

Investigations of HSC punching shear capacity in flat slabs

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ABSTRACT

Slabs punching shear capacity for normal strength concrete (NSC) and high strength concrete has been investigated in this paper. Due to the significance of concrete technology in the construction industry, more attention has been paid to high strength concrete in this paper. Then, detailed comparison is carried to evaluate the outcome by referring to several existing standards.

Slabs punching tests have been collected from the reported results in the literature. Forty-seven tested slab specimens have been grouped from the available published information. In this work, the collected specimens are studied thoroughly, and a conclusion has been drawn from the preliminary investigation that punching shear failure is a common feature in the forty-seven specimens. The collected concrete slab specimens have diversified cylinder compressive strength (f'_c) ranged from 14.4 MPa to 119 MPa. However, the application of (f'_c) in existing codes is restricted to a limit as mention hereafter. American Concrete Institute (ACI-14) limits the practical application of f'_c to 69MPa, while The Australian Concrete Structures Standard (AS-94) limits f'_c to 50 MPa. The recent evolvement in concrete technology has made the production of HSC with f'_c much greater than the aforementioned values affordably reachable. Therefore, the present research attempts to bridge this gap and goes beyond the standards restrictions. This has been achieved by proposing a new design equation for punching shear through applying a regression analysis. The accuracy of the proposed equation and the existing equations have been examined by utilizing statistical analysis [Arithmetical mean (\bar{x}), Variation (VAR), Standard Deviation (SD) and Coefficient of Variation (COV)] to the punching shear failure strength values. The proposed method results for \bar{x} , VAR, SD and COV are 1.575, 0.364, 0.1299 and 23.128% respectively, and these are smaller when compared with the other 6 existing code methods.

Keywords: Flat slab, Punching Shear, High Strength Concrete, Normal Strength Concrete

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1. Introduction

Concrete technology has been evolving through the last few decades, and that has triggered the opportunities for reevaluating existing design methods and equations. One of these highlighted methods is punching shear in flat slab. Slabs punching shear capacity is controlled by several parameters, and one of these significant factors is the concrete strength. That makes it worth to assess the standards by implementing concrete strength beyond the limits.

Cracks are often generated when load is nearly 70% of the ultimate load in flat slabs. Cracks may surround a column; however, the slab is stable and it is possible to have it loaded and unloaded safely. Also, the slab ultimate capacity would not be affected[1]. This is a clue that the failure is not generally governed by a pure shear controlled by the concrete diagonal tensile strength. Here, a decision can be made that in order to have a

better understanding for punching shear failure, the characteristics of the un-cracked concrete area surrounding the columns have to be identified accurately [1].

Since concrete technology has evolved rapidly in the last century, diversified concrete strength range is now available in batch plants all over the world. That also made HSC cost comparable to NSC; therefore, it is used in medium as well as long span concrete beam and girders. Moreover, HSC has been employed for durability purposes in many structures.

HSC can be defined as a concrete mix that has a compressive strength greater than 55 MPa[2]. The reinforced concrete flat slab system is a widely used structural system. Its formwork is very simple and therefore could be more economic, as no beams or drop panels are used. However, the catastrophic nature of the failure exhibited at the experimental results of (47) reinforced concrete flat slab have been taken from existing research. Some of connection between the slab and the column has concerned engineers.

The area located at a column's vicinity shown in Fig. (1) is classified as the most critical area when slab strength is evaluated since flexural (bending moment and shear forces) stresses are concentrated in that area. Whereas, an unrestricted slab flexural capacity might be significantly higher than the critical failing load. Here, the slab punching shear strength can be enormously improved in transferring higher forces through the slab-column connection [3].

1.1. Experimental results

In this research, the available literature is utilized in providing experimental tests for slab punching shear failure. All the aforementioned samples have failed in punching shear. Some of the specimens are circular, square or rectangular slabs in which both NSC or HSC have been employed. The concrete f'_c for the studied samples are diversified between 14.4 MPa to 119 MPa. These slabs' results have been collected from the following references [4].

Concrete technology has been evolving for the last few decades, and ever since concrete strength has broken all the records. Therefore, researchers have been investigating the influence of concrete super-strengthening on resisting capacity practically and theoretically. One of these investigated areas in this research is slab punching shear resistance by demonstrating and examining punching capacity equation for both HSC and NSC[5].

