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Predicting the Compressive Strength of Concrete Modified by Nanoparticles and Exposed to Fire

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Abstract: *The incorporation of Nano-particles in concrete as partial replacements for cement is considered as one of the solutions to improve the mechanical properties of the structural elements under fire exposure. The current study aims to investigate the effect of incorporating Nano-silica (NS) and/or Nano-clay (NC) in concrete on the compressive strength of concrete at ambient temperatures and after fire exposure. The current study develops predictive models to estimate the compressive strength of concrete modified with NS and/or NC at ambient temperatures and after fire exposure. Data of 208 cubic specimens of 100 mm obtained from the literature were chosen as a database for the proposed models. The specimens are divided into three groups. The first group includes 52 specimens for modeling the compressive strength of concrete modified with NS and/or NC at ages of 7, 28, 56 and 90 days. The second group includes 156 specimens for modeling the compressive strength of concrete modified with NS and/or NC exposed to fire for 1 or 2 hours after 28 days of curing. The third group includes 169 specimens represents a combination of the first two groups for all specimens that tested at 28 days and for all durations of fire exposure. The input parameters for the models of the first group are: a) Replacement level of cement with NS, b) Replacement level of cement with NC, and c) Curing Time (CT). The input parameters for the second group models are: a) Replacement level of cement with NS, b) Replacement level of cement with NC, and c) Temperature degree (TEMP). The input parameters for the third group models are: a) Replacement level of cement with NS, b) Replacement level of cement with NC, and c) Temperature degree, and d) Exposure duration (D). The output parameter for all models is the concrete compressive strength (f_c). The results obtained from the constructed models for the strength of concrete exposed to fire effect are in good agreements with the available experimental results from the literature. Best correlations were attained among the compressive strength and cement substitution with NS and/or NC. To predict the compressive strengths of concrete modified with NS and/or NC at ambient temperatures and after fire effect, predictive models utilizing multivariate regressions were proposed. The full quadratic model appears to be the best model with highest correlation, highest coefficient of determination, and least RMSE when compared to other proposed models. The pure quadratic model is the second-best model for predicting the compressive strength of concrete modified with NS and/or NC at different curing periods and at different durations of fire exposure.*

Key Word*: Nano-silica; Nano-clay; Multivariate regression; Prediction; Compressive strength*

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I. Introduction

Concrete is one of the construction materials that is characterized by its compressive strength, durability and its resistance to fire. The behavior of concrete is a complex material and its properties can change dramatically when exposed to high temperatures. The incorporation of minerals as additives in concrete due to its benefits in improving the performance of the concrete and in reducing the construction cost has been extensively used. As a result of continuous developments in Nano technology, various forms of Nano sized materials were available. The Nano materials have particle size less than 100 nm [1]. The nanomaterials have been used as partial substitution for cementitious materials in concrete to improve the physical and the mechanical properties of concrete as well as to improve the permeability of concrete as a result of the small size and the larger surface area of the nanoparticles [2]. Many researchers have used Nano-silica and Nano-kaolin as supplementary cementitious materials in concrete to improve its durability. Calcium Silica Hydrate gel formed by the reaction between Ca $(OH)_2$ and Nano materials as pozzolanic materials has the responsibility for the improvement of the concrete properties. The effect of incorporating Nano silica and Nano clay as partial replacements for cement in concrete on the durability of concrete exposed to fire has been investigated [3]. The resistance of concrete to fire effect is one of the major concerns that affects the life time and the structural function of concrete structures. The behavior of concrete exposed to high temperatures is a complex behavior as well as its strength decreases as the temperature increases. Many factors affect the decrease in the concrete strength such as the type of aggregate, water/cement ratio, cement content [4], rate of heating, insulating

properties of concrete, exposure duration, and thermal incompatibility between aggregates and cement paste [5]. The reduction in the concrete compressive strength due to fire exposure reached about 20% for temperatures up to 400 °C and reached about 70% for temperatures up to 800 °C. The fire resistivity properties of concrete are determined using fire test methods conforming ASTM-E119 [6]. Little researches have been conducted on investigating the fire effect on concrete modified with natural pozzolan. The incorporation of NS and NC in concrete as cement replacement improved the mechanical properties of concrete at ambient temperature up to 200 °C [3]. The mechanical properties of concrete decrease as the temperature increase above 300 °C [7-8]. Many researchers have investigated the effect of incorporating various supplementary cementitious materials such as Fly Ash, Ground Granulated Blast Furnace Slag, Silica Fume and MetaKaolin [9] in concrete as cement replacement to overcome the strength deterioration of concrete exposed to fire effect [10-13]. Many researchers have applied regression analysis to predict the concrete properties [14-19]. Prediction models for the mechanical properties of concrete after burning using linear regression and artificial neural network (ANN) have been proposed [20]. Four predictive models for the prediction of thermo-mechanical properties of rubber-modified recycled aggregate concrete utilizing ANN, random forest, logistic regression, and multiple linear regression have been proposed [21].
The present study aims to investigate and predict the complex effects of incorporating Nano-silica, Nano-clay as partial cement replacements in concrete on the strength of concrete exposed to fire effect. The used predictive models in this study are multilinear model (MLM), pure quadratic model (PQM), interaction model (IM), and full quadratic model (FQM). Different conditions for partial replacement of cement with NS and NC, temperature degree and exposure duration, were utilized as key data inputs in the proposed models.

II. Experimental work

The experimental work presented in this study is obtained from the literature [3]. The bulk densities of the used crushed limestone as coarse aggregate and sand as fine aggregate were 1618 kg/m^3 and 1675 kg/m^3, respectively. Type I cement was used. Available local NS with particle size ranged from 13-75 nm was used. The used NC is produced from heat treatment of kaolin. The used water was the normal tap water. The quantities of coarse aggregate, fine aggregate, cement and water were 1170, 656, 400 and 180 kg/m^3, respectively.

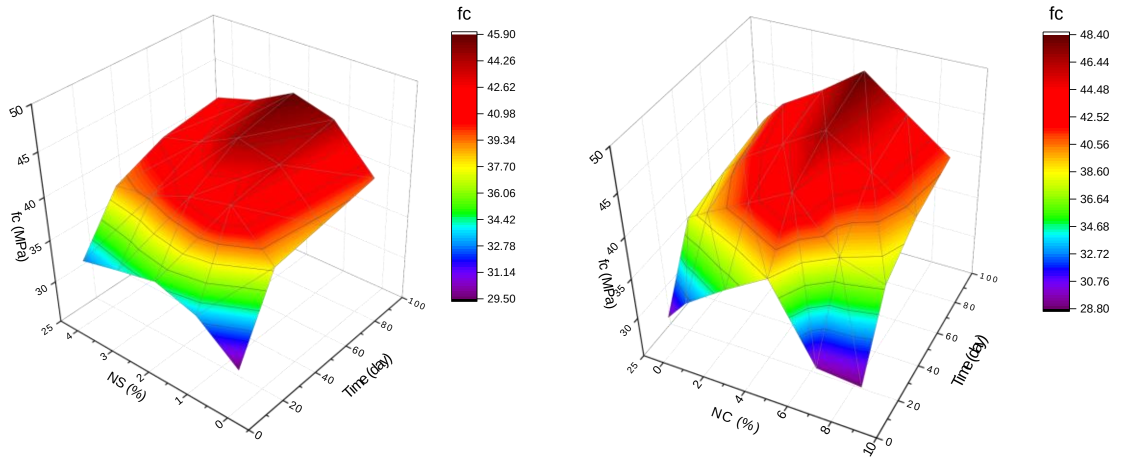
A total of 208 concrete cubes of 100 mm of different concrete mixes with various levels of replacement of cement with NS and/or NC have been tested under compression. The experimental work focused on investigating the effect of replacing cement with NS and/or NC on the compressive strength of concrete exposed to fire. The levels of cement substitution with NS ranged from 1% to 4%. The replacement levels of cement with NC were 1%, 3%, 5%, 7% and 9%. The levels of replacement of cement with the combination of NS and NC were (0.5%+4.5%), (1%+4%) and (1.5%+3.5%). The experimental work was divided into two parts. The first part has been conducted on 52 concrete cube specimens of 100 mm. The specimens were tested under compression at periods of 7, 28, 56 and 90 days at ambient temperature. The second part has been conducted on 156 concrete cube specimens of 100 mm exposed to elevated temperatures and tested under compression after 28 days of curing. The specimens were tested after exposure to temperatures ranged from 200 °C to 800 °C. The exposure periods were one and two hours.

