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Predicting the flowability of UHPC and identifying its significant influencing factors using an accurate ANN model

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Abstract
In this research, a one-hidden layer artificial neural network paradigm (ANN) was created to forecast the slump flow of ultra-high-performance concrete (UHPC). To achieve this goal, 3,200 ANNs were evaluated to estimate the fresh UHPC's slump flow utilizing 793 observations. The performance metrics measured on training and test data subsets were in the same order of magnitude, thereby pointing out the proper work of the *k-fold* validation procedure. The results of the connection weight approach analysis (CWA) indicated that water dosage had the highest positive importance in slump flow, preceding the superplasticizer volume ratio. Other factors that positively influenced slump flow were the water-to-powder ratio, the dosage of high-alkali glass powder, the water-to-binder ratio, and limestone concentration. The most negative influences on rheology were the high-alumina FC3R and metakaolin. The ANN accurately predicted the slump flow of UHPC, while the results of the CWA analysis were well-correlated with previous research.

Keywords: ANN; slump flow; k-fold validation; connection weight approach; supplementary cementitious materials.

Predicción de la trabajabilidad del UHPC e identificación de sus factores de influencia significativos utilizando un modelo ANN preciso

Resumen
En esta investigación, se desarrolló un modelo de red neuronal artificial de una capa oculta para pronosticar el flujo estático del concreto de ultra alto rendimiento (UHPC). Se evaluaron 3200 redes neuronales artificiales para estimar el flujo estático del UHPC fresco utilizando 793 observaciones. Las métricas de rendimiento medidas en los subconjuntos de datos de entrenamiento y de testeo estuvieron en el mismo orden de magnitud, lo que indica el trabajo adecuado del procedimiento de validación cruzada *k-fold*. Los resultados del análisis de enfoque de peso de conexión (CWA) indicaron que el contenido de agua tuvo la mayor importancia positiva en el flujo estático, precediendo a la relación de volumen del superplastificante. Otros factores que influyeron positivamente en el flujo estático fueron la relación agua-polvos-totales, la dosificación de polvo de vidrio con alto contenido de álcali, la relación agua-aglutinante y la dosificación del carbonato cálcico. La influencia más negativa en la reología fueron el FC3R alto en alúmina y el metacaolín. La ANN predijo con precisión el flujo de asentamiento de UHPC, mientras que los resultados del análisis CWA se correlacionaron bien con investigaciones previas.

Palabras clave: ANN, flujo estático; validación cruzada tipo *k-fold*; moldeo de conexión de pesos; materiales cementantes suplementarios.

1 Introduction

1.1 UHPC definition, application, and main challenges

The affordability, resilience, and durability of concrete position it as a widely used construction material. While conventional concrete (CC) has limitations in meeting contemporary needs, collaborative efforts from 1997 to 2002 resulted in ultra-high-performance concrete (UHPC) [1-2]. UHPC, with superior properties, is reinforced with microsteel fibers and defined by ACI 239R-18 as concrete with a minimum compressive strength of 150 MPa. Its microscopic

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structure and fiber reinforcement contribute to exceptional performance, with a focus on minimizing heterogeneity [3-5]. UHPC employs various reactive powders and maintains a low water content for improved performance [6,7]. Furthermore, UHPC is characterized by its low water content, which lessens the thickness of interfacial transition zones within the cement particles by confining cement particles in small spaces. The disadvantage of this technique is that it reduces the workability of the paste, which requires including superplasticizers in the paste [8]. This concrete is, therefore, objectively designed to exhibit improved ductility in addition to high compressive strength [9].

The popularity of UHPC is growing, evident in its increased applications in bridge construction for both highway and pedestrian use. It finds use in onshore and offshore infrastructures, with notable benefits in earthquake- or impact-prone regions. Recent studies highlight its application in post-stressed railway sleepers, aiming for cost-efficiency and durability. Field tests on prestressed precast UHPC pilings have also been conducted across various structures [10-25].

Nevertheless, while UHPC boasts excellent mechanical performance, its high cost, attributed to expensive constituents and the excessive use of natural resources, hinders widespread adoption [26-29]. To address environmental concerns, waste by-products have been incorporated as supplementary cementitious materials (SCMs) [30-34]. Moreover, the lack of codified guidelines for material and structural designs poses challenges to the utilization of UHPC mixtures with these SCMs [35].

