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

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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 ($\sigma_c$), tensile ($\sigma_t$), and flexural ($\sigma_f$) 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 ($\sigma_c$) 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$_4^{2-}$ 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).
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,
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]:

\[
Y = Y_0 + \frac{X}{(C + D \times X)}
\]

(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:

\[
Y = X + m \left( n X + 1 \right)^{0.5},
\]

(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 \((\sigma_c)\) of cement mortar only (FA = 0%):

\[
\sigma_c = a \left( \frac{w}{c} \right)^b (t)^c.
\]

(3a)

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

\[
\sigma_c = a \left( \frac{w}{c} \right)^b (t)^c + d \left( \frac{w}{c} \right)^e (FA)^g.
\]

(3b)

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

\[
\sigma_t = a \left( \frac{w}{c} \right)^b (t)^c + d \left( \frac{w}{c} \right)^e (FA)^g.
\]

(4)

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

\[
\sigma_f = a \left( \frac{w}{c} \right)^b (t)^c + d \left( \frac{w}{c} \right)^e (FA)^g.
\]

(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 \((\sigma)\)) 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 (\(\sigma)\) of 14% and
3. Mechanical Properties

3.2. Compressive Strength

(1) Cement Mortar. A total of 318 compressive strength ($\sigma_c$) data for the cement mortar were collected from various research studies (Table 1). The compressive strength ($\sigma_c$) 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 ($\sigma$) 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 ($\sigma_c$) data for cement mortar modified with fly ash were collected from the literature (Table 1). $\sigma_c$ ranged from 15 MPa to 88 MPa with a mean of 40 MPa, a std.

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

<table>
<thead>
<tr>
<th>Dependent variable (y-axis)</th>
<th>Independent variable (x-axis)</th>
<th>Vipulanandan correlation model (equation (1))</th>
<th>Hoek–Brown model (equation (2))</th>
<th>No. of data</th>
<th>Figure number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_c$ of cement mortar only</td>
<td>$Y_0$</td>
<td>$C$</td>
<td>$D$</td>
<td>RMSE (MPa)</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Split tensile strength, $\sigma_t$ (MPa)</td>
<td>0.018</td>
<td>6.7</td>
<td>0.250</td>
<td>0.090</td>
<td>0.98</td>
</tr>
<tr>
<td>Split tensile strength, $\sigma_t$ (MPa) for cement mortar modified with fly ash</td>
<td>0.200</td>
<td>6.0</td>
<td>0.100</td>
<td>0.108</td>
<td>0.97</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$d$</th>
<th>$e$</th>
<th>$f$</th>
<th>$g$</th>
<th>$h$</th>
<th>$i$</th>
<th>RMSE (MPa)</th>
<th>$R^2$</th>
<th>No. of data</th>
<th>Equation number</th>
<th>Figure number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_c$ of cement mortar only</td>
<td>7.8</td>
<td>$-0.75$</td>
<td>0.21</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>5.4</td>
<td>0.80</td>
<td>316</td>
<td>(3a)</td>
<td>Figure 7</td>
</tr>
<tr>
<td>$\sigma_c$ of cement mortar modified with fly ash</td>
<td>7.8</td>
<td>$-0.75$</td>
<td>0.21</td>
<td>0.46</td>
<td>$-1.01$</td>
<td>0.25</td>
<td>0.3</td>
<td>---</td>
<td>---</td>
<td>6.4</td>
<td>0.83</td>
<td>493</td>
<td>(3b)</td>
<td>Figure 9</td>
</tr>
<tr>
<td>$\sigma_t$ of cement mortar modified with fly ash</td>
<td>0.65</td>
<td>$-1.2$</td>
<td>0.12</td>
<td>0.13</td>
<td>0.12</td>
<td>0.27</td>
<td>0.01</td>
<td>---</td>
<td>---</td>
<td>0.40</td>
<td>0.83</td>
<td>89</td>
<td>(4)</td>
<td>Figure 10</td>
</tr>
<tr>
<td>$\sigma_f$ of cement mortar modified with fly ash</td>
<td>2.50</td>
<td>$-0.7$</td>
<td>0.13</td>
<td>0.11</td>
<td>$-0.10$</td>
<td>0.16</td>
<td>0.1</td>
<td>---</td>
<td>---</td>
<td>0.90</td>
<td>0.80</td>
<td>83</td>
<td>(5)</td>
<td>Figure 11</td>
</tr>
</tbody>
</table>

