

Experimental Investigation and Numerical Analysis of the Effect of Magnesium Oxide Nanoparticles on the Mechanical Properties of Roadway Concrete

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Abstract

Nanoparticles can play a significant role in enhancing the properties and performance of concrete used in roadway construction. Nanoparticles can help improve the durability of concrete by reducing permeability and enhancing resistance to various deleterious processes, such as freeze-thaw cycles, chemical attack from road salts, and alkali-silica reaction. This research explores the potential of magnesium oxide nanoparticles as partial substitutes for cement to serve as dense barriers against liquid penetration into concrete. Unidirectional compression and splitting tensile tests were conducted to evaluate the compressive and tensile strengths of concrete specimens incorporating 0%, 0.1%, 0.5%, 1.0%, and 1.5% magnesium oxide nanoparticles at ages of 7 and 28 days. Additionally, the permeability and water absorption rate of the concrete were assessed. Scanning electron microscopy images are utilized to visually demonstrate the uniform dispersion of nanoparticles within the cement paste. Findings reveal that even a small quantity of nanoparticles leads to a significant enhancement in the mechanical properties of concrete and a reduction in water permeability. Additionally, behavioural models employing genetic algorithm programming are developed to characterize the time-dependent properties of nanoparticle-blended concrete specimens under varying compressive and tensile stress conditions at different ages.

Keywords: Nanoparticle-blended concrete, Durability, Water permeability, Genetic Algorithm (GA) programming, Compressive strength

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1. Introduction

Reducing permeability and ensuring the durability and longevity of concrete are paramount concerns in concrete preparation. Concrete with minimal permeability exhibits robust resistance against chemical attacks from sulfates, carbonates, and chlorine, thereby preventing concrete degradation and steel corrosion. In hydraulic structures like dams, canals, drains, and water tanks, concrete permeability plays a pivotal role in structural design [1-3]. Moreover, concrete permeability is critical in structures such as sewage tanks, gas purifiers, and pressure tanks in atomic reactors, as well as hydraulic channels, where resistance against other materials or gases is essential. Furthermore, with advancements in nanotechnology, engineers and researchers are actively exploring innovative methods to incorporate nanomaterials into concrete [1, 4]. By enhancing concrete efficiency and bolstering resistance against penetration, these efforts aim to improve the stability and longevity of structures. Nanoparticles, materials with at least one dimension in the nanometer scale, possess unique physical and chemical properties that differ significantly from their bulk counterparts [5-7]. When introduced into concrete, these nanoparticles can interact with the cementitious matrix, influencing its microstructure and ultimately affecting the mechanical properties of the final product.

2. Literature Review

In recent years, the utilization of nanoparticles has experienced significant development across various engineering disciplines [8-10]. One notable application of nanoparticles lies in reinforcing concrete, where their exceptional properties exert a substantial influence on the mechanical behavior of the material [11-13]. Research findings indicate that the incorporation of diverse nanoparticles, such as ZrO_2 , Fe_3O_4 , TiO_2 , nano-silica and Al_2O_3 , leads to notable enhancements in the

mechanical properties and durability of concrete [14, 15]. Specifically, nano-silica particles have been shown to augment the mechanical properties and diminish the permeability of concrete by effectively filling the pores of the cement paste and promoting pozzolanic reactions. Similarly, the use of nano SiO_2 particles has demonstrated the ability to bolster the compressive strength and resistance to water penetration in concrete, further reducing its permeability [16]. The incorporation of nanoparticles alongside polypropylene fibers has been observed to enhance the cold resistance and compressive strength of concrete pavement, while concurrently reducing its permeability and porosity. Additionally, Naderi et al. [17] investigated the influence of various temperature cycles on the permeability and surface resistance of concrete specimens containing permeation-reducing agents, namely Supergel and Mesocrete, utilizing the cylindrical chamber test. Utilizing MATLAB software in three-dimensional space, they established a close relationship between permeability and concrete strength, which can be described by a first-degree plane equation with a correlation coefficient of approximately 91%. Moreover, Lee et al. [18] explored the preparation and mechanical characteristics of nanoalumina composites. Their findings indicated that incorporating nanomaterials in concrete enhances both compressive and tensile strength, alters the rate of strength gain over time, and accelerates the speed of strength development. Thus, even with small amounts of nanoalumina, a significant increase in the tensile and compressive strength of lightweight concrete can be observed. Furthermore, Takabi et al. [19] investigated the optimal utilization of microsilica to mitigate reinforcement corrosion in marine concrete structures. Their study, conducted over 18 months at various intervals, revealed that incorporating 10% microsilica into the concrete mixture with a water-cement ratio of 34% significantly enhances the

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durability of reinforcement against corrosion, thereby prolonging the service life of marine structures. Previous research has shown that incorporating nano-MgO into cement-treated clay can improve its mechanical properties [20-22].

