: ACI 318, Coarse Aggregate, Concrete Shear Strength, Eurocode 2, Size Effect*

Nomenclature

a	Shear span, distance from concentrated load to support (mm)
b	Beam width (mm)
COV	Coefficient Of Variation
d	Beam effective depth (mm)
d_a	Maximum aggregate diameter (mm)
f'_c	Concrete compressive strength (MPa)
h	Beam depth (mm)
k	Size effect factor according to Eurocode 2
M_u	Bending moment (kNm)
P	Load (kN)
SD	Standard Deviation
SR	Strength Ratio
V_u	Shear force (kN)
v	Concrete shear stress (MPa)
v_{code}	Concrete shear stress capacity according to design code (MPa)
v_{test}	Concrete shear stress capacity based on test result (MPa)
v_0	Concrete shear stress capacity according to plastic limit analysis (MPa)
x	Distance from support to a point along the beam (mm)
β	Brittleness number
λ_s	Size effect factor acccording to ACI 318-19
ρ	Longitudinal reinforcement ratio

I. Introduction

The rapid development in construction has made it possible to create very high-strength concrete [1].

In order to create this type of concrete, there should be no coarse aggregate used in the mix. The coarse aggregate will create a weak point in concrete, thus limiting the concrete strength. There are many researches on how to increase the strength of concrete, with or without coarse aggregate, even stronger. Some solutions involve adding steel fibers to the concrete mix [2]-[5] and using fiber sheets or bars to strengthen further the concrete [6]-[9].

In designing a reinforced concrete structure, a designer should ensure that the structure would not fail during its designed lifetime. The structure should have enough strength against bending moment, axial force, shear, and torsion. The structure should also meet the serviceability criteria, such as deflection, drift, and vibration. With the advance in technology, the behavior of the structures can be modeled with high accuracy [10]-[11], [30]-[32].

When a structure does not have enough strength, it will fail in a ductile or brittle manner. Between these two types of failure, brittle failure is highly undesirable. In brittle failures, such as shear failure, the structures fail abruptly without any obvious signs. This brittle behavior even worsens in high-strength concrete, as the concrete matrix becomes more homogeneous than normal-strength concrete. Therefore, the shear design should ensure that the shear strength is not less than the flexural strength at all points in the beam or other concrete members [12]-[13].

Up to the present, shear behavior in concrete is still being investigated. According to Joint ACI-ASCE Committee 445 [14], the concrete shear transfer mechanism can be divided into five mechanisms, namely shear stress in the uncracked concrete compression zone, interface shear transfer (aggregate interlock), dowel

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action, arch action, and residual tensile stress. These mechanisms are affected by various parameters, like shear span to effective depth ratio (*a*/*d*), concrete strength, longitudinal reinforcement ratio (ρ), axial force, and size effect.

From the previous studies on concrete without coarse aggregate, it has been shown that the concrete shear strength of high strength concrete increases as the longitudinal reinforcement ratio increases [15]-[17].

When the longitudinal reinforcement ratio is increased from the minimum to maximum ratio, the increase in shear strength can reach 82.82 percent without steel fibers [15] and 108 percent with the addition of 0.1 percent steel fibers [16]. The higher increase in shear strength when the steel fibers are added, as shown in [16], is in accordance with the results of previous studies [2]. Christianto et al. [17] have shown that the influence of longitudinal reinforcement ratio on shear strength of concrete beams without coarse aggregate is proportional to $\rho^{4/9}$.

For a geometrically similar structure, the nominal stress at maximum load should be the same (independent of the structural size). However, this behavior is not applicable for shear failure as shown by Leonhardt and Walther [18]. In other words, the nominal stress at the maximum load decreases as the structural size increases (depends on the structural size), which is also known as the size effect. This anomaly on concrete beam shear has been investigated by many researchers, such as Kani and Bažant. According to Kani [19], there is a considerable influence of beam depth on the concrete shear stress. Later on, Bažant and Kim [20] have concluded that consideration of size effect should come from the dimensional analysis of energy release rate in fracture front. For concrete beams without coarse aggregate, Christianto et al. [21] have shown that there is a 70.95 percent reduction in shear stress when the beam depth increases from 6 to 18 cm.