In this work, slabs' punching shear capacity has been evaluated based on the following six codes: ACI-14[6], CAN-84⁽²⁾, AS-94⁽³⁾, IRAQ-87⁽⁴⁾, EGY-07⁽⁵⁾ and SYR-04⁽⁶⁾. The equations presented in the aforementioned codes for determining slab punching design strength have a limit which makes these equations not applicable when the limit is exceeded. Therefore, the effects of HSC high strength cannot be emphasized, and hence it is very critical to develop an equation to evaluate punching shear capacity for concrete strength that surpasses the limits available in the aforementioned codes.

1.2. Existing methods for predicting punching shear strength of flat slabs

A comparison is conducted to evaluate slabs' punching shear capacities by examining the equations available in the codes (1-6) utilized in this study. This is done by employing the concrete experimental strength for the slabs failed by punching shear in determining the punching shear resistance V_{c-cal} which is used instead V_{n-cal} throughout the rest of this research [e.g., per ACI-14 code: $V_{c-cal}=0.75 V_{n-cal}$]. Table (1) shows the codes' equations which are used to analyze the tested slab punching shear[7].

2. Proposed method

Most specimens tested and referred to by the ACI code have been mainly NSC concrete with $f'_c < 55$ MPa [8]. In this work, an equation has been developed by employing a regression analysis based on 30 available HSC ($f'_c > 55$ MPa) tests to identify slabs' punching shear capacity for HSC.

When a statistical manipulation has been applied for the studied tests data and validated with the available results, it has been comprehended those equations for computing the slab punching shear capacity available in ACI code (and some other codes) are not satisfactory for HSC. This confirms that most ACI code design equations have been developed based on NSC tests.

Therefore, an empirical equation is formed to evaluate HSC slabs punching shear capacity. This aforementioned equation has been fundamentally derived to satisfy HSC punching shear evaluation[9].

In the regression analysis, the 47 test results have been investigated to reach a simple safe design method for punching shear that gives the lowest potential coefficient of variation value (V_{c-test}/V_{c-cal}). This has led to the following prediction equation for V_{c-prop} :

$$V_c = 0.33 \left[1 + \frac{2}{\beta_c} \right] \left(f'_c \right)^{0.314} b_o d \leq 0.67 \left(f'_c \right)^{0.314} b_o d$$

The length of the critical perimeter is taken at distance of $\left(\frac{d}{2} \right)$ form the face of column as shown in Fig. (2)