1.2 Importance of workability

Concrete's flowability, crucial for efficient construction, is defined as its ability to work without significant homogeneity loss [36,37]. Assessing this property, often done through a slump cone test, determines how easily fresh concrete can be compacted, finished, and placed on-site without immediate segregation. Customized concrete mixes cater to specific construction types, and flowability is classified as high, medium, low, extremely low, or very low [38]. In concrete technology, flowability is paramount, and advanced mix design procedures alone are insufficient for longevity if proper pouring and compaction are compromised. Hence, understanding factors influencing flowability is imperative.

In the context of UHPC, substituting typical reactive powders with alternative SCMs necessitates rigorous experimental validation to ensure effectiveness [6]. New mixture designs with fewer environmental impacts can alleviate barriers to UHPC popularity. However, mandatory lab experimentation is complex due to cost, duration, and labor intensity. Statistical modeling techniques offer a simplified approach to concrete mix design but face challenges with the large number of variables and complex relationships in UHPC, making traditional regression techniques less effective [38-40].

1.3 Artificial Neural Networks

Artificial Neural Networks (ANNs) have become prominent computational tools for modeling real-life problem-solving, offering insight into complex relationships between input and output data pairs [41]. Widely applied in civil engineering, ANNs demonstrate competence in solving intricate engineering problems related to traffic management, water resources engineering, structural health monitoring, structural classification, materials simulation, and concrete mix design [6,42-47]. The scientific literature reflects a growing trend in using ANNs to forecast the mechanical properties of various cement-based materials [44-47].

ANNs have also been utilized to predict the performance of UHPC through data-driven approaches but limited studies conducted mostly focused on strength forecasting [48,49]. Despite the effectiveness of ANNs in ensuring prediction accuracy, their application to predict the flowability properties of UHPC, especially when incorporating multiple SCMs, remains a subject of inquiry and requires further exploration.

1.4 Research objectives, significance, and organization

This research aims to create a model utilizing an ANN approach to simulate the UHPC flowability. Given the intricate composition and rheological behavior of UHPC, particularly in terms of fresh mix flowability, developing an efficient mix design is challenging. The study incorporates a Connection Weight Approach (CWA) into the ANN model, conducting a sensitivity analysis to elucidate the impact of mixture features on flowability. The significance of this work lies in its potential to streamline the UHPC mix design process by offering a reliable tool for predicting flowability properties. The developed ANN model could assist engineers and researchers in optimizing UHPC mixture composition, reducing waste, and improving production efficiency. The research methodology involved data collection on the flowability properties of UHPC mixtures, data preprocessing, construction of an ANN model using collected data and relevant mix design parameters, and rigorous assessment of model accuracy and reliability through statistical analyses and comparisons with a testing data subset.

2 Data collection

This study has meticulously compiled a comprehensive database incorporating results from 927 slump tests performed on UHPC mixes with various SCMs. Among these, 210 observations stem from in-house experiments conducted in different studies [47,48], while 717 observations were sourced from international proceedings on UHPC, including events like Kassel 2004, 2008, 2012, and 2016, PhD dissertations, and research published in civil engineering journals. Notably, only UHPC mixture proportions providing virtual packing density or sufficient information to estimate it were included. Approximately 80% of the data relates to the static test as per ASTM C1437, with variations in cones' shapes and dimensions in different published research. To ensure consistency, slump flow values were standardized to the ASTM cone using transformation factors [48]. The experimental campaign initially focused on ASTM III cement, with no quartz powder (QP) in the mixtures but various mineral admixtures (see Fig. 1). The

Figure 1. Mineral admixtures used in this research. From left to right: silica fume, fly ash, GGBFS, glass powder (GP), rice husk ash (RHA), fluid catalytic residue (FC3R), metakaolin (MK), and limestone powder (LP)
Source: The authors.

