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Research Article

Characterizing and Modeling the Mechanical Properties of the Cement Mortar Modified with Fly Ash for Various Water-to-Cement Ratios and Curing Times

Warzer Qadir, Kawan Ghafor, and Ahmed Mohammed

Collage of Engineering, Department of Civil Engineering, University of Sulaimani, Sulaymaniyah, Kurdistan Region, Iraq

Correspondence should be addressed to Ahmed Mohammed; ahmed.mohammed@univsul.edu.iq

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Despite many research studies on the effect of the fly ash content (FA) on the mechanical behavior of the cement mortar, there has not been an extensive study investigating the effect of FA, curing time (t), and water-to-cement ratio (w/c) on the compressive (σ_c), tensile (σ_t), and flexural (σ_f) strengths of cement mortar. Therefore, this study investigates the subject which could be beneficial for the building and construction field. In this study, more than 1000 data on the mechanical properties of the cement mortar modified with different percentages of fly ash varying from 5% to 75% (by dry weight of the cement) were collected from the literature. The statistical analysis and modeling were performed on the collected data. The w/c of the cement mortar ranged from 0.20% to 0.80%, and the compressive, split tensile, and flexural strengths of cement mortar modified with fly ash and cured up to 90 days ranged from 15 MPa to 88 MPa, 0.4 MPa to 5 MPa, and 1 MPa to 10 MPa, respectively. The Vipulanandan model was also used and compared with the Hoek–Brown model to correlate the mechanical properties of cement mortar modified with fly ash. The results of this study showed that there is a good relationship between the compressive strength (σ_c) and w/c, curing time, and fly ash content. The compressive, split tensile, and flexural strengths of cement mortar quantified well as a function of w/c, fly ash content, and curing time using a nonlinear relationship.

1. Introduction

Cement mortar is defined as a mixture of cementitious material, fine aggregate, and water in either the unhardened or hardened state [1]. Cement mortar utilized as a binder in building blocks (bricks, stones, and concrete masonry units) seal the gaps between them and is used for decoration. Ordinary Portland cement (OPC) mortar, commonly known as OPC mortar or cement mortar, was created by mixing OPC, fine aggregate, and water [1, 2]. Addition of fly ash enhances the performance, mechanical properties, and durability of mortar in the hardened form. Also, the addition of fly ash decreases CO_2 emission and may reduce the negative environmental effect caused by cement production [3]. Fly ash (FA) also reacts with cement by binding $Ca(OH)_2$ with free silica through a pozzolanic reaction. Among the wastes from coal combustion products, only fly ash is widely used for mineral mixture in mortar for its various advantages [4, 5]. The utilization of fly ash in mortar and concrete has increased significantly because of high siliceous and aluminous contents [6–8]. Cement mortar with fly ash usually has retardation of hydration and delay of setting time due to the presence of SO^{-2} ions in the fly ash surface; with lower w/c, mortar usually has higher strength due to the presence of many cement hydrates [4]. Several studies have shown that the fly ash is effective for improving various properties of mortar. The benefits of using fly ash are that it reduces the cost of the mortar, emission to the environment, and the hydration temperature at the early age and can improve the workability of mortar [9, 10].

Workability, strength, and durability are three basics properties of mortar [11, 12]. Several scientific types of researches have been performed to understand the effect of fly ash on the physical and mechanical properties of cement mortar (Table 1).

Table 1: Summary properties of cement mortar modified with fly ash.

Reference	Country	Fly ash, FA (%)	w/c	Curing time, t (days)	Compressive strength, σ_c (MPa)	Split tensile strength, σ_t (MPa)	Flexural strength, σ_f (MPa)	Tests
[3]	Turkey	0–20	0.5–0.62	7, 28, 90	29–56	—	—	Compressive strength
[4]	South Korea	30, 60	0.4–0.49	3, 7, 28, 90	16–37	—	—	Compressive strength
[5]	India	0–30	0.44	3, 7, 28, 50	23–54	—	—	Compressive strength
[8]	India	0–25	0.5	7, 28, 90	10–32	1.5–5	—	Compressive and split tensile strengths
[11]	Turkey	0–18	0.5–0.58	28	7–12	—	—	Compressive strength
[13]	Sweden	0–40	0.46	1, 3, 7, 28	7–60	—	2–8	Flexural and compressive strengths
[14]	China	0–55	0.3	28, 90	70–81	1.5–3.8	5–14	Compressive, split tensile, and flexural strengths
[15]	Spain	0–50	0.5	7, 28	26–40	—	3–7	Compressive and flexural strengths
[16]	Turkey	30	0.5	2, 7, 28	19–50	—	—	Compressive and flexural strengths
[17]	Norway	0–35	0.5	1, 28, 90	12–72	—	3–9	Flexural and compressive strengths
[18]	India	10	0.32–0.38	28	45–88	—	—	Compressive strength
[19]	Iraq	0–20	0.56	7, 28, 90	23–43	—	4–7	Compressive and flexural strengths
[20]	Belgium	0–35	0.25–0.80	1, 3, 7, 14, 90	12–60	—	3–8	Compressive and flexural strengths
[21]	Turkey	0–10	0.5	7, 28	28–38	—	2–7	Flexural and compressive strengths
[22]	India	0–70	0.48	7, 14, 28, 56, 90	3–30	0.4–3	—	Compressive and split tensile strengths
[23]	India	0–40	0.25–0.55	7, 28, 90	13–84	—	—	Compressive strength
[24]	Malaysia	0–7	0.5	7, 14, 28	19–31	—	—	Compressive strength
Remarks	10 countries	Varied from 0 to 70%	Varied from 0.25 to 0.85	Varied from 1 day up to 90 days	Varied from 3 MPa to 88 MPa	Varied from 0.4 MPa to 5 MPa	Varied from 2 MPa to 14 MPa	Compressive, split tensile, and flexural strength tests were used

Compressive strength is one of the most important properties of hardened mortar that describes its quality and performance for construction works. In addition, most of the other properties such as tension, flexural, shear, and bond strengths with steel reinforcement will be improved in parallel with the increase in compressive strength of the cement mortar [22–25]. The significant improvements in the compressive and split tensile strengths of cement mortar due to the incorporation of fly ash were observed [26, 27].