Table 1. summarizes the codes equations used to estimate punching shear of slab

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|--|
| <p>ACI 318M-14⁽¹⁾: $V_c = 0.17 \phi \lambda \left[1 + \frac{2}{\beta_c} \right] \sqrt{f'_c} b_o d, V_c = 0.083 \phi \lambda \left[2 + \frac{\alpha_s d}{b_o} \right] \sqrt{f'_c} b_o d$ &</p> <p>$V_c = 0.33 \phi \lambda \sqrt{f'_c} b_o d$, V_c is the least value (Punching shear resistance provided by concrete). ϕ = strength reduction factor equal to 0.75 β_c = is the ratio of the long side to short side of the column, λ = factor which equals (0.85) for sand-light weight concrete, (0.75) for all light weight concrete, and (1) for normal weight concrete b_o = perimeter of critical section for slabs and footings, mm, Fig.(2), α_s = factor which equals 40 for interior columns, 30 for edge columns and 20 for corner columns, This root ($\sqrt{f'_c}$) has a limited value which shall not exceed $\frac{25}{3}$ MPa (i.e. using an upper limit to f'_c of approximately 69 MPa). The punching shear strength values vary with concrete compressive strength (f'_c). They are proportional to f'_c. This square root expression was adopted by Moe[10], who concluded that the shear failure is controlled primarily by the tensile- splitting strength[11], which is assumed proportional to $\sqrt{f'_c}$.</p> |
| <p>CAN-84⁽²⁾: $V_c = 0.12 \left[1 + \frac{2}{\beta_c} \right] \sqrt{f'_c} b_o d \leq 0.24 \sqrt{f'_c} b_o d$</p> |
| <p>AS-94⁽³⁾: $V_c = b_o d (f_{cv})$ & $f_{cv} = 0.17 \left[1 + \frac{2}{\beta \eta} \right] \sqrt{f'_c} \leq 0.34 \sqrt{f'_c}$</p> <p>Where $\beta \eta$ = ratio of longest column dimension to shorter column dimension. Also, the square root of ($\sqrt{f'_c}$) is considered in this design approach, which is similar to ACI-08 code. But AS-9 gave an upper limit of 50 MPa for f'_c.</p> |
| <p>IRAQ-87⁽⁴⁾: $V_c = \frac{1}{8} \left[1 + \frac{2}{\beta_c} \right] \sqrt{\frac{f_{cu}}{\gamma_m}} b_o d \leq 0.25 \sqrt{\frac{f_{cu}}{\gamma_m}} b_o d$</p> <p>Where f_{cu} = specified compressive strength of concrete cube, MPa, the cube strength is equal to $1.25 * f'_c$, γ_m = strength reduction factor for compressive strength concrete is equal to 1.5</p> |
| <p>EGY-07⁽⁵⁾:</p> <p>$V_c = 0.8 \left(\frac{\alpha d}{b_o} + 0.2 \right) \sqrt{\frac{f_{cu}}{\gamma_c}} b_o d, V_c = 0.316 \left(0.5 + \frac{b}{h} \right) \sqrt{\frac{f_{cu}}{\gamma_c}} b_o d, V_c = 0.316 \sqrt{\frac{f_{cu}}{\gamma_c}} b_o d$</p> <p>& $V_c = 1.6 b_o d$</p> <p>α = factor which equals (4) for interior columns, (3) for edge columns and (2) for corner columns, b, h = short and long side of the column, respectively</p> |
| <p>SYR-04⁽⁶⁾: $V_c = \phi \left[0.16 + \frac{b}{3h} \right] \sqrt{f'_c} b_o d \leq 0.31 \phi \sqrt{f'_c} b_o d$</p> <p>$\phi$ = strength reduction factor equal to 0.8</p> |

3. Results and discussion

The 47 concrete compressive strengths presented in the literature have been well utilized to figure out slabs punching shear capacity based on the different standards data. Then, a comparison between the calculated strengths from the following codes ACI-14⁽¹⁾, CAN-84⁽²⁾, AS-94⁽³⁾, IRAQ-87⁽⁴⁾, EGY-07⁽⁵⁾, SYR-04⁽⁶⁾ and the equation developed in this research has been arranged [12].

The comparison is set in a way to emphasize the link between V_{test}/V_{c-cal} ratio to f'_c . The ratio V_{test}/V_{c-cal} shows whether a certain standards — the strength evaluation equation — is safe or not[10]. Greater ratios mean the code (standards) is super-conservative but not economic. On the other side, smaller ratios mean the code is not safe. The results of the analysis are illustrated, where a curve of V_{test}/V_{c-cal} versus f'_c is plotted to show the effect of concrete strength on the safety provided by each method, see Figs. (3 to 9). It can be noticed from these figures that the following standards ACI-08⁽¹⁾, CAN-84⁽²⁾, AS-94⁽³⁾, IRAQ-87⁽⁴⁾, SYR-04⁽⁶⁾ offer less conservativity when (f'_c) is increased. That means the safety factor is sharply decreased as the concrete strength increases [i.e. a negative slope is obtained from results of V_{test}/V_{c-cal} . versus f'_c], while the proposed method (equation) has a slight increase in safety when (f'_c) is increased.

Generally, in case of high strength concrete the ACI-14⁽¹⁾, CAN-84⁽²⁾, AS-94⁽³⁾, IRAQ-87⁽⁴⁾, SYR-04⁽⁶⁾ approaches tend to be very unsafe when (f'_c) increases. Whereas, the proposed method is more conservative in the case of HSC. From Figs. (3 to 9) the best fit correlating line for the scattered points (V_{test}/V_{c-cal} .) is called Relative Capacity Strength Value (RCSV)[13], and it can be written as follows:

