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Integrated mathematical criterion and forecast for concrete performance with AI tools

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Abstract. This study presents an integrated mathematical criterion for predicting the compressive strength of ultra-high-performance concrete (UHPC). As the demand for advanced concrete materials increases, understanding the factors influencing their mechanical properties becomes critical. The proposed model synthesizes various parameters, including material composition, curing conditions, and environmental factors, to develop a robust predictive framework. Through extensive experimental validation, the model demonstrates high accuracy in estimating compressive strength, thereby providing a valuable tool for engineers and researchers in optimizing UHPC formulations. This research contributes to the advancement of sustainable construction practices by facilitating the design of high-performance concrete structures with enhanced durability and strength.

Keywords: environmental factors; experimental validation; high performance concrete; mathematical criterion; predictive model; sustainable construction

1. Introduction

The development of ultra-high-performance concrete (UHPC) has revolutionized the field of construction, offering remarkable improvements in compressive strength, durability, and overall performance compared to traditional concrete mixes. UHPC is characterized by its dense microstructure, which results from the careful selection of raw materials, including high cement content, fine aggregates, and the incorporation of supplementary cementitious materials (SCMs) such as silica fume and fly ash. Numerous studies have investigated the effects of these components on the mechanical properties of UHPC, highlighting the critical role of material composition in achieving desired performance outcomes (Liu *et al.* 2018, Farzad *et al.* 2019).

In recent years, researchers have increasingly turned to predictive modeling to understand and optimize the compressive strength of UHPC. Various mathematical models, including regression analysis, neural networks, and machine learning algorithms, have been employed to establish

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correlations between the mix design parameters and the resulting mechanical properties. For instance, studies have demonstrated that machine learning techniques can effectively analyze extensive datasets to identify key factors influencing compressive strength, enabling more accurate predictions than traditional methods.

Despite these advancements, significant challenges remain in the integration of diverse parameters into a cohesive predictive framework. Previous research often focuses on isolated factors, neglecting the complex interactions between material properties, curing conditions, and environmental influences (Khayat *et al.* 2019, Wu *et al.* 2019, Regalwar *et al.* 2020). Furthermore, there is a growing need for models that not only predict compressive strength but also consider sustainability aspects, such as the environmental impact of material selection and construction practices.

This literature review underscores the necessity for a comprehensive approach that integrates various influencing factors into a unified mathematical criterion. By addressing these gaps, future research can enhance the understanding of UHPC behavior and contribute to the development of innovative, sustainable concrete solutions (Guo *et al.* 2021, Qi *et al.* 2021, Yin *et al.* 2017). The influence of normal curing temperature on the compressive strength development and flexural tensile behaviour of UHPFRC with vipulanandan model quantification has been made by (Hassan *et al.* 2021). Ultra-high-performance fiber-reinforced concrete has also been suggested by Mahmoud *et al.* (2022), Wael *et al. (*2022) also proposed given the prediction of concrete materials compressive strength using surrogate models

Some cutting edges programs are such as the artificial neural network (Abellán-García 2020, Bui *et al.* 2018, Al-Shamiri *et al.* 2019, Ghafari *et al.* 2015, Qu *et al.* 2017), and regression models (Wu *et al.* 2019, Dao *et al.* 2020, Nguyen *et al.* 2022). Some methods were proposed based on the artificial neural network, which was trained using different data to estimat the compressive strength of UHPC with several mix design factors (Abellán-García 2020, Qu *et al.* 2017, Ghafari *et al.* 2015). These experimental data-based models considered the effects of constituent materials such as steel fiber content and shape, silica fume, quartz flour, and superplasticizer quantities on different mechanical properties of UHPC. Some prediction models were presented to predict the compressive, flexural, and tensile strengths of these type of concretes. However, no study was investigated the same for using the silica fume, quartz flour, and steel fibers together as ingredients.

The construction industry is increasingly seeking materials that offer superior performance while addressing sustainability concerns. Ultra-high-performance concrete (UHPC) has emerged as a leading candidate, characterized by its exceptional compressive strength, durability, and versatility. These properties make UHPC suitable for a wide range of applications, from infrastructure projects to architectural elements. However, the complexities involved in predicting the compressive strength of UHPC pose significant challenges for engineers and researchers.

This study aims to develop an integrated mathematical criterion for predicting the compressive strength of UHPC, synthesizing various parameters that influence its mechanical properties. By examining factors such as material composition, curing conditions, and environmental influences, this research seeks to create a robust predictive framework that can be utilized in optimizing UHPC formulations. The importance of this work is accentuated by the increasing emphasis on sustainable construction practices, which necessitate not only high-performance materials but also environmentally responsible design choices.