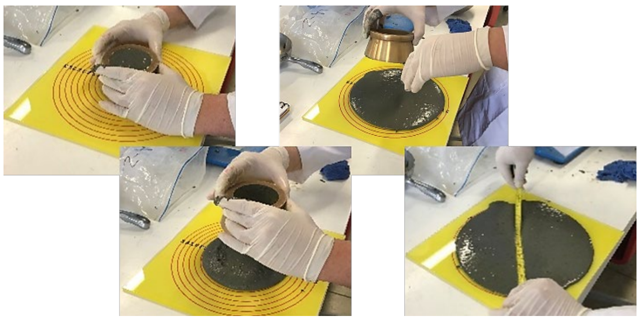

Figure 2. Measurement of the slump flow of UHPC using the cone of the ASTM C1437
Source: The authors.

database expanded to include different cement types, aggregate possibilities ranging from no-aggregate to coarse-aggregate-UHPC, and the use of QP, incorporating findings from relevant research. The slump flow test involved measuring the diameter of the static slump immediately after the UHPC mixing process, following ASTM C1437 specifications, utilizing a truncated cone-shaped mold and flat plate, with the spread mortar diameter measured in four directions to calculate the slump flow (see Fig. 2).

3 Methodology

3.1 Data preprocessing

Data preprocessing involves outliers' detection and normalization. Outliers, defined as significant deviations from a dataset's general behavior, were identified using bivariate boxplots and Cook's distance [49-51]. Further information on these procedures can be found in [48,52-53]. At the end of this process, the database without outliers contained 793 observations.

For its part, data normalization is essential for training ANN regression models. It overcomes issues related to scale and distribution of input variables by bringing them to a common scale (0 to 1 in our case). Normalization ensures equal contribution of each feature to the learning process, prevents dominant features from overshadowing others, and enhances convergence, allowing the model to learn efficiently [48].

Finally, the cleaned and normalized database was split into 80% for training and 20% for testing. Additionally, the training base was divided into four for *k-fold validation*. This rigorous approach enhances the reliability and robustness of the trained network, improving its generalization capability for more accurate regression predictions [47,48].

3.2 Training procedure

The resilient backpropagation algorithm (RProp) was adopted to train the ANN [55]. The RProp is similar to the conventional backpropagation algorithm, but it is considerably faster and does not require any free parameters (like learning rate). Additionally, it uses feed-forward neural networks to perform supervised batch learning, which has been widely adopted in deep learning applications. The principle of RProp is that the derivative size and step size should not negatively affect the weighting step. Therefore, the direction of the weight update is determined solely by the sign of the derivative. Fig. 3 illustrates the application of the RProp algorithm in the current research.

The nonlinearity nature of the ANN is provided by the activation function known as log sigmoid. The method of this activation function has been well-documented in ANN applications in the concrete engineering field [6,47,48].

3.3 ANN architecture definition using k-fold validation

To define the optimal hidden layer neurons, *k-fold* validation combined with the average root mean squared error (RMSE) is employed [Eq. (1)]. Here, *k-fold* validation involves dividing the dataset into *k* equally sized subsets, or "folds," and then training the neural network on *k-1* folds while validating its performance on the leftover partition. This procedure is realized *k* times, with every partition utilized as the validation dataset once. The average RMSE, which measures the prediction error of the model, is calculated across all *k* folds [48].

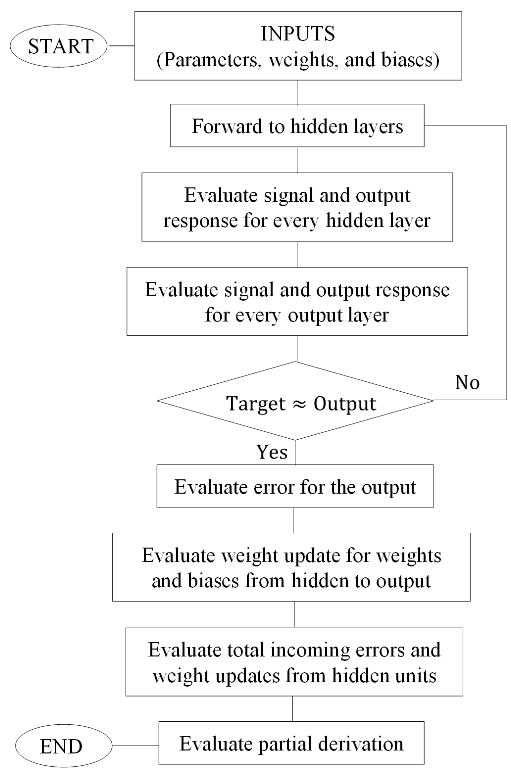

Figure 3. The RProp algorithm.
Source: The authors

By varying the hidden layer's number of neurons in the *k-fold* validation process, the performance of the ANN model is obtained for different configurations. The hidden layer's number of neurons is varied over a range of values, and the configuration that results in the lowest average RMSE is selected as the optimal number of neurons. In this manner, the most effective neural network architecture is identified to achieve a balance between model complexity and prediction accuracy for the current concrete engineering problem [6].