Predicting concrete properties is crucial for determining the durability and performance of concrete structures. Traditional experimental methods for assessing these properties are often time-consuming, costly, and prone to errors due to various factors such as the presence of interfering ions and limitations of laboratory equipment. With advancements in concrete science, developing predictive models can offer a more efficient and accurate alternative, saving time and resources. Artificial neural networks have emerged as a valuable tool in civil engineering for modeling complex systems and predicting concrete properties [23-25]. In recent studies, neural network models have demonstrated effectiveness in predicting various concrete properties. For instance, Garcia et al. [26] developed neural network models to predict the compressive strength and slump flow of ultra-high-performance concrete. Their models incorporated different materials such as recycled glass powder, fluid catalytic cracking residues, and limestone powder, showcasing the versatility and applicability of neural networks in concrete prediction. Zhang et al. [27] proposed a hybrid neural network approach to predict the pore pressure and temperature of fire concrete, crucial for preventing explosive spalling. Miri et al. [28] conducted a study investigating the influence of wollastonite nanoparticles on the mechanical properties, durability, and resistance to water penetration of concrete samples at different ages. Their findings revealed significant improvements in bending strength (by 63%), compressive strength (by 9%), and resistance to water penetration (by about 50%) with the substitution of 10% nano wollastonite for cement. Bescopelni et al. [29] compared the performance of three machine learning

algorithms—CatBoost, k-nearest neighbor, and support vector regression—in predicting the compressive strength of concrete. Moreover, Okrancic et al. [30] investigated the compressive strength, tensile strength, chloride ion permeability, and gas permeability of concrete. They employed artificial neural networks to predict these properties, utilizing a multilayer neural network structure comprising an input layer, two hidden layers, and an output layer with interconnected nodes in each layer. In the neural network structure, the input data is defined in the input layer and transmitted directly to the hidden layers, where computations take place. Subsequently, the output layer presents the calculated data as output. The results of studies have demonstrated the feasibility of establishing predictive relationships for determining the strength and permeability of high-performance concrete using artificial neural networks. For example, Reshno et al. [31] delved into the engineering properties of fiber super-strength self-compacting concrete and employed a hybrid neural network approach alongside Radial Basis Function (RBF) to predict its rheological properties. Notably, among the two artificial neural networks, ANN-GA exhibited higher prediction accuracy. Collectively, these studies underscore the potential of neural network models in accurately predicting a diverse range of concrete properties, thereby offering valuable insights for concrete engineering applications.

The review of existing studies reveals that while the impact of various types of nanoparticles on the mechanical properties and permeability of concrete has been extensively explored, the effect of magnesium oxide nanoparticles remains largely unexplored. In this study, magnesium oxide nanoparticles were incorporated into concrete mixes as a replacement for cement. Subsequently, the influence of these nanoparticles was investigated through mechanical resistance tests conducted at different ages. Additionally,

scanning electron microscope images were employed to elucidate the functioning of nanoparticles and their distribution within the concrete matrix. The innovative aspect of this research lies in examining the influence of magnesium oxide nanoparticles on the permeability of hydraulic structures. To investigate the impact of increasing nanoparticle percentages on the mechanical properties of concrete and determine the optimal percentage increase, different water-to-cement ratios are employed. Given the intricate behavior of concrete and its characteristic variations stemming from changes in material quality, quantity, and environmental conditions, devising an appropriate mixing plan tailored to implementation conditions and project requirements poses a significant challenge. This complexity escalates with the growing number of parameters affecting bulk concrete. In light of advancements in science, neural networks have emerged as a powerful tool for modeling nonlinear, multi-variable equations across various engineering disciplines, including bulk concrete mixing design. Recognizing the efficacy of this approach, already demonstrated by prior researchers, leveraging neural networks can streamline the mixing plan process, thus saving costs and time for large-scale projects. Consequently, this research endeavors to predict the concrete mixing plan incorporating nanoparticles using neural networks in conjunction with the genetic algorithm method. The input parameters of the model encompass the weights of coarse and fine-grained materials (differentiated by granulation), water weight, cement weight, water-to-cement ratio, nanoparticle percentage, and other additives.