II.1. Compressive Strength of Specimens at Ambient Temperature

The results of compressive strength, f_c of the concrete cubes at different conditions of replacement of cement with NS, NC, and hybrid combination of NS and NC at various curing durations are presented in Fig.1 and Table 1. It was clear from Fig.1 that the compressive strength of concrete has increased as the percentage of cement replacement with NS increases up to 2%. Also, the compressive strength of concrete has increased as the percentage of cement replacement with NC increases up to 5%. It was clear from Table 1 that the optimum levels of combined incorporation of NS and NC as partial replacements for cement in concrete were 1% and 4%, respectively to improve the compressive strength of concrete.

Table 1: Compressive strength for hybrid specimens at various curing durations

NS (%)	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5
NC (%)	4.5	4	3.5	4.5	4	3.5	4.5	4	3.5	4.5	4	3.5
Duration (day)	7	7	7	28	28	28	56	56	56	90	90	90
***fc* (MPa)**	31.5	31.8	33.8	42.3	43.7	43.1	44.1	45.6	45	45.2	46.9	46.2



(a) Cement replacement with NS (b) Cement replacement with NC

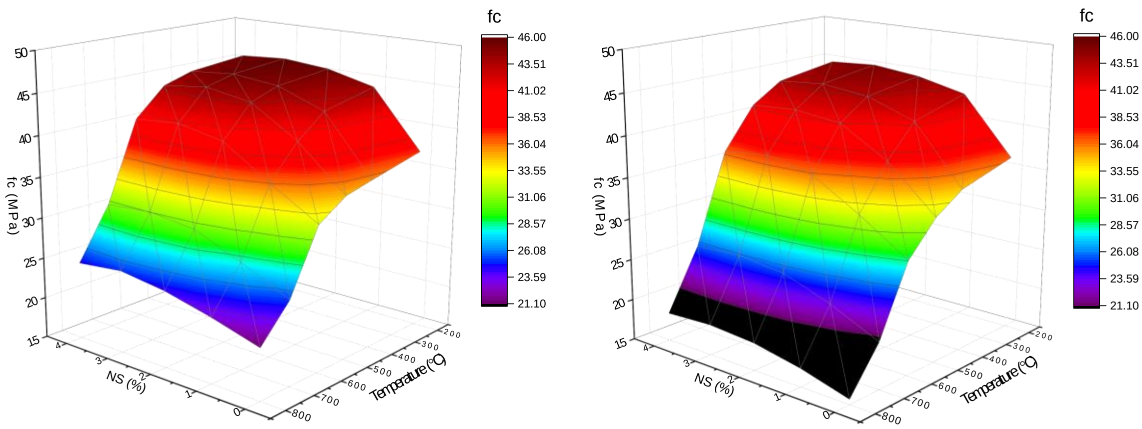
Fig.1 Compressive strengths (At ambient temperatures)

II.2. Compressive Strength for Specimens Exposed to Fire

The compressive strengths of concrete exposed to fire after 28 days of curing are shown in Table 2, Fig.2, and Fig.3. It was clear from Fig.2 that the compressive strength of concrete exposed to elevated temperatures for different durations (1 or 2 hours) has increased as the percentage of cement replacement with NS increased up to 3%. Also, Fig.3 shows that the compressive strength of concrete has increased as the percentages of cement replacement with NC increased up to 5%. It was clear from Table 2 that the optimum levels of combined incorporation of NS and NC as partial replacements for cement in concrete exposed to elevated temperatures for different durations were 1% and 4%, respectively to improve the compressive strength of concrete after 28 days of curing.

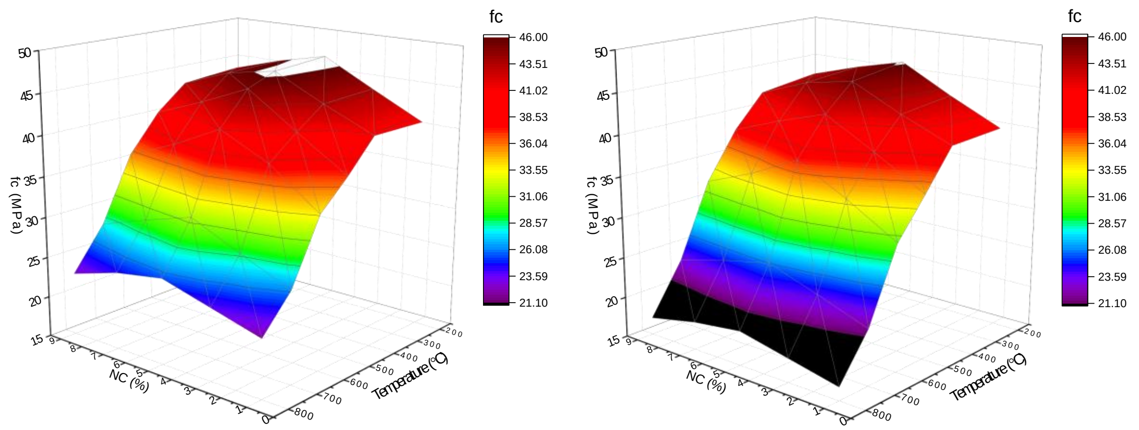
Table 2: Compressive strengths of hybrid specimens at various durations of fire exposure

D	NS (%)	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5
	NC (%)	4.5	4	3.5	4.5	4	3.5	4.5	4	3.5
1 hour	Temperature (°C)	200	200	200	400	400	400	500	500	500
	fc (MPa)	44	45.4	44.8	42.1	43.6	42.6	39.6	41.3	40.1
	Temperature (°C)	600	600	600	700	700	700	800	800	800
	fc (MPa)	35.3	37.3	35.9	28	28.7	28.1	23.1	24.1	23.3
2 hours	Temperature (°C)	200	200	200	400	400	400	500	500	500
	fc (MPa)	43.1	44.5	43.9	40.9	42.5	41.4	37.3	38.5	37.8
	Temperature (°C)	600	600	600	700	700	700	800	800	800
	fc (MPa)	31.8	32.8	32.3	23.3	23.8	23.4	17.4	17.9	17.5



(a) Fire exposure duration = 1 hour (b) Fire exposure duration = 2 hours

Fig.2 Compressive strengths (Cement Replacement with NS)



(a) Fire exposure duration = 1 hour (b) Fire exposure duration = 2 hours

Fig.3 Compressive strengths (Cement Replacement with NC)

III. Methods

III.1. Multiple Linear Regression

Regression analysis is considered as an effective statistical method for predicting the existence of relationship between multiple variables. It is commonly utilized in the predictions of the mechanical properties of concrete. Multiple regression investigates the relationships among a variety of independent and dependent variables. Equation (1) represents the form of the general equation of multiple linear regression.

$$Y = a + \sum_{i=1}^{n} b_i x_i + \varepsilon$$

(1)

Where, Y is referring to the dependent variable, x_i is referring to the independent variable, n is the number of variables, b_i is referring to the coefficients of regression, a is a constant, and ε is error.