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 ($\sigma_c$) data for the cement mortar were collected from various research studies (Table 1). The compressive strength ($\sigma_c$) 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 ($\sigma$) 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 ($\sigma_c$) data for cement mortar modified with fly ash were collected from the literature (Table 1). The $\sigma_c$ ranged from 15 MPa to 88 MPa with a mean of 40 MPa, a std.
deviation ($\sigma$) 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 ($\sigma_t$) data for cement mortar for curing time up to 90 days were collected (Table 1). The tensile strength ($\sigma_t$) varied from 0.4 MPa to 6 MPa with a mean of 1.9 MPa, a std. deviation ($\sigma$) 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 ($\sigma_t$) 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 ($\sigma$) of 0.8 MPa (Table 2). The histograms were also analyzed and showed more than 76% of the total $\sigma_t$ was between 1.8 and 3.6 MPa, as shown in Figure 4(b). Based on AD and $P$ values, the probability distribution of $\sigma_t$ 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 ($\sigma_f$) 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 ($\sigma$) 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 ($\sigma$) 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 $\sigma_c$ 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 $\sigma_c$, w/c, and curing time (t) was not directly observed, the compressive strength ($\sigma_c$) 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:

$$
\sigma_c = \frac{7.84^{0.26}}{w/c^{0.75}}, \quad \text{no. of data} = 316, \quad R^2 = 0.80.
$$

#### 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 $\sigma_c$, w/c, and FA (%) up to 90 days of curing (Figure 8).

#### 4.4. Relationship between Measured and Predicted Compressive Strengths ($\sigma_c$) of Cement Mortar Modified with Fly Ash

The $\sigma_c$ 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 ($\sigma_c$) (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:

$$
\sigma_c = \frac{7.84^{0.26}}{w/c^{0.75}} + \frac{0.464^{0.25} FA^{0.3}}{w/c^{1.01}}, \quad \text{no. of data} = 493, \quad R^2 = 0.82.
$$

---

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

**Figure 3:** Frequency distribution for the flexural strength of cement mortar was a 3-parameter Weibull distribution.

**Figure 4:** Histogram of percent of fly ash (FA) added to the cement mortar.

**Figure 5:** Frequency distribution for the flexural strength of cement mortar modified with fly ash.

**Figure 6:** Histogram of percent of fly ash (FA) added to the cement mortar.

**Figure 7:** Histogram of percent of fly ash (FA) added to the cement mortar.
The 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 is shown in Figure 3.

The three-parameter lognormal distribution of the tensile strength for cement mortar and the three-parameter Weibull distribution of the tensile strength for cement mortar modified with fly ash (FA) up to 90 days of curing are displayed in Figure 4.

The 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 is presented in Figure 5.
4.5. Relationship between Measured and Predicted Split Tensile Strengths of Cement Mortar Modified with Fly Ash.

The $\sigma_t$ of cement mortar was influenced by $w/c$, curing time, and FA (%). The tensile strength ($\sigma_t$) 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:

$$\sigma_t = \frac{(7.8t^{0.26})}{(w/c^{0.75})}$$

$\sigma_t$ = (7.8 $t^{0.26}$)/(w/c$^{0.75}$)

No. of data = 316
RMSE = 5.4MPa

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

4.6. Relationship between Measured and Predicted Flexural Strengths of Cement Mortar Modified with Fly Ash. The flexural strength ($\sigma_f$) of cement mortar was influenced by $w/c$, curing time, and FA (%). The flexural strength ($\sigma_f$) was correlated with the $w/c$, curing time, and percentage of fly ash using a linear relationship (equation (9)).
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 ($\sigma_f$), as shown in Figure 11:
\[ \sigma_t = \frac{2.5^{0.13}}{w/c^{0.7}} + \frac{0.11r^{0.16}FA^{0.1}}{w/c^{0.1}} , \text{ no. of data} = 83, \ R^2 = 0.80. \]  

(9)

Based on the nonlinear model parameter \( a \) (equation (5)), the FA content had a lowest effect on the increase of the \( \sigma_t \) 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 \( \sigma_t \) and \( \sigma_c \) 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 (\( \sigma_t \)) and compressive strength (\( \sigma_c \)) 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 (\( \sigma_c \)) and Flexural Strength (\( \sigma_f \))

4.8.1. Cement Mortar. The variation of \( \sigma_t \) and \( \sigma_c \) 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 \( \sigma_c \) increased with the increase of the \( \sigma_t \) (Figure 13). The variation of \( \sigma_t \) and \( \sigma_c \) 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 \( \sigma_t \) of cement mortar increased from 4 to 8 MPa when the \( \sigma_c \) 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 \( \sigma_t \) and \( \sigma_c \) 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).

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%.
(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.

Acknowledgments

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References

[21] H. Biricik and N. Sarier, “Comparative study of the characteristics of nano silica-, silica fume- and fly ash-incorporated...


[29] C. Vipulanandan and A. Mohammed, “Smart cement modified with iron oxide nanoparticles to enhance the piezoresistive behavior and compressive strength for oil well applications,” *Smart Materials and Structures*, vol. 24, no. 12, article 125020, 2015.


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