3. Materials and Methods

3.1. Materials

Commercially available magnesium oxide (MgO) nanoparticles were acquired in the form of a 1000 ppm water-based colloidal nano-suspension from Mehrgan Shimi Company

(Tehran, Iran). This colloidal dispersion facilitated homogenous distribution of the nanoparticles throughout the mortar and concrete mixtures, enhancing their efficacy while maintaining cost-effectiveness. The physical and chemical characteristics of magnesium oxide nanoparticles are shown in Table 1, and the image of magnesium oxide nanoparticles powder and the related TEM (Transmission Electron Microscopy) and X-ray diffraction (XRD) images are shown in Figure 1. The specific surface area and average particle size of the magnesium oxide nanoparticles were obtained from the manufacturer's data (Mehrgan Shimi Company, Tehran, Iran).

Table 1. Characteristics nanoparticles

Nanoparticle size	40 nm
Special surface	90 m ² /gr
Purity	99 %
Apparent density	0.95 gr/m ³
crystal phase	Single crystal type
Almost spherical	Shape
color	Milky white

The cements utilized in all experiments were Type II Portland cement sourced from the Sufian Cement factory and packaged in bags. The water used for sample construction in this project was obtained from the urban water supply network of the Tabriz University Concrete Laboratory. Standard sand was employed as the sand component in cement mortar. The fine-grained material used in concrete samples was sand from the Seram factory, characterized by a water absorption percentage of 0.9%, a modulus of elasticity of 3.12, and a specific gravity of 2.81. The gravel materials utilized in this project consisted of fine and coarse gravel from the Seram factory, featuring a water absorption percentage of 0.65% and a dry weight of gravel of 2.69. The maximum grain diameter utilized was 19 mm. After grading and approval, the gravel was stored in the laboratory and utilized in all experiments. The superplasticizer utilized in this project was E.M. POWERPLAST, conforming to ASTM-C494 standards, and

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manufactured by Abadgaran Company for the production of high-strength and self-compacting concrete. Table 2 presents the specifications of the superplasticizer. The grading of coarse and fine aggregates adheres to the criteria specified in ASTM C33/C33M standards [32]. To ascertain the granulation curve of the aggregates utilized, a sieve analysis was conducted in accordance with ASTM C136/C136M standards. The sampling weights for the granulation tests were determined based on the requirements outlined in these regulations [33].

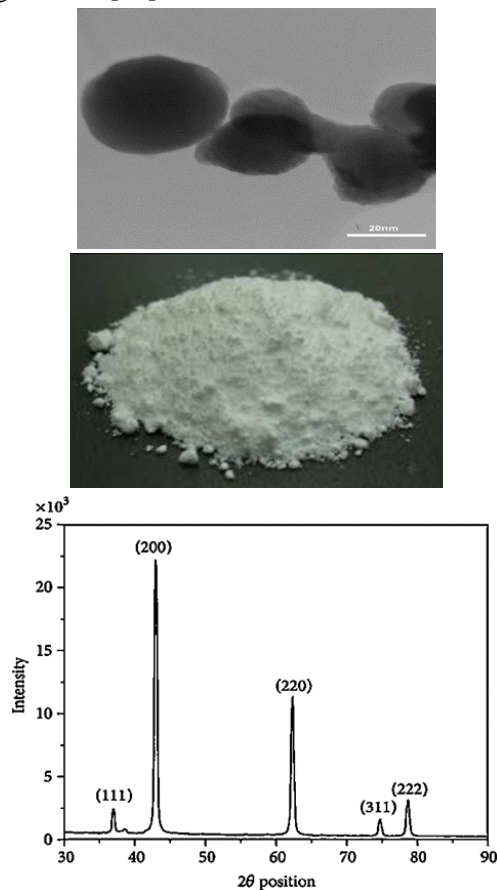


Figure 1. Magnesium oxide nanoparticle powder and its TEM and XRD images

Table 2. Super plasticizers specifications

Amount of particles	30%
Density	1.15 kg/m ³
Mixing plans	1-1.25%
Appearance	Liquid with a yellow color