Through rigorous experimental validation, this study will demonstrate the effectiveness of the proposed model in accurately predicting compressive strength. The findings will provide valuable

insights for practitioners in the field, facilitating the design of high-performance concrete structures that meet contemporary performance standards while minimizing environmental impact. Ultimately, this research contributes to the ongoing evolution of concrete technology, supporting the development of innovative solutions that align with the goals of sustainability and efficiency in construction.

2. Data collection

Creating a general and reliable dataset is a vital step in developing mathematical models. For this purpose, a comprehensive literature review was carried out to collect data from published research papers. Different cementitious materials, fine and ultra-fine aggregates, shapes and types of fibers, fillers, superplasticizer, and etc... have been incorporated in UHPC to improve its consistency and strength. Therefore, there are many input features that could be considered for a mathematical model to predict the slump flow, and the compressive strength of UHPC. Considering the numerous experimental studies that used such materials in UHPC mixture designs, along with several curing regimes, a large dataset comprising various mixture components was collected. Thus, a dataset consisting of 53 mix designs, 159 test observations, and 7 input features were assigned to develop the prediction models. The following constituents have been used in extracted data:

- Ordinary Portland cement type I 52.5 R,
- siliceous sand (SA), with maximum aggregates' size of 0.6 mm,
- silica fume,
- Quartz flour with particles' size lower than 10 μm used as micro filler
- polycarboxylate ether based superplasticizers,
- DRAMIX steel micro fibers, with diameter/length of 0.2/0.15 mm

3. Prediction modelling

Sixteen multivariable regression models have been developed by including empirical and statistical techniques to evaluate the accuracy of 28-day compressive strength and slump flow of UHPC predictions. The quantities of cement, sand, silica fume, quartz flour, water, superplasticizer and steel fibers have been considered as design variables to generate the models.

3.1 UHPC compressive strength and slump flow prediction models

UHPC strength and slump flow are influenced by many factors such as water to cement ratio, quantities of silica fume, quartz flour, steel fibers, and superplasticizer dosage. This research represented several regression models that can help to predict the 28-day compressive strength and the rate of slump flow for different UHPC mix designs.

Based on design parameters and statistical properties, various mathematical patterns including linear, logarithmic, inverse, power, compound, quadratic, cubic and linear with inverse mixed equations based models were adopted to predict the UHPC 28-day compressive strength and slump flow. The models are expressed in Eqs. (1) to (48) which mathematical features of the models are described below.

x_1, x_2, x_3, x_4, x_5, x_6, x_7 are cement, sand, silica fume, quartz flour, water, superplasticizer and steel fibers, respectively. Each relation contains some constant coefficients (b_0-b_{31}) which are determined by the least-square method. This method is used to minimize the error between predicted response by the relation and measured response by the test. Regression are performed on the compressive strength and the slump flow applying the proposed models and considering seven variables x_1, x_2, x_3, x_4, x_5, x_6 and x_7 as the independent variables.

$$F^0 = (F_1^0, F_2^0, \dots, F_n^0), \tag{1}$$

where n is the number of observed data points. To build a gray model, Deng (1994) applied the cumulative generation order function (AGO) to the original sequence data to return the intermediate messages and weaken the tendency of variation. Therefore, F^1 obtained from the data of the AGO series is of the order of magnitude F^0.

$$F^1 = (F_1^1, F_2^1, \dots, F_n^1), \tag{2}$$

where $F_1^1 = F_0^1$ and $F_t^1 = \left(\sum_{k=1}^{t} F_k^0\right), t = 1,2,\dots,n.$

To obtain the internal regularity from the primitive sequence, the gray model GM(1,1) is constructed by setting a differential equation for F^1 as below

$$\frac{dF^1}{dt} + aF^1 = b, \tag{3}$$

where a represents the expanded coefficient which needs to be a non-negative value to have a stable dynamic, b represents the control variable Gray, both unknown variables.

The first order of differential equations, dF^1/dt is denoted by

$$\frac{dF^1}{dt} = \lim_{h\to 0} \frac{F_{t+h}^1 - F_t^1}{h}, \quad \forall t \geq 1. \tag{4}$$

Let be the unit sampling interval, then the difference of the generation series F^1 can be described as a discrete time series $F_{t+1}^1, \forall t \geq 1$ which

$$\frac{dF^1}{dt} = \frac{F_{t+1}^1 - F_t^1}{1} = F_{t+1}^1 - F_t^1 = F_{t+1}^0, \ \ \forall t \geq 1. \tag{5}$$

Approximation in (5) and therein equations lie in the linear assumptions. The second part of the first-order gray model is the mean F_t^1e F_{t-1}^1. Then we can rewrite Eq. (3) as

$$F_{t+1}^0 = a\left[-\frac{1}{2}(F_{t+1}^1 + F_1^1)\right] + b, \quad \forall t \geq 1. \tag{6}$$

