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Prediction of Shear Capacity of Reactive Powder Reinforced Concrete Beams

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ABSTRACT: Reactive Powder Concrete is used in specialized structures for its high compressive strength, dense and homogeneous microstructure, and high tensile strength, particularly when steel fibers are included in the mix. Despite its increasing use in structural applications, current design code provisions do not adequately address the shear behavior of RPC beams, and most available predictive models are derived from conventional concrete or very limited samples, leading to significant inaccuracies. Therefore, this study aimed to develop more accurate shear capacity prediction equations for RPC beams by analyzing experimental data reported by previous researchers. A database of 36 RPC beam specimens was compiled from the literature, covering a wide range of parameters, including the compressive strength, steel fiber volume fraction, shear span-to-depth ratio, and longitudinal reinforcement ratio. All collected RPC beams failed in shear and without shear reinforcement to study the capacity of concrete alone to resist shear loads. To develop accurate equations for estimating the shear capacity of RPC, researchers have focused on two aspects. The first aspect involved modifying the existing equations by recalibrating the constant coefficients of the collected data. The second aspect was to achieve more accurate equations by attempting to predict new formulas using updated coefficients. Statistical regression analysis was conducted to derive the proposed equations, yielding a significantly improved correlation with the experimental results compared with the existing models. The proposed equation exhibited a lower standard deviation and coefficient of variation than the equations suggested by other researchers. Coefficient of variation values for the proposed equations ranged from 11.059% to 11.411%, while for the modified equations ranged from 11.482% to 14.133%. Both the modified and proposed equations are simpler and more convenient for engineering applications owing to the simplicity of the numbers and constant coefficients. To obtain more reliable, proposed equations, a larger amount of experimental data must be obtained in the future.

KEYWORDS: Reactive powder concrete (RPC); ultra-high-performance concrete; shear capacity; predictive model; steel fibers; shear- span-to-depth ratio; regression analysis

1 Introduction

Reactive Powder Concrete (RPC) is a specialized concrete whose microstructure is optimized by precisely grading all the particles in the mix to achieve maximum density [1]. In recent decades, Reactive Powder Concrete, which is a type of ultra-high-performance concrete, was recognized as one of the most advanced cementitious composites developed. It represents the future direction for the development of building concrete materials [2]. The use of RPC yields high-strength, high-ductile concrete with optimized material use and contributes to economic, sustainable, and eco-friendly constructions [3]. RPC is produced through fine sand particle packing, a low water-to-binder ratio, steel fibers in optimal proportions, and often silica fume enrichment and a superplasticizer at the correct dose. It is composed of very fine powders (cement, sand, quartz powder, and silica fume), steel fibers (optional), and superplasticizer. Due to its high

strength, good workability, and high durability, it has been successfully used for buildings and bridges in the past decades [4]. These unique features enhance mechanical properties, including tensile strength, reduced cracking width and number, and improved energy absorption. RPC's advantages have drawn growing interest in structural applications that demand ultra-high strength, compactness, and durability. RPC should be employed in various engineering fields, such as civil, marine, nuclear power plants, petroleum, and military constructions [5]. The outstanding performance of RPC is due to microstructural improvement processes applied to cementitious materials, including excluding coarse aggregates, using superplasticizing agents to lower the water/cement ratio, and incorporating fibers and cementitious components like silica fume [6].

Among the major considerations governing the functionality of structural concrete members is shear behavior, which is obviously more difficult to predict than flexure. The shear deformation should be strongly considered for better accuracy in most simulations of structural modeling [7]. The structural behavior of RPC beams in shear differs significantly from that of normal reinforced concrete because of the contribution of increasing homogeneity, fiber bridging mechanisms, and the initiation of limiting crack widths. Therefore, the design equations adopted for normal or high-strength concrete continuously fail to faithfully predict the shear capacity of RPC beams. This lack has led to the need for more accurate models covering the material's special properties. Major design codes like ACI [8], Eurocode [9], and other current practice codes do not provide specific provisions for shear in RPC, which represents a difficulty for engineers seeking to combine this material into practical structural design. The first suggestions for design RPC construction projects were mentioned in 2002 by the French Association of Civil Engineers (AFGC)-2002, and they were modified in 2013 by the same association [10] (<https://www.mdpi.com/2673-4117/5/2/43>). Suggestions were made for the design of RPC beams by the Japan Society of Civil Engineers (JSCE) [11] (<https://www.mdpi.com/2673-4117/5/2/43>) and the Korea Concrete Institute (KCI-2012) [12] (<https://www.mdpi.com/2673-4117/5/2/43>). Many researchers have conducted experimental studies to predict the shear strength of RPC beams with various parameters, examining the effects of fiber volume fraction, shear-span-to-depth ratio, longitudinal reinforcement ratio, and compressive strength. However, the results are still disjointed across different studies, and no unified predictive formula using different experimental results for different researchers has been widely implemented. The compressive strength of RPC was very high compared to conventional concrete. A direct relationship was observed between steel fiber content and compressive strength, with a notable increase of 13.5% [13]. Ultra-high-performance fiber-reinforced concrete exhibits substantial variation in mixing ratios and strengths depending on the intended research purpose, yet a general design method remains difficult to develop. The inclusion of 2% volume fraction steel fibers significantly increases the shear and flexural strengths of ultra-high performance fiber reinforced concrete (UHPFRC) beams. In particular, steel fiber inclusion changed the mode of failure of beams from diagonal shear failure to flexural failure [14]. To address this gap, the present study collected and analyzed a detailed database of previously tested RPC beams reported in literature. By incorporating this database, the study aimed to detect the most influential parameters governing shear resistance and to develop empirical equations capable of providing accurate predictions across a wide range of RPC parameters and structural idealization.

2 Literature Review

Over the past few decades, limited research has been conducted to study the shear performance of reactive powder concrete (RPC) beams; hence, in this section, relevant studies were reviewed.

In a study conducted by Bae et al. [14], the main variables examined included the fiber volume fraction (0% and 2%), shear span-to-depth ratio (2.0, 3.4, and 6.6), and the compressive strength of the matrix (high strength and ultra-high strength). The results indicated a 95% increase in diagonal shear cracking strength

attributable to the incorporation of 2% steel fibers, as well as a significant enhancement in shear strength with a decrease in the shear span-to-depth ratio.

Ashour et al. [15] conducted tests on fibrous rectangular high-strength reinforced concrete beams under combined flexural and shear loading. The beams were singly reinforced and without transverse reinforcement. The main variables that were used in this work were the steel fiber volume fraction, longitudinal rebar ratio, and the shear span to effective depth ratio (a/d). The concrete matrix compressive strength was about 93 MPa. Two empirical equations were proposed to predict the shear strength of high-strength fiber-reinforced concrete beams without transverse reinforcement.

Sarsam et al. [16] made an empirical expression to predict the shear capacity of RPC beams without web reinforcement by testing fifteen singly reinforced rectangular beams. The main variables were the steel fibers' volume fractions, ratio of longitudinal reinforcement, shear span to effective depth ratio (a/d), and silica fume content. The compressive strength of the tested beams was 110 MPa. The research contains a comparison of the results obtained by the suggested empirical expressions and formulas suggested by other researchers.

Fahmi et al. [17] presented an investigation that includes shear strength performance of RPC deep beams. They tested seven deep beams cast from reactive powder concrete; the variables consist of shear span to effective depth ratio (a/d) and percentage of silica fume in the concrete mix. They studied the effect of these parameters on the results of deflection, concrete strain, mode of failure, and ultimate load-carrying capacity.

Tu'ma [18] studied the shear capacity of RPC beams reinforced by different types of longitudinal bars, including carbon fiber-reinforced polymer (CFRP) and steel reinforcement. The experimental study included twelve cast RPC beams divided into three groups: the first group was reinforced by steel reinforcement, the second group was reinforced by smooth CFRP bars, and the last group was reinforced by local manufacturing treatment of the surface sand-coated CFRP bars. The parameters that were included were the shear span to effective depth ratio and longitudinal reinforcement ratio. The study includes a comparison between the experimental results and those obtained by the yield line theory. The key finding is that the shear capacity of the yield line theory resulted in a shear strength of three times the shear strength for steel reinforcement and 4.5 times for sand-coated CFRP bars.

Mohammed [19] investigated the shear strength of simply supported reactive powder concrete beams without web reinforcement. The test included seven beams, two of them made with reactive powder concrete RPC (without coarse aggregate) and five beams cast with modified reactive powder concrete MRPC (with coarse aggregate). The experimental findings have shown that the coarse aggregate had enhanced the shear behavior, and the ultimate load capacity of the tested beams was increased when increasing the steel fiber volume fraction content and longitudinal steel reinforcement ratio.

Li et al. [20] designed and fabricated eight high-strength reinforced RPC beams to study the shear performance under a symmetrical concentrated load. They observed the development of diagonal cracks and failure mode, the effect of shear span to effective depth ratio (a/d), transverse reinforcement ratio, and longitudinal reinforcement ratio on the cracking load, shear strength capacity, and deflection. They concluded that the shear capacity increases with the increase of the stirrups ratio and longitudinal ratio and decreases with the increase of the shear span ratio. The shear span ratio has the greatest impact on the failure mode and deformation capacity. The researchers suggested that the shear strength formula suitable for reinforced RPC beams should be adopted to enhance the consistency of the theoretical predictions with the measured values.