Many researchers and design codes have proposed various formulas for computing shear strength contributed by concrete. Many of these formulas have been developed using strength or yield criterion and verified by a data test of normal strength concretes with coarse aggregate. Due to this reason, these formulas might not be used for high-strength concrete. Using these formulas for high-strength concrete would create uncertainties in safety ensured by the formulas or design codes and even more uncertainties when the size effect is not considered. Because the shear failure on high-strength concrete is very brittle, the size effect and the fracture mechanics become more significant.

Theoretically, the best design approach is to use NonLinear Fracture Mechanics (NLFM) [22]. The simplest form of this approach is Bažant's size effect law, shown in Fig. 1 and the following equation for shear stress (v):

$$v = v_0\left(1+\beta\right)^{-0.5} \tag{1}$$

where v_0 is shear stress according to plastic limit analysis and β is brittleness number, defined by Bažant as shown in the following equation:

$$\beta = \frac{d}{25d_a} \tag{2}$$

where d is the effective depth and d_a is the maximum aggregate diameter [22].

Size effect behavior can be predicted using brittleness numbers. According to ACI Committee 446 [23], for $0.1 \leq \beta \leq 10$, the concrete shear behavior will be closer to the nonlinear fracture mechanics solution. For $\beta < 0.1$, the size effect can be ignored for an error below 4.7%. In this range, the size effect is not significant and the plastic limit analysis (based on strength criterion) can be used. For $\beta >$ 10, the size effect can be represented using the straight line with a slope of –1/2 in Fig. 1, which is the Linear Elastic Fracture Mechanics (LEFM) solution.

Since the application of NLFM is quite complicated, the simple approach would be using size effect correction on the plastic limit analysis or LEFM. The first approach is preferred, as it is possible to introduce only relatively minor corrections to the formulas present in the design codes. Of course, the formula needs to be slightly scaled up because, for normal sizes, it should give about the same load capacity as before, even after the reduction for the typical structure size according to the size effect law has been introduced [22]. As the structure size increase, the behavior becomes more brittle, and the error of the first approach increase. For large size structures or for certain types of failure (anchor pullout, diagonal shear), which is known to be very brittle, the second approach based on LEFM is expected to give more realistic results [22].

Some design codes have included size effect correction in their concrete shear strength formulas. JSCE has adopted size effect correction as a function of $\beta^{-1/4}$ which is motivated by the Weibull statistical theory [24]. On the other hand, the CEB-FIP formula and Eurocode 2 have adopted size effect correction as a function of $(1 + \beta^{-1/2})$ which is purely based on empirical data [24]-[25]. In ACI 318-19, the size effect is accounted in the form of Bažant's size effect law, given by Eq. (1) [26].

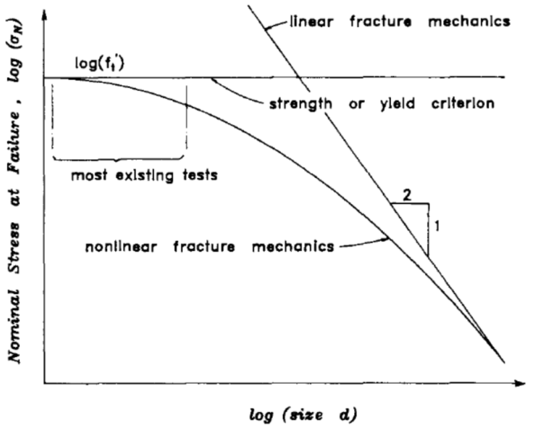

Fig. 1. Bilogarithm plot of size effect on nominal stress [15]

When minimum stirrups are provided in concrete beams, ACI 318-19 [26] ignores the size effect on the concrete shear strength.