$$\begin{aligned} \text{RCSV for ACI -14 Code} &= 2.366 - \frac{f'_c}{175.31} && \text{for } f'_c \text{ in MPa} \\ \text{RCSV for CAN-84 Code} &= 2.462 - \frac{f'_c}{165.02} && \text{for } f'_c \text{ in MPa} \\ \text{RCSV for AS-94 Code} &= 1.738 - \frac{f'_c}{233.77} && \text{for } f'_c \text{ in MPa} \\ \text{RCSV for IRAQ-87 Code} &= 3.236 - \frac{f'_c}{125.53} && \text{for } f'_c \text{ in MPa} \\ \text{RCSV for EGY-07 Code} &= 2.317 + \frac{f'_c}{32.24} && \text{for } f'_c \text{ in MPa} \\ \text{RCSV for SYR-04 Code} &= 2.242 - \frac{f'_c}{181.17} && \text{for } f'_c \text{ in MPa} \\ \text{RCSV for Proposed Equation} &= 1.506 + \frac{f'_c}{898.53} && \text{for } f'_c \text{ in MPa} \end{aligned}$$

3.1. Statistical calculation of $V_{test} / V_{calculated}$

A comprehensive investigation is conducted to evaluate slabs punching shear strengths theoretically and experimentally. made on the theoretical punching shear resistance estimations and the corresponding results from experimental tests. This investigation emphasizes the differences between estimated theoretical and experimental strength values. A comparison between the experimental and theoretical strength has been presented.

Table (2) summarize the statistical results of the computer analysis for the tested punching shear of slab. The arithmetical mean (\bar{x}), Variation (VAR)⁽¹³⁾, Standard Deviation (SD)⁽¹⁴⁾ and Coefficient of Variation (COV)⁽¹⁵⁾ values were computed for the different methods considered herein.

The table shows that proposed method gives a better data representation. The proposed method gives lower VAR and SD values which are 0.1299 and 0.364, respectively. These values are considered the best when compared with the second-best values of AS-94 method which are 0.1366 and 0.374. The proposed method gives lowest COV value which is 23.128% when compared to the second-best value of ACI-14 method which is 24.720%. This reduction in VAR, SD and COV values validate the adequacy of the new proposed approach suggested in this study[14].

Table 2. Statistical results

| No. | Method | \bar{x} | VAR | SD | COV% | High | Low | No.<1 |
|-----|------------------------|-----------|--------|-------|--------|------|------|-------|
| 1 | ACI-14 ⁽¹⁾ | 2.009 | 0.2415 | 0.497 | 24.720 | 3.53 | 0.94 | 1 |
| 2 | CAN-84 ⁽²⁾ | 2.083 | 0.2810 | 0.536 | 25.723 | 3.68 | 0.98 | 1 |
| 3 | AS-94 ⁽³⁾ | 1.470 | 0.1366 | 0.374 | 25.442 | 2.59 | 0.69 | 4 |
| 4 | IRAQ-87 ⁽⁴⁾ | 2.738 | 0.4739 | 0.696 | 25.420 | 4.83 | 1.29 | 0 |
| 5 | EGY-07 ⁽⁵⁾ | 4.256 | 4.2974 | 2.095 | 49.239 | 9.70 | 1.56 | 0 |
| 6 | SYR-04 ⁽⁶⁾ | 1.897 | 0.2275 | 0.482 | 25.412 | 3.35 | 0.89 | 1 |
| 7 | Proposed method | 1.575 | 0.1299 | 0.364 | 23.128 | 2.48 | 0.77 | 2 |