Said et al. [21]. Presented a study that aims to evaluate the effectiveness of using ultra-high-performance fiber-reinforced concrete (UHPFRC) as a strengthening technique to improve the shear strength of RC beams. For this goal, twelve RC beams were tested under a four-point loading up to failure. One beam

was kept as a control specimen without strengthening, and the other eleven beams were strengthened using different strengthening schemes. The main parameters considered in this experimental work were the thickness of the UHPFRC layer; the number of strengthening sides; the volume fraction of steel fibers; the distribution length of UHPFRC layers (strengthening the entire length, strengthening one-third of the length, strengthening using vertical and inclined strips); and strengthening schemes (casting or anchoring system).

Latief and Almayah [22] investigated the shear capacity of RPC rectangular beams using two groups designed for shear failure. The variables adopted in this work included the shear span-to-effective depth ratio (a/d), longitudinal reinforcement ratio, and effective depth of the tested beams. Based on the experimental results, the shear capacity was found to be 5% to 22% higher than the theoretical shear capacity using the equations according to the Japanese code.

Salah et al. [23] investigate the shear behavior of rebar-free UHPC panels with a thickness of 4 in. (101.6 mm) and 2.0% volumetric content of straight steel fibers. The panels were tested under combined shear and axial loads using the Universal Panel Tester (UPT) facility. The UPT experiments were complemented with small-scale direct tension tests (DTT) and large-scale tension strip tests (TST) to investigate the effect of UHPC tensile characteristics on shear. The panels exhibited ductile responses with post-peak residual shear capacities higher than 20% of the maximum shear stress, with the TSTs providing an improved correlation to UHPC shear compared to the DTTs.

Tamov et al. [24] made a study aimed at developing engineering methods for calculating the shear strength of UHPC I-beams using statistical learning techniques. The models were based on extensive datasets, including both the authors' own experimental results and data from other researchers. Artificial neural networks (ANNs) and regression analysis methods were used to develop the models. The tasks were implemented using the STATISTICA software package. Nonlinear expressions were developed for engineering calculations, allowing for the determination of the shear strength of UHPC beams, accounting for the shear span and structural parameters, including section geometry, UHPC strength characteristics, and fiber and shear reinforcement ratios. The proposed formulas reduce the discrepancy between theoretical and experimental data by up to 2.4 times compared to calculations by methods adopted in codes. The specimens of reactive powder-reinforced concrete beams, as detailed in references [16–18,20,22], were utilized for regression analysis; all other beams were excluded from the database.

3 Research Significance

Despite the numerous studies that have investigated the mechanical and structural performance of reactive powder concrete beams, the researchers' and design codes' provisions have shown limited attention to formulating a unified expression to evaluate the shear in such beams. Therefore, the present work formulated four proposals and modified five formulas for other researchers to accurately predict the shear strength of RPC beams having steel fiber and a comparable loading setup without web reinforcement, failing in shear, using data collected from the literature.

4 Methodology of Research

The methodology of the current research provided a targeted review of existing empirical equations established by previous studies, illustrated below (two equations suggested by Ashour et al. [15], two equations suggested by Sarsam et al. [16], and one equation suggested by Bunni [25]) for comparison with the previous data collected. The calculation involved a regression analysis of concrete shear capacity (V_c) for RPC beams using the data of 36 beams collected from accessible literature, including variables such as the dimensions of the tested beams, compressive strength (f'_c), shear span to effective depth ratio (a/d),

longitudinal reinforcement ratio (ρ), and fiber factor (F), which is a function of length, diameter, volume fraction, and shape of steel fibers as shown in Table 1. Examination of modifying and suggested equations is conducted using statistical properties, which denote the consistency between calculated and experimental findings of these equations and the results of tested beams. The regression analysis was performed using the Solver tool in the Microsoft Excel program. The coefficients of a proposed equation were calculated based on the minimum difference between the experimental and calculated shear values. This difference ratio represents the objective function, and it is calculated using the following formula:

$$\text{Diff. Ratio (D.R.)} = \frac{\sum_{i=1}^n \frac{ABS(V_{c\ exp.} - V_{c\ calc.})}{V_{c\ exp.}}}{n} \times 100\% \quad (1)$$

Then, the coefficients were rounded to familiar constants to obtain a simple equation.

The difference ratio (D.R.) represents the average absolute percentage difference between the predicted and experimental values.

Table 1: Experimental data accumulated from former studies.

Reference No.	Beam Symbol	b	d	a/d	ρ	F	f'_c	$V_{c\ exp}$
16	B2	100	112	3.5	0.03	0.1625	94	66.5
	B3	100	112	3.5	0.03	0.325	98	70
	B4	100	112	3.5	0.03	0.4875	103	77.5
	B5	100	112	3.5	0.03	0.65	110	82.5
	B6	100	112	3.5	0.04	0.65	110	107.5
	B7	100	112	3.5	0.05	0.65	110	112.5
	B8	100	112	3.5	0.03	0.65	101	77.5
	B9	100	112	3.5	0.03	0.65	93.4	75
	B10	100	112	2.5	0.03	0.65	110	125
	B11	100	112	3	0.03	0.65	110	97.5
	B12	100	112	4	0.03	0.65	110	62.5
	B13	100	112	4.5	0.03	0.65	110	59.5
	B14	100	112	2.5	0.03	0.325	98	100
	B15	100	112	4.5	0.03	0.325	98	55
17	DB1	110	250	1.5	0.0244	0.52	111	307.5
	DB2	110	250	1.5	0.0244	0.52	108.6	290
	DB3	110	250	1.5	0.0244	0.52	95.3	260
	DB4	110	250	2	0.0244	0.52	114.9	277.5
	DB5	110	250	1.75	0.0244	0.52	114.9	245
	DB6	110	250	1.25	0.0244	0.52	106.1	382.5
	DB7	110	250	1	0.0244	0.52	106.1	405
18	S1	150	82	3.5	0.0717	1.2	108.5	123
	S2	150	82	3	0.0717	1.2	108.5	133
	S3	150	82	3.5	0.0454	1.2	108.5	118
	S4	150	82	3	0.0454	1.2	108.5	129

(Continued)

Table 1 (continued)

Reference No.	Beam Symbol	b	d	a/d	ρ	F	f'_c	$V_{c_{exp}}$
22	SH1	150	144	2.43	0.0465	1.44	117	291.6
	SH2	150	144	2.43	0.0465	1.44	117	280
	SH3	150	144	2.43	0.0465	1.44	117	230.1
	SH4	150	96	2.5	0.0314	1.44	117	126.6
	SH5	150	165	2.5	0.0461	1.44	117	303.1
	SH6	150	240	2.5	0.061	1.44	117	492.3
20	L1-1	150	215	1.51	0.0658	0.65	117.2	656
	L1-2	150	215	2.26	0.0658	0.65	117.2	356
	L1-3	150	215	3.02	0.0658	0.65	117.2	335
	L2-1	150	215	2.26	0.0443	0.65	117.2	300.5
	L2-2	150	215	2.26	0.0804	0.65	117.2	425

Note: where: b is the width of the beam, d is the effective depth, a/d is shear span to effective depth ratio, ρ is the reinforcement ratio, F is the Steel fiber factor, f'_c is the compressive strength of concrete, and $V_{c_{exp}}$ is experimental concrete shear capacity of beams.

The statistical properties used in this study:

- (1) Mean or average value (Avg.) of ratios of experimental to calculated shear strength values for RPC beams, which are calculated using the following formula:

$$\text{Avg.} = \sum_{i=1}^n \left(\frac{V_{c_{exp.}}}{V_{c_{calc.}}} \right) / n \quad (2)$$

where,

$V_{c_{exp}}$ = experimental concrete shear capacity of beams (kN).

$V_{c_{calc.}}$ = calculated concrete shear capacity of beams (kN).

n = number of beams.

- (2) Standard deviation (S.D.) of ($V_{c_{exp.}}/V_{c_{calc.}}$), which is accounted for using the formula below:

$$\text{S.D.} = \sqrt{\sum_{i=1}^n \left(\frac{V_{c_{exp.}}}{V_{c_{calc.}}} - \text{Avg.} \right)^2 / n} \quad (3)$$

- (3) Coefficient of variation (C.O.V.) for values of ($V_{c_{exp.}}/V_{c_{calc.}}$), which is calculated using the following formula:

$$\text{C.O.V.} = (\text{S.D.}/\text{Avg.}) \times 100\% \quad (4)$$

- (4) Coefficient of Determination, which is a statistical tool that refers to the accuracy of the suggested formula; its value ranges between 0 and 1. The optimum value is approaching 1.

- (5) Range value, which denotes the difference between maximum and minimum values as follows:

$$\text{Range} = \text{Max} \left(\frac{V_{c_{exp.}}}{V_{c_{calc.}}} \right) - \text{Min} \left(\frac{V_{c_{exp.}}}{V_{c_{calc.}}} \right) \quad (5)$$

The value of Avg. expresses the safety or unsafety of the proposed equations, where the optimum value is unity. As this value is larger than unity, the proposed equation is more conservative, while as it is smaller than unity, the proposed equation is more unsafe. The values of S.D., C.O.V., and Range are considered measures of dissipation or the amount of deviation between the analytical and experimental results. As these values are smaller and approach zero, the correlation between the analytical and experimental is better.