Frosch et al. [27] have shown that, if the minimum stirrups are provided, the size effect only needs to be accounted for $d > 2500$ mm. It should be noted that the stirrups only reduce the size effect but do not eliminate it [24].

This paper presents the evaluation of the size effect on the shear strength of concrete beams without coarse aggregate by comparing several formulas from the design codes. The paper begins with a brief explanation of previous research on concrete shear strength, particularly the size effect. Then, the details of the concrete specimens, the test methods, and the formulas used for comparison will be explained in the next section. Then the results are presented in the form of tables and graphs, followed by an explanation of the test results. The paper concludes with proposed modified formulas to represent better the size effect behavior shown by the specimens on this research.

II. Methods

The concrete specimens used in this research have been made from ordinary portland cement, water, silica fume, silica sand from sieve No. 30 (0.6 mm), and No. 50 (0.3 mm), marble powder from sieve No. 200 (0.075 mm), and superplasticizer. Coarse aggregates have not been used to reach high compressive strength. The materials used are listed in Table I.

In this research, five pairs of concrete beams with 6 cm width, 110 cm length, and varied height of 6 cm, 9 cm, 12 cm, 15 cm, and 18 cm have been tested using two-point symmetric loading. The shear span to effective depth ratio (a/d) of the beam specimens has been held constant at 2.744. Two No. 16 longitudinal bars have been placed in the beams, with the centroid of the bars at 16 mm from the bottom of the beam. Transverse reinforcement has not been used in this research. Concrete compressive strength has been tested using cylinder specimens with 10 cm diameter and 20 cm height. The beam specimens and the beam model for analysis can be seen in Fig. 2.

TABLE I
SAMPLE'S MATERIAL COMPOSITION

Material	Density (kg/m^3)	Ratio
Water	1000	0.19
Cement	3150	1
Silica fume	2200	0.2
Silica sand	2617.8	1.1
Marble powder	2563	0.1
Superplasticizier	7850	0.025

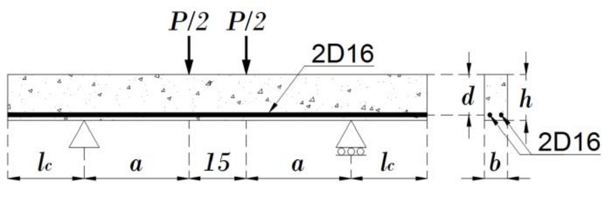

Fig. 2. Concrete beam model with two-point symmetrical loading

For evaluation of test results, three design codes will be used, which comprise ACI 318-14, ACI 318-19, and Eurocode 2. In the absence of axial load and transverse reinforcement on normal-weight concrete, ACI 318-14 [28] gives concrete shear strength as:

$$v_{code} = 0.17\sqrt{f_c^{'}} \tag{3}$$

for the simplified method, and:

$$v_{code} = \min\begin{cases} 0.16\sqrt{f_c^{'}} + 17\rho V_u d/M_u \\ 0.16\sqrt{f_c^{'}} + 17\rho \\ 0.29\sqrt{f_c^{'}} \end{cases} \tag{4}$$

for the detailed method, taking into account the effect of a/d in $V_u d/M_u$ and ρ.

ACI 318-19 still uses Eq. (3) when minimum transverse reinforcement is provided in the beam. For general cases without axial load, ACI 318-19 [26] gives a new formula for concrete shear strength as:

$$v_{code} = 0.66\lambda_s\left(\rho\right)^{1/3}\sqrt{f_c^{'}} \leq 0.42\sqrt{f_c^{'}} \tag{5}$$

where the size effect factor (λ_s) is computed using:

$$\lambda_s = \sqrt{\frac{2}{1+d/250}} \leq 1 \tag{6}$$

The size effect factor always equals 1 when minimum transverse reinforcement is provided.