III.2. Multiple Nonlinear Regression Analysis

The estimation of the dynamic relationship between the independent and the dependent variables can be made by using nonlinear regression analysis. This approach helps in selecting the right model. Various forms of multiple nonlinear regression, such as pure quadratic and full quadratic versions, have been investigated.

III.3. Assessment of Model Performance

The predictive model performance is assessed according to the statistical measures such as the coefficient of determination (R^2) and the root mean square error (RMSE). These measures estimate the power of the prediction models to predict the compressive strength of concrete modified with NS and NC. Equations (2) and (3) represent the mathematical expressions for R^2 and RMSE, respectively.

$$R^2 = \left[\frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\sum_{i=1}^{n} (x_i - \bar{x})^2)(\sum_{i=1}^{n} (y_i - \bar{y})^2)}} \right]^2$$

(2)

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - y_i)^2}$$

(3)

Where, x_i is referring to the results from experimental work, y_i is referring to the predicted data, $\bar{x}$ is the mean of the experimental results, $\bar{y}$ is the mean of predicted values, and n is the number of data set.

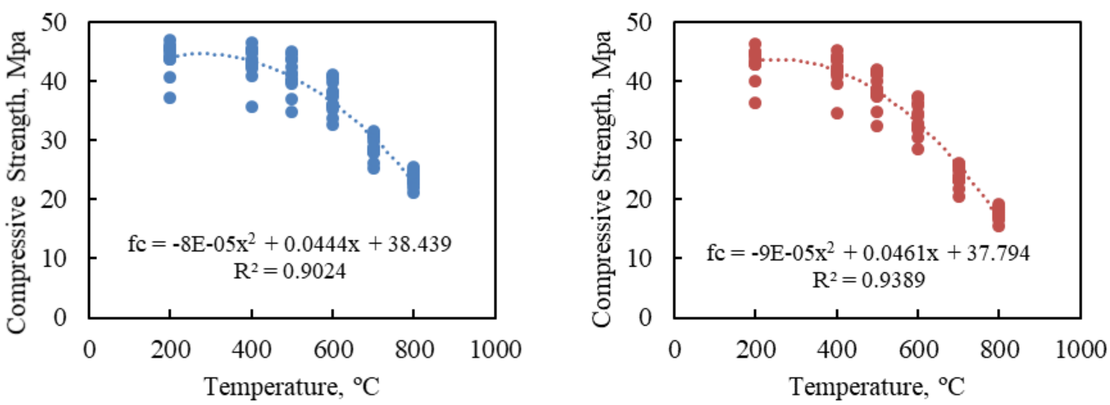
IV. Results and discussion

Table 3 presents the summary of data statistics of the constructed models.

Table 3: Data Statistics for all models

Group	Case	Parameter	N	Min.	Max.	Mean	Std. Dev.
1	At ambient temperature	NS Replacing Cement, %	52	0	4	1.00	1.27
		NC Replacing Cement, %	52	0	9	2.85	2.91
		Curing Time (*CT*), day	52	7	90	45.3	31.44
		Compressive Strength (f_c), MPa	52	28.9	48.4	40.3	5.14
2	After 1-hour fire exposure	NS Replacing Cement, %	78	0	4	1.00	1.26
		NC Replacing Cement, %	78	0	9	2.85	2.90
		Temperature (*TEMP*), °C	78	200	800	533	198.48
		Compressive Strength (f_c), MPa	78	21.2	47.0	36.34	8.02
	After 2-hours fire exposure	NS Replacing Cement, %	78	0	4	1.00	1.26
		NC Replacing Cement, %	78	0	9	2.92	2.90
		Temperature (*TEMP*), °C	78	200	800	533	198.48
		Compressive Strength (f_c), MPa	78	15.6	48.2	33.15	9.73
3	Combination	NS Replacing Cement, %	169	0	4	1	1.26
		NC Replacing Cement, %	169	0	9	2.85	2.89
		Temperature (*TEMP*), °C	169	25	800	494.2	233.6
		Fire Duration (*D*), hour	169	0	2	1.385	0.627
		Compressive Strength (f_c), MPa	169	15.6	47.0	35.22	8.85

The trends of the compressive strength (f_c) of concrete specimens with temperature degree are presented in Fig.4. It seems to be nonlinear relationship.



(a) Fire exposure duration = 1 hour (b) Fire exposure duration = 2 hours

Fig.4 Compressive strength trends

All the proposed predictive models to predict the compressive strength of concrete are explored in the following section. The models are compared to find the best model for the prediction of the compressive strength of the modified concrete with NS and/or NC exposed to fire. The used symbols for all proposed equations are (f_c) for the compressive strength, (*NS)* for replacement level of cement with Nano-silica, (*NC)* for replacement level of cement in concrete with Nano-clay, (*CT)* for curing time, (*TEMP)* for temperature degree, and (*D)* for the duration of fire exposure.

IV.1. Predictive models for concrete compressive strength at ambient temperature

The mathematical expressions for the predicted compressive strength for MLM, PQM, IM, and FQM are presented in Equations (4) to (7), respectively for concrete modified with NS and/or NC at curing durations ranged from 7 days to 90 days at ambient temperature.

$$f_c = 34.513 + 0.052NS + 0.001NC + 0.126CT \quad (4)$$

$$f_c = 28.683 + 1.951NS + 1.517NC + 0.391CT - 0.449NS^2 - 0.187NC^2 - 0.003CT^2 \quad (5)$$

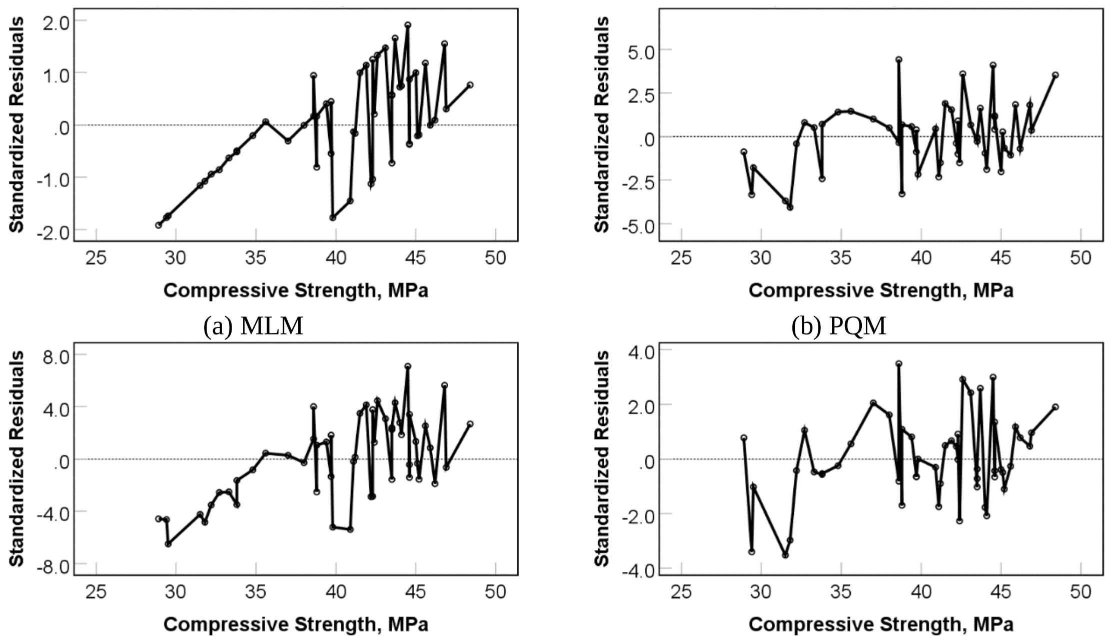
$$f_c = 35.238 - 0.201NS - 0.316NC + 0.109CT + 0.485NS \times NC + 0.002NS \times CT + 0.005NC \times CT \quad (6)$$