3.4 ANN performance evaluation

The capability of the model to calculate the targeted response was evaluated based on four parameters: (i) the RMSE; (ii) the coefficient of determination [R^2 , Eq. (2)]; (iii) the mean absolute error [MAPE, Eq. (3)], and (iv) the normalized mean bias error [NMBE, Eq. (4)].

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(a_i - \widehat{a_i})^2}{n}} \quad (1)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(a_i - \widehat{a_i})^2}{\sum_{i=1}^{n}\widehat{a_i}^2} \quad (2)$$

$$\mathrm{MAPE}(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{|a_i - \widehat{a_i}|}{|\widehat{a_i}|} \quad (3)$$

$$\mathrm{NMBE}(\%) = \frac{100}{n}\left(\frac{\sum_{i=1}^{n}(a_i - \widehat{a_i})^2}{\bar{a}_i}\right) \quad (4)$$

Where,

n: the number of data points in the training and testing sets.
a_i: the targeted response.
$\widehat{a_i}$: the predicted response.
$\bar{a}_i$: the mean of the targeted response.

3.5 Connection weight approach

A CWA is a method used to interpret and understand the internal workings of ANNs [56], which are often called "black boxes" due to their complexity and non-linearity. This approach involves analyzing the weights assigned to the connections between neurons in the neural network. It is possible to gain insights into the relative importance of different input features or variables by examining the magnitude and direction of these weights. This approach is useful in interpreting and explaining the decision-making process of ANN used in the concrete investigation by recent research [6,48,57]. Engineers and practitioners in the cementitious materials field will better understand the effect of concrete's components on its characteristics.

4 Results and discussion

4.1 Model description and performance

This study developed an ANN model with a unique one-hidden layer by employing the R statistical language and the *neuralnet* function. Sixteen different architectures were tested for each activation function, and 100 models were computed for each architecture to mitigate the effect of the connection's initial weight allocation. As a result, a total of 3,200 ANN approaches were established to forecast the slump flow of fresh UHPC utilizing the earlier mentioned 793 test result records. These networks consisted of an input layer containing the input nodes, a hidden layer of computational neurons, and an output layer. The input signals were grouped into two classes:

- The volume ratio of UHPC-making ingredients: including cement (PC), silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBFS), waste ground glass powder (GP), rice husk ash (RHA), fluid catalytic residue (FC3R), metakaolin (MK), limestone powder (LP), water (W), polycarboxylate-based high-range water reducer admixture (HRWR), quartz powder (QP), and total aggregate (A).
- UHPC's features: the maximum size of aggregate (MSA), water-to-binder ratio (WB), water-to-total powders ratio (WP), and virtual packing density (VPD), which represents the relationship between components.

The VPD is not typically included in scientific articles but was estimated using the available data, particularly the mean particle size (d_{50}) and the mixture proportion. The calculation of VPD was based on the compressive packing model theory [58-60]. Fig. 4 depicts the average RMSE obtained in the most favorable initial weight allocation versus the hidden layer's number of neurons. It is evident that three neurons in the hidden layer of the ANN result in the minimum RMSE. Therefore, the ANN configuration shown in Fig. 5 was selected for implementation.

The performance of the ANN model was measured using the metrics listed in Table 1. Based on these results, it can be concluded that the ANN approach predicts UHPC slump flow reasonably well, with R^2 values of 0.97 and 0.91 for training and testing subsets, respectively. The regression plot shown in Fig. 6 also shows the good performance of the ANN model. Furthermore, the performance metrics on train and test data subsets are in the same order of magnitude, indicating proper implementation of the *k-fold* validation method [6,47,48].