Contrary to ACI 318-19, Eurocode 2 [25] gives size effect factor (k) in the form of:

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2 \tag{7}$$

For members without transverse reinforcement and axial load, shear strength provided by the concrete is computed using:

$$v_{code} = \max\begin{cases} 0.18k\left(100\rho\left(f_c^{'} - 1.6\right)\right)^{1/3} \\ 0.035k^{3/2}\left(f_c^{'} - 1.6\right)^{1/2} \end{cases} \tag{8}$$

where ρ should not be more than 0.02.

The comparison has been made on concrete shear strength based on test results ($v_{test} = V_u/bd$), ACI 318-14 Simplified (Eq. (3)), ACI 318-14 Detailed (Eq. (4)), ACI 318-19 (Eq. (5)), and Eurocode 2 (Eq. (8)). The comparison will be presented in terms of strength ratio ($SR = v_{test}/v_{code}$) in the table and graph against the effective depth (d).

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In computing *SR* for ACI 318-14 Detailed method, the critical section that will give the lowest *SR* value should be assumed. The lowest *SR* is likely to be at $d \cot \theta/2$ from the point of loading [29]. In this research, it is assumed that the lowest *SR* will be at $x = d$ (maximum shear force) and $x = a/2$. The size effect behavior on concrete shear stress will also be checked following Bažant's size effect law.

III. Results and Discussions

The test results of cylinder and beam specimens are given in Table II. The concrete compressive strength (f'_c) ranges from 58.51 MPa to 99.80 MPa, with an average of 82.75 MPa. All the beams have failed in shear.

Corresponding strength ratios for each method are listed in Table III and plotted into a graph against effective depth in Fig. 3.

From Fig. 3, all the methods give a downward trend, especially from beam depth of 6 cm (d = 4.4 cm) to 9 cm (d = 7.4 cm). For ACI 318-14 Detailed and ACI 318-19 method, there is no obvious downward trend from beam depth of 9 cm to 18 cm (d = 16.4 cm). The most significant downward trend can be seen in Fig. 3 for ACI 318-14 Simplified and Eurocode 2 methods. By increasing the beam depth from 6 cm to 18 cm, the highest *SR* reductions for these two methods reach 72.0% and 73.8% respectively. Compared to that, the reduction reaches 67.5% for ACI 318-14 Detailed and 56.6% for ACI 318-19 method.

TABLE II
TEST RESULTS

Beam ID	Cylinder Specimen		Beam Specimen	
	P (kN)	f'_c (MPa)	P (kN)	Failure Type
1.0B-1	752.5	95.82	37.02	Shear
1.0B-2	707.6	90.10	37.62	Shear
1.5B-1	783.8	99.80	37.02	Shear
1.5B-2	727.1	92.57	37.78	Shear
2.0B-1	459.6	58.51	35.03	Shear
2.0B-2	541.2	68.91	52.76	Shear
2.5B-1	723.7	92.15	49.26	Shear
2.5B-2	708.7	90.24	45.86	Shear
3.0B-1	466.8	59.44	31.74	Shear
3.0B-2	612.1	79.94	48.61	Shear

TABLE III
COMPARISON OF STRENGTH RATIO (*SR*)

Beam ID	ACI 318-14 Simplified	ACI 318-14 Detailed		ACI 318-19	Euro-code 2
		$x = d$	$x = a/2$		
1.0B-1	4.2163	2.4716	2.4714	2.0335	3.3995
1.0B-2	4.4185	2.5902	2.5900	2.1311	3.5274
1.5B-1	2.4583	1.4411	1.5329	1.4100	1.9951
1.5B-2	2.6048	1.5269	1.5990	1.4940	2.0885
2.0B-1	2.1640	1.2686	1.3906	1.3903	1.6129
2.0B-2	3.0007	1.7591	1.9904	1.9279	2.2952
2.5B-1	1.8823	1.2874	1.4246	1.3159	1.5081
2.5B-2	1.7712	1.2069	1.3364	1.2382	1.4143
3.0B-1	1.2378	0.8417	0.9320	0.9256	0.9249
3.0B-2	1.6313	1.1670	1.2797	1.2199	1.2776
Mean	2.5385	1.5560	1.6547	1.5086	2.0044
SD	1.0671	0.5678	0.5333	0.3939	0.8692
COV	0.42	0.36	0.32	0.26	0.43