The stress-strain behavior of materials such as concrete, glass fiber-reinforced polymer concrete, fine sands grouted with sodium silicate, sulfate-contaminated clay soil, smart cement modified with nanomaterials, and cement mortar were predicted using the Vipulanandan model [28–33].

In this study, data were collected from the literature, and statistical analysis and modeling were performed (Tables 1 and 2). Depending on the literature data, no correlation was observed between compressive strength, FA content, and w/c up to 90 days of curing. The influence of w/c, curing time, and FA content on the compressive, split tensile, and flexural strengths of cement mortar was quantified using a nonlinear model. The specific objectives were as follows:

(i) To investigate statistical variation of the mechanical properties, water-to-cement ratio, fly ash content, and curing time of cement mortar

(ii) To investigate and quantify the relationships of the compressive strength of cement mortar with w/c and FA (%) cured up to 90 days

(iii) To investigate the nonlinear relationship to evaluate the effect of w/c, curing time, and fly ash on the compressive, tensile, and flexural strengths of cement mortar

(iv) To develop the correlation relation between the compressive, flexural, and tensile strengths of cement mortar modified with FA using the Vipulanandan correlation model

2. Materials and Methods

2.1. Data Collection. The focus of this study was on the statistical variation and correlations between compressive,

Table 2: Statistical parameters of the properties of cement mortar with and without fly ash.

	Statistical parameters	w/c	Compressive strength, σ_c (MPa) (up to 90 days of curing)	Split tensile strength, σ_t (MPa) (up to 90 days of curing)	Flexural strength, σ_f (MPa) (up to 90 days of curing)
Cement mortar	No. of data	179	318	79	33
	Range	0.20–0.80	3–88	0.4–6	2–13
	Mean (μ)	0.46	30	1.9	7.2
	Std. deviation (σ)	0.11	12	1.0	2.58
	COV (%)	24	40	53	35
Cement mortar modified with fly ash	No. of data	178	318	33	67
	Range	0.25–0.65	15–88	0.4–5	1–10
	Mean (μ)	0.47	40	2.6	6.2
	Std. deviation (σ)	0.08	15.6	0.8	1.8
	COV (%)	19	39	30	29

tensile, and flexural strengths with *w/c* and curing time for the cement mortar modified with fly ash.

2.2. Regression Analysis (Nonlinear Model). Regression analysis was performed to develop the relationships between the compressive, tensile, and flexural strengths of the cement mortar as a function of *w/c*, fly ash, and curing time up to 90 days.

2.3. Modeling

2.3.1. Vipulanandan Correlation Model. The relationship between compressive strength and tensile and flexural strengths was developed using the following Vipulanandan correlation model [33, 36–44]:

$$Y = Y_0 + \frac{X}{(C + D * X)}, \tag{1}$$

where Y is the cement mortar property of the dependent variable, i.e., tensile strength or flexural strength; Y_0, C, and D are model parameters summarized in Table 3; and X is the cement mortar property of the independent variable (x-axis), i.e., compressive strength.

The Vipulanandan correlation model was also compared to the Hoek–Brown model used in the literature [45]. The Hoek–Brown model is defined as follows:

$$Y = X + m\left(n\frac{X}{m} + 1\right)^{0.5}, \tag{2}$$

where m and n are Hoek–Brown parameters (Table 4).

2.4. Nonlinear Model (NLM). The compressive, split tensile, and flexural strengths of cement mortar modified with fly ash (FA) were affected by the curing time (t) and water-to-cement ratio (*w/c* (%)) [33]. The effects of FA (%), t (days), and *w/c* (%) of the cement mortar were separated as follows:

Compressive strength (σ_c) of cement mortar only (FA = 0%):

$$\sigma_c = a\left(\frac{w}{c}\right)^b (t)^c. \tag{3a}$$

Compressive strength (σ_c) of cement mortar modified with fly ash:

$$\sigma_c = a\left(\frac{w}{c}\right)^b (t)^c + d\left(\frac{w}{c}\right)^e (t)^f (\mathrm{FA})^g. \tag{3b}$$

Tensile strength (σ_t) of cement mortar modified with fly ash:

$$\sigma_t = a\left(\frac{w}{c}\right)^b (t)^c + d\left(\frac{w}{c}\right)^e (t)^f (\mathrm{FA})^g. \tag{4}$$

Flexural strength (σ_f) of cement mortar modified with fly ash:

$$\sigma_f = a\left(\frac{w}{c}\right)^b (t)^c + d\left(\frac{w}{c}\right)^e (t)^f (\mathrm{FA})^g. \tag{5}$$

Based on data collected from various research studies in the literature, the correlation parameters (a, b, c, d, e, f, and g) were calculated using least-squares multiple regression analysis, as summarized in Table 4.

3. Results and Analyses

3.1. Statistical Analysis

3.1.1. Water-to-Cement Ratio (w/c). Based on the total of 179 *w/c* data for the cement mortar collected from various research studies (Table 1), the *w/c* for the cement mortar ranged from 0.20 to 0.80% with a mean of 0.46% and a standard deviation (std. deviation (σ)) of 0.11%, as summarized in Table 2. The number of data points in each set of *w/c* values was considered. More than 50% of the total *w/c* of the cement mortar ranged between 0.3% and 0.5%, as shown in Figure 1(a). Based on the total of 178 water-to-binder ratio (*w/b*) data for the cement mortar modified with FA (Table 1), the *w/c* ranged from 0.25% to 0.65% with a mean of 0.47% and a standard deviation of 0.08% (Table 2). Almost 55% of the total *w/b* data ranged between 0.45% and 0.55%, as shown in Figure 1(b).