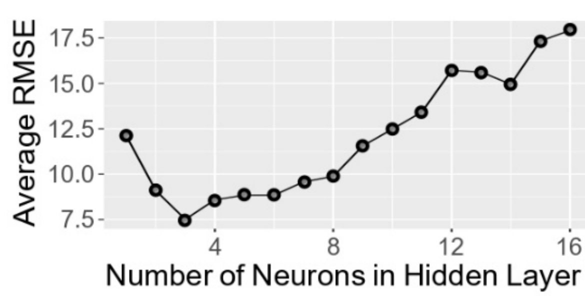

Figure 4. Average RMSE obtained during the *k-fold* validation training versus the number of neurons in the hidden layer.
Source: The authors

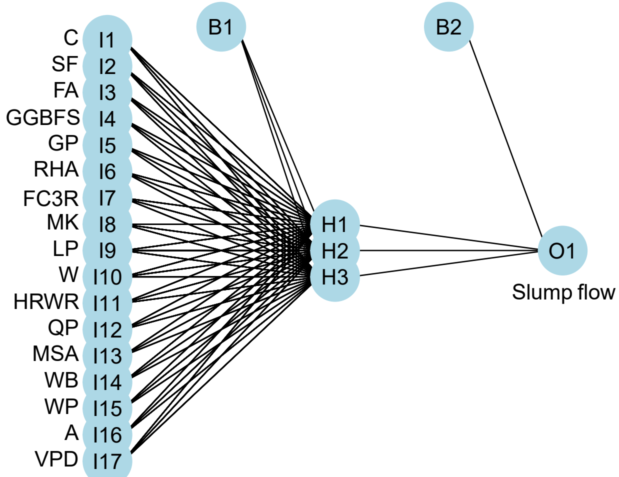

Figure 5. Chosen ANN architecture for predicting the UHPC slump flow.
Source: The authors

Table 1.
Performance metrics of the ANN regression model.

Subset	RMSE	R^2	MAPE	NMBE
Train	7.509	0.971	4.477%	-2.175%
Test	9.603	0.909	5.372%	-0.137%

Source: The authors.

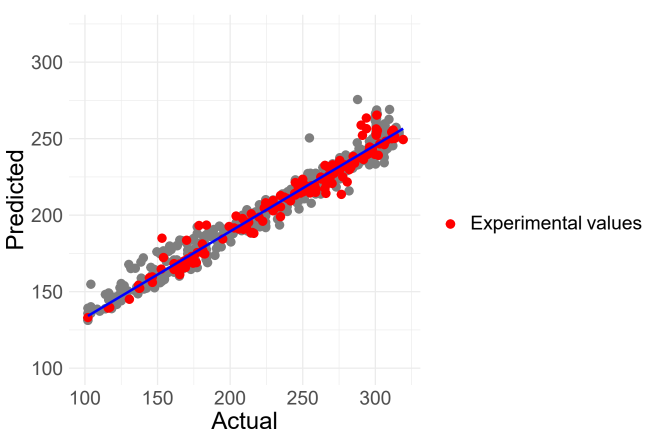

Figure 6. ANN regression plot discriminating the experimental UHPC's slump flow values.
Source: The authors

4.2 *CWA findings and discussion*

A summary of the findings obtained by the CWA is shown in Fig. 7. The results of the CWA analysis were consistent with expectations, indicating that water content (W) had the highest positive importance in predicting slump flow, followed by HRWR dosage. Other variables that positively influenced slump flow were those related to the water amount (WP, WB), demonstrating relative importance. The dosages of LP, FA, and GP also show a positive influence on the flowability of the mixture. A similar pattern of results was observed in previous studies in this area [6,61].

The significance of LP dosage in the improvement of UHPC rheological performance has been well-established in previous research. Yu, Spiesz, and Brouwers [62] concluded that LP utilized as a partial substitution for C could significantly enhance the flowability of UHPC, emphasizing its importance as a supplementary material in UHPC production. Furthermore, recent studies [63,64] have highlighted the positive impact of LP on the UHPC's mechanical durability features, making it a promising addition to modern concrete technology. Additionally, LP has shown the ability to mitigate the cement-polycarboxylate incompatibility in UHPC, which poses a serious concern in the application of this excellent cementitious material [65-67].

The fly ash, on the other hand, significantly affects the rheological properties of UHPC. Its particles' spherical shape improves the concrete mixture's flowability, workability, and cohesion. It reduces internal friction, allowing for smoother movement of particles. This results in enhanced stability, reduced segregation, and improved overall rheological performance of UHPC [48]. On the other hand, fly ash is still an ultra-fine powder that demands water in concrete. Therefore, the fly ash addition produces a limited positive effect as shown in Fig. 7.