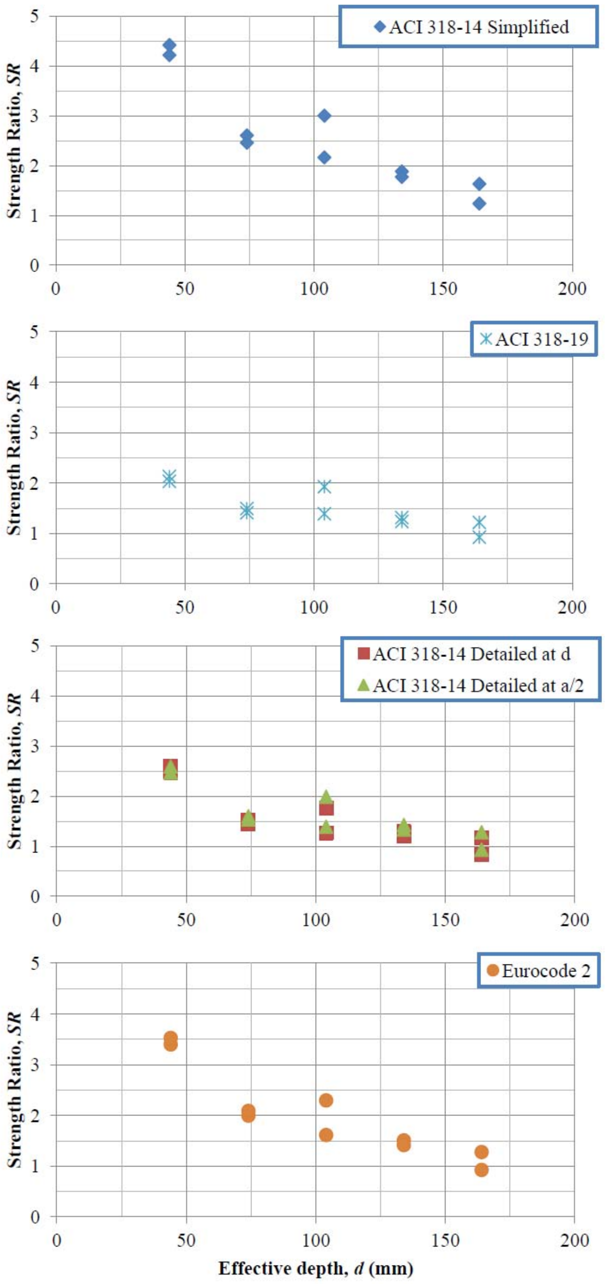

Fig. 3. Strength ratio (*SR*) vs. effective depth

The significant downward trend in Fig. 3 can be caused by the fact that the concrete shear strength formulas have not accounted for the dependence on effective depth (size effect) correctly. For ACI 318-14 Simplified method, the formulas are simply a function of concrete strength.

Therefore, it is expected that this method gives a significant downward trend. For Eurocode 2 method, the downward trend might occur because the size effect correction has been derived from purely empirical data.

Except for beam ID 3.0B-1, all the beams have failed at shear stress greater than the shear strength computed from code formulas (*SR* > 1). Even though there is a beam with *SR* less than 1, there is no SR value less than 0.5. For ACI 318-14 Simplified method, ACI 318-14 Detailed method,

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and ACI 318-19 method, there is no *SR* value less than 0.75, which corresponds to the strength reduction factor for shear. For Eurocode 2 method, there is no *SR* value less than 2/3, which corresponds to the inverse of partial safety factor for concrete material in persistent and transient design conditions.

According to Table III, ACI 318-19 method yields the lowest Coefficient Of Variation (*COV*) of 0.26. This shows that shear strength prediction using ACI 318-19 method gives the lowest variation in *SR* for shear stress of concrete beams without coarse aggregate being tested.