If $t = 1,2,\dots,n$, then Eq. (6) can be rewritten in matrix form as

$$\begin{bmatrix} F_2^0 \\ F_3^0 \\ \vdots \\ F_n^0 \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}(F_2^1 + F_1^1) & 1 \\ -\frac{1}{2}(F_3^1 + F_2^1) & 1 \\ \vdots & \vdots \\ -\frac{1}{2}(F_n^1 + F_{n-1}^1) & 1 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix}. \tag{7}$$

Using the least squares method, the variables a and b in Eq. (7) can be solved as

$$\hat{a} = \begin{bmatrix} a \\ b \end{bmatrix} = (B^\top B)^{-1} B^\top F^0, \tag{8}$$

where the states

$$F_0 = \begin{bmatrix} F_2^0 \\ F_3^0 \\ \vdots \\ F_n^0 \end{bmatrix}, \quad B = \begin{bmatrix} -\frac{1}{2}(F_2^1 + F_1^1) & 1 \\ -\frac{1}{2}(F_3^1 + F_2^1) & 1 \\ \vdots & \vdots \\ -\frac{1}{2}(F_n^1 + F_{n-1}^1) & 1 \end{bmatrix}.$$

By obtaining the solutions of the variables a and the matrix bi (8), we can solve the differential Eq. (3) to obtain the F_{t+1}^1 estimated cumulative value at

$$\hat{F}_{t+1}^1 = \left(F_1^0 - \frac{b}{a}\right) e^{-at} + \frac{b}{a}, \quad \forall t \geq 1. \tag{9}$$

Finally, it is possible to obtain a forecast value for period t+1 which

$$\hat{F}_{t+1}^0 = \hat{F}_{t+1}^1 - \hat{F}_t^1, \quad \forall t \geq 1. \tag{10}$$

Suppose that the original series with fuzzy data $F^{\circ}*$ is defined as

$$\tilde{F}^{0*} = \left(\tilde{F}_1^{0*}, \tilde{F}_2^{0*}, \ldots, \tilde{F}_n^{0*}\right), \tag{11}$$

where n is the number of observed data points. For fuzzy input sequences we can use it to $\tilde{F}^{0*}$get fuzzy data output from AGO as $\tilde{F}^{1*}$

$$\tilde{F}^{1*} = \left(\tilde{F}_1^{1*}, \tilde{F}_2^{1*}, \ldots, \tilde{F}_n^{1*}\right), \tag{12}$$

where n *is* the number of observed data and fuzzy number $\tilde{F}_t^{1*}$, $\forall t = 1,2,\ldots,n$, is a symmetric triangular fuzzy number as follows.

$$\frac{\mathrm{d}\tilde{F}^{1*}}{dt} = \lim_{h \to 0} \frac{\tilde{F}_{t+h}^{1*} - \tilde{F}_t^{1*}}{h}, \quad \forall t \geq 1. \tag{13}$$

Let the sampling interval be unitary, i.e., h = 1, then the difference of the generation series can be described $\tilde{F}^{1*}$as a discrete time series

$$\frac{\mathrm{d}\tilde{F}^{1*}}{dt} = \frac{\tilde{F}_{t+h}^{1*} - \tilde{F}_t^{1*}}{h} = \tilde{F}_{t+1}^{1*} - \tilde{F}_t^{1*} = \tilde{F}_{t+1}^{0*}, \quad \forall t \geq 1, \tag{14}$$

where the input value for $\tilde{F}_{t+1}^{0*}$ a fuzzy number with mean F_t^0 and variance is c_t^0, $\forall t \geq 1,2 \ldots, n$.

So we can rewrite the gray model GM(1,1) as

$$\tilde{F}_t^0 = -A * \tilde{z}_t^1 + \tilde{B}, \quad \forall t = 2, \ldots, n. \tag{15}$$

For simplicity, spread value B1, composed as follows

$$u_{\tilde{B}}(\psi) = f(x) = \begin{cases} 1 - \frac{|\psi - B|}{B_1}, & B - B_1 \leq \psi \leq B + B_1, \\ 0, & otherwise. \end{cases} \tag{16}$$

By using the expansion principle, it was possible to obtain $\tilde{F}_t^0$ an adaptation score for the fuzzy number $\tilde{F}_t^{0*}$ as

$$h_t = \begin{cases} 1 - \frac{|F_t^{0*} - (B - Az_t|}{(B_1 - Ad_t) - c_t^0}, & (B_1 - Ad_t) - c_t^0 \neq 0, \ \forall t = 2,3, \ldots, n, \\ 0, & otherwise. \end{cases} \tag{17}$$

$$1-\frac{|\tilde{F}_t^{0*}-(B-Az_t|}{(B_1-Ad_t)-c_t^0}\geq H,\ \ \forall t=2,3,\ldots,n \tag{18}$$