The positive influence of GP on concrete can be attributed to its remarkably low water absorption characteristics [7,30,68], which in turn improves the rheology of the concrete. Furthermore, the incorporation of GP in the mixture leads to an augment in alkaline concentration due to its high Na_2O concentration [69,70]. Consequently, the liquid phase's higher alkalinity results in the paste's lower shear strength, contributing to increased flowability [7,71,72]. Moreover, it is also relevant to glass particles having almost zero water absorption. Therefore, when partially replacing other components, the inclusion of GP provides more free water to contribute to the rheology properties of concrete [70].

Moreover, MSA has a slightly positive influence on the rheological features of the fresh-state UHPC. In this sense, sand's maximum size and gradation are critical factors influencing the rheological behavior of this high-performance cementitious composite. Typically, UHPC employs manufactured crushed and classified quartz as micro sand with an MSA value of 600 µm, which may necessitate

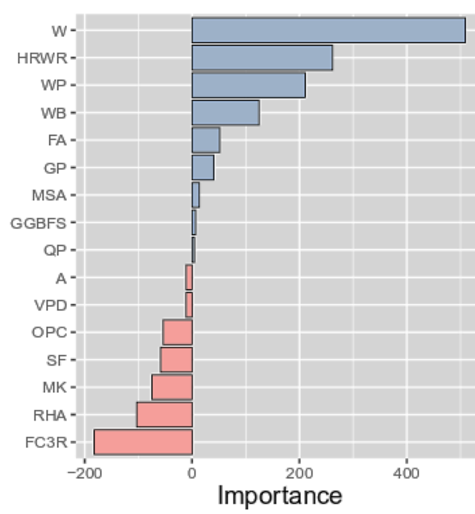

Figure 7. Findings depicted in the CWA analysis.
Source: The authors

an increase in binder proportion to ensure adequate flowability [73]. This is due to the fact that smaller sand grains lead to a larger specific surface, requiring a higher amount of paste to achieve the desired workability. Consequently, when the sand volume is fixed, the utilization of sand with a larger maximum particle size can be considered to improve rheological performance and mitigate shear thickening behavior [73,74]. Thus, the larger the particle size, the larger the slump flow of UHPC.

Continuing with the analysis of the CWA results, the following list of UHPC-making materials appears to have a positive but non-significant influence on the rheological features of the UHPC: GGBSF, QP, and VPD.

On the one hand, the collective findings of several recent studies shed light on the significant impact of GGBFS on the rheology and mechanical properties of concrete, supporting the results depicted in Fig. 7. Bature et al. [75] conducted experiments revealing that the addition of GGBFS to concrete resulted in a notable reduction in its dynamic yield stress, leading to improved workability and pumpability. Gokce [76] corroborated these findings, demonstrating that incorporating GGBS into self-compacting concrete notably enhanced its flow consistency. For its part, Torres et al. [77] conducted a comprehensive study examining the impact of different superplasticizers on the reactive powder concrete's workability and compressive strength when this SCM was incorporated. The results underscored the significant role of superplasticizer type and composition in influencing concrete spread, viscosity, and compressive performance. This effect was found to be far more significant than the GGBSF. Moreover, as per Zang et al. [78], finer particles of slag with sizes up to 30 microns negatively influenced the rheology of concrete, while coarser particles with sizes between 30 and 45 microns had the opposite effect.

To sum up, the above paragraph highlights the findings from recent studies that collectively emphasize that the impact of GGBFS on the rheology of concrete is limited and depends upon its particle size more than chemical reactions [75-79]. The latter supports the results observed in the CWA analysis.

For its part, QP is a constituent of a typical UHPC mixture proportion whose main objective is to contribute to obtaining the desired concrete packing density [79,80]. Similarly, to what we will see occurs with VPD, the CWA analysis shows that this component has a positive effect but is of limited relevance to the UHPC's slump flow value.