$$f_c = 28.038 + 4.224NS + 2.361NC + 0.374CT - 0.99NS^2 - 0.296NC^2 - 0.003CT^2 - 0.963NS \times NC + 0.002NS \times CT + 0.005NC \times CT \quad (7)$$

Fig.5 shows the normal probability of the standardized residuals for the proposed predictive models for the compressive strength of concrete modified with NS and/or NC tested at durations ranged from 7 days to 90 days at ambient temperature. The regression lines run through 52 values of compressive strength. It was noticed that there is independency of errors from each other. The residuals appear uniformly distributed around zero for compressive strengths greater than 35 MPa for MLM and for IM, while the residuals appear uniformly distributed around zero for PQM and for the FQM for all data.

Table 4 displays the summary of statistics of all strength models. Based on F static, the significance is less than 0.0005. The constructed models for the compressive strength are statistically significant with confidence levels more than 99.95%. The greater value of R^2 is obtained from FQM (90.87%) which designates a good fit. The least value of RMSE is obtained from FQM (1.537). The coefficients of the mathematical expressions of the compressive strength are assessed to recognize the contribution of each parameter utilized in the experiments.

Fig.6 shows the plot of the experimental and the predicted strengths on the data order of the test results. It shows a similarity between predicted values of the compressive strength and experimental results. It was clear that FQM for the compressive strength of concrete modified with NS and/or NC has the highest R^2 and the lowest RMSE so, FQM fits the data better than other predictive models.



(a) MLM (b) PQM

(c) IM (d) FQM

Fig.5 Normal probability of standardized residuals (At ambient temperature)

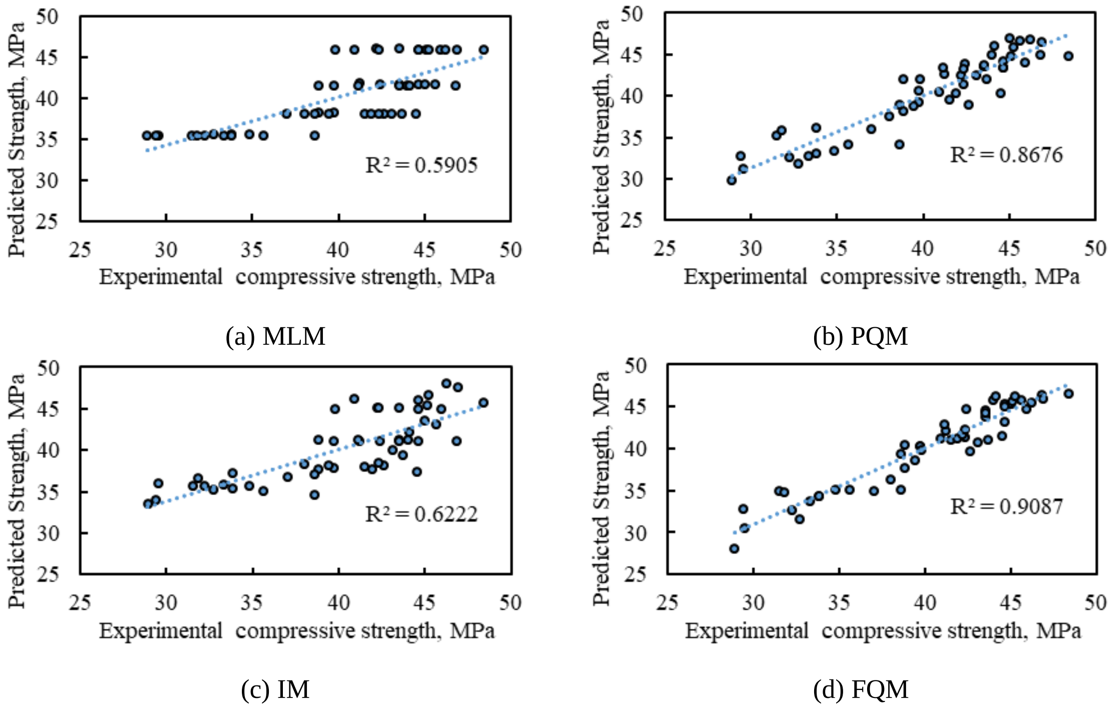


Fig.6 Experimental values versus predicted compressive strengths (At ambient temperature)

Table 4: Statistical summary of the proposed models (At ambient temperature)

Model	R^2 (%)	RMSE	F-value	P-Value
MLM	59.05%	3.255	23.073	2.16E-09
PQM	86.76%	1.851	41.195	2.82E-17
IM	62.22%	3.127	10.352	1.35E-07
FQM	90.87%	1.537	40.790	3.98E-18

IV.2. Predictive models for compressive strength of concrete exposed to fire for one hour

The mathematical expressions for the predicted compressive strength for MLM, PQM, IM, and FQM are presented in Equation (8) to Equation (11), respectively for concrete modified with NS and/or NC exposed to temperatures ranged between 200 ºC and 800 ºC for one hour after 28 days of curing.

$$f_c = 52.618 + 1.361NS + 0.419NC - 0.035TEMP \tag{8}$$

$$f_c = 35.319 + 1.532NS + 0.949NC + 0.044TEMP - 0.018NS^2 - 0.067NC^2 - 0.00007968TEMP^2 \tag{9}$$

$$f_c = 50.777 + 2.175NS + 0.87NC - 0.032TEMP - 0.292NS \times NC - 0.001NS \times TEMP - 0.001NC \times TEMP \tag{10}$$

$$f_c = 31.348 + 5.872NS + 2.977NC + 0.048TEMP - 0.838NS^2 - 0.232NC^2 - 0.00007968TEMP^2 - 1.46NS \times NC - 0.001NS \times TEMP - 0.001NC \times TEMP \tag{11}$$

Fig.7 shows the normal probability of the standardized residuals for the proposed predictive models for the compressive strength of concrete modified with NS and/or NC exposed to temperatures ranged between 200 ºC and 800 ºC for one hour after 28 days of curing. The regression line runs through 78 values of compressive strength. The residuals appear uniformly distributed around zero for compressive strengths greater than 30 MPa for MLM and for IM, while the residuals appear uniformly distributed around zero for PQM and FQM for all values of compressive strength.