3.1.2. Fly Ash Content (FA (%)). Based on the total 69 fly ash (FA) percent used to modify the cement mortar, the data ranged from 5% to 75% with a std. deviation (σ) of 14% and

Table 3: Model parameters for compressive, tensile, and flexural strength relationships of cement mortar with and without fly ash (FA).

Dependent variable (y-axis)	Independent variable (x-axis)	Vipulanandan correlation model (equation (1))					Hoek–Brown model (equation (2))				No. of data	Figure number
		Y_0	C	D	RMSE (MPa)	R^2	m	n	RMSE (MPa)	R^2		
Split tensile strength, σ_t (MPa), for cement mortar only	Compressive strength, σ_c (MPa)	0.018	6.7	0.250	0.090	0.98	−0.005	−0.68	0.092	0.98	52	Figure 12
Split tensile strength, σ_t (MPa), for cement mortar modified with fly ash		0.200	6.0	0.100	0.108	0.97	−0.001	−0.56	0.111	0.97	27	
Flexural strength, σ_f (MPa), for cement mortar only		0.580	4.0	0.057	0.451	0.92	−0.004	−0.38	0.457	0.92	27	Figure 13
Flexural strength, σ_f (MPa), for cement mortar modified with fly ash		−0.510	2.5	0.070	0.381	0.95	−0.004	−0.38	0.399	0.95	56	

Table 4: Nonlinear model (NLM) parameters for the mechanical properties of cement mortar with and without fly ash.

Model parameters	a	b	c	d	e	f	g	h	i	RMSE (MPa)	R^2	No. of data	Equation number	Figure number
σ_c														
Cement mortar only	7.8	−0.75	0.21	—	—	—	—	—		5.4	0.80	316	(3a)	Figure 7
Cement mortar modified with fly ash	7.8	−0.75	0.21	0.46	−1.01	0.25	0.3	—	—	6.4	0.83	493	(3b)	Figure 9
σ_t of cement mortar modified with fly ash	0.65	−1.2	0.12	0.13	0.12	0.27	0.01	—	—	0.40	0.83	89	(4)	Figure 10
σ_f of cement mortar modified with fly ash	2.50	−0.7	0.13	0.11	−0.10	0.16	0.1	—	—	0.90	0.80	83	(5)	Figure 11

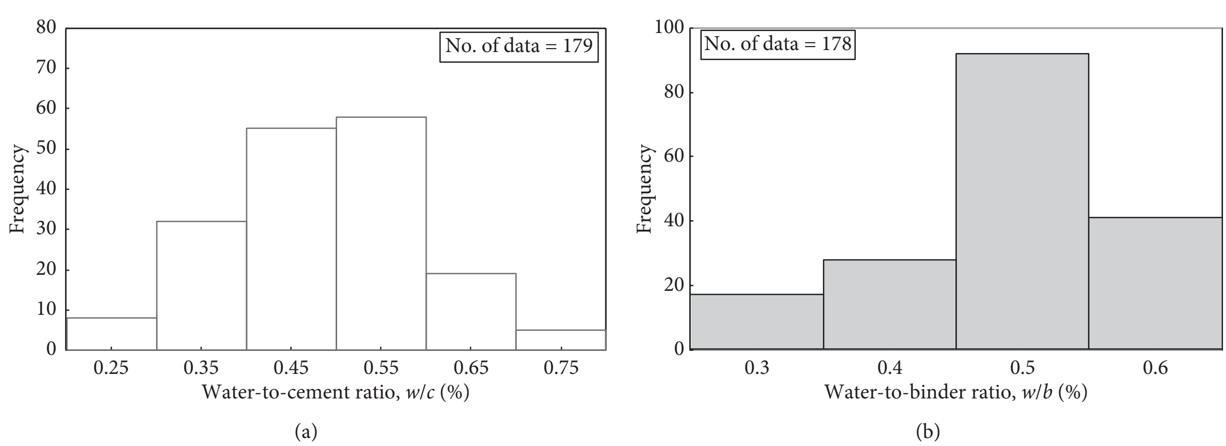


Figure 1: Histogram of the water-to-cement ratio (w/c) for (a) cement mortar and (b) cement mortar modified with fly ash (FA).

COV of 65%. About 70% of the total FA varied between 5% and 25%, as shown in Figure 2.

3.2. Mechanical Properties

3.2.1. Compressive Strength

(1) Cement Mortar. A total of 318 compressive strength (σ_c) data for the cement mortar were collected from various research studies (Table 1). The compressive strength (σ_c) of the cement mortar up to 90 days of curing varied from 3 MPa to 66 MPa with a mean of 30 MPa, a std. deviation (σ) of 12 MPa, and a COV of 40% (Table 2). Different distribution tests for the compressive strength of cement mortar were performed. The Weibull frequency distribution for the compressive strength of cement mortar was observed based on the Anderson–Darling (AD) statistic and P values (Figure 3(a)).

(2) Cement Mortar Modified with FA. A total of 318 compressive strength (σ_c) data for cement mortar modified with fly ash were collected from the literature (Table 1). The σ_c ranged from 15 MPa to 88 MPa with a mean of 40 MPa, a std.

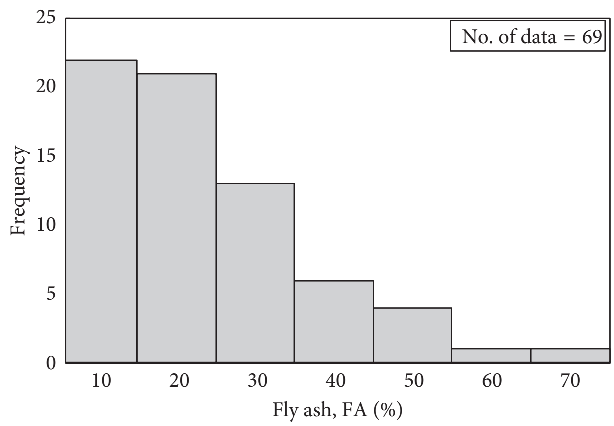


Figure 2: Histogram of percent of fly ash (FA) added to the cement mortar.

deviation (σ) of 15.6 MPa, and a COV of 39% (Table 2). Based on the AD and P values, the probability distribution was a 3-parameter Weibull distribution, as shown in Figure 3(b).