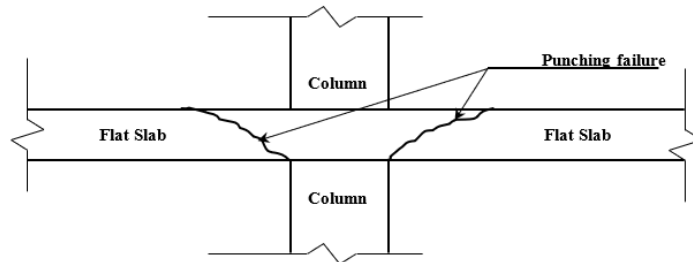


Figure 1. Punching shear failure of flat slab⁽¹¹⁾

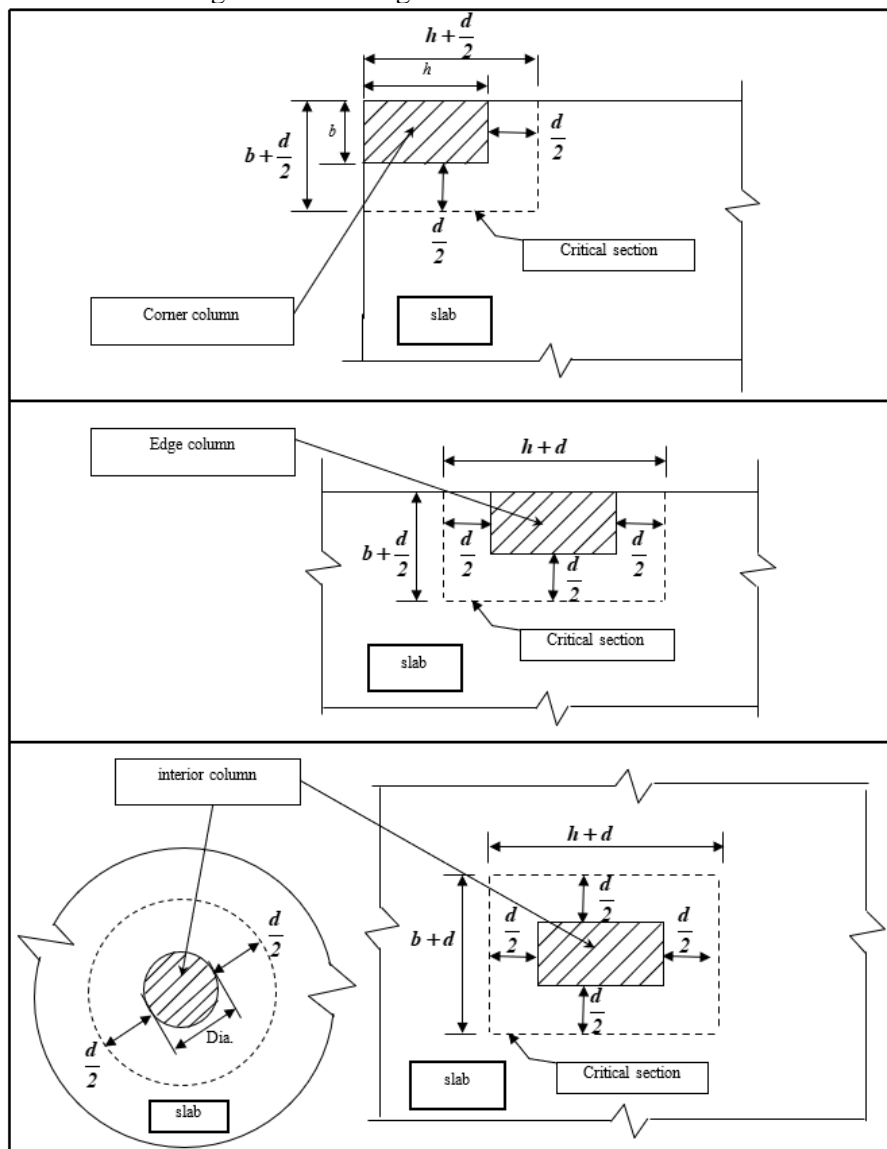


Figure 2. Perimeter b_o computation (critical section for punching shear in slab)

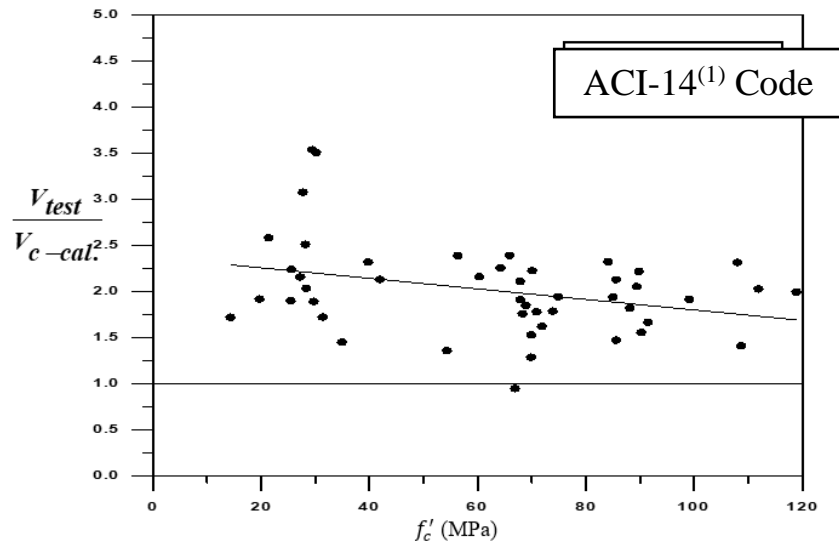


Figure 3. Effect of compressive strength of concrete on RCSV of punching shear according to ACI-14⁽¹⁾ Code.