Table 5 displays the summary of statistics of all strength models. Based on F static, the significance is less than 0.0005. The constructed models for the compressive strength are tremendously statistically significant with levels of confidence more than 99.95%. The greater value of R^2 is obtained from FQM (97.49%) that shows a good fit. The least value of RMSE is obtained from FQM (1.262). PQM has a determination coefficient of 94.05% close to that of FQM (97.49%). Also, the RMSE of PQM is 1.945, which is less than that of MLM and IM. PQM designates a good fit for the data than that of MLM and IM because PQM has R^2 and RMSE values better than that of MLM and IM.

Fig.8 displays the scattered plot of the test results and the predicted strengths on the data order of the test results. It shows a match between predicted values of the compressive strength and experimental results. It was clear that the predictions of FQM are in well agreement with the experimental values and fits data better than other predictive models for the compressive strength of concrete modified with NS and/or NC because the model has the highest R^2 and the lowest RMSE.

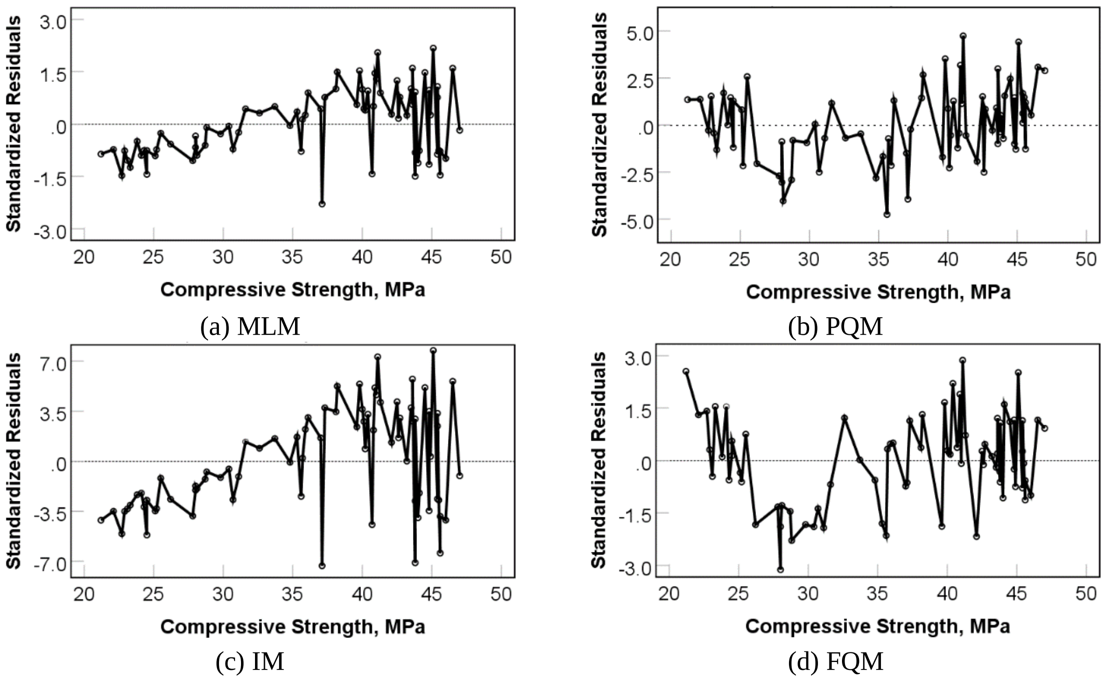


Fig.7 Normal probability of standardized residuals (1-hour of fire exposure)

Table 5: Statistical summary of the strength models (1-hour of fire exposure)

Model	R^2 (%)	RMSE	F-value	P-Value
MLM	79.63%	3.598	96.442	1.67E-25
PQM	94.05%	1.945	158.14	2.68E-40
IM	80.22%	3.546	40.554	3.37E-22
FQM	97.49%	1.262	260.53	1.49E-49

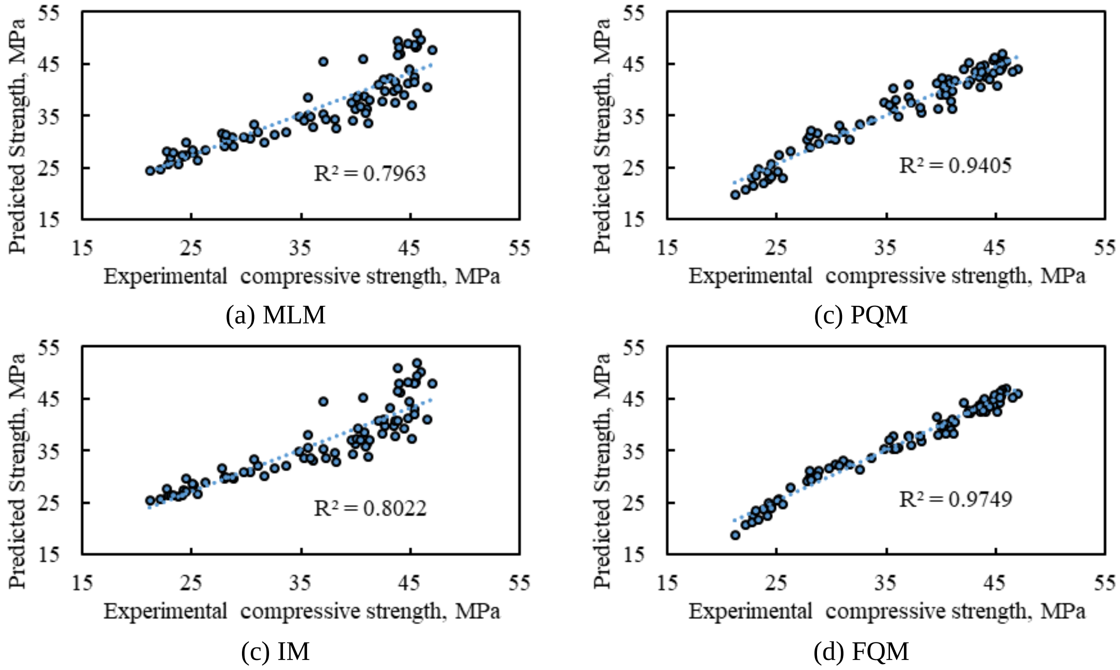


Fig.8 Experimental values versus predicted values (1-hour of fire exposure)

IV.3. Predictive models for compressive strength of concrete exposed to fire for two hours

The mathematical expressions for the predicted compressive strength for MLM, PQM, IM, and FQM are presented in Equations (12) to (15), respectively for concrete modified with NS and/or NC exposed to temperatures ranged between 200 ºC and 800 ºC for two hours after 28 days of curing.

$$f_c = 54.353 + 1.283NS + 0.403NC - 0.044TEMP$$
(12)

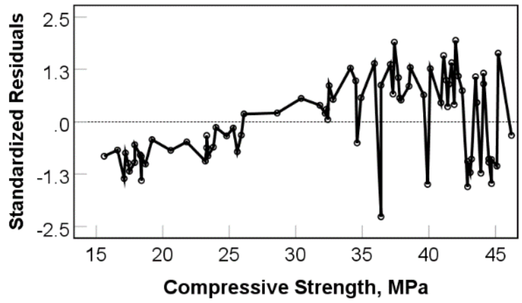
$$f_c = 34.874 + 1.461NS + 0.879NC + 0.046TEMP - 0.023NS^2 - 0.06NC^2 - 0.00009043TEMP^2$$
(13)

$$f_c = 52.382 + 2.19NS + 0.865NC - 0.041TEMP - 0.282NS \times NC - 0.002NS \times TEMP - 0.001NC \times TEMP$$
(14)