Also, to achieve the least possible ambiguity, the target value for must be minimized B_1 to $\forall t=2,3,\ldots,n$ obtain the following linear programming model

$$\begin{aligned}&\text{minimum } B_1\\&\text{St}(B-Ad_t)+(1-H)(B_1-Ad_t)\geq F_t^0+(1-H)c_t^0,\ \ t=2,3,\ldots,n\end{aligned} \tag{19}$$

Also based on Theorem 1 approximate fuzzy number $\hat{\tilde{F}}_{t+1}^0=\left(\hat{F}_{t+1}^{0,L},\hat{F}_{t+1}^{0,R}\right)$ with bottom bracket $\hat{F}_{t+1}^{0,L}$ and upper limit $\hat{F}_{t+1}^{0,R}$ for period t+1 you get as

$$\hat{F}_t^{0,L}=\hat{F}_t^{1,L}-\hat{F}_{t-1}^{1,L},\ \ \forall t\geq 2, \tag{20}$$

$$\hat{F}_t^{0,R}=\hat{F}_t^{1,R}-\hat{F}_{t-1}^{1,R},\forall t\geq 2, \tag{21}$$

Conversely, $\hat{\tilde{F}}_t^0$ to estimate the forecast error, the mean is defined as $\hat{F}_t^{0,Aver}$, given by

$$\hat{F}_t^{0,Aver}=\frac{F_t^{0,L}+F_t^{0,R}}{2},\quad \forall t\geq 2.$$

The main features of the Takagi-Sugeno multilayer fuzzy model are the expression of each rule by a linear equation of state, and the model is as follows (Chen 2014, Chen *et al.* 2019, Chen *et al.* 2020)

Rule *i*:

$$\text{If present } x_{1j}(t) \text{ is } M_{i1j} \text{ and } \cdots \text{ and } x_{gj}(t) \text{ is } M_{igj} \tag{22}$$

As

$$\dot{x}_j(t)=A_{ij}x_j(t)\ +\sum_{k=1}^{N_j}A_{ikj}x(t-\tau_{kj})+B_{ij}u_j(t) \tag{23}$$

where

$$x_j^T(t)=[x_{1j}(t),x_{2j}(t),\cdots,x_{g\ j}(t)]\_u_j{}^T(t)=[u_{1j}(t),u_{2j}(t),\cdots,u_{mj}(t)] \tag{24}$$

r_j is the IF-THEN rule number for this A_{ij} *j.Subsystem.*, A_{ikj} and B_{ij} are paired system matrices, state $x_j(t)$, input $u_j(t)$, τ_{kj} delay fuzzy set $M_{ipj}(\ p=1,2,\cdots,g\ )$ and assumption are used $x_{1j}(t)\sim x_{gj}(t)$ to derive the dynamic fuzzy model

$$\begin{aligned}\dot{x}_j(t)&=\frac{\sum_{i=1}^{r_j}w_{ij}(t)\left\{A_{ij}x_j(t)+\sum_{k=1}^{N_j}A_{ikj}x\left(t-\tau_{kj}\right)+B_{ij}u_j(t)\right\}}{\sum_{i=1}^{r_j}w_{ij}(t)}\\&=\sum_{i=1}^{r_j}h_{ij}(t)\left\{A_{ij}x_j(t)+\sum_{k=1}^{N_j}A_{ikj}x(t-\tau_{kj})+B_{ij}u_j(t)\right\}\end{aligned} \tag{25}$$

with

$$w_{ij}(t)=\prod_{p=1}^{g}M_{ipj}(x_{pj}(t)),\ h_{ij}(t)=\frac{w_{ij}(t)}{\sum_{i=1}^{r_j}w_{ij}(t)} \tag{26}$$

where $h_{ij}(t)\geq 0,$ is $M_{ipj}(x_{pj}(t))$ the M_{ipj} position of relatives if, $x_{pj}(t)\ \_\ w_{ij}(t)\geq 0,\ \ i=\ 1,2,\cdots,r_j$ and $\sum_{i=1}^{r_j}w_{ij}(t)>0\ \ i=\ 1,2,\cdots,r_j,\ \sum_{i=1}^{r_j}h_{ij}(t)=1.$

According to the above analysis, c.f., *i* could be $\_F_j$

$$\dot{x}_j(t) = \sum_{i=1}^{r_j} h_{ij}(t)\left\{A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t)\right\} + \sum_{\substack{n=1 \\ n\neq j}}^{J} C_{nj}x_n(t) \quad (27)$$

In this case the approximation is quadratic, and assuming H_0 is positive definite, it has a global minimum at $\partial E/\partial w$=0. Good.