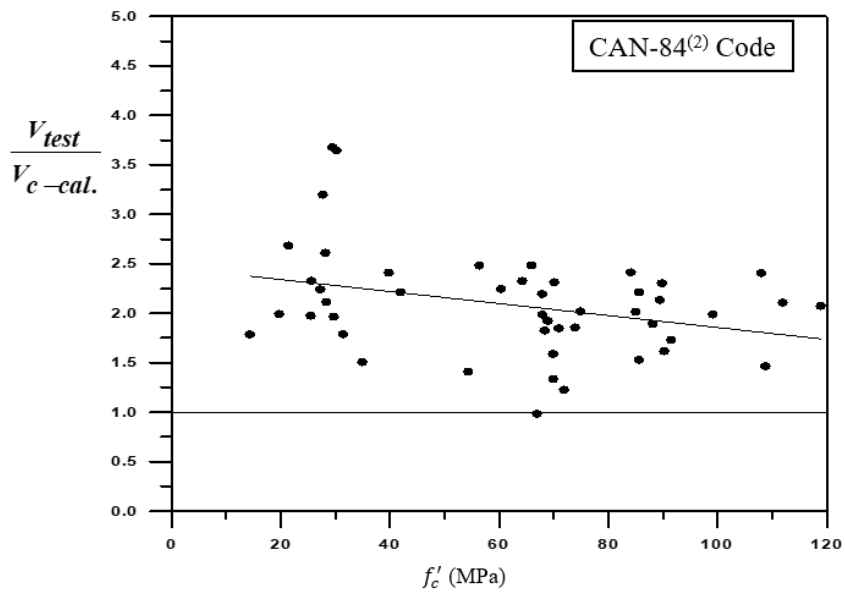


Figure 4. Effect of compressive strength of concrete on RCSV of punching shear according to CAN-84⁽²⁾ Code

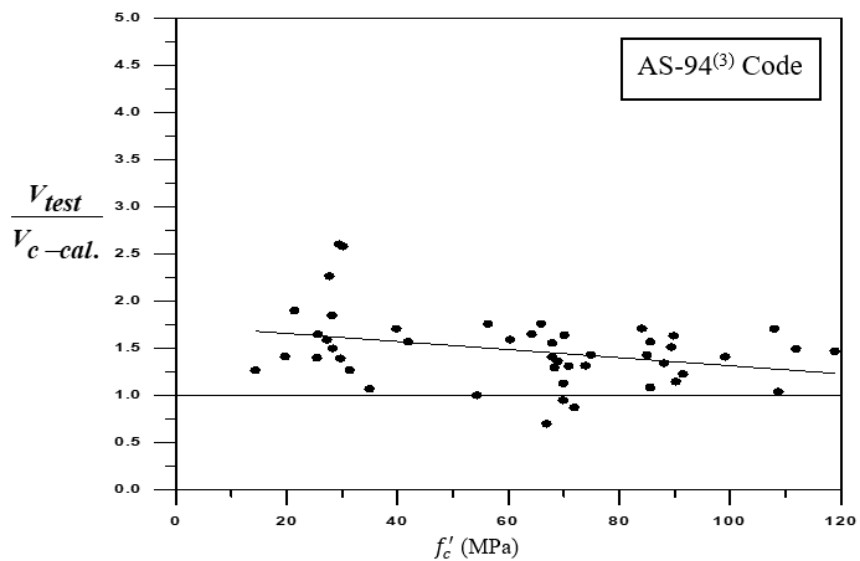


Figure 5. Effect of compressive strength of concrete on RCSV of punching shear according to AS-94⁽³⁾ Code