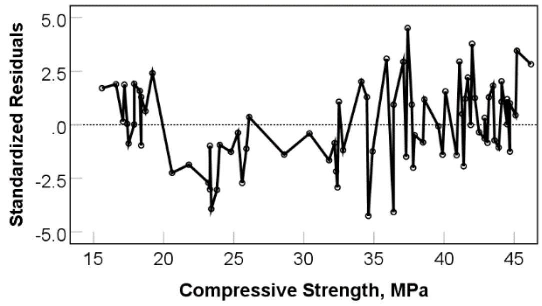
$$f_c = 30.862 + 5.696NS + 2.828NC + 0.05TEMP - 0.797NS^2 - 0.216NC^2 - 0.00009043TEMP^2$$
$$-1.378NS \times NC - 0.002NS \times TEMP - 0.001NC \times TEMP$$
(15)

Fig.9 shows the normal probability of the standardized residuals for the proposed predictive models for the compressive strength of concrete modified with NS and/or NC exposed to temperatures ranged between 200 ºC and 800 ºC for two hours after 28 days of curing. The regression lines run through 78 values of compressive strength. The residuals appear uniformly distributed around zero for compressive strengths greater than 27 MPa for MLM and for IM, while the residuals appear uniformly distributed around zero for PQM and FQM. Table 6 displays the summary of statistics of all strength models. Based on F static, the significances (p) values for the proposed models are extremely low, indicating a strong data model especially for FQM for the compressive strength.

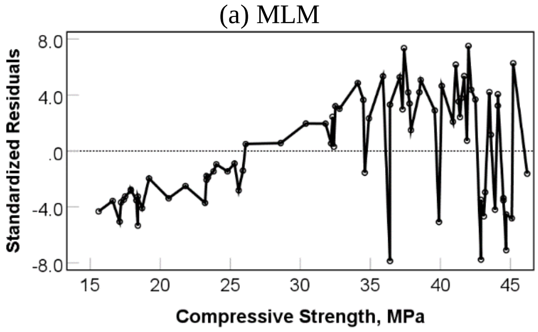
The value of R^2 is 98.30% for FQM, it is greater than that of MLM, PQM and IM which designates a good fit. RMSE is 1.260 for FQM, it is less than that of MLM, PQM and IM. PQM has a determination coefficient of (96.19%) slightly less than that of FQM (98.30%). Also, the RMSE of PQM is 1.889, it is less than that of MLM and IM. Fig.10 shows the scattered plot of the experimental and predicted strengths on the data order of the test results. It shows that the predicted values are closer to values revealed experiments. It was clear FQM for the compressive strength of concrete modified with NS and/or NC has the highest R^2 and the lowest RMSE so FQM fits data better than other predictive models.



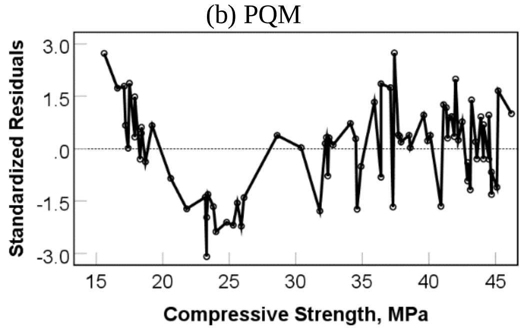
(a) MLM



(b) PQM

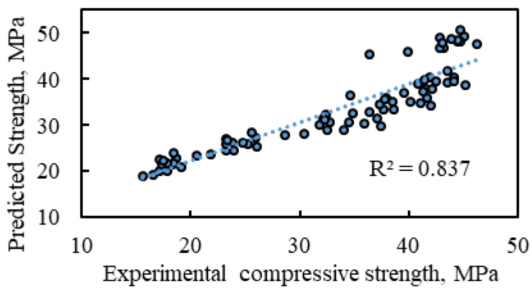


(c) IM

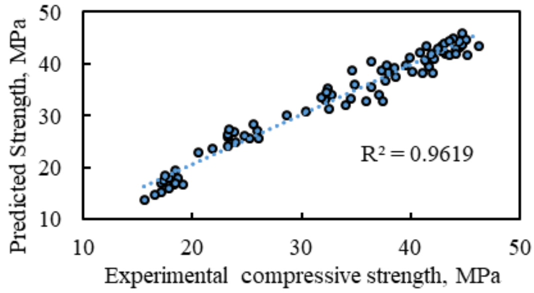


(d) FQM

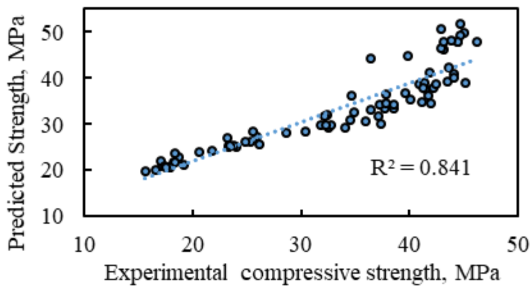
Fig.9 Normal probability of standardized residuals (2-hours of fire exposure)



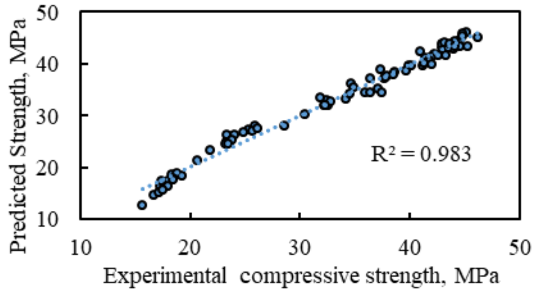
(a) MLM



(b) PQM



(c) IM



(d) FQM

Fig.10 Experimental values versus predicted compressive strengths (2-hours of fire exposure)

Table 6: Statistical summary of the strength models (2-hours of fire exposure)

Model	R^2 (%)	RMSE	F-value	P-Value
MLM	83.70%	3.905	126.66	4.51E-29
PQM	96.19%	1.889	252.22	4.98E-47
IM	84.10%	3.856	52.896	1.81E-25
FQM	98.30%	1.260	388.05	3.25E-55

IV.4. Predictive models for strength of concrete modified with Nano materials and exposed to fire

The following predictive models for the compressive strength were constructed based on 169 specimens. The mathematical expressions for the predicted compressive strength for MLM, PQM, IM, and FQM are presented in Equations (16) to (19), respectively for concrete modified with NS and/or NC exposed to temperatures ranged between 25 ºC and 800 ºC for exposure durations up to 2 hours after 28 days of curing.

$$f_c = 47.292 + 1.205NS + 0.373NC - 0.031TEMP + 0.771D \quad (16)$$

$$f_c = 36.862 + 1.561NS + 0.961NC + 0.045TEMP + 1.499D - 0.067NS^2 - 0.074NC^2 - 0.00008505TEMP^2 - 1.563D^2 \quad (17)$$

$$f_c = 41.055 + 0.869NS + 0.337NC - 0.007TEMP + 7.209D - 0.205NS \times NC + 0.419NS \times D + 0.175NC \times D - 0.02TEMP \times D \quad (18)$$

$$f_c = 35.155 + 4.499NS + 2.392NC + 0.06TEMP - 4.917D - 0.823NS^2 - 0.226NC^2 - 0.00008505TEMP^2 + 1.871D^2 - 1.348NS \times NC + 0.419NS \times D + 0.175NC \times D - 0.009TEMP \times D \quad (19)$$

Fig.11 shows the normal probability of the standardized residuals for the proposed predictive models for the compressive strength of concrete modified with NS and/or NC exposed to temperatures ranged between 25 ºC and 800 ºC for exposure durations up to 2 hours after 28 days of curing. The regression lines run through 169 values of compressive strength. The residuals appear uniformly distributed around zero for compressive strengths greater than 25 MPa for MLM and for IM, while the residuals appear uniformly distributed around zero for PQM and for FQM. Table 7 displays the summary of statistics of all strength models. Based on F static, the significances (p) values for the proposed models are extremely low, indicating a strong data model especially for FQM for the compressive strength.