3.2. Sample Preparation

The concrete samples were mixed according to ACI 211 regulations and by weight method. In this project, the grade of cement is 350 kg/m³. The ratio of coarse to fine stone materials is 1:1, the largest size is 19 mm and the total weight of the mixture is 2345 kg/m³. Table 3 shows the mixing plan of concrete samples with W/C=0.61. To evaluate the effect of MGO on concrete properties, five concrete mixtures were prepared with varying MGO replacement levels: 0% (control), 0.1%, 0.5%, 1.0%, and 1.5% by weight of cement. The values (percentages) of MgO were selected based on a comprehensive review of existing literature and standards, such as ASTM C150/C150M for Portland cement. Previous studies have demonstrated that varying the MgO content within a certain range can significantly influence the physical and mechanical properties of the cementitious materials [22, 34, 35]. Therefore, a range of MgO percentages was chosen to explore these effects systematically. Additionally, the selection was guided by the specific objectives of the research, aiming to optimize the performance characteristics of the cement while adhering to industry standards. The chosen values also consider practical constraints and the typical composition of raw materials used in cement production.

Table 3. Mixing plan of concrete samples with 0.61 w/c

Sample ID	Description	w/cm	Quantities				
			Nano Material (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Water (kg/m ³)
N	Base sample	0.61	0	336	684	1155	205
M21	0.1% MgO		0.35	335.65	684	1155	205
M22	0.5% MgO		1.75	334.25	684	1155	205
M23	1.0% MgO		3.5	332.5	684	1155	205
M24	1.5% MgO		5.25	330.75	684	1155	205

3.3. Testing Methods

The primary challenge with nanoparticles is their poor dispersion and tendency to clump, leading to an uneven distribution within mortar and concrete mixtures. This clumping phenomenon results in the formation of lumps and voids in the cement paste, ultimately diminishing the mechanical strength of mortar and concrete. To ensure proper dispersion and create a homogeneous environment for nanoparticles within mortar and concrete mixtures, a specific procedure is followed. Nanomaterials are first added to water and then combined with cement, followed by mixing the mixture for 5 minutes using an ultrasonic device. This process facilitates optimal and uniform distribution of nanoparticles. To verify the optimal distribution of nanoparticles in mortar and concrete mixtures, scanning electron microscope (SEM) images are captured from fractured concrete samples. Additionally, all procedures related to the preparation of mortar samples adhere to ASTM standards, encompassing mixing plans, mixing techniques, mold preparation, maintenance, testing protocols, and environmental conditions. Compression samples are molded into 50 mm cubes, with 3 samples crafted for both 7-day and 28-day compressive strength tests. Concrete tensile samples are formed using cylindrical molds measuring 150 x 300 mm. Upon extraction from the water source, the samples undergo testing in accordance with ASTM standards.

The compressive strength testing is conducted in accordance with the BS1881 standard, where the sample is positioned under the machine and subjected to increasing loads until it reaches failure, with the results being recorded accordingly. It is important to note that throughout all stages of the experiments, the temperature is maintained within the range of 18 to 22 degrees Celsius. Figure 2 illustrates the failure state of both the standard and tested samples. For determining the tensile strength, the Splitting test method is employed. As

depicted in Figure 3, the test sample and support rod are positioned using a clamp to secure the support strips, ensuring that the support rod and the axis of the sample are directly aligned beneath the center of the support block. The load is then uniformly applied at a constant speed ranging from 689 to 1380 kPa/min until the sample fractures. The maximum load at the point of rupture, as indicated by the testing apparatus, is recorded for analysis.



Figure 2. Cubic sample under compression test and the satisfactory state of rupture of the tested samples



Figure 3. Cylindrical sample in the splitting test

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4. Results

In this section, we evaluate the laboratory work conducted in this research along with the corresponding results. Given the extensive number of mixing plans and samples produced (a total of 144 mixing plans and 432 concrete samples), only a select number of results pertaining to samples demonstrating optimal mechanical resistance will be presented and discussed here.

4.1. Compressive Strength Test

In order to assess the compressive strength of various concrete mixtures, a total of 216 cubic samples measuring $50 \times 50 \times 50 \text{ mm}^3$ were fabricated, with three samples prepared for each age interval of 7 and 28 days. The average compressive strength values for the 0.54 water-to-cement (W/C) ratio are presented in Table 4. Figure 4 illustrates the changes in compressive strength relative to the percentage of magnesium oxide nanoparticles replacement. The horizontal axis represents the replacement percentage of magnesium oxide nanoparticles, while the vertical axis denotes the average compressive strength in kg/cm^2 . The results indicate a notable increase in compressive strength with the addition of magnesium oxide nanoparticles. Specifically, at 1% replacement of magnesium oxide nanoparticles, the increase in compressive strength for concrete samples at ages 7 and 28 days is observed to be 26% and 18%, respectively. This enhancement can be attributed to the compatible interaction between magnesium oxide nanoparticles and cement hydration, thereby accelerating the cement hydration process. Furthermore, the superior stability and uniform distribution of magnesium oxide nanoparticles play a significant role in enhancing the mechanical properties of concrete. SEM images depicted in Figure 5 corroborate the uniform dispersion of nanoparticles within the concrete matrix. Moreover, the observed increase in compressive strength of concrete containing magnesium oxide nanoparticles compared to