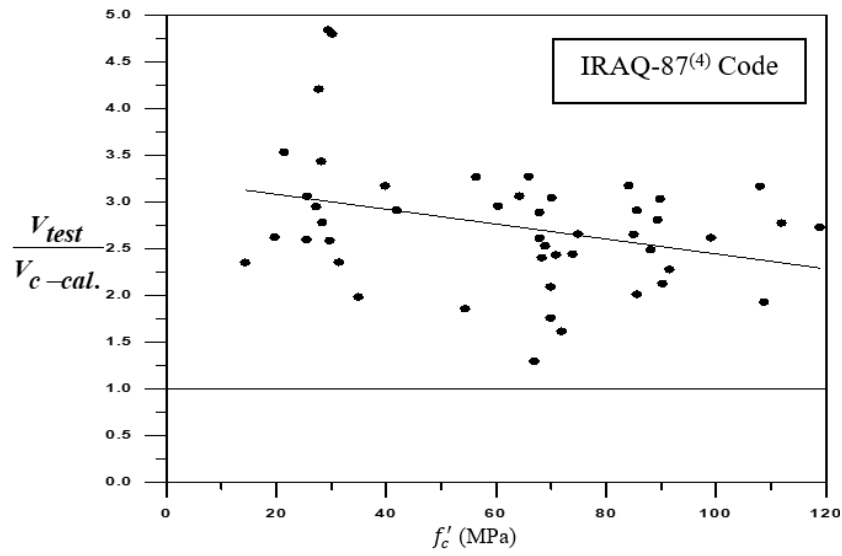


Figure 6. Effect of compressive strength of concrete on RCSV of punching shear according to IRAQ-87⁽⁴⁾ Code

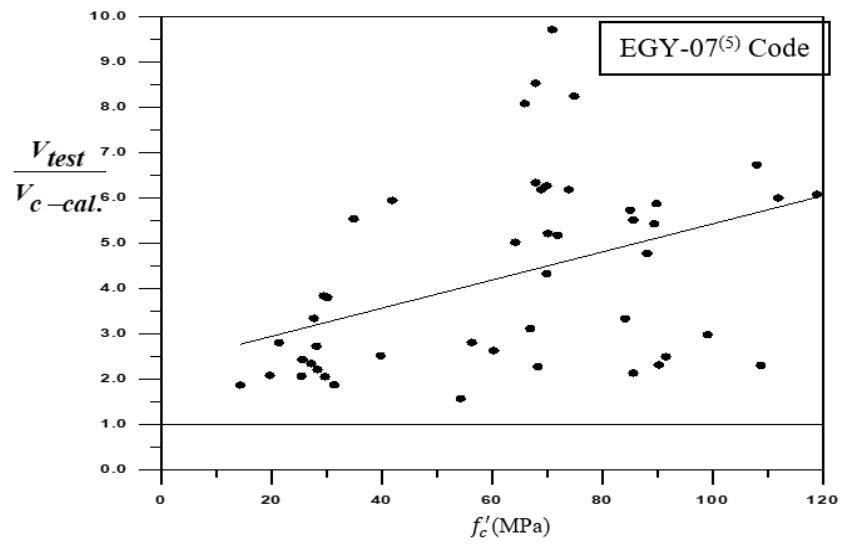


Figure 7. Effect of compressive strength of concrete on RCSV of punching shear according to EGY-07⁽⁵⁾ Code

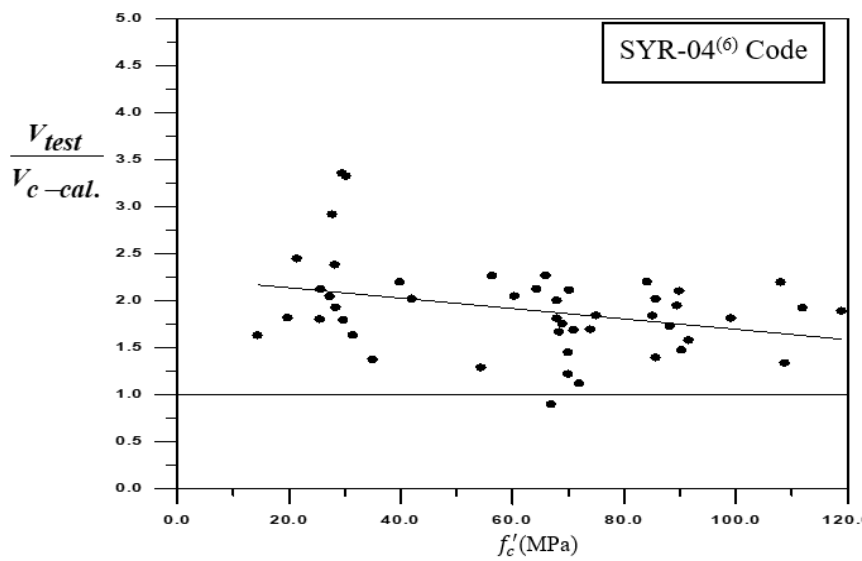


Figure 8. Effect of compressive strength of concrete on RCSV of punching shear according to SYR-04⁽⁶⁾ Code