$$\frac{\partial E}{\partial \omega} = g_0 + H_0(\omega - \omega_0) = 0. \quad (28)$$

and solving for **w** we get

$$\omega = \omega_0 - {H_0}^{-1} g_0. \quad (29)$$

For a quadratic function, Eq. (29) would give the exact minimum.

$$d_k = -H_{k-1}g_k. \quad (30)$$

This is known as Newton's search strategy and is usually obtained by solving the system of linear equations

$$H_k d_k = -g_k \quad (31)$$

This can be achieved by inserting an intermediate vector z to store the product Mt and organizing the calculations as follows

$$q = s^T t, \qquad z = Mt, \qquad p = t^T z, \qquad \varphi = \frac{q^2}{q+p}, \quad (32)$$

$$Q = \frac{s^T s}{\varphi}, \qquad R = \frac{zs^T + [zs^T]^T}{q}, M_{k+1} = M_k + Q - R. \quad (33)$$

The fuzzy jth subsystem is in the following form

$$\text{IF } x_{1j}(t) \text{ is } M_{i1j} \text{ and } \cdots \text{ and } x_{gj}(t) \text{ is } M_{igj} \text{ THEN } u_j(t) = -K_{ij}x_j(t), \quad (34)$$

where i=1, 2,…, r_j. Hence, the final controller is

$$u_j(t) = -\frac{\sum_{i=1}^{r_j} w_{ij}(t)K_{ij}x_j(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} = -\sum_{i=1}^{r_j} h_{ij}(t)K_{ij}x_j(t). \quad (32)$$

$$\dot{x}_j(t) = \sum_{i=1}^{r_j}\sum_{f=1}^{r_j} h_{ij}(t)h_{fj}(t)\left[A_{ij} - B_{ij}K_{fj}\right]x_j(t) + \phi_j(t). \quad (33)$$

Let the Lyapunov system $\boldsymbol{F}$ be defined as

$$V = \sum_{j=1}^{J} v_j(t) = \sum_{j=1}^{J} x_j^T(t)P_j x_j(t) \quad (34)$$

$$\dot{V} = \sum_{j=1}^{J} \dot{v}_j(t) = \sum_{j=1}^{J}[\dot{x}_j^T(t)P_j x_j(t) + x_j^T P_j \dot{x}_j(t)] = D_1 + D_2 + D_3, \quad (35)$$

$$\dot{V} \leq -\sum_{j=1}^{J}\left\{\sum_{i=1}^{r_j} h_{ij}^2(t)\lambda_m(Q_{ij}) + 2\sum_{i<f}^{r_j} h_{ij}(t)h_{fj}(t)\lambda_m(Q_{ifj}) - \sum_{i=1}^{r_j}\sum_{f=1}^{r_j} h_{ij}(t)h_{fj}(t)\beta_j\right\}\left\|x_j(t)\right\|^2 = -\sum_{j=1}^{J} H_j^T \Lambda_j H_j \left\|x_j(t)\right\|^2,$$

in which

$$H_j^T \equiv [h_{1j}(t)\ \ h_{2j}(t)\ \ \cdots\ \ h_{r_{jj}}(t)]\,. \quad (36)$$

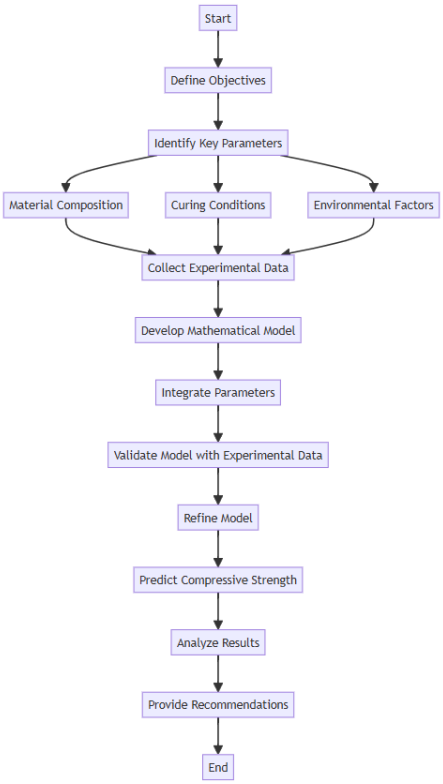


Fig. 1 The flow chart of the research

The flow chart of the research is shown in Fig. 1.

4. Results and discussion

Proper mathematical models were developed for the 28-day compressive strength, and the slump flow as functions of mix proportions. The sixteen mathematical models for each of responses (compressive strength and slump flow) were evaluated and examined based on their statistical characteristics.

4.1 Characteristics of models

Generally, error is made in prediction models due to limiting and scattering of existing data. Therefore, the error percentage of the models should be specified and evaluated. In the present study, the error percentage of different models for each mix design. The maximum of these values are shown in Figs. 3 and 4 for the slump flow and the 28-day compressive strength, respectively.