Table 1 illustrates the data of the tested beams and the results of the tests. The data involves different parameters that effect on shear capacity of RPC beams as follows:

- Width of beam (b) ranges from 100 to 150 mm.
- Effective depth (d) ranges from 112 to 250 mm.
- a/d ratio ranges from 1 to 4.5
- reinforcement ratio (ρ) ranges from 2.44% to 8.04%
- Steel fiber factor (F) ranges from 0.1625 to 1.44
- Compressive strength (f'_c) ranges from 93.4 to 117.2 MPa.

The ranges of these parameters represent good data to obtain an accurate equation for shear capacity. The factor (F) is calculated as follows:

$$F = V_f \times \frac{l}{d} \times \beta \quad (6)$$

where:

V_f = Volumetric ratio for steel fibers.

$\frac{l}{d}$ = Length to diameter ratio for steel fiber.

β = Bond factor.

5 Discussion of the Results

5.1 Shear Capacity Equations

In this paper, the composed equations of shear capacity (V_c) for RPC beams were audited through evaluating their results with the collected data from prior studies of 36 samples established in different conditions, since every equation for each author was suggested according to its particular tested samples. These equations were summarized as follows:

Ashour et al. (1):

$$V_c \text{ calc.} = \left[0.7\sqrt{f'_c} + 7F \right] \frac{d}{a} + 17.2\rho_w \frac{d}{a} \quad (7)$$

Ashour et al. (2):

$$V_c \text{ calc.} = \left[2.11f'_c{}^{\frac{1}{3}} + 7F \right] \left[\rho_w \frac{d}{a} \right]^{\frac{1}{3}} \quad (8)$$

Bunni:

$$V_c \text{ calc.} = 2.3 \left[f'_c \rho \frac{d}{a} \right]^{\frac{1}{3}} + 3.11 \left(F \frac{d}{a} \right)^{0.735} \quad (9)$$

Sarsam et al. (1):

$$V_c \text{ calc.} = 0.8 (100\rho)^{\frac{1}{3}} \left(\frac{400}{d} \right)^{\frac{1}{4}} \left(\frac{f'_c}{20} \right)^{\frac{1}{3}} + 15 f'_c \rho \left(\frac{a}{d} \right)^{-2} (F)^{0.24} \quad (10)$$

Sarsam et al. (2):

$$V_c \text{ calc.} = 4.56 f'_c \rho \frac{d}{a} + 5.9 \left(F \frac{d}{a} \right)^{0.5} \quad (11)$$

By applying the above equations, it can be investigated whether these equations can be used properly to design the concrete shear capacity (V_c) for RPC beams, as indicated in Table 2. According to the statistical properties mentioned above (Eqs. (2)–(5)) and coefficient of determination (R^2), the following performance was observed:

1. Ashour (1) and (2), and Bunni equations were very low, with the average values equal to 1.919, 2.610, and 2.469. However, the equations of Sarsam (1) and (2) were more reliable in calculating the ultimate shear capacity for RPC beams with average values equivalent to 0.837 and 0.933, respectively.
2. The Sarsam (1) equation showed a weaker correlation with the experimental results according to the coefficient of variation (C.O.V.) of 31.136, while the Ashour (1) and (2) equations illustrate a slight accuracy with C.O.V. equal to 20.212 and 20.106. On the other hand, Bunni's formula shows good agreement with the C.O.V. of 18.600, respectively. Sarsam (2) indicated the best correlation among others, with a coefficient of variation equal to 14.461.

Based on the outcomes examined, it is obvious that there is a considerable variation between experimental and calculated results, as shown in Fig. 1.

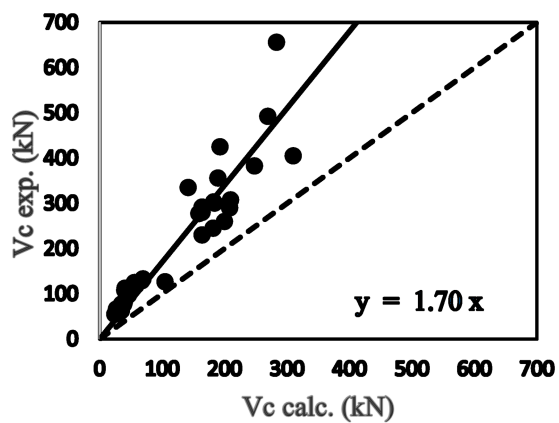
Table 2: Previous research $V_{c_{exp}}/V_{c_{calc}}$ ratio of the concrete shear capacity of beams.

Beam No.	Ashour 1	Ashour 2	Bunni	Sarsam 1	Sarsam 2
B2	2.462	2.704	2.408	1.215	1.201
B3	2.250	2.544	2.304	1.149	1.110
B4	2.195	2.542	2.356	1.169	1.111
B5	2.078	2.455	2.333	1.144	1.077
B6	2.670	2.907	2.836	1.209	1.160
B7	2.757	2.824	2.809	1.070	1.035
B8	2.001	2.352	2.236	1.141	1.066
B9	1.981	2.317	2.204	1.166	1.081
B10	2.249	3.325	3.034	1.123	1.236
B11	2.105	2.756	2.572	1.122	1.121
B12	1.799	1.945	1.876	0.999	0.909
B13	1.927	1.925	1.881	1.062	0.951
B14	2.296	3.249	2.860	1.105	1.192
B15	2.273	2.174	2.007	1.128	1.076
DB1	1.467	3.202	2.645	0.636	0.955
DB2	1.393	3.036	2.506	0.612	0.915
DB3	1.302	2.810	2.312	0.618	0.897

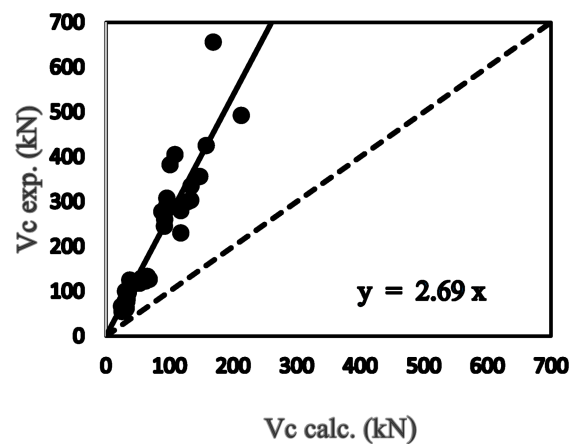
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Table 2 (continued)

Beam No.	Ashour 1	Ashour 2	Bunni	Sarsam 1	Sarsam 2
DB4	1.745	3.154	2.706	0.905	1.073
DB5	1.348	2.663	2.247	0.641	0.847
DB6	1.543	3.790	3.048	0.596	1.050
DB7	1.307	3.726	2.899	0.417	0.917
S1	2.068	1.979	2.264	0.716	0.736
S2	1.917	2.033	2.279	0.615	0.695
S3	2.038	2.211	2.402	0.983	0.972
S4	1.910	2.296	2.440	0.872	0.935
SH1	1.778	2.474	2.634	0.742	0.915
SH2	1.707	2.376	2.529	0.713	0.879
SH3	1.403	1.952	2.079	0.586	0.722
SH4	1.208	1.854	1.875	0.696	0.786
SH5	1.660	2.272	2.428	0.715	0.855
SH6	1.828	2.311	2.563	0.631	0.782
L1-1	2.316	3.886	3.611	0.416	0.749
L1-2	1.881	2.412	2.346	0.468	0.590
L1-3	2.366	2.500	2.504	0.712	0.722
L2-1	1.634	2.323	2.178	0.564	0.683
L2-2	2.204	2.694	2.665	0.465	0.594
AV.	1.919	2.610	2.469	0.837	0.933
R2	0.936	0.927	0.965	0.964	0.965
S.D	0.388	0.525	0.357	0.261	0.174
COV	20.212	20.106	14.461	31.136	18.600
Range	1.549	2.032	1.736	0.799	0.647