3.2.2. Split Tensile Strength

(1) Cement Mortar. A total of 79 tensile strength (σ_t) data for cement mortar for curing time up to 90 days were collected (Table 1). The tensile strength (σ_t) varied from 0.4 MPa to 6 MPa with a mean of 1.9 MPa, a std. deviation (σ) of 1.0 MPa, and a COV of 53% (Table 2). Based on AD and P values, the probability distribution was a 3-parameter log-normal distribution, as shown in Figure 4(a).

(2) Cement Mortar Modified with FA. A total of 33 tensile strength (σ_t) data for cement mortar modified with fly ash were collected (Table 1). The tensile strength of cement mortar modified with fly ash varied from 0.4 MPa to 5 MPa with a mean of 2.6 MPa and a std. deviation (σ) of 0.8 MPa (Table 2). The histograms were also analyzed and showed more than 76% of the total σ_t was between 1.8 and 3.6 MPa, as shown in Figure 4(b). Based on AD and P values, the probability distribution of σ_t of cement mortar modified with fly ash was a 3-parameter Weibull distribution.

3.2.3. Flexural Strength

(1) Cement Mortar. A total of 33 flexural strength (σ_f) data for cement mortar up to 90 days of curing were collected and are summarized in Table 1. The flexural strength varied from 2 MPa to 13 MPa with a mean of 7.2 MPa and a std. deviation (σ) of 2.58 MPa (Table 2). The statistical analysis and the histograms were performed for each flexural strength data set to identify the distribution. Different distribution tests for the flexural strength of cement mortar were performed. Based on the AD and P values, the gamma frequency distribution for the flexural strength of cement mortar was selected (Figure 5(a)).

(2) Cement Mortar Modified with FA. A total of 67 flexural strength data for cement mortar modified with fly ash were collected and are summarized in Table 1. The flexural strength ranged from 1 MPa to 10 MPa with a mean of 6.2 MPa and a std. deviation (σ) of 1.8 MPa, as summarized in Table 2. Depending on the AD and P values, the smallest extreme value frequency distribution for the flexural strength of cement mortar modified with fly ash was selected, as shown in Figure 5(b).

4. Property Correlation

4.1. Relationship between Compressive Strength and w/c of Cement Mortar. More than 300 data for compressive strength and w/c of cement mortar at different curing times up to 90 days were collected from various research studies. There were no correlations between the σ_c and w/c up to 90 days of curing (Figure 6).

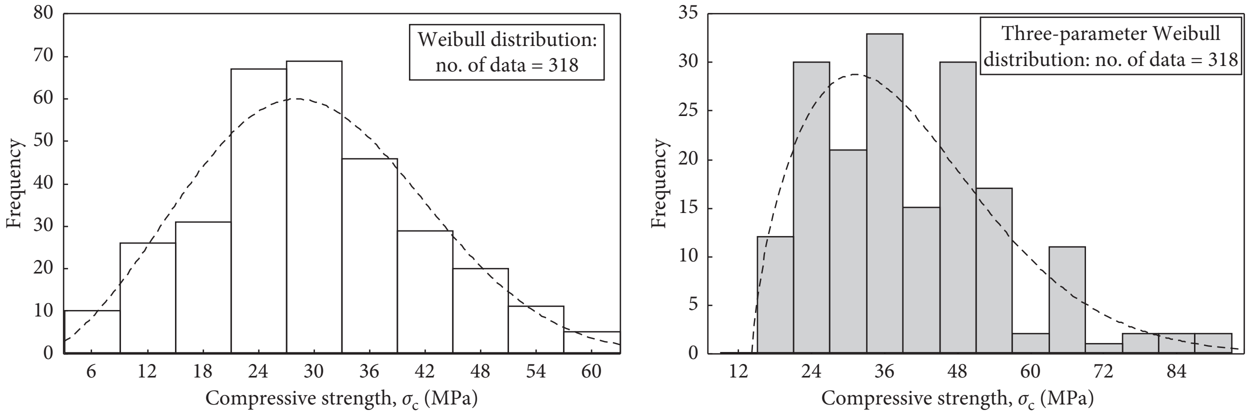
4.2. Relationship between Measured and Predicted Compressive Strengths of Cement Mortar. Since the relationship between the σ_c, w/c, and curing time (t) was not directly observed, the compressive strength (σ_c) was correlated with the independent variables (i.e., w/c and curing time) using a nonlinear relationship (equation (6)), as shown in Figure 7. The model parameters were obtained from least-squares multiple regression analyses (Table 3). Based on the nonlinear model parameter a (equation 3a), the compressive strength of cement mortar was affected by w/c and curing time. The model parameters, R^2, and RMSE are summarized in Table 3:

$$\sigma_c = \frac{7.8t^{0.26}}{w/c^{0.75}}, \quad \text{no. of data} = 316, \ R^2 = 0.80. \tag{6}$$

4.3. Relationship between Compressive Strength and Fly Ash. More than 100 data for compressive strength and w/c of cement mortar at different curing times up to 90 days were collected from various research studies. Also, there were no correlations between the σ_c, w/c, and FA (%) up to 90 days of curing (Figure 8).