The case of the influence of the VPD on the UHPC's rheological features can be a little bit controversial when comparing it to other typologies of concrete. The studies reviewed in the field of concrete engineering indicate that particle packing density plays a significant role in the rheological properties of concrete. Ghoddousiet al. [81] demonstrated in their work published in 2014 that exists an optimal packing density for self-consolidating concrete mixtures, which leads to improved velocity and rheological properties. In general, higher packing densities can result in mixtures that require less water, thereby reducing the amount of cement needed. For its part, Chateau [82] provided an overview of the impact of particle properties on packing characteristics and presented predictive models for packing density in particle mixtures. Mehdipour & Khayat [83] conducted a review on the influence of packing features of colloidal and non-colloidal particles on the rheo-physical properties of cementitious suspensions and concluded that the rheological features are mainly influenced by the relative solid packing fraction. Collectively, these studies suggest that optimizing particle packing density can enhance the concrete rheological features and potentially reduce the amount of cement required. However, in the case of UHPC, this situation is negatively compensated by the necessity of ultra-fine particles to obtain the high packing density values that reach values over 0.8 when conventional concrete's around 0.6 [70]. These ultra-fine particles, such as SF with an average particle size of about 0.15 microns, thereby augmenting drastically the specific surface of the mixture [84,85]. This balance could be the explanation for why VPD appears to be positive but with non-relevant importance in the slump flow of UHPC, contrary to what happens in other concrete types.

The CWA analysis indicates the little adverse effect of aggregate (A) on UHPC's workability. In this sense, Yang et al. [86] found that the addition of angular manufactured sand, the typical aggregate utilized in UHPC, can negatively affect the flowability and volume stability of this special concrete. According to this research work, the incorporation of quartz angular micro sand might disturb the UHPC particle packing skeleton, leading to a deterioration of the slump flow values.

The next component to be commented on is cement (C), which, as expected, displays a negative influence on the UHPC slump flow. Portland cement clinker's mineral composition, which includes C_3S, C_2S, C_3A, and C_4AF, is a significant factor that affects the workability of any type of fresh concrete. Gypsum is incorporated into the clinker to grind the cement, and each mineral composition reacts with water at different rates and requires different amounts of water. As such, the mineral composition can affect the cement paste's rheological properties. Ions like SO_4^{2-}, OH^-, Na^+, and K^+ may be released into the water when cement comes into contact with water, which can influence the adsorption of the superplasticizer onto cement particles, thereby influencing cement paste rheological performance [87]. The cement's fineness also impacts the cement paste's rheological performance since fine cement particles hydrate faster than coarser ones and require more water for a given flowability. Many researchers have extensively studied cement's chemical and physical features, and the results indicate that an increase in cement dosage can reduce the flowability of fresh concrete [88]. For instance, Hope et al. [88] found that cement with high Al_2O_3 or C_2S contents requires more water, while cement with high ignition loss, C_3S content, or high carbonate concentration demands less water for a given slump. Mork et al. [89] noted that reducing the gypsum-to-hemihydrate ratio can decrease the yield stress of concrete for cement with high C_3A and alkalis content, but the effects were less pronounced for cement with lower C_3A and alkalis content. Dils et al. [90] examined the impact of cement's chemical composition and refinement on the rheological properties of UHPC and discovered that cement with a high C_3A and specific surface, a high alkali content, and a low SO_3 content provided poor flowability.

For its part, Chen & Kwan [91] showed that an increase in cement dosage could decrease the fresh concrete's workability, increasing the yield stress and apparent viscosity, particularly at higher water-to-cement ratios. At lower water content, the addition of superfine cement can improve the rheological properties of cement paste by filling the voids, increasing the packing density, and releasing the water between cement particles, leading to a thicker water film coating the particles in the cement paste. However, at higher water dosages, the addition of superfine cement may not have an obvious influence on the water film thickness due to the high specific surface area, which can increase plastic viscosity and yield stress [87,91]. Hence, the aforementioned pieces of research support the obtained CWA results (Fig. 7).

Regarding the SF, which is UHPC's most common SCM to enhance mechanical and durability properties. However, excessive dosage of SF can worsen the flowability of UHPC owing to the SF's small particle size. SF particles are so fine that they augment the specific surface area of the mixture, leading to a greater demand for water and superplasticizers to maintain the required workability. The WB in UHPC is closely linked to the SF content because of the aforementioned reasons [28]. These explanations are in line with the findings presented in Fig. 7.

Incorporating metakaolin (MK) into the UHPC leads to a reduction in slump flow, as the replacement ratio of this SCM increases. This reduction in flowability can be attributed to the accelerating effect of MK on the hydration process, which is supported by the high pozzolanic activity index observed at the early ages of this concrete-making ingredient. Additionally, the high content of amorphous SiO_2 and Al_2O_3, as well as the porous non-spherical particles of MK contribute to the negative impact on workability [92,93]. Moreover, these pieces of research also suggested that the chemical reaction of reactive SiO_2 and Al_2O_3 content of MK can generate enormous heat during the hydration process, which can worsen flowability. Therefore, it should be noted that previous studies have demonstrated that incorporating MK into concrete requires more water or superplasticizer to achieve the desired level of flowability [94,95].