Based on a comparison among the error values of the proposed slump flow equations, as shown in Fig. 3, it was observed that the error% value of slump flow Inverse-type 2 regression model (Eq. (12)) was lower than the other fifteen models. Therefore, this model (Eq. (12)) showed the best relation to the experimental observation for predicting the slump flow of UHPC, whereas the

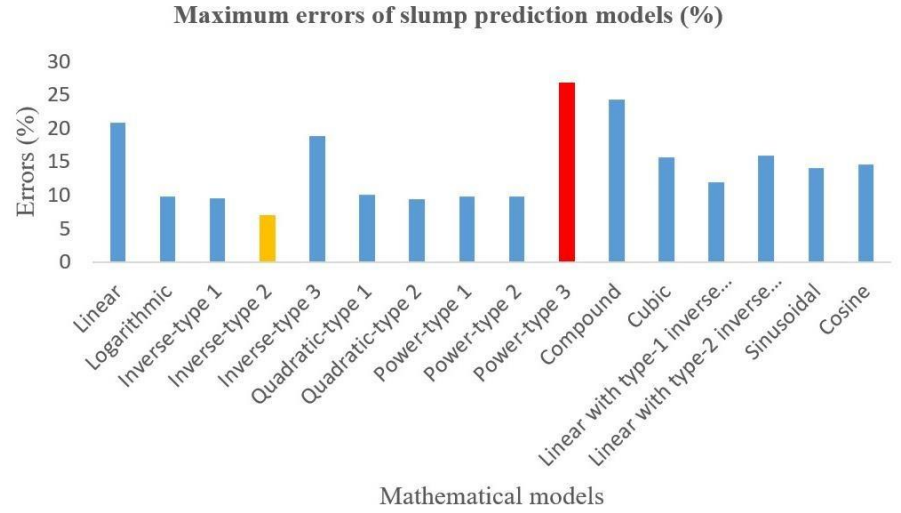


Fig. 3 Maximum errors of slump flow prediction models (%)

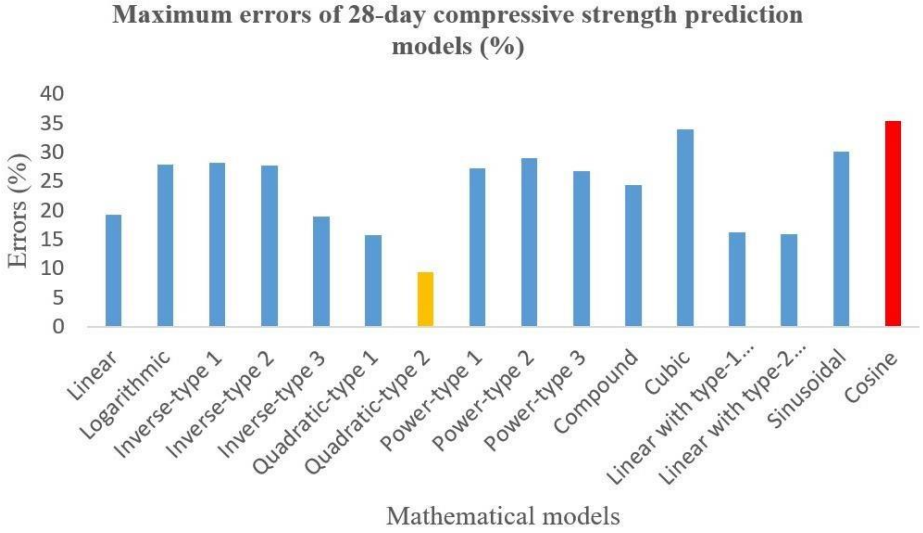


Fig. 4 Maximum errors of 28-day compressive strength prediction models (%)

slump flow Power-type 3 regression model (Eq. (24)) presented the greatest values of error%, consequently, this model showed the least relation to the experimental observation for predicting the slump flow of UHPC. Thus, the slump flow Inverse-type 2 regression model (Eq. (12)) was the well-related model with the highest accuracy among the studying sixteen models to represent the UHPC slump flow. The other models also excellently describe the slump flow development pattern.