4.4. Relationship between Measured and Predicted Compressive Strengths (σ_c) of Cement Mortar Modified with Fly Ash. The σ_c was correlated with the independent variables (i.e., w/c, FA, and curing time) using a nonlinear relationship (equation (7)). The model parameters were obtained from least-squares multiple regression analyses (Table 3). The model parameters, R^2, and RMSE are summarized in Table 3. A unique relationship was observed between measured and predicted compressive strengths (σ_c) (Figure 9). Based on the nonlinear model parameter a (equation 3b), the curing time had the highest effect on the increase of the compressive strength compared with the FA content:

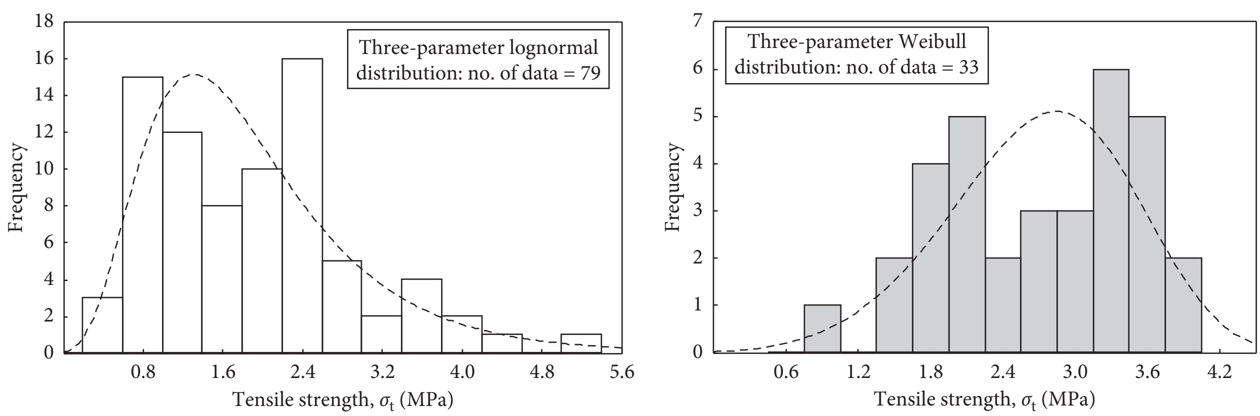
$$\sigma_c = \frac{7.8t^{0.26}}{w/c^{0.75}} + \frac{0.46t^{0.25}\text{FA}^{0.3}}{w/c^{1.01}}, \quad \text{no. of data} = 493, \ R^2 = 0.82. \tag{7}$$



(a)

(b)

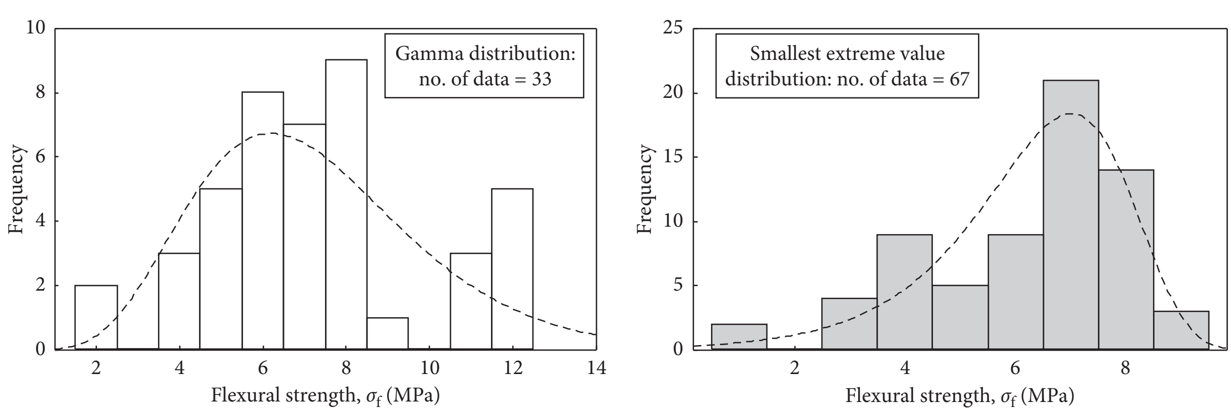
FIGURE 3: Statistical distribution of the compressive strength for (a) cement mortar and (b) cement mortar modified with fly ash (FA) up to 90 days of curing.



(a)

(b)

FIGURE 4: (a) Three-parameter lognormal distribution of the tensile strength for cement mortar and (b) 3-parameter Weibull distribution of the tensile strength for cement mortar modified with fly ash (FA) up to 90 days of curing.



(a)

(b)

FIGURE 5: Statistical distribution of the flexural strength for (a) cement mortar and (b) cement mortar modified with fly ash (FA) up to 90 days of curing.