The determination coefficient (R^2) is 97.37% and 94.07% for FQM and PQM, respectively. The values of R^2 are greater than that of MLM and IM which designates a good fit. RMSE is 1.432 for FQM, it is less than that of MLM, PQM and IM. Also, the RMSE of PQM is 2.149, it is less than that of MLM and IM.

Fig.12 shows the scattered plot of the experimental and predicted compressive strengths on the data order of the test results. It shows that the predicted values are very close to values revealed experiments. It was clear that FQM for the compressive strength of concrete modified with NS and/or NC has the highest R^2 and the lowest RMSE so, FQM suits the data in a more improved form than other predictive models. FQM better fits the data of all the predictive models for the compressive strength in this study.

Table 7: Statistical summary of the strength models

Model	R^2 (%)	RMSE	F-value	P-Value
MLM	66.80%	5.086	82.490	3.03E-38
PQM	94.07%	2.149	280.35	9.60E-93
IM	80.86%	3.862	60.314	1.23E-50
FQM	97.37%	1.432	377.11	1.6E-112

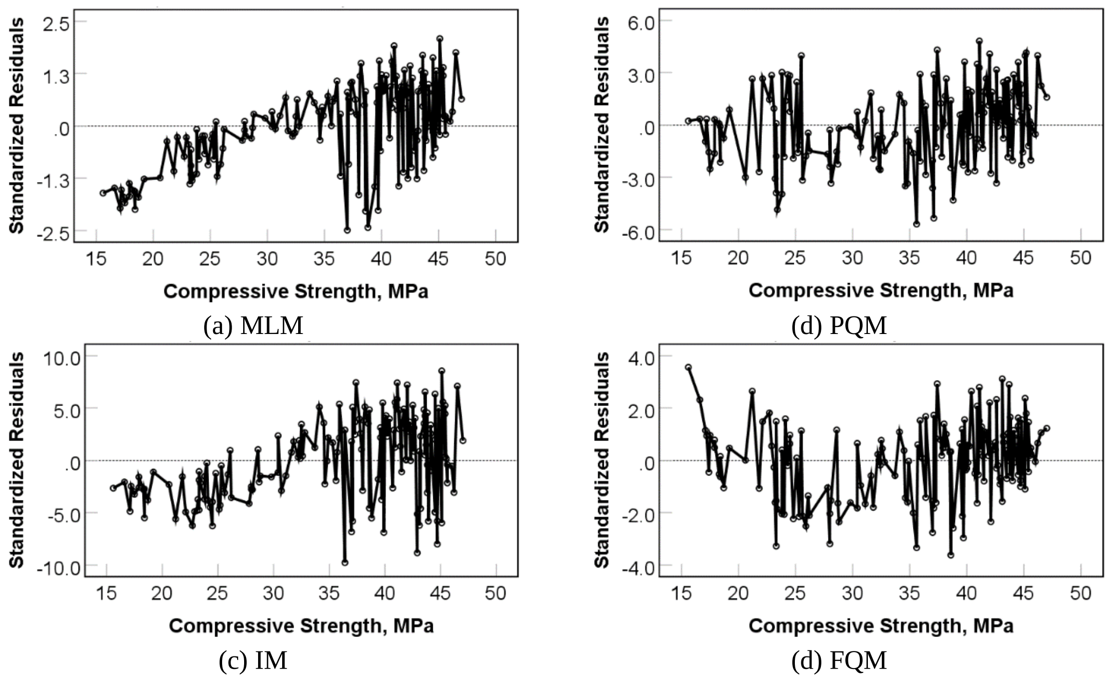


Fig.11 Normal probability of standardized residuals

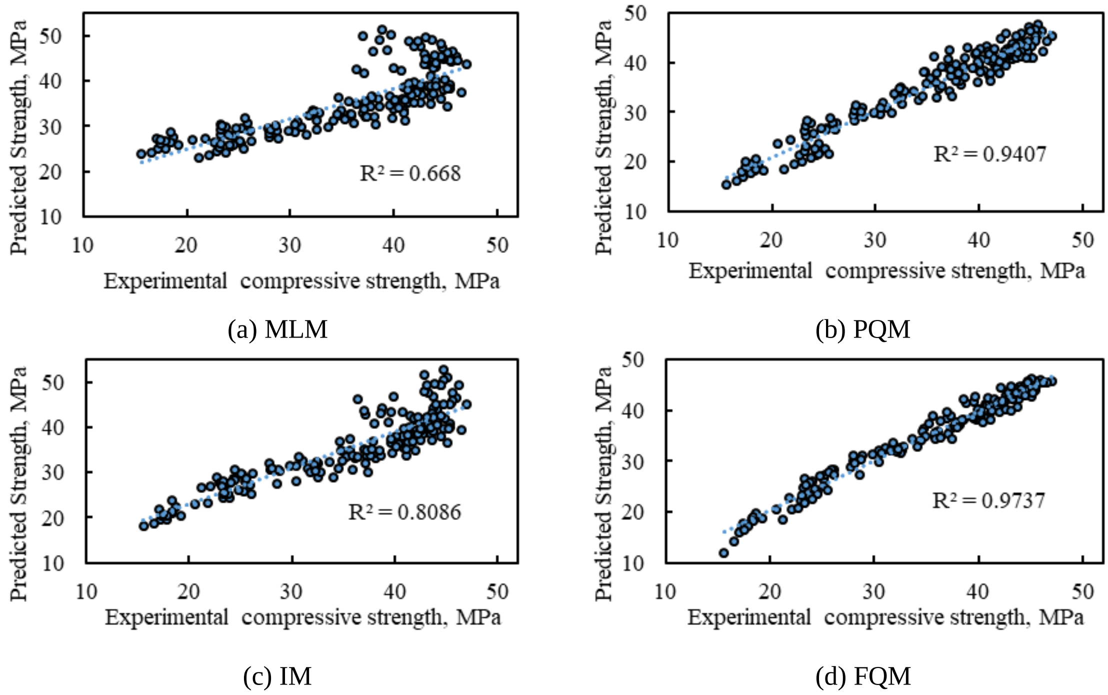


Fig.12 Experimental values versus predicted compressive strengths

V. Conclusion

Sixteen predictive models for compressive strength concrete modified with NS and/or NC as replacements for cement and exposed to fire were suggested. The models were linear model, pure quadratic model, interaction model, and full quadratic model. The trainings were made based on the results of 208 tests. The conclusions are summarized as follow:

1. The incorporation of NS in concrete as partial replacement for cement has improved the compressive strength of concrete at ambient temperatures for replacement levels up to 2% at elevated temperatures for replacement levels up to 3%.
2. The incorporation of NC in concrete as partial replacement for cement has improved the compressive strength of concrete at ambient temperatures and at elevated temperatures for replacement levels up to 5%.