Contrary to ACI 318-19 method, ACI 318-14 Simplified and Eurocode 2 method yield *COV* of 0.42 and 0.43 respectively. These two methods give the highest *SR* variation from the four methods considered in this research.

In order to evaluate further the size effect, the bi-logarithm plot as in Fig. 1 has been made. First, the size effect correction function should be selected. Three functions that are considered are in the form of Bažant's size effect law, LEFM ($\beta^{-1/2}$), and Eurocode 2 method ($1 + \beta^{-1/2}$). Because the size effect factor in Eurocode 2 is purely empirical, the proposed formula might only apply to the specimen size range used in this research, which is impractical size to actual construction. The ($1 + \beta^{-1/2}$) function also gives a horizontal asymptote for large size. This means that there is no size effect for large size concrete beam, which is cannot be justified.

Since high-strength concrete without coarse aggregate is very brittle, it might be reasonable to use the LEFM solution. However, in this research, not all the specimens have $\beta > 10$ and it might be better to fit the test results to the NLFM solution. Thus, the size effect correction function will follow Bažant's size effect law as given in Eq. (1).

In order to account for the variation of concrete strength (f'_c) and longitudinal reinforcement ratio (ρ) in the concrete specimen, the Y-axis of Fig. 1 will be taken as shear stress divided by a function of f'_c and ρ. Because ACI 318-19 size effect factor is similar to Bažant's size effect law, the effect of concrete compressive strength will be taken as $(f'_c)^{1/2}$ and the effect of longitudinal reinforcement ratio will be taken as $\rho^{1/3}$. This leads to the normalized shear stress ($v\rho^{-1/3}(f'_c)^{-1/2}$) as plotted in the Y-axis of Fig. 4. For the X-axis, the value of the brittleness number (using Eq. (2)) has been selected. The computational results are given in Table IV.

TABLE IV
NORMALIZED SHEAR STRESS AND SR FOR EQ. (9)

Beam ID	*h* (mm)	β	$v\rho^{-1/3}(f'_c)^{-1/2}$	*v* (MPa)	*SR*
1.0B-1	60	2.93	1.3421	6.8534	1.0238
1.0B-2	60	2.93	1.4065	6.6457	1.0729
1.5B-1	90	4.93	0.9306	4.7887	0.8718
1.5B-2	90	4.93	0.9860	4.6120	0.9238
2.0B-1	120	6.93	0.9176	2.8309	0.9940
2.0B-2	120	6.93	1.2724	3.0722	1.3784
2.5B-1	150	8.93	0.8685	2.9177	1.0528
2.5B-2	150	8.93	0.8172	2.8873	0.9906
3.0B-1	180	10.93	0.6109	1.9987	0.8117
3.0B-2	180	10.93	0.8051	2.3179	1.0697

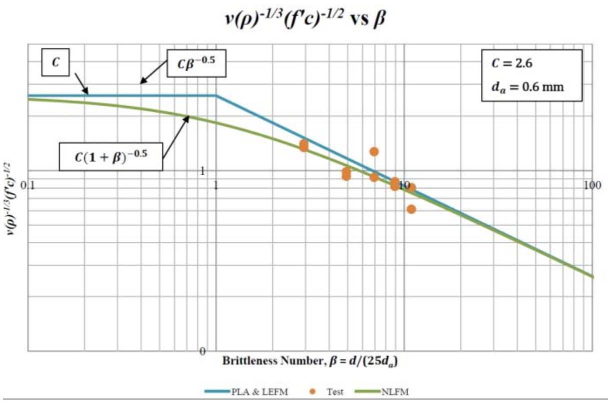

Fig. 4. Normalized shear stress ($v\rho^{-1/3}(f'_c)^{-1/2}$) vs brittleness number

In order to determine the shear formula, the constant *C*, which is normalized shear stress according to strength criterion ($v_0\rho^{-1/3}(f'_c)^{-1/2}$), needs to be determined. Using the test results in Fig. 4, the constant *C* is taken as 2.6. By using this value, the size effect behavior on shear strength of no-coarse aggregate concrete beams can be represented by the following equation:

$$v = 2.6\rho^{1/3}\sqrt{f_c^{'}}\left(1+\beta\right)^{-0.5} \tag{9}$$

In Fig. 4, it can be seen that the test results follow Bažant's size effect law. The test results start approaching LEFM solution for beam height of 15 cm ($\beta = 8.93$) and 18 cm ($\beta = 10.93$).