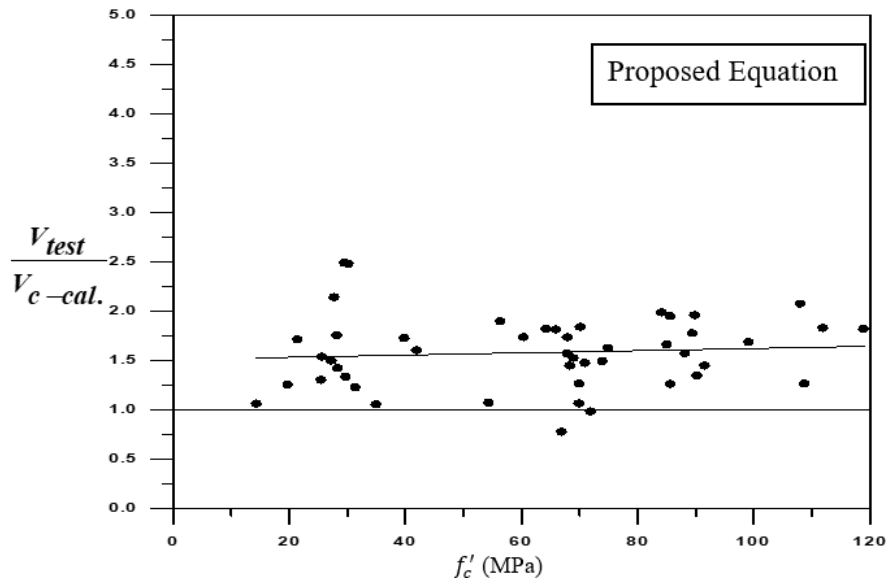


Figure 9. Effect of compressive strength of concrete on RCSV of punching shear according to Proposed Equation

4. Conclusions

Based on this work, the following conclusions are drawn:

1. In case of high strength concrete the ACI-14⁽¹⁾, CAN-84⁽²⁾, AS-94⁽³⁾, IRAQ-87⁽⁴⁾, SYR-04⁽⁶⁾ approaches tend to be very unconservative with the increase (f'_c), while the proposed method will be more conservative in the case of HSC, see Figs. (3 to 9).
2. Table (2) shows that the COV of the ratio ($V_{test}/V_{c-cal.}$) is in descending order 49.239, 25.723, 25.442, 25.420, 25.412, 24.720 and 23.128 respectively using EGY-07⁽⁵⁾, CAN-84⁽²⁾, AS-94⁽³⁾, IRAQ-87⁽⁴⁾, SYR-04⁽⁶⁾, ACI-14⁽¹⁾ and proposed method which gives advantage to the proposed approach.
3. Most results of EGY-07⁽⁵⁾ indicate conservative prediction of strength with high arithmetic mean of ($V_{test}/V_{c-cal.}$) equal to 4.256. While the proposed method led to improve results compared to EGY-07⁽⁵⁾. The proposed method gives conservative strength values with low arithmetic mean of ($V_{test}/V_{c-cal.}$) equal to 1.575, see Figs. (7 and 9).
4. ACI-14⁽¹⁾ code cannot be applicable for concrete compressive strength (f'_c) up to 69MPa, where the term ($\sqrt{f'_c}$) has a limited value which shall not exceed $\frac{25}{3}$ MPa. Further, the AS-94⁽³⁾ code gave an upper limit of 50 MPa for concrete compressive strength.
5. The ACI-14⁽¹⁾, CAN-84⁽²⁾, AS-94⁽³⁾, IRAQ-87⁽⁴⁾, SYR-04⁽⁶⁾ show that when (f'_c) increased safety is sharply dropped, and this means that the suggest method is the most accurate when it is compared to the other methods.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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