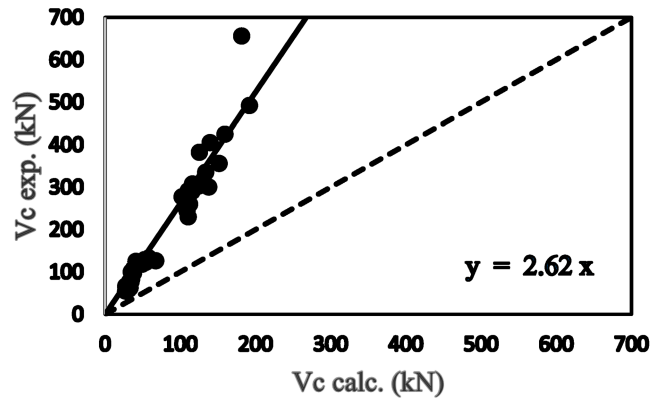


(a) Ashour 1

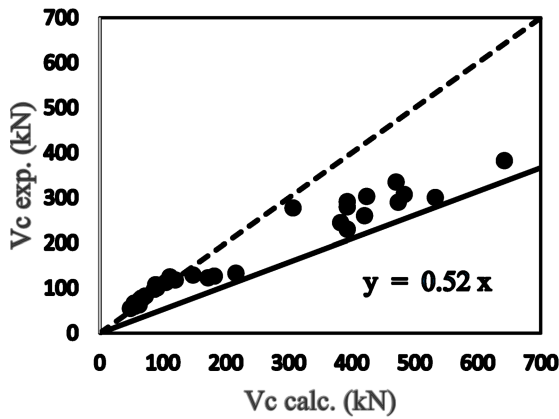


(b) Ashour 2

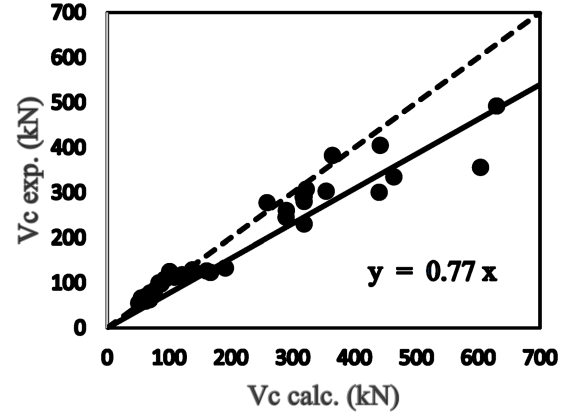
Figure 1: (Continued)



(c) Bunni



(d) Sarsam 1



(e) Sarsam 2

Figure 1: (a–e) Exp./calc. ratio of concrete shear capacity of beams for previous research.

5.2 Modified Shear Capacity Equations

Based on the assessed limitations of current models, there is a clear need to derive equations that provide better agreement with the experimental database, which represents the primary objective of this study. To achieve this, two distinct modification approaches were adopted. In the first approach, the structural frameworks of the existing models were revised, and their empirical parameters were re-optimized using non-linear regression analysis, as presented in Eqs. (12)–(16). Rather than only adjusting numerical constants, specific functional terms and exponents were modified to reflect the underlying physical behavior more accurately. The optimal coefficients were determined by minimizing the Difference Ratio (D.R.), with minor rounding applied to simplify practical implementation.

Modified Ashour et al. (1):

$$V_c \text{ calc.} = \left[0.85\sqrt{f'_c} + 4.5F + 150\rho \right] \left(\frac{d}{a} \right)^{\frac{2}{3}} \quad (12)$$

Modified Ashour et al. (2):

$$V_c \text{ calc.} = \left[\frac{20}{3} \sqrt{f'_c} + 12F \right] \sqrt{\rho \frac{d}{a}} \quad (13)$$

Modified Bunni:

$$V_c \text{ calc.} = 6 \sqrt{f'_c \rho \frac{d}{a} + 7 \left(F \frac{d}{a} \right)} \quad (14)$$

Modified Sarsam et al. (1):

$$V_c \text{ calc.} = \frac{8}{3} \sqrt{\frac{f'_c}{20}} + 5 f'_c \rho \left(\frac{a}{d} \right)^{-2} \sqrt{F} \quad (15)$$

Modified Sarsam et al. (2):

$$V_c \text{ calc.} = 1.8 f'_c \rho \frac{d}{a} + 10 \left(F \frac{d}{a} \right)^{\frac{1}{3}} \quad (16)$$

The modified equations were more familiar due to the simplicity of numbers and constant coefficients in comparison with the existing equations, which makes the modified equations more practical, as shown in Table 3, which reveals this compatibility based on the average values and the coefficient of variation (C.O.V.) for all modified equations vs. existing ones. This consistency can be well observed via Fig. 2, which exhibits excellent compliance between experimental and theoretical relationships, better than the (exp./calc.) ratio revealed in Fig. 1 above.

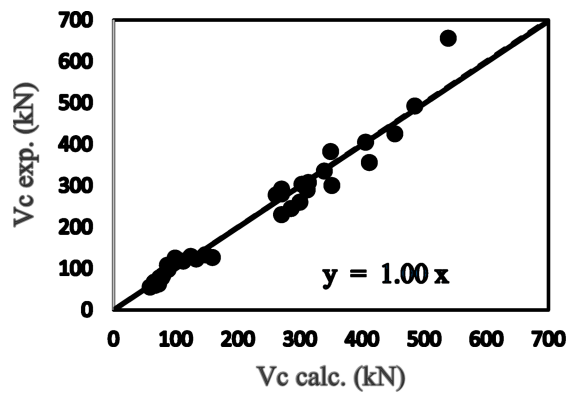
Table 3: Modified previous research $V_{c_{exp}}/V_{c_{calc}}$ ratio of the concrete shear capacity of beams.

Beam No.	Modified Ashour 1	Modified Ashour 2	Modified Bunni	Modified Sarsam 1	Modified Sarsam 2
B2	1.016	0.963	1.040	0.951	1.177
B3	1.002	0.966	1.016	0.949	1.035
B4	1.041	1.017	1.046	0.998	1.022
B5	1.039	1.024	1.034	1.004	0.995
B6	1.240	1.155	1.196	1.246	1.205
B7	1.197	1.081	1.139	1.246	1.177
B8	0.999	0.999	1.005	0.990	0.953
B9	0.987	1.001	1.004	1.002	0.937
B10	1.258	1.311	1.281	1.331	1.274
B11	1.108	1.120	1.115	1.126	1.090
B12	0.861	0.829	0.847	0.788	0.804
B13	0.886	0.837	0.864	0.769	0.809
B14	1.144	1.166	1.204	1.233	1.243
B15	0.931	0.860	0.917	0.777	0.920
DB1	0.980	1.146	1.066	1.053	1.088
DB2	0.930	1.092	1.014	1.008	1.033

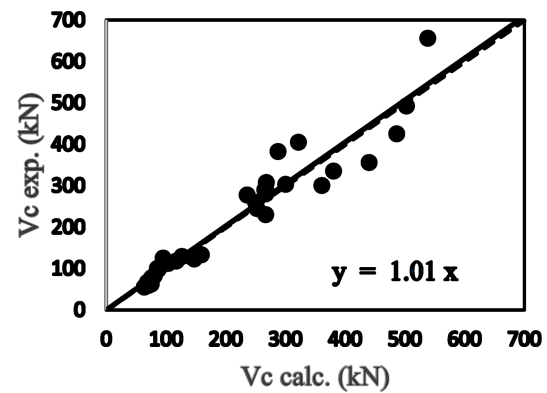
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Table 3 (continued)

Beam No.	Modified Ashour 1	Modified Ashour 2	Modified Bunni	Modified Sarsam 1	Modified Sarsam 2
DB3	0.866	1.039	0.955	0.990	0.963
DB4	1.060	1.176	1.131	1.131	1.133
DB5	0.856	0.971	0.921	0.919	0.932
DB6	1.094	1.329	1.205	1.148	1.243
DB7	0.998	1.259	1.108	0.952	1.160
S1	0.922	0.833	0.881	1.032	0.909
S2	0.899	0.834	0.868	0.988	0.898
S3	1.050	1.005	1.008	1.140	1.006
S4	1.036	1.017	1.000	1.139	1.016
SH1	1.077	1.092	1.029	1.127	1.086
SH2	1.034	1.048	0.988	1.082	1.043
SH3	0.850	0.861	0.812	0.889	0.857
SH4	0.794	0.878	0.778	0.881	0.802
SH5	0.999	1.009	0.953	1.053	1.003
SH6	1.015	0.979	0.965	1.028	1.016
L1-1	1.217	1.218	1.227	1.013	1.215
L1-2	0.864	0.809	0.843	0.880	0.866
L1-3	0.987	0.880	0.936	1.053	0.981
L2-1	0.855	0.832	0.839	0.883	0.868
L2-2	0.938	0.874	0.924	0.949	0.934
AV.	1.001	1.003	1.004	1.021	1.019
R2	0.979	0.962	0.973	0.989	0.977
S.D	0.115	0.142	0.125	0.131	0.131
COV	11.482	14.133	12.428	12.817	12.814
Range	0.464	0.520	0.503	0.563	0.473