normal concrete can be attributed to the nanoparticle's filling properties and its ability to connect and bridge microcracks. SEM images captured from the fracture surfaces of compressed concrete samples containing 0.5% nanoparticles further confirm the successful dispersion of nanoparticles within the concrete mix achieved through ultrasonic wave utilization.

Table 4. Compressive strength of concrete

Sample ID	Compressive strength (kg/m^2)		
	7 days	14 days	28 days
N	212	305	370
E21	245	350	423
E22	288	370	447
E23	269	365	439
E24	257	355	428

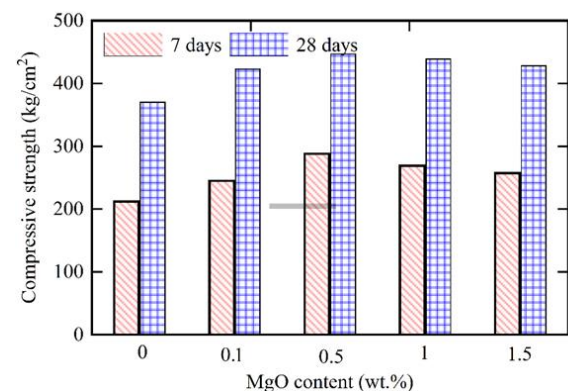


Figure 4. Compressive strength of concrete containing magnesium oxide nanoparticles with $w/c = 0.54$

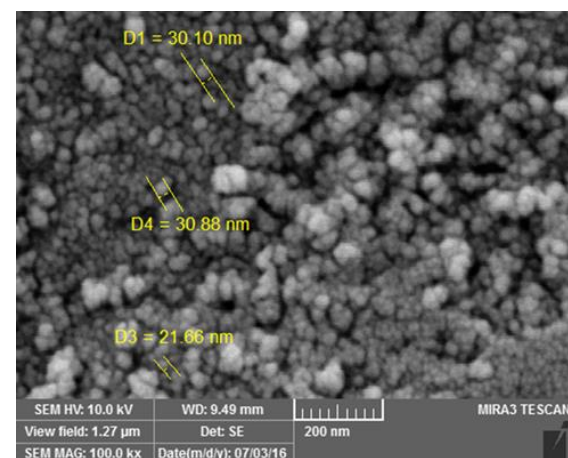


Figure 5. SEM image of the fracture surfaces of the compression concrete sample containing 0.5% nano magnesium oxide

4.2. Tensile Strength Test

To evaluate the tensile strength of various concrete mixtures, 216 cylindrical samples measuring 15 x 30 cm were prepared, with three samples crafted for each age interval of 7 and 28 days. It is important to note that these samples were produced from the same mixture utilized for compression samples, concurrently with them. The average tensile strength values for the 0.54 water-to-cement (W/C) ratio are presented in Table 5. Additionally, Figure 6 illustrates the variations in tensile strength relative to the percentage of magnesium oxide nanoparticles replacement. The results indicate that increasing the amount of nanoparticles up to 1% leads to an increase in tensile strength, followed by a subsequent decrease. The resistance level remains relatively constant upon mixing this material into concrete, but declines as the nanoparticle concentration increases. This decline may be attributed to the agglomeration and accumulation of nanoparticles at higher weight percentages. Notably, magnesium oxide nanoparticles exhibit a higher surface adhesion force, thereby enhancing their tendency to accumulate at higher weight percentages. The findings reveal that the tensile strength initially increases and then decreases with the augmentation of magnesium oxide nanoparticles. Specifically, the increase in tensile strength for concrete samples containing 1% magnesium oxide nanoparticles at ages 7 and 28 days is measured at 39% and 22%, respectively. Moreover, it is observed that this increase diminishes with older ages, while being more pronounced in younger ages, indicating the influence of early cement paste hardening and increased initial concrete setting. Furthermore, even in the worst-case scenario, the tensile strength of concrete improves by 6% with the addition of 0.2% nanoparticles. This underscores the role of magnesium oxide nanoparticles in creating strong bonds between concrete components, thereby impeding the propagation of microcracks within the concrete matrix. The

tensile strength of concrete specimens was also significantly influenced by the incorporation of MGO nanoparticles. As illustrated in Figure 6, the tensile strength generally increased with the addition of MGO up to 1.0% replacement level at both ages.