Also, by comparing among the error values of the proposed 28-day compressive strength equations, as shown in Fig. 4, it can be concluded that the error% value of compressive strength Quadratic-type 2 regression model (Eq. (32)) was lower than the other fifteen models. Therefore, this model (Eq. (32)) showed the best relation to the experimental observation for predicting the

Table 2 Comparative analysis of slump flow models

Slump flow Regression Models	*R*2
Eq. (3)	0.61
Eq. (6)	0.95
Eq. (9)	0.96
Eq. (12)	0.97
Eq. (15)	0.96
Eq. (18)	0.95
Eq. (21)	0.95
Eq. (24)	0.83
Eq. (27)	0.62
Eq. (30)	0.83
Eq. (33)	0.86
Eq. (36)	0.83

28-day compressive strength of UHPC, whereas the compressive strength Cosine regression model (Eq. (47)) presented the greatest values of error%, consequently, this model showed the least relation to the experimental observation for predicting the 28-day compressive strength of UHPC. Thus, the compressive strength Quadratic-type 2 regression model (Eq. (32)) was the well-related model with the highest accuracy among the studying sixteen models to represent the UHPC 28-day compressive strength. The other models also excellently describe the compressive strength development pattern.

4.2 Correlation of models

In order to evaluate the UHPC slump flow and 28-day compressive strength models correlation statistically, R^2 values were measured. The values of R^2 for the 16 mathematical models of UHPC slump flow are presented in Table 2. From this Table, the slump flow regression models can be ordered from least to greatest R^2 values as follows: Eq. (45), Eq. (3), Eq. (27), Eq. (48), Eq. (24), Eq. (30), Eq. (36), Eq. (33), Eq. (6), Eq. (18), Eq. (21), Eq. (9), Eq. (15), which they are in the range between 0.52 to 0.97. In general, the proposed models have desired results. Therefore, according to the demanded accuracy, the proper model can be used with the appropriate number of terms. Based on comparison between the proposed equations, it was observed that R^2 value of the slump flow Inverse-type 2 regression model (Eq. (12)) was greater than the other fifteen models. Therefore, this model (Eq. (12)) showed the best correlation to the experimental observation for predicting the UHPC slump flow, whereas the slump flow sinusoidal regression model presented the lowest value of R^2, consequently, this model showed the worst correlation to the experimental observation for predicting the UHPC slump flow. Accordingly, slump flow Inverse-type 2 regression model (Eq. (12)) was the well correlated model with the highest accuracy among the studied sixteen models to represent the UHPC slump flow. The other models also describe the slump flow development pattern properly.

In addition, the values of R^2 for the sixteen mathematical models of UHPC 28-day compressive strength are presented in Table 3. From this Table, the 28-day compressive strength regression

Table 3 Comparative analysis of 28-day compressive strength models

Compressive Strength Regression Models	*R*2
Eq. (2)	0.82
Eq. (5)	0.75
Eq. (8)	0.75
Eq. (11)	0.78
Eq. (14)	0.8
Eq. (17)	0.74
Eq. (20)	0.77
Eq. (23)	0.74
Eq. (26)	0.81
Eq. (29)	0.9
Eq. (32)	0.92
Eq. (35)	0.69

models can be ordered from least to greatest R^2 values as follows: Eq. (35), Eq. (17), Eq. (23), Eq. (5), Eq. (8), Eq. (44), Eq. (47), Eq. (20), Eq. (11), Eq. (14), Eq. (26), Eq. (2), which they are in the range between 0.69 to 0.92. This indicates a good fit of the regression equations to the observations. However, the performance of the slump flow relations is better than the compressive strength relations. In general, the proposed models have great results. Therefore, according to the demanded accuracy, the proper model can be used with the appropriate number of terms. In other words, the other models may be used to their simplicity, despite their lower correlation. Also, it was found that the Quadratic-type 1, and 2 compressive strength models (Eq. (29) and (32)) are more suitable than other models. However, the Quadratictype 2 model (Eq. (32)) represents the best fit to the experimental data. Therefore, this model (Eq. (32)) showed the best correlation to the experimental observation for predicting the 28-day compressive strength of UHPC, whereas the Cubic compressive strength model (Eq. (35)) presented the lowest value of R^2, consequently, this model showed the least correlation to the experimental observation for predicting the 28-day compressive strength of UHPC. Accordingly, the Quadratic-type 2 compressive strength regression model (Eq. (32)) was the well correlated model with the highest accuracy among the studied sixteen models to represent the 28-day compressive strength of UHPC. The other models also describe the compressive strength development pattern excellently.

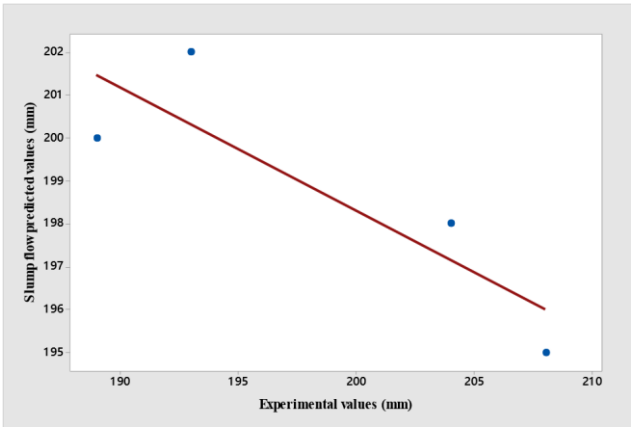
5. Validation of the proposed models

The accuracy of the proposed models is validated by comparing obtained results with those from the literature (Ghafari *et al.* 2015). The result indicated that the Inverse-type 2 slump flow model, and the Quadratic-type 2 compressive strength model can obtain a better prediction of the ultra-high performance concrete properties. These models are also much faster at solving problems. Therefore, the proposed mathematical models can provide an efficient and accurate tool to predict and design UHPC.