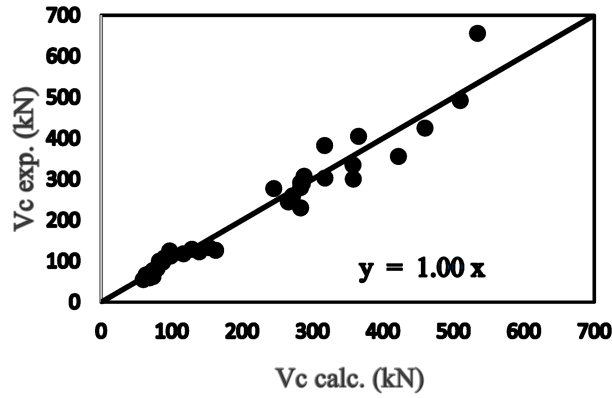


(a) Modified Ashour 1

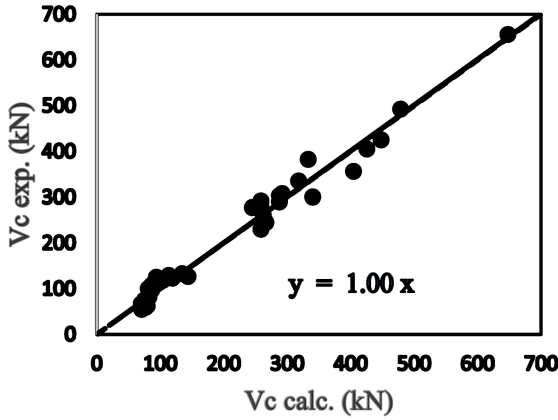


(b) Modified Ashour 2

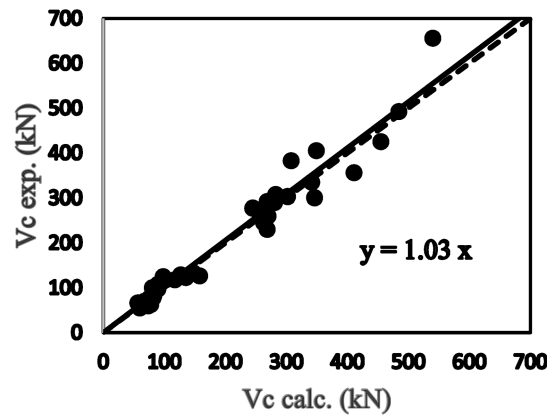
Figure 2: (Continued)



(c) Modified Bunni



(d) Modified Sarsam 1



(e) Modified Sarsam 2

Figure 2: (a–e) Modified previous research exp./calc. ratio of the concrete shear capacity of beams.

5.3 Proposed Shear Capacity Equations

The second aspect to achieve more adequate equations is by trying to predict new formulas with new coefficients represented by (C_1 , C_2 , C_3 , C_4 , and C_5), as displayed in Eqs. (17)–(20) below. The formulas of the proposed equations are based on the contribution of the affected parameters and modified from the previous study [26]. The regression analysis is performed in several attempts to achieve the rational values for these parameters.

Eq. (1):

$$V_c \text{ calc.} = C_1 f_c'^{C_2} \rho^{C_3} \left(\frac{d}{a} \right)^{C_4} (1 + C_5 F) \quad (17)$$

Eq. (2):

$$V_c \text{ calc.} = (C_1 f_c'^{C_2} + C_3 \rho) \left(\frac{d}{a} \right)^{C_4} (1 + C_5 F) \quad (18)$$

Eq. (3):

$$V_c \text{ calc.} = \frac{C_1 f_c^{C_2} \rho^{C_3}}{1 + C_4 \frac{a}{d}} (1 + C_5 F) \quad (19)$$

Eq. (4):

$$V_c \text{ calc.} = \frac{C_1 (f_c^{C_2} \rho^{C_3})}{1 + C_4 \frac{a}{d}} (1 + C_5 F) \quad (20)$$

Based on the collected data from previous studies, the regression analysis leads to the achievement of new constants for (C1–C5); therefore, the suggested equations can be demonstrated as follows:

Proposed Eq. (1):

$$V_c \text{ calc.} = 4.5 \sqrt{f_c'} \rho^{\frac{1}{3}} \left(\frac{d}{a} \right)^{\frac{2}{3}} \left(1 + \frac{1}{5} F \right) \quad (21)$$

Proposed Eq. (2):

$$V_c \text{ calc.} = \left(\sqrt{f_c'} + 130 \rho \right) \left(\frac{d}{a} \right)^{\frac{2}{3}} \left(1 + \frac{1}{5} F \right) \quad (22)$$

Proposed Eq. (3):

$$V_c \text{ calc.} = \frac{8 \sqrt{f_c'} \rho^{\frac{1}{3}}}{1 + 0.9 \frac{a}{d}} \left(1 + \frac{1}{5} F \right) \quad (23)$$

Proposed Eq. (4):

$$V_c \text{ calc.} = \frac{1.8 \left(\sqrt{f_c'} + 130 \rho \right)}{1 + 0.9 \frac{a}{d}} \left(1 + \frac{1}{5} F \right) \quad (24)$$

The proposed formulas indicated better agreement than original and modified equations exhibited above between experimental and theoretical results for reinforced reactive powder concrete (RPC) beams without web reinforcements, as illustrated in Table 4 below through regression outcomes represented by average value (Av.), standard deviation (S.D.), coefficient of variation (C.O.V.), coefficient of determination, and range of experimental to calculated shear strength values. All equations revealed accurate and thorough results, which can be utilized in the design of such beams. This convergence between experimental and calculated results can be observed in Fig. 3 below.

Moreover, this paper examined and evaluated each proposed equation through the relationship between the Exp./Calc. ratio and the variables applied in the calculation of the concrete shear capacity of beams, like shear span to effective depth ratio (a/d), compressive strength (f_c'), longitudinal reinforcement ratio (ρ), and fiber factor (F), as shown in Figs. 4–7, respectively. These figures specified that all values of the relation between $V_c \text{ exp.}/V_c \text{ calc.}$ and the affected parameters are almost near 1, which demonstrates the validity of these equations for a wide range of variables apart from some minor deviations observed in Figs. 4d, 5c and 6b,d, in addition to Fig. 7b.

Table 4: Proposed $V_{c_{exp}}/V_{c_{calc}}$ ratio of the concrete shear capacity of beams.

Beam No.	Proposal 1	Proposal 2	Proposal 3	Proposal 4
B2	0.978	0.975	0.990	0.975
B3	0.977	0.980	0.990	0.980
B4	1.024	1.035	1.037	1.035
B5	1.025	1.044	1.038	1.045
B6	1.213	1.248	1.228	1.248
B7	1.179	1.206	1.193	1.206
B8	1.005	1.012	1.017	1.012
B9	1.011	1.007	1.024	1.007
B10	1.241	1.264	1.231	1.239
B11	1.093	1.114	1.093	1.101
B12	0.849	0.865	0.871	0.877
B13	0.874	0.891	0.911	0.917
B14	1.116	1.119	1.107	1.097
B15	0.908	0.911	0.946	0.937
DB1	0.965	0.968	0.974	0.965
DB2	0.920	0.921	0.928	0.917
DB3	0.881	0.868	0.888	0.864
DB4	1.037	1.045	1.029	1.024
DB5	0.838	0.844	0.835	0.831
DB6	1.087	1.085	1.120	1.104
DB7	0.992	0.990	1.060	1.045
S1	0.955	0.942	0.967	0.942
S2	0.931	0.919	0.932	0.908
S3	1.067	1.093	1.080	1.093
S4	1.052	1.078	1.053	1.065
SH1	1.082	1.124	1.073	1.101
SH2	1.039	1.079	1.031	1.057
SH3	0.854	0.887	0.847	0.868
SH4	0.819	0.844	0.813	0.827
SH5	1.003	1.042	0.996	1.021
SH6	1.021	1.043	1.013	1.023
L1-1	1.205	1.223	1.214	1.217
L1-2	0.855	0.868	0.848	0.850
L1-3	0.977	0.991	0.978	0.980
L2-1	0.824	0.856	0.816	0.838
L2-2	0.955	0.944	0.947	0.924
AV.	0.996	1.009	1.003	1.004
R2	0.979	0.979	0.977	0.977
S.D	0.110	0.115	0.111	0.114
COV	11.059	11.411	11.077	11.354
Range	0.422	0.421	0.419	0.421