Table 5. Results of tensile strength of concrete samples

Sample ID	Compressive strength (kg/m ²)		
	7 days	14 days	28 days
N	26	33	40
E21	29.5	36.5	43.9
E22	39.2	41.3	49.8
E23	37.4	39.7	47.8
E24	35.2	37.7	45.4

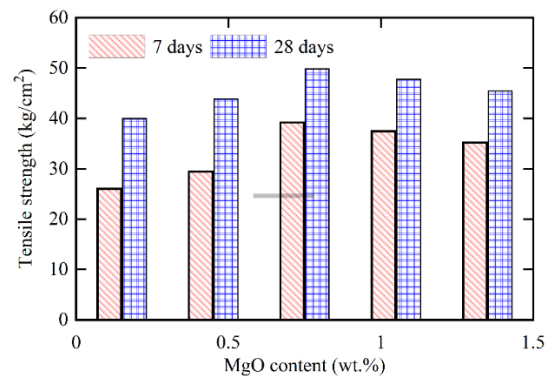


Figure 6. Tensile strength of concrete containing magnesium oxide nanoparticles with w/c = 0.54

4.3. Water Permeability and Absorption

The results of the water absorption and permeability tests are depicted in Figure 7. The enhancement in permeability observed in samples containing magnesium oxide nanoparticles can be attributed to the effective role and favorable dispersion of these nanoparticles, facilitating better pore filling and subsequently reducing matrix porosity. This ultimately results in the formation of dense cement composites characterized by low permeability and moisture absorption. The figure presents the percentage of improvement achieved. The findings reveal that as the nanoparticle content increases, water absorption tends to rise, whereas permeability decreases, owing to the filling properties of

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magnesium oxide nanoparticles. Specifically, the average water absorption and permeability for samples containing 1.5% magnesium oxide nanoparticles are recorded as 6.08% and 104%, respectively. The role of magnesium oxide nanoparticles as fillers in concrete contributes to increased cohesion and reduced permeability. A summary of the percentage increase in mechanical strength of concrete samples incorporating nanomaterials compared to the control sample is provided in Table 6. It is evident that the optimal percentage for magnesium oxide nanoparticles is 1% by weight of cement.

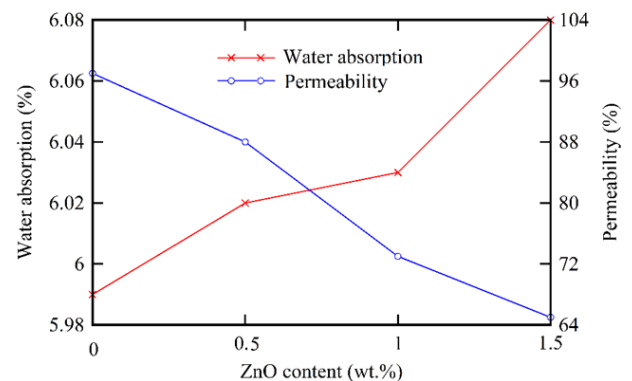


Figure 7. Effect of weight fraction of magnesium oxide nanoparticles on water absorption and permeability of concrete samples

Table 6. Increase in mechanical strength, permeability and water absorption of magnesium oxide nanoparticles reinforced concrete samples compared to the control sample

MgO content	Water absorption	Permeability	Tensile strength		Compressive strength	
	28 day	28 day	7 day	28 day	7 day	28 day
0.1 wt.%	5.985%	96.2%	12%	8%	9%	10%
0.5 wt.%	6.02%	89.3%	36%	18%	14%	13%
1.0 wt.%	6.03%	73.6%	39%	26%	22%	17%
1.5 wt.%	6.08%	65.1%	30%	14%	11%	12%

5. Neural Network Model

In the present study, artificial neural networks (ANNs) are employed to predict the influence of magnesium oxide nanoparticles on the mechanical properties of concrete. This involves numerical modeling based on laboratory experimentation results, where the obtained time-series data are subsequently utilized to train the neural networks. The dataset derived from laboratory experiments accounts for the impact of magnesium oxide nanoparticles on concrete properties. Through this approach, the intricate relationship between nanoparticle content and concrete mechanical behavior can be effectively captured and predicted.