For its part, the incorporation of RHA in concrete results in a decrease in the slump flow value of UHPC, and this effect becomes more significant with an increase in the amount of RHA used (i.e., as the percentage of partial substitution of RHA increases, the factor A value decreases). The negative impact on the rheology of the concrete can be attributed to the non-spherical shape and porosity of RHA particles [48]. The use of materials with higher surface area and water absorption reduces the availability of free water in UHPC. This lower free water content increases friction between the solid particles in the bulk paste, resulting in highly viscous concrete with a lower slump flow. Additionally, replacing cement with RHA by weight leads to a higher paste volume due to RHA's lower density, which reduces the amount of free water available. Therefore, incorporating RHA necessitates greater water and/or superplasticizer contents to achieve the desired workability, as previously reported by [96-97].

Finally, the highest degree of importance is attributed to FC3R. This can be ascribed to the increased formation of ettringite with higher levels of FC3R substitution for C in the concrete, as evidenced in previous studies [48,92], resulting in decreased flowability. Additionally, it has been demonstrated in several investigations that the incorporation of FC3R in concrete necessitates higher water content to achieve the desired workability [48,92,93].

5 Conclusions

The present study proposes a novel approach for predicting the UHPC slump flow using ANN. During the *k-fold* validation of the training process, the initial weight allocation and number of neurons in the hidden layer were chosen to minimize the RMSE between the actual and predicted values. Accordingly, 3,200 ANN models were constructed using the 793 observations to predict the slump flow of UHPC. The optimized ANN model consisted of seventeen nodes in the input layer, three computational neurons in the hidden layer, and an output layer. The ANN paradigm showed proper accuracy in the prediction of the considered response, achieving an R^2 value in the testing subset of 0.91. The CWA approach demonstrated that water content (W) had the highest positive importance in predicting slump flow, followed by superplasticizer content HRWR. Other factors that positively influenced slump flow prediction were the water-to-powder ratio (WP), water-to-binder ratio (WB), limestone content (LP), and recycled glass powder (GP), all of which demonstrated relative importance. The study also found that the maximum size of aggregate (MSA) was a critical factor influencing the UHPC's rheological performance. Cement displayed a negative influence on the UHPC slump flow. In this sense, the mineral composition of Portland cement clinker, gypsum, and the fineness of cement were factors that affected the rheological behavior of this cementitious material. It is also relevant to highlight that the findings depicted by the CWA analysis were well-correlated with experimental works around the world, which supports the models created.

6 Impact, limitations, and future research

In this study, we have introduced a novel, optimized one-hidden layer ANN model for the accurate prediction of UHPC slump flow, thereby contributing to the advancement of computational methodologies in civil engineering. The ANN model was rigorously tested against a comprehensive dataset of 793 observations, which were further validated through k-fold cross-validation. The resultant ANN demonstrated remarkable accuracy, achieving an R^2 value of 0.91 in the testing subset. Beyond mere prediction, the study also employed the CWA analysis to identify critical factors influencing the slump flow of UHPC, thereby providing a comprehensive tool for both prediction and understanding the underlying mechanics of UHPC flowability.

Although the ANN approach presented in this study showed promising results in predicting the slump flow of UHPC, some limitations must be acknowledged. First, the dataset used for training and testing the model was limited to the components listed in the manuscript. Therefore, future research should aim to include a broader range of UHPC-making materials (i.e., other SCM, mineral admixtures, and so on) to validate the performance of the ANN approach across a wider range of UHPC compositions.

Second, while the CWA approach identified important factors that influence the slump flow of UHPC, it is important to note that the analysis was based solely on the data used in this study. Therefore, future research should include additional factors and variables that may impact the rheological behavior of UHPC. For instance, the mixing procedure or the addition of ice to the mixture.

Lastly, the current study focused solely on predicting the slump flow of UHPC in the fresh state. Future research should aim to extend this approach to predict other important properties of UHPC, such as compressive strength, flexural strength, and durability.

In summary, the results of this study provide a promising approach for predicting the slump flow of UHPC using an ANN model and identifying important factors that influence its rheological behavior. However, further research is necessary to validate these findings across a broader range of UHPC compositions and to extend this approach to predict other important properties of UHPC.

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