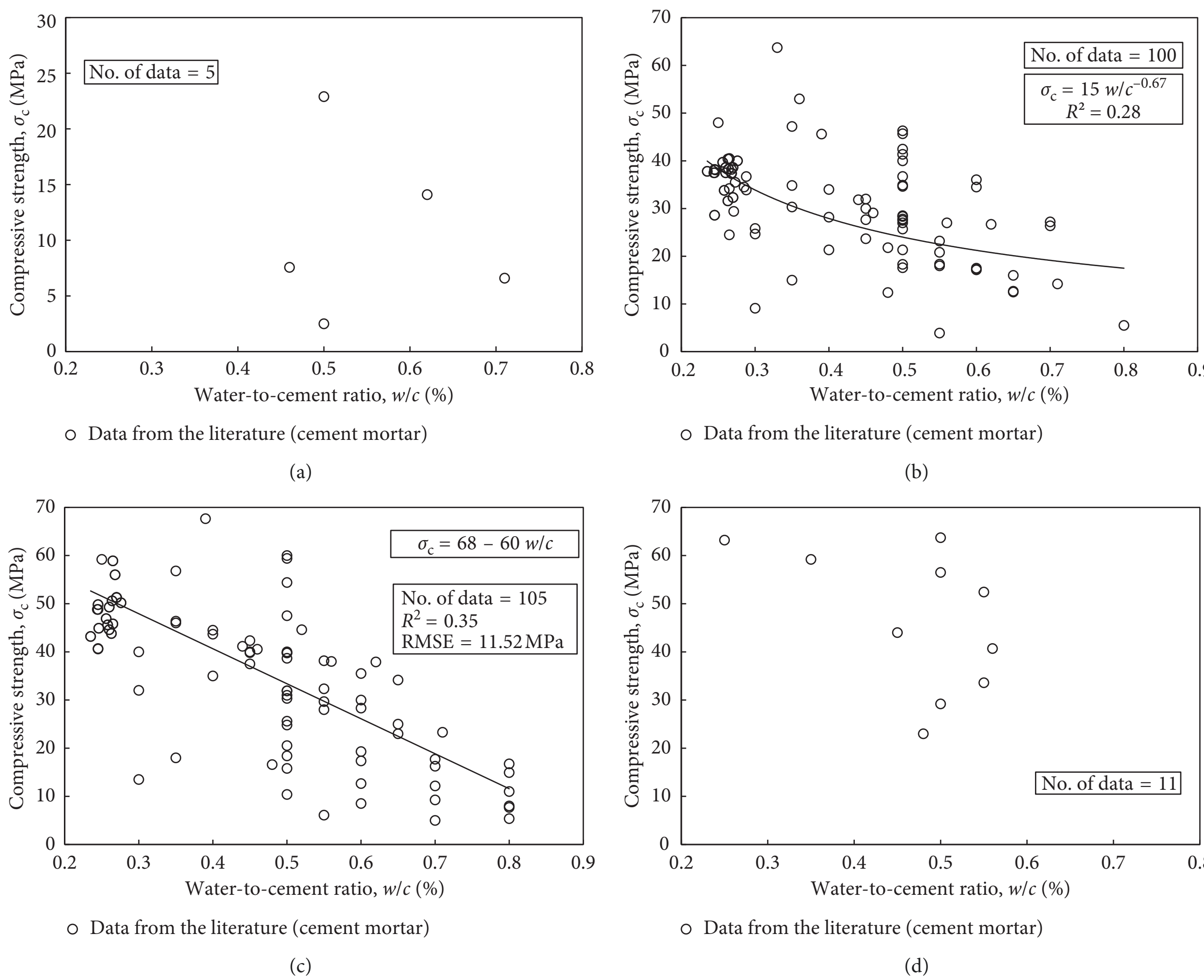


Figure 6: Variation between w/c and compressive strength of cement mortar at different curing times: (a) 1 day; (b) 7 days; (c) 28 days; (d) 90 days.

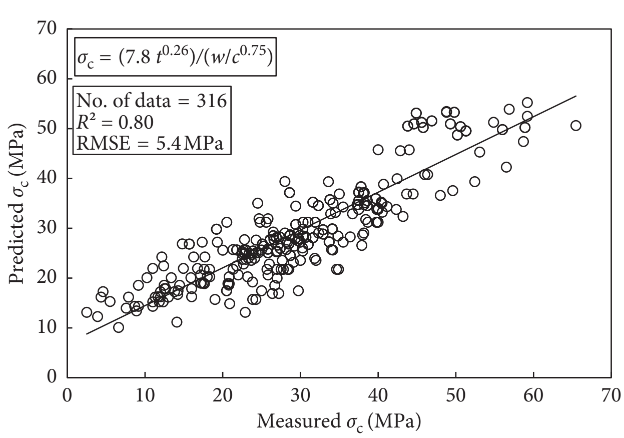


Figure 7: Relationship between measured and predicted compressive strengths for cement mortar.

4.5. Relationship between Measured and Predicted Split Tensile Strengths of Cement Mortar Modified with Fly Ash. The σ_t of cement mortar was influenced by w/c, curing time, and FA (%). The tensile strength (σ_t) was correlated with the w/c, curing time, and FA (%) using a nonlinear relationship (equation (8)). The model parameters were obtained from multiple regression analyses using the least-squares method. The model parameters, R^2, and RMSE are summarized in Table 3. A good relationship was observed between tested and predicted tensile strengths, as shown in Figure 10:

$$\sigma_t = \frac{0.65t^{0.12}}{w/c^{1.2}} + \frac{0.13t^{0.27}\mathrm{FA}^{0.01}}{w/c^{0.12}}, \quad \text{no. of data} = 89,\ R^2 = 0.83. \tag{8}$$

Depending on the nonlinear model parameter a (equation (4)), the fly ash content had a lowest effect on the increase of the σ_t compared with w/c and curing time.

4.6. Relationship between Measured and Predicted Flexural Strengths of Cement Mortar Modified with Fly Ash. The flexural strength (σ_f) of cement mortar was influenced by w/c, curing time, and FA (%). The flexural strength (σ_f) was correlated with the w/c, curing time, and percentage of fly ash using a linear relationship (equation (9)).