In essence, a biological neural network comprises neurons that are intricately connected and functionally interdependent. Each neuron may be linked to a multitude of others, resulting in a vast network of neurons and connections. The functionality of neural networks is inspired by the efficiency of

biological neurons. Artificial neurons, which are counterparts of biological neurons, consist of two fundamental components: the educational and functional aspects. During training, artificial neurons learn to respond to specific input patterns, whereas during performance, they provide corresponding outputs when presented with recognized input patterns. This model allows artificial neural networks to mimic the behavior of biological neural networks, enabling them to learn from data and make predictions or classifications based on learned patterns.

Artificial neural networks (ANNs) stand as vital tools in various scientific and engineering domains, offering the capability to unveil latent relationships within data gathered from design calculations and experiments. These networks hold promise in addressing analogous problems by leveraging learned patterns. In this study, an ANN is employed to forecast the mechanical properties of concrete fortified with magnesium oxide nanoparticles. The utilized ANN model integrates neural networks with a genetic

optimization algorithm, which operates as a directional stochastic optimization technique gradually converging toward the optimal solution. To assess the efficacy of the employed ANN models, it is imperative to employ metrics that can gauge the models' performance against both the dataset and experimental results. As such, the following indicators have been adopted to evaluate the models and subsequently compare their efficacy:

Maximum value

Minimum value

Average

Standard deviation

Each metric is computed independently to provide a comprehensive assessment. Evaluation of the neural networks in this research is based on criteria such as mean square error (MAE) and root mean square error (RMSE). Additionally, the coefficient of determination, coupled with the correlation coefficient between the predicted values of the neural network and the output data derived from numerical modeling, serves as a pertinent criterion to gauge the network's predictive capability. These evaluation criteria collectively provide insights into the performance and effectiveness of the employed neural network models.

In this research, the optimization process involves considering parameters related to magnesium oxide nanoparticles, such as the percentage of nanoparticles by cement weight, the amount of cement, and the water-cement ratio, which are associated with various

concrete mixing designs. These parameters serve as inputs for the genetic algorithm to maximize the minimum resistance and permeability at different ages. Additionally, the genetic algorithm determines optimal values for concrete components such as cement, water, and nanoparticles to achieve optimization goals simultaneously. The data analysis is conducted using MATLAB software. After training the neural network under various topologies (including networks with one, two, and three hidden layers, each with different numbers of neurons), the optimal topology is determined. A superior solution entails fewer cycles and less time required to reach the network error limit. However, since the weights and initial biases of the network are randomly chosen, the assessment of network superiority is based on intuitive evaluation across multiple runs with different weights and biases. To facilitate training and testing, the collected data is randomly partitioned into training, validation, and testing datasets. Specifically, 70% of the data is allocated for training purposes, while the remaining 30% is equally divided between validation and testing. The neural network structure employed in this research is depicted in Figure 8, showcasing artificial neurons interconnected through weighted connections, each with input weights, transfer functions, and output functions. The flowchart of the genetic algorithm for optimizing neural network training is illustrated in Figure 9, demonstrating the iterative process of selecting optimal network parameters to enhance performance.

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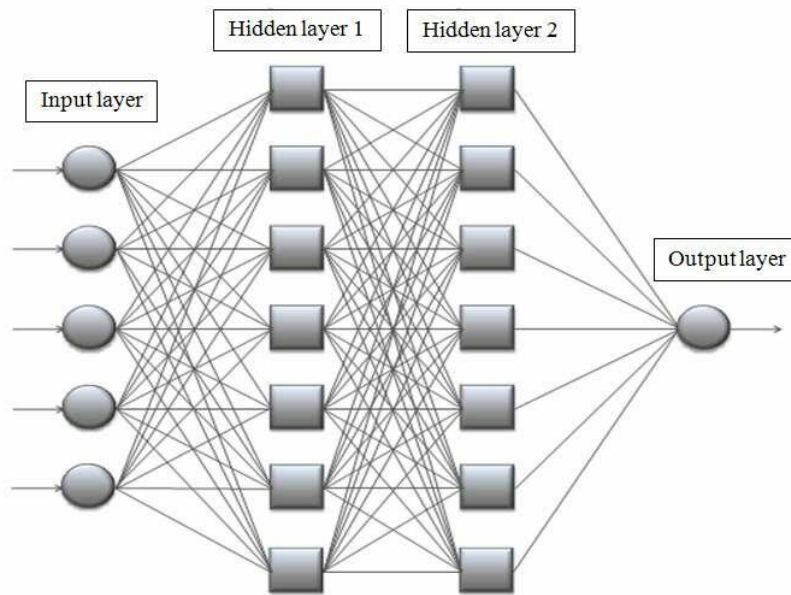