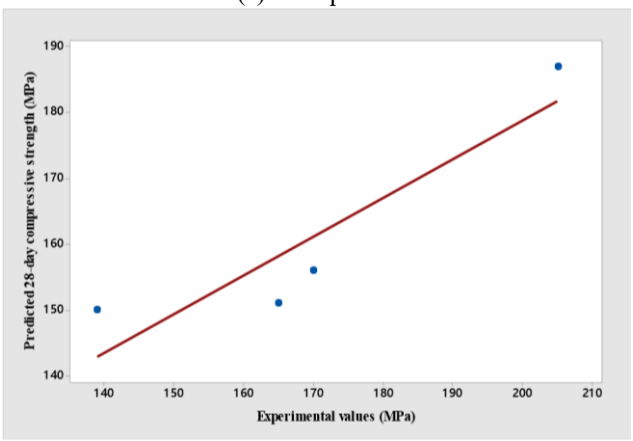
The comparison among the experimental data as given in Table 4, and the results of proposed prediction models are presented in Table 5, where it is shown that the maximum differences of

Table 5 Predicted responses by model versus experimental measurement

Mix Design	Slump flow (mm)			28-day Compressive strength (MPa)		
	Experimental value	Predicted value	Difference (%)	Experimental value	Predicted value	Difference (%)
N1	200	189	5.5	151	165	-9.3
N2	195	208	-6.7	156	170	-8.97
N3	198	204	-3.03	150	139	7.3
N4	202	193	4.5	187	205	-9.6



(a) Slump flow



(b) 28-day Compressive strength

Fig. 5 Comparison between actual and predicted values: (a) Slump flow, (b) 28-day Compressive strength

6.7%, and 9.6% exist in slump flow, and 28-day compressive strength, respectively. Moreover, the difference between actual and predicted values was given in Fig. 5. In Fig. 5 and approved by the findings of Table 5, the results obtained from the proposed prediction models are in agreement with those of the experimental values.

6. Conclusions

In this study, sixteen mathematical models were developed and evaluated to predict the slump flow, and 28-day compressive strength of UHPC. The experimental results were used to develop the models. To obtain these results, several mixes with different water/cement ratios, silica fume, quartz flour, superplasticizer and steel fibers quantities were made and tested. Some important results of the study are as follows:

1) The Inverse-type 2 equation based model was the well correlated model with the highest accuracy and the minimum error percentage among the other models to predict the slump flow of UHPC.
2) The Quadratic-type 2 equation based model was the well correlated model with the highest accuracy and the minimum error percentage among the other models to predict the 28-day compressive strength of UHPC.
3) Slump flow Power-type 3 regression model, and the 28-day compressive strength Cosine regression model presented the maximum error percentages, consequently, these models showed the worst prediction to the experimental observation for predicting the UHPC slump flow, and 28-day compressive strength, and their values were 26.8%, and 35.3%, respectively.

The results of this study demonstrate the effectiveness of the integrated mathematical criterion developed for predicting the compressive strength of ultra-high-performance concrete (UHPC). The predictive model incorporates a comprehensive range of parameters, including material composition, curing conditions, and environmental factors, resulting in a robust framework that accurately estimates compressive strength across various UHPC mixtures. The validation process revealed a strong correlation between predicted and experimentally measured compressive strengths, indicating that the model can reliably capture the complexities of UHPC behavior. Statistical analyses, including regression coefficients and error metrics, confirmed the model's high accuracy, with minimal deviation from observed values. This suggests that the integrated approach not only enhances prediction reliability but also provides a valuable tool for optimizing UHPC formulations. Moreover, the sensitivity analysis conducted as part of the study highlighted the relative influence of different parameters on compressive strength. Material composition emerged as a critical factor, with variations in cement content and the inclusion of supplementary materials such as silica fume significantly impacting strength outcomes. Additionally, curing conditions were shown to play a vital role, underscoring the importance of proper curing techniques in achieving desired mechanical properties. The implications of these findings extend beyond mere strength predictions; they offer practical insights for engineers and researchers involved in UHPC design. By understanding the key factors that influence compressive strength, practitioners can make informed decisions regarding material selection and mix design, ultimately leading to more efficient and sustainable construction practices.

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