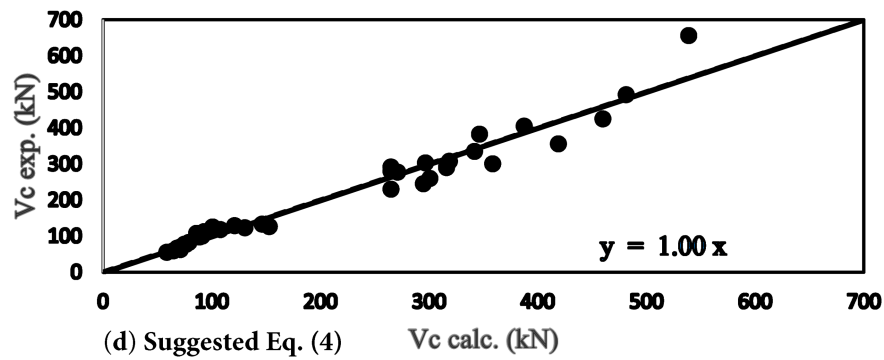
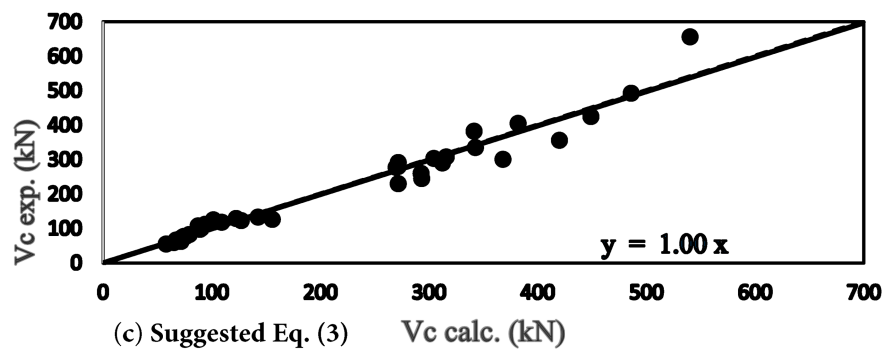
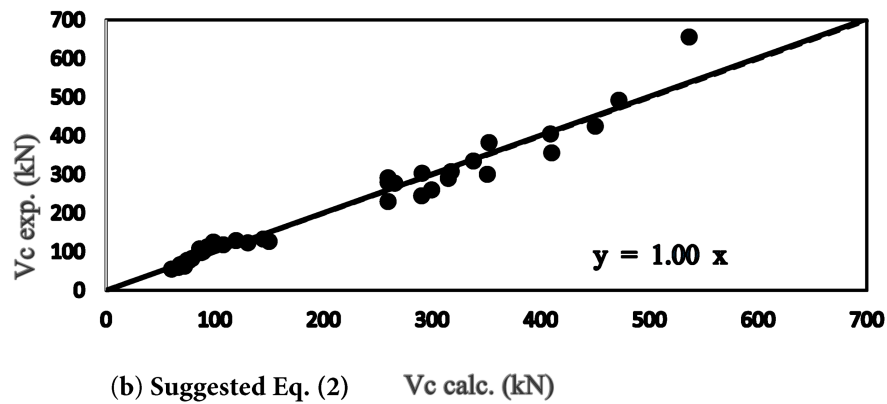
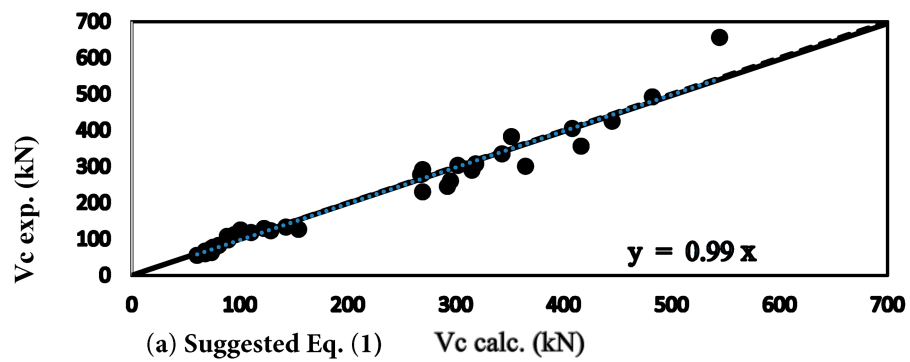


Figure 3: (a–d) The relationship between exp./calc. values of the concrete shear capacity of beams for the suggested equations.

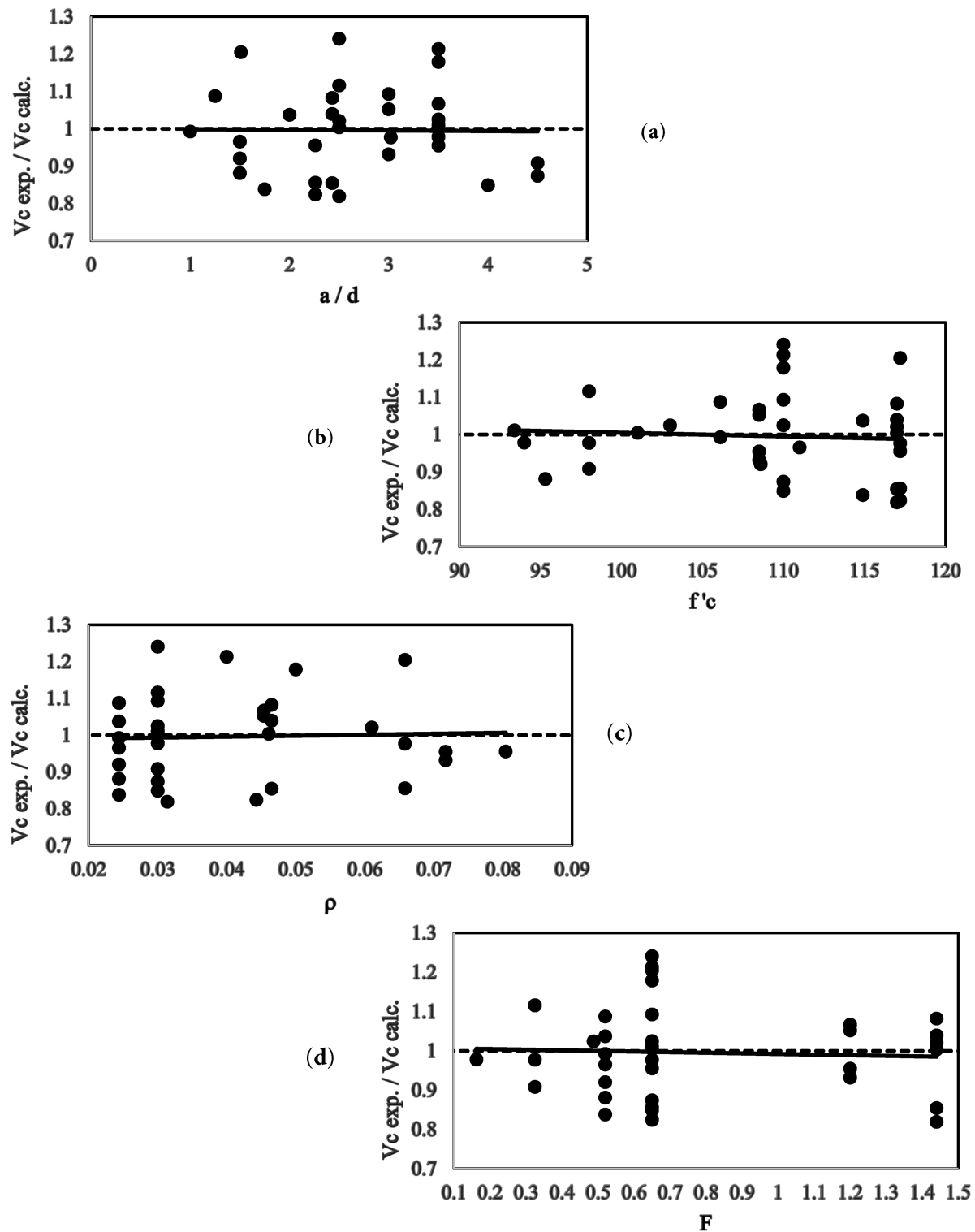


Figure 4: Proposed Formula (1): the relationship between exp./calc. ratio of concrete shear capacity of beams with (a) Shear span to effective depth ratio (a/d), (b) Compressive strength ($f'c$), (c) Longitudinal reinforcement ratio (ρ), and (d) Fiber factor (F).