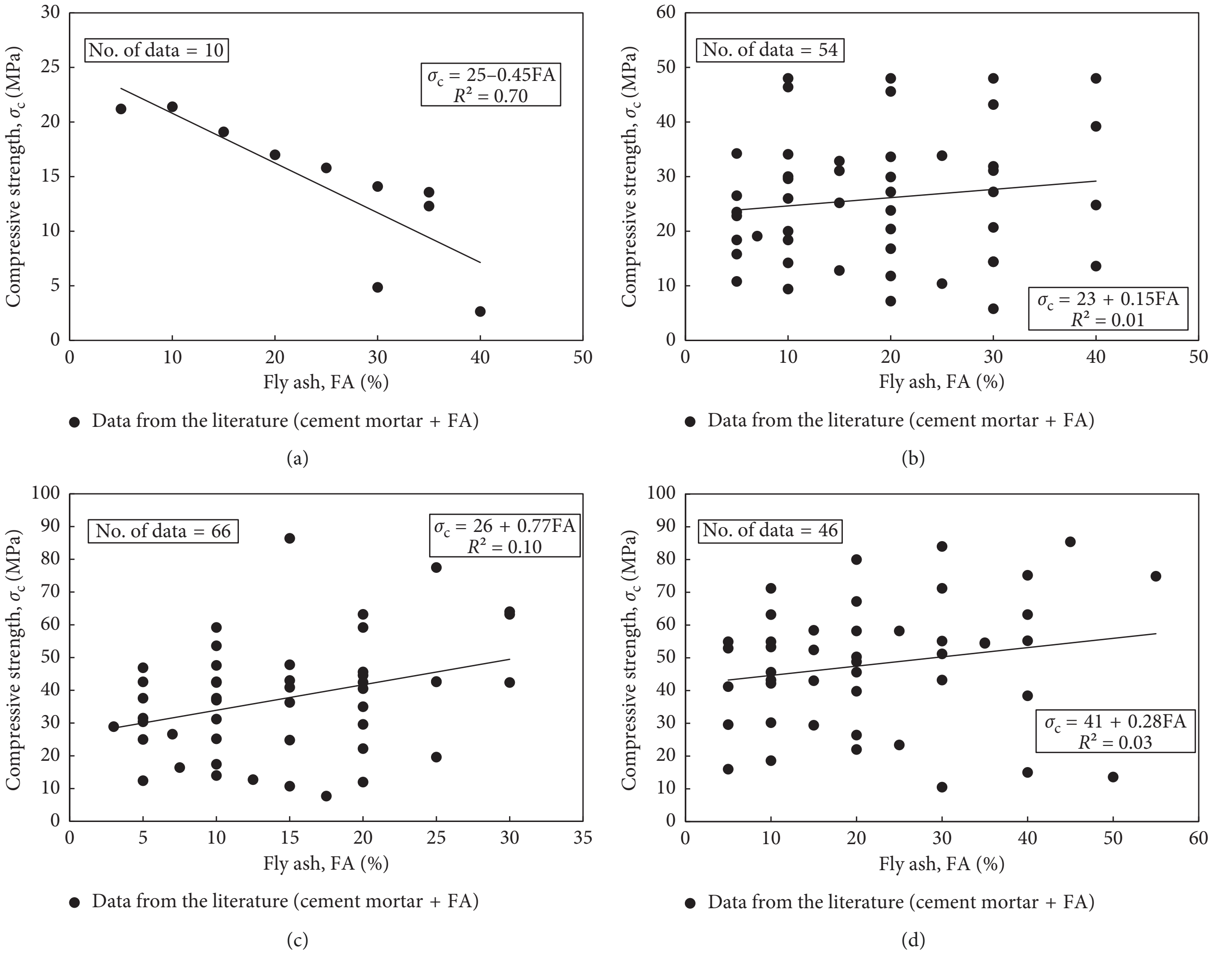


Figure 8: Variation between percentage of fly ash and compressive strength of cement mortar at different curing times: (a) 1 day; (b) 7 days; (c) 28 days; (d) 90 days.

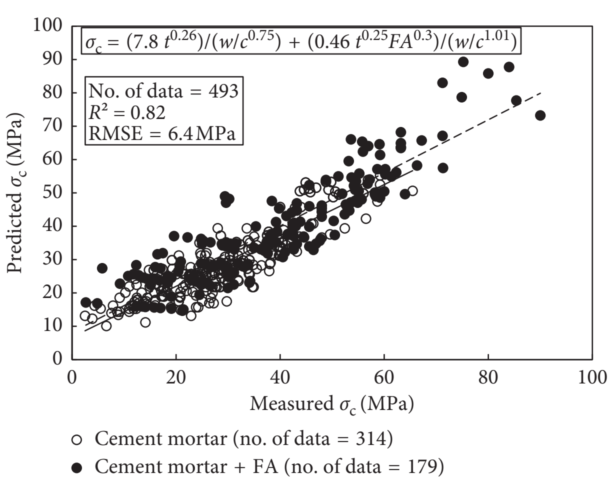


Figure 9: Relationship between measured and predicted compressive strengths for cement mortar modified with fly ash (FA).

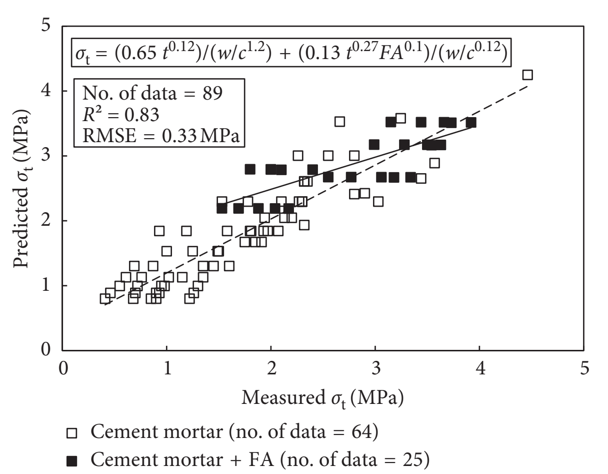


Figure 10: Relationship between measured and predicted split tensile strengths for cement mortar with and without fly ash (FA).

The model parameters were obtained from multiple regression analyses using the least-squares method. The model parameters, R^2, and RMSE are summarized in Table 3. Good relationships were observed between measured and predicted flexural strengths (σ_f), as shown in Figure 11:

$$\sigma_f = \frac{2.5t^{0.13}}{w/c^{0.7}} + \frac{0.11t^{0.16}\mathrm{FA}^{0.1}}{w/c^{0.1}}, \quad \text{no. of data} = 83, \; R^2 = 0.80. \tag{9}$$

Based on the nonlinear model parameter a (equation (5)), the FA content had a lowest effect on the increase of the σ_f compared with *w/c* and curing time.

4.7. Relationship between Compressive Strength and Split Tensile Strength

4.7.1. Cement Mortar. The variation of σ_t and σ_c for the total of 52 cement mortar data was represented using equation (1) and compared to the Hoek–Brown model (equation (2)) used in the literature (Figure 12). The model parameters Y_0, C, and D, R^2, and RMSE were 0.018, 6.7, 0.25, 0.98, and 0.09 MPa, respectively (Table 4). Both models have the same R^2, but the RMSE of the Vipulanandan correlation model was less than the RMSE of the Hoek–Brown model, as summarized in Table 3.