The shear strength according to Eq. (9) and the corresponding *SR* is given in Table IV. Eq. (9) gives a better prediction than ACI 318-19 method, with an average *SR* of 1.019 and *COV* of 0.15. There is also no downward trend on the *SR* vs effective depth graph for the proposed formula as can be seen in Fig. 5.

Contrary to Eq. (9), ACI 318-19 does not give size effect correction for beams with effective depth less than 25 cm, even though the size effect can be seen in Fig. 4.

Because the highest brittleness number in this research is already greater than 10, there should be a size effect even though the beam depth is less than 25 cm. This might occur because ACI 318-19 does not account for the influence of maximum aggregate diameter.

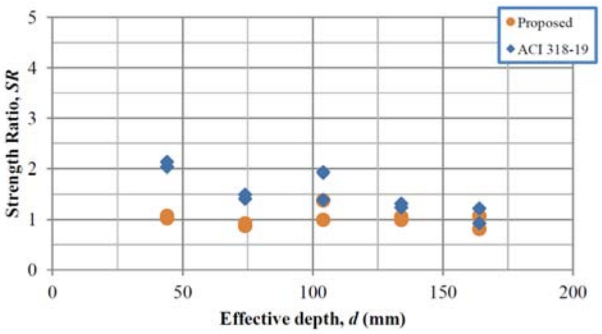

Fig. 5. Strength ratio (*SR*) vs. *d* for Eq. (5) and Eq. (9)

Even though Eq. (9) gives better results, half of the beam specimens have failed at shear stress less than the shear strength computed from Eq. (9). Eq. (9) gives the lowest *SR* value of 0.8117. This indicates that Eq. (9) should not be used directly for the design. A safety factor needs to be applied to Eq. (9) so that it can be used for design.

IV. Conclusion

Compared to ACI 318-14 and Eurocode 2 method, ACI 318-19 method gives the best prediction of the shear strength of concrete beams without coarse aggregate, with an average *SR* of 1.5086 and *COV* of 0.26. ACI 318-19 does not show a significant downward trend on *SR* vs effective depth compared with ACI 318-14 and Eurocode 2 method. Even though the lowest *SR* is still greater than the design code's safety factor, these shear formulas might not be used for large beams because of the strong size effect on no-coarse aggregate concrete beams.

There is a size effect behavior on shear strength of no-coarse aggregate concrete beam that agrees well with Bažant's size effect law. ACI 318-19 and Eurocode 2 method cannot capture this behavior because the influence of maximum aggregate diameter (d_a) is not explicitly shown in their formulas. For concrete beams that have been tested ($d_a = 0.6$ mm and d ranges from 4.4 cm to 16.4 cm), size effect behavior on shear strength can be described by $v = 2.6\rho^{1/3}(f'_c)^{1/2}(1 + \beta)^{-1/2}$ with $\beta = d/(25d_a)$. This equation should not be used for design without additional safety factors.

For beam height of 18 cm ($d = 16.4$ mm), the size effect behavior tends to approach the linear elastic fracture mechanics (LEFM) solution with an inclined asymptote of –1/2. Since the beams practically used in construction are larger than the beams tested, the consideration of using size effect correction on LEFM should be made for better accuracy.

For future research, the influence of maximum aggregate diameter needs to be investigated. A wider range of beam size or depth will be needed to improve the proposed equation. A solution based on LEFM needs to be considered as the no-coarse aggregate concrete beam size that will be used in construction might have a high brittleness number.

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