3. The combined incorporation of NS and NC as partial replacements for cement in concrete has improved the compressive strength of concrete at ambient temperatures and at elevated temperatures for replacement levels of 1% and 4% with NS and NC, respectively.
4. The significance (p) values of all the proposed predictive models for the compressive strength are close to zero, indicating that these models are good models for the data.
5. The full quadratic model has the greater value of R^2 (90.87%) and the least value of RMSE (1.537) which designates a good fit for concrete compressive strength at various curing periods ranged between 7 and 90 days and at ambient temperature.
6. For the predictive models for the compressive strength of concrete exposed to fire exposure for one hour after 28 days of curing, the full quadratic model has the greatest value of R^2 is (97.49%) and least value of RMSE is (1.262) which designates a good fit. The pure quadratic model has a determination coefficient of 94.05% close to that of the full quadratic model (97.49%). Also, the RMSE of the pure quadratic model is 1.945, it is less than that of the MLM and IM.
7. The determination coefficient (R^2) is 98.30% for the full quadratic model for the compressive strength of concrete exposed to fire exposure for two hours after 28 days of curing, it is greater than that of multilinear, pure quadratic and interaction models which designates a good fit. RMSE is 1.260 for the full quadratic model, it is less than that of multilinear, pure quadratic and interaction models.
8. For the predictive models for concrete exposed to temperature ranged from 25°C to 800 °C and exposure durations to fire up to 2 hours after 28 days of curing, the determination coefficients (R^2) are 97.37% and 94.07% for the full quadratic model and the pure quadratic model, respectively. The values of R^2 are greater than that of multilinear and interaction models which designates a good fit. RMSE is 1.432 for the full quadratic model, it is less than that of multilinear, pure quadratic and interaction models. Also, the RMSE of the pure quadratic model is 2.149, it is less than that of the multilinear model and the interaction model.
9. The determination coefficients (R^2) of all pure quadratic models are close to R^2 for the full quadratic models. So, the pure quadratic model is the second-best model for predicting the compressive strength.
10. The high level of correlation for the prediction of the compressive strength of concrete modified with NS and/or NC and exposed to elevated temperatures is obtained from the full quadratic strength models with less prediction error and with best data fit when compared to other predictive models. RMSE of the pure quadratic models are slightly greater than that of the full quadratic models, which indicates that both full quadratic and pure quadratic models show no significance difference in their predictions. The proposed models can be utilized to predict the effect of various replacement levels of cement in concrete with NS and/or NC on the compressive strength of concrete exposed to elevated temperature, but within the range of replacements considered in the construction of the models.

References

[1]. ASTM E2456-06 (2012). Standard Terminology Relating to Nanotechnology. ASTM International, West Conshohocken, PA.

[2]. Shah, S. P., Hou, P., & Cheng, X. (2015). Durability of cement-based materials and nano-particles: A review. Springer International Publishing Switzerland. K. Sobolev, S.P. Shah (eds.). Nanotechnology in Construction.

[3]. Elsayd, A., Fathy, I. (2019). Experimental study of fire effects on compressive strength of normal-strength concrete supported with nanomaterials additives. OSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 16(1), 28-37.

[4]. Hosny, H., and Abo Elmagd, S. (1994). Fire of Reinforced Concrete Structures. Dar Elnasher for Egyptian University, 1994.

[5]. Sha, W., & Pereira, G. B. (2001). Differential scanning calorimetry study of ordinary portland cement paste containing metakaolin and theoretical approach of metakaolin activity. Cement & Concrete Composites, 23(6), 455-461.

[6]. ASTM-E119 (2010). Standard Test Methods for Fire Tests of Building Construction and Materials. American Society for Testing and Materials, West Conshohocken, PA, USA.

[7]. He, C., Makovicky, E., & Osbæck, B. (1994). Thermal stability and pozzolanic activity of calcined kaolin. Applied Clay Science, 9(3), 165-187.

[8]. Dunster, A. M., Parsonage, J. R., & Thomas, M. J. K. (1993). The pozzolanic reaction of metakaolinite and its effects on portland cement hydration. Journal of Materials Science, 28(5), 1345-1350.

[9]. Scrivener, K. L. Nanotechnology and cementitious materials. Nanotechnology in construction 3 (pp. 37-42). Springer Berlin Heidelberg.

[10]. Ibrahim, R. K., Hamid, R., & Taha, M. R. (2012). Fire resistance of high-volume fly ash mortars with nanosilica addition. Construction & Building Materials, 36, 779-786.

[11]. Mendes, Alessandra Ferreira Bragança (2017): Fire resistance of concrete made with Portland and slag blended cements. Monash University. Thesis.

[12]. Czoboly, O., Harman, B., Lublóy, É., Balázs, G. L., & Nehme, S. G. (2012). Concrete with silica fume in fire. Építőanyag, 64(1-2), 22-26.

[13]. Poon, C., Azhar, S., Anson, M., & Wong, Y. (2003). Performance of metakaolin concrete at elevated temperatures. Cement & Concrete Composites, 25(1), 83-89.

[14]. Imran, H., Al-Abdaly, N. M., Shamsa, M. H., Shatnawi, A., Ibrahim, M., & Ostrowski, K. A. (2022). Development of prediction model to predict the compressive strength of eco-friendly concrete using multivariate polynomial regression combined with stepwise method. Materials, 15(1), 317.

[15]. Sobhani, J., Najimi, M., Pourkhorshidi, A. R., & Parhizkar, T. (2010). Prediction of the compressive strength of no-slump concrete: A comparative study of regression, neural network and ANFIS models. Construction & Building Materials, 24(5), 709-718.

[16]. Atici, U. (2011). Prediction of the strength of mineral admixture concrete using multivariable regression analysis and an artificial neural network. Expert Systems with Applications, 38(8), 9609-9618.
[17]. Chithra, S., Kumar, S. R. R. S., Chinnaraju, K., & Alfin Ashmita, F. (2016). A comparative study on the compressive strength prediction models for high performance concrete containing nano silica and copper slag using regression analysis and artificial neural networks. Construction & Building Materials, 114, 528-535.
[18]. Dahish, H. A., Elsayed, M., Mohamed, M. and Elymany, M. (2021). Experimental investigation on the effect of using crumb rubber and recycled aggregate on the mechanical properties of concrete. ARPN Journal of Engineering and Applied Sciences, 16(21), 2157-2168.
[19]. Unamba, U. K., Nwajagu, E. S., Abutu, J. & Agbo-Anike, O. J. (2021). Predictive Model of the Compressive Strength of Concrete Containing Coconut Shell Ash as Partial Replacement of Cement Using Multiple Regression Analysis. International Journal of Innovative Science and Research Technology, 6(8), 600-608.
[20]. Kadhum, M. (2015). Prediction of mechanical properties of reactive powder concrete by using artificial neural network and regression technique after the exposure to fire flame. Jordan Journal of Civil Engineering, 9(3), 381-399.
[21]. Feng, W., Wang, Y., Sun, J., Tang, Y., Wu, D., Jiang, Z., Wang, J., & Wang, X. (2022). Prediction of thermo-mechanical properties of rubber-modified recycled aggregate concrete. Construction & Building Materials, 318, 125970.

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