4.7.2. Cement Mortar Modified with FA. A total of 27 cement mortar modified with fly ash data were used to investigate the correlation between the tensile strength (σ_t) and compressive strength (σ_c) using the Vipulanandan correlation model (equation (1)), as shown in Figure 12. The model parameters Y_0, C, and D, R^2, and RMSE were 0.2, 6, 0.1, 0.97, and 0.1 MPa, respectively (Table 3).

4.8. Relationship between Compressive Strength (σ_c) and Flexural Strength (σ_f)

4.8.1. Cement Mortar. The variation of σ_f and σ_c for the total of 27 cement mortar data was represented using equation (1) and compared to the Hoek–Brown model (equation (2)) used in the literature (Figure 13). The σ_c increased with the increase of the σ_f (Figure 13). The variation of σ_f and σ_c was represented using the Vipulanandan correlation model (equation (1)), and the model parameters Y_0, C, and D, R^2, and RMSE were 0.58, 4, 0.057, 0.92, and 0.45 MPa, respectively (Table 3). The σ_f of cement mortar increased from 4 to 8 MPa when the σ_c increased from 20 to 50 MPa for cement mortar. The Vipulanandan correlation model predicted the relationship between the compressive and flexural strengths of the cement mortar better than the Hoek–Brown model (Figure 13).

4.8.2. Cement Mortar Modified with FA. The variation of σ_f and σ_c for the total of 56 cement mortar data was represented using equation (1) and compared to the Hoek–Brown model (equation (2)) used in the literature (Figure 13). The model parameters of equation (1), Y_0, C, and D, R^2, and RMSE were 0.46, 3.7, 0.07, 0.93, and 0.48 MPa respectively (Table 3). The flexural strength of cement mortar increased from 4 to 8 MPa when the compressive strength increased from 20 to 50 MPa for cement mortar. The Vipulanandan correlation model predicted the relationship between the compressive and flexural strengths of the cement mortar better than the Hoek–Brown model (Figure 13).

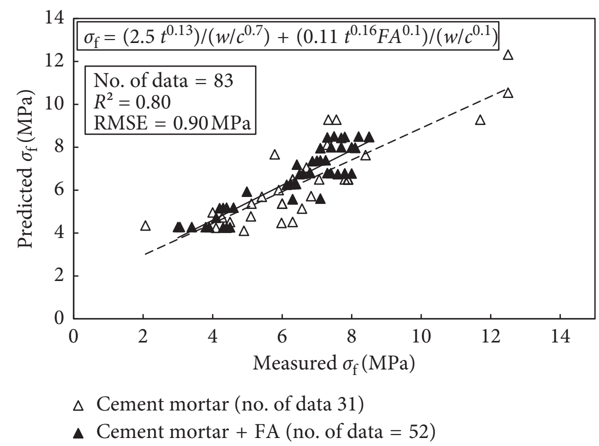


Figure 11: Relationship between measured and predicted flexural strengths for cement mortar with and without fly ash (FA).

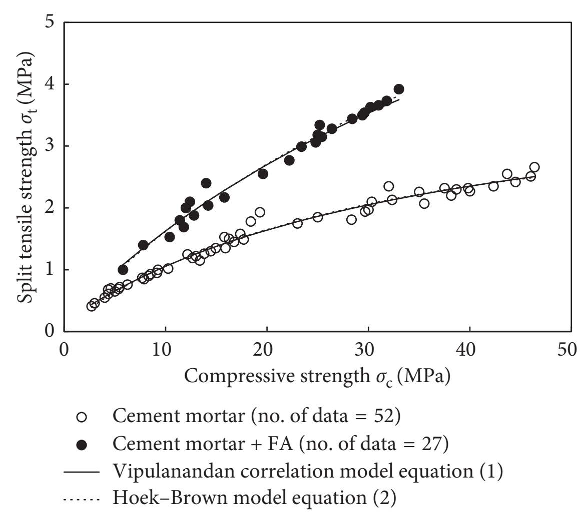


Figure 12: Variation of split tensile and compressive strengths of cement mortar with and without fly ash (FA).

Form the data analyses and modeling, it can be concluded that the FA enhanced the tensile strength only and it had the lowest effect on the compressive and flexural strengths compared with *w/c* and curing time.

5. Conclusions

Based on over 1000 data collected from various research studies and mathematical models, the following points were advanced:

(1) There were no direct correlations observed between the compressive strength and water-to-cement ratio (*w/c*) up to 90 days of curing.

(2) Depending on the statistical analysis and modeling, the typical percentage of fly ash used to modify the cement mortar ranged between 5% and 70%.

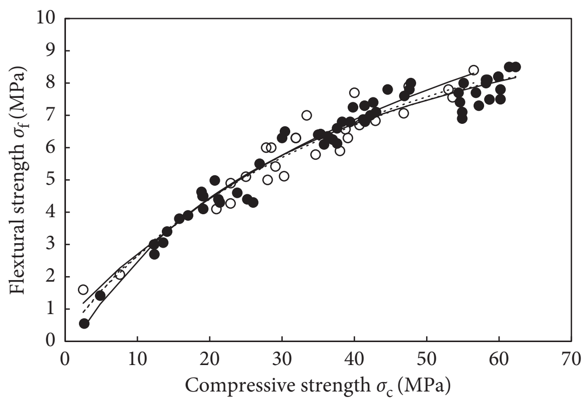


Figure 13: Variation of flexural and compressive strengths of cement mortar with and without fly ash (FA).

(3) Based on the NLM parameters, the fly ash had the lowest effect on the increase of the compressive and flexural strengths of the cement mortar. The tensile strength of cement mortar improved up to 50% with additional FA.

(4) Form the data analyses and modeling, it can be concluded that the FA enhanced the tensile strength only and it had the lowest effect on the compressive and flexural strengths compared with *w/c* and curing time.

Data Availability

All the data used in our study have been cited within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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