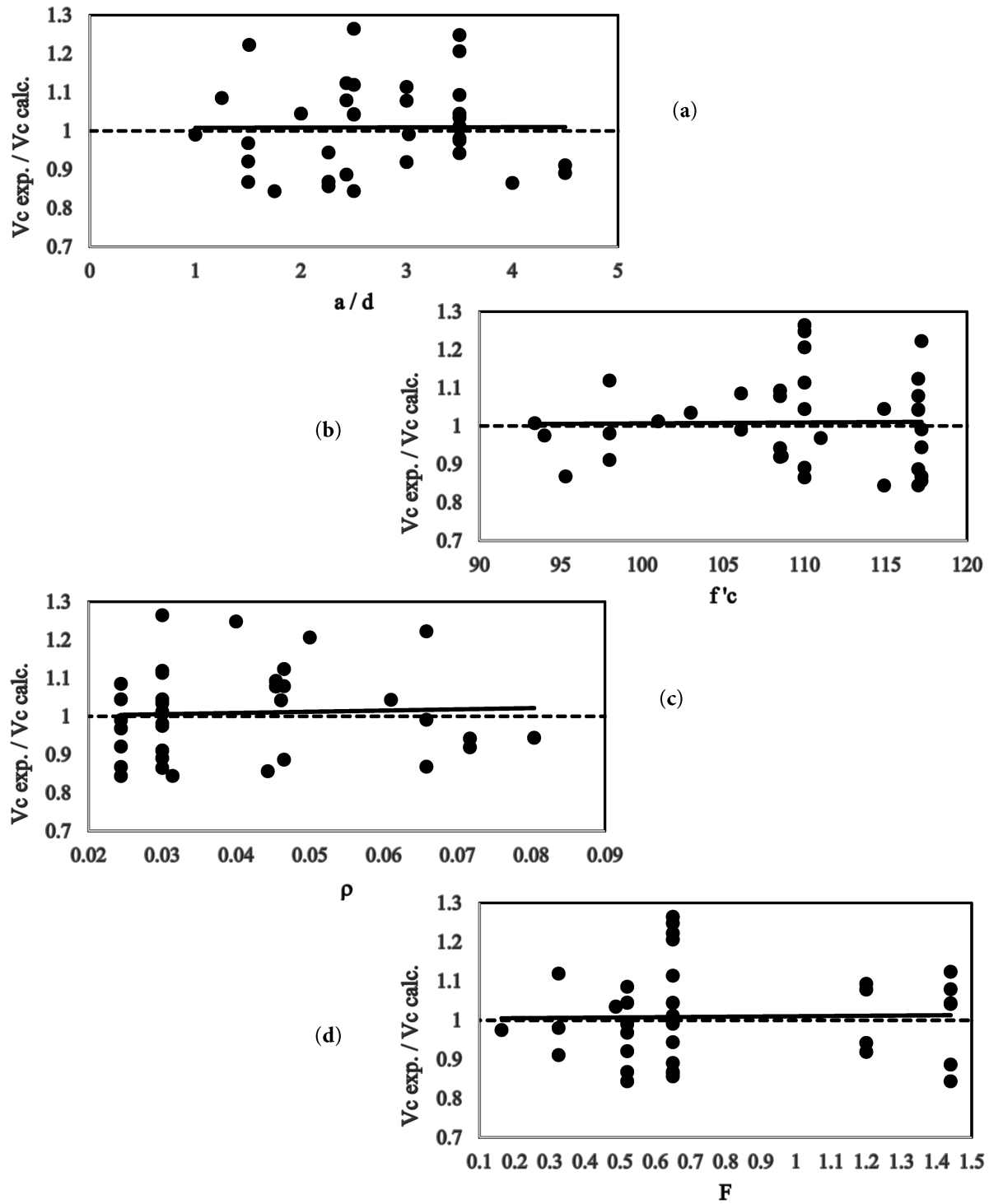


Figure 5: Proposed Formula (2): the relationship between exp./calc. ratio of concrete shear capacity of beams with (a) Shear span to effective depth ratio (a/d), (b) Compressive strength ($f'c$), (c) Longitudinal reinforcement ratio (ρ), and (d) Fiber factor (F).

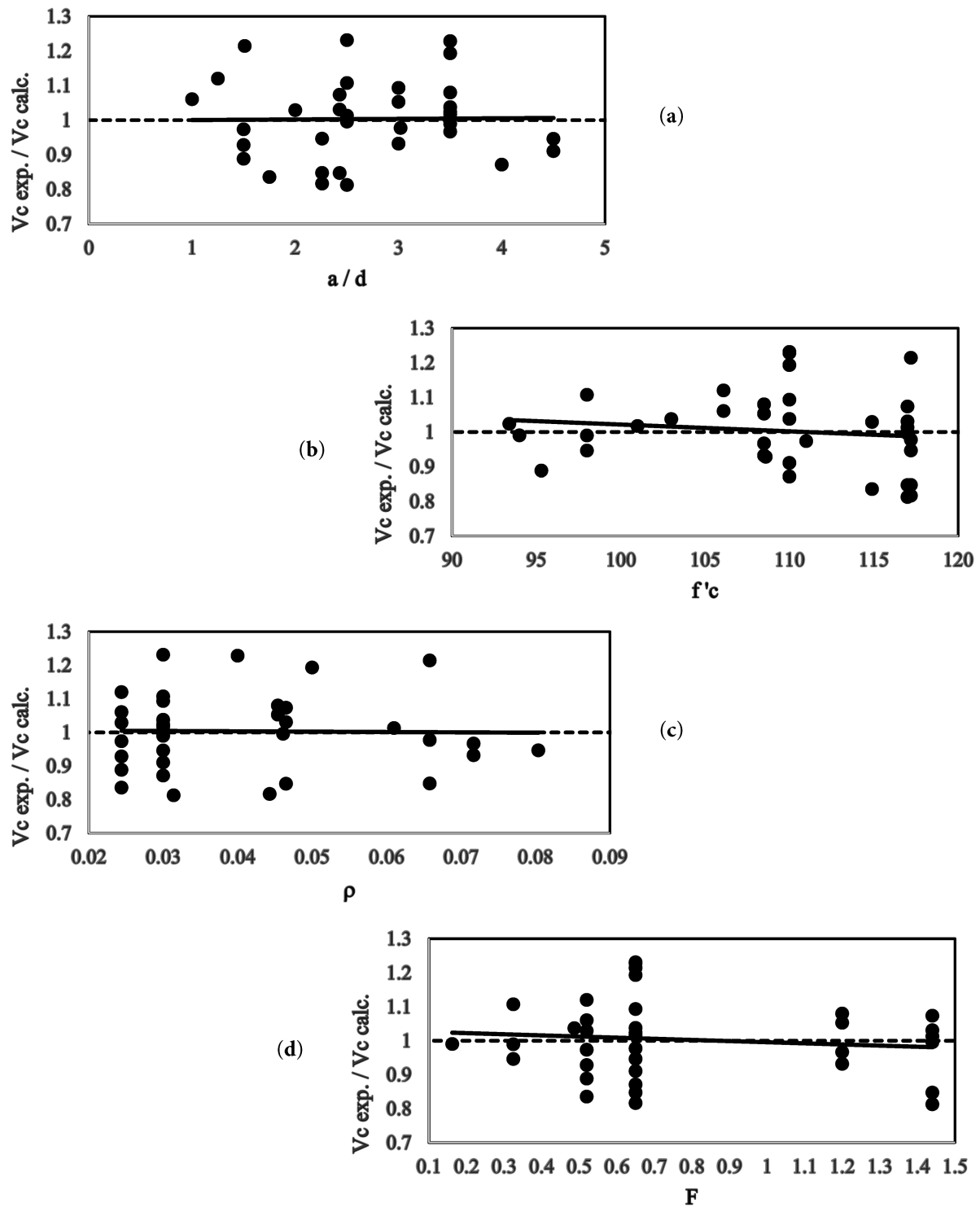


Figure 6: Proposed Formula (3): the relationship between exp./calc. ratio of concrete shear capacity of beams with (a) Shear span to effective depth ratio (a/d), (b) Compressive strength ($f'c$), (c) Longitudinal reinforcement ratio (ρ), and (d) Fiber factor (F).

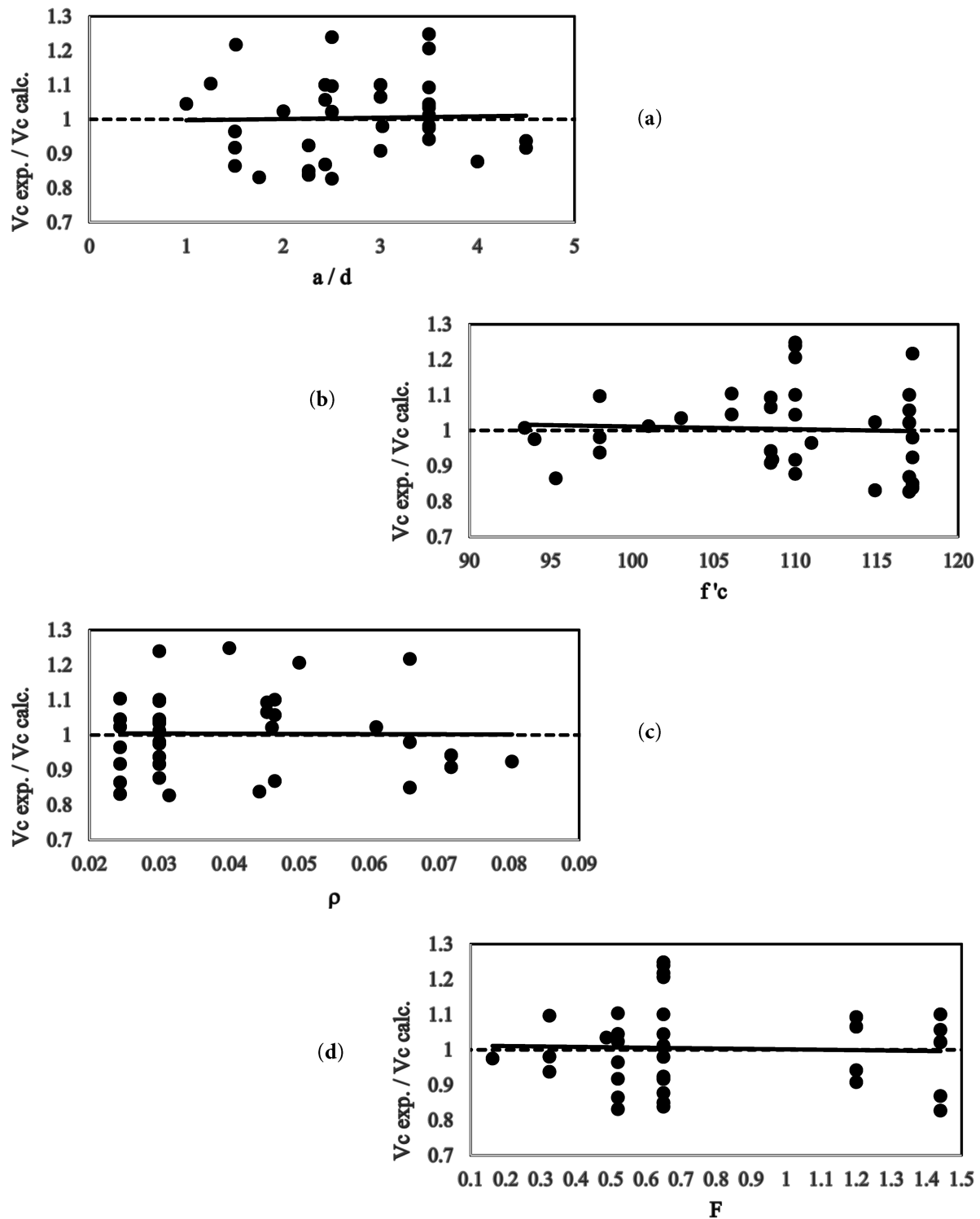


Figure 7: Proposed Formula (4): the relationship between exp./calc. ratio of concrete shear capacity of beams with (a) Shear span to effective depth ratio (a/d), (b) Compressive strength (f'_c), (c) Longitudinal reinforcement ratio (ρ), and (d) Fiber factor (F).

By comparing the proposed equations with the developed ones, it can be noted that:

1. Mathematically, the proposed equations are simpler than the modified equations.
2. The proposed equations are slightly more accurate than the modified ones in terms of standard deviation, coefficient of variation, and range of experimental to calculated shear strength values.
3. The proposed equations are more sensitive to the factors that affect the values of shear strengths than the modified equations.

6 Conclusions

From the current research that modified previous equations of other studies and suggested four new formulas to determine the concrete shear capacity (V_c) for reactive powder-reinforced concrete beams, the following conclusions were drawn:

1. The importance of obtaining new equations that are realistic and accurate to evaluate the shear capacity (V_c) for reactive-powder-reinforced concrete beams.
2. The existing equations are not competent to calculate the concrete shear capacity compared to the experimental results gathered from different research.
3. The modification made to the existing equations has resulted in an obvious improvement between experimental and calculated results.
4. The proposed equations offer precise and clear results compared to the experimental outcomes in calculating the concrete shear capacity (V_c) for RPC beams.
5. Both modified and proposed equations can be applied to design equations of shear capacity of beams with a modest preference for the proposed formulas.
6. Previous equations were constructed based on specific experimental results for each study, while the modified and proposed equations were derived based on different experimental results from several prior studies.
7. The current proposed equations can be improved in the future, depending on the availability of more experimental data for the same type of beams.
8. The proposed equations are specified for RPC beams failed by shear, comparable loading conditions, with compressive strength ranges from 75 to 120 MPa without transvers reinforcement for a/d does not exceed 4.5 and for F does not exceed 1.5.
9. In the future, the proposed equations need more accurate calibration for their coefficients for a wide range of experimental data on RPC beams.
10. The experimental data involves some specimens that can be classified as deep beams based on the value of the a/d ratio; therefore, with the availability of more experimental data, the equation can branch into two equations, one for ordinary beams and the other for deep beams.
11. The direct application of the proposed equations to other member types or parameter ranges should be avoided until further independent experimental data becomes available.

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Availability of Data and Materials: The data used and analyzed in the current study are available in the references and on request from the corresponding author.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Cao X, Deng X, Jin LZ. Experimental study on shear capacity of cementitious composite RPC beams using high strength steel. *Proc Instg Civ Eng Struct Build*. 2021;174(4):276–91. doi:10.1680/jstbu.19.00051.
2. Wenzhon Z. Literature review of reactive powder concrete. *J Build Struct*. 2015;36(10):44–58. doi:10.14006/j.jzjgxb.2015.10.006.
3. Kumar AS, Bharati RJ, Simon KM. Shear strength of steel fiber reinforced reactive powder concrete & geopolymer concrete—a comparison. In: *Proceedings of the International Web Conference in Civil Engineering for a Sustainable Planet (ICCESP 2021)*; 2021 Mar 5–6; Kollam, India. p. 357–66. doi:10.21467/proceedings.112.43.
4. Jin Q, He D, Cao X, Fu F, Chen Y, Zhang M, et al. Shear strength prediction of high-strength steel reinforced reactive powder concrete beams. *Adv Concr Constr*. 2024;17(2):75–92. doi:10.12989/acc.2024.17.2.072.
5. Kannan Rajkumar PR, Mathangi DP, Sudha C, Neelamegam M. Experimental investigation of reactive powder concrete exposed to elevated temperatures. *Constr Build Mater*. 2020;261:119593. doi:10.1016/j.conbuildmat.2020.119593.
6. Shen L, Ding M, Chen K, Feng C, Yang B, Elchalakani M. The mechanical behavior of RPC under combined shear and compressive loads. *Cem Concr Compos*. 2021;121:104071. doi:10.1016/j.cemconcomp.2021.104071.
7. Bonopera M, De Matteis G. Analysis of the shear deformation in simply supported prestressed concrete girder-bridges. *Procedia Struct Integr*. 2026;78:1143–50. doi:10.1016/j.prostr.2025.12.146.
8. ACI CODE-318-25 building code requirements for structural concrete (ACI 318M-25) and commentary (ACI 318R-25) [Internet]. Farmington Hills, MI, USA: American Concrete Institute; 2025 [cited 2026 Jan 1]. Available from: https://www.concrete.org/store/productdetail.aspx?ItemID=318U25&Language=English&Units=US_Units.
9. European Committee for Standardization. Eurocode 2: design of concrete structures-part 1 [Internet]. Brussels, Belgium: European Committee for Standardization; 2004 [cited 2026 Jan 1]. Available from: <https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-2-design-concrete-structures>.
10. Association Francaise du Genil Civil (AFGC). Ultra-high performance fiber reinforced concrete. Paris, France: AFGC; 2013. 358 p.
11. Japan Society of Civil Engineers (JSCE). Recommendations for design and construction of ultra-high-strength fiber reinforced cement composites with multiple fine cracks (HPFRCC). Tokyo, Japan: Japan Society of Civil Engineers; 2008. 113 p.
12. Korea Concrete Institute. Design recommendations for ultra high performance concrete (K-UHPC), KCI-M-12-003. Seoul, Republic of Korea: Korea Concrete Institute; 2012.
13. Wang Z, Li H, Zhang X, Chang Y, Wang Y, Wu L, et al. The effects of steel fiber types and volume fraction on the physical and mechanical properties of concrete. *Coatings*. 2023;13(6):978. doi:10.3390/coatings13060978.
14. Bae BI, Lee MS, Choi CS, Jung HS, Choi HK. Evaluation of the ultimate strength of the ultra-high-performance fiber-reinforced concrete beams. *Appl Sci*. 2021;11(7):2951. doi:10.3390/app11072951.
15. Ashour SA, Hasanain GS, Wafa FF. Shear behavior of high-strength fiber reinforced concrete beams. *ACI Struct J*. 1992;89(2):176–84. doi:10.14359/2946.
16. Sarsam KF, Al-Shaarbaf IAS, Ridha MMS. Experimental investigation of shear-critical reactive powder concrete beams without web reinforcement. *Eng Technol J*. 2012;30(17):2999–3022. doi:10.30684/etj.30.17.5.
17. Fahmi HM, Al-Shaarbaf IAS, Ahmed AS. Behavior of reactive powder deep beams. *Al Mansour J*. 2013;20(1):1–22.
18. Tu'ma NH. Evaluation of the shear strength of reactive powder concrete beam reinforced with fiber reinforced polymer bars by yield-line theory. *J Misan Res*. 2015;11(22):22–34.

19. Mohammed MH. Shear behavior of reactive powder concrete beams with and without coarse aggregate. *AUT J Civ Eng.* 2018;2(1):87–96. doi:10.22060/ceej.2017.12210.5145.
20. Li Y, Yang H, Liu C. Experimental study on shear behavior of reactive powder concrete beams. *J Phys Conf Ser.* 2021;2148(1):012032.
21. Said A, Elsayed M, El-Azim AA, Althoey F, Tayeh BA. Using ultra-high performance fiber reinforced concrete in improvement shear strength of reinforced concrete beams. *Case Stud Constr Mater.* 2022;16:e01009. doi:10.1016/j.cscm.2022.e01009.
22. Latief HS, Almayah AA. Experimental investigation of the behavior of reactive powder concrete beams with and without shear reinforcement. *Passer J Basic Appl Sci.* 2024;6:189658. doi:10.24271/psr.2024.189658.
23. Salah A, Kalliontzis D, Lawler JS, Wagner EI. Shear behavior of reinforcing bar-free ultra-high-performance concrete considering axial load effects and fiber alignment. *ACI Struct J.* 2025;122(2):51743306. doi:10.14359/51743306.
24. Tamov MM, Rudenko OV, Salib MIF. Modeling of shear strength of ultra-high-performance concrete beams using statistical learning tools. *Jour.* 2025;4(2):7–20. doi:10.23947/2949-1835-2025-4-2-7-20.
25. Bunni ZJ. Shear strength in high-strength fiber reinforced concrete beams [master's thesis]. Baghdad, Iraq: University of Technology; 1998.
26. Al-Khafaji JM, Al-Shaarbaf IAS, Sultan WH. Shear behavior of fibrous self compacting concrete deep beams. *J Eng Dev.* 2014;18(6):36–58.