Figure 8. Example of the structure of the neural network used in the research

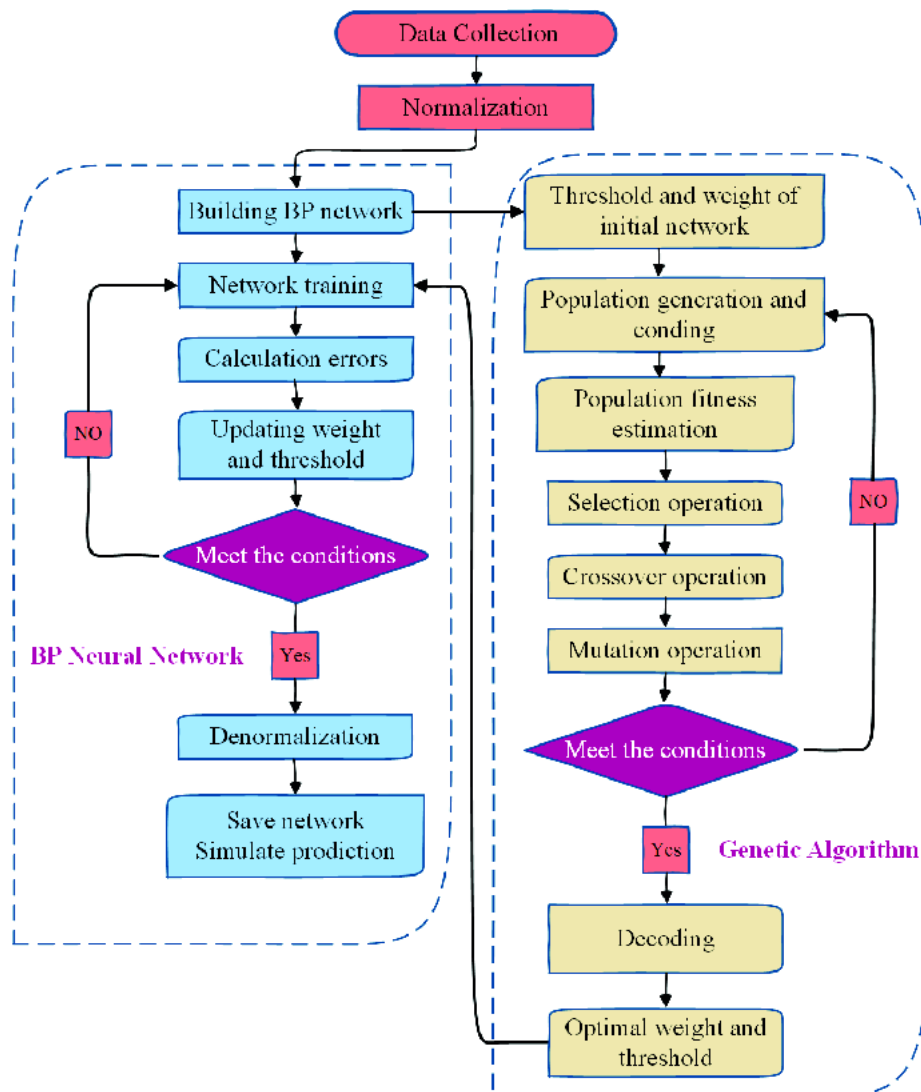


Figure 9. Flowchart of genetic algorithm to optimize neural network training in research

The genetic programming model for predicting the compressive strength of concrete was executed in the MATLAB environment, and the optimal model was identified after conducting ten runs of the program. The graphs illustrating the variations of static parameters across different generations are presented in Figure 10. As anticipated, the algorithm's performance enhances with the progression of generations. Following the iterative process, the proposed tree structure for the compressive strength model of concrete reinforced with magnesium oxide nanoparticles is depicted in Figure 11. In this figure, "FT" denotes the nanoparticle quantity, while "A" signifies the concrete age. The mathematical relationship related to this tree and the relationship between MGO content (FC, wt.%) and compressive strength (f'_c , MPa) can be described by the equation as:

$$f_b = \sqrt{0.0774FC} - 0.0503FC + \sqrt{0.0774f'_c} + 0.0774f'_c - 0.4226$$

where FC is the MgO content (wt.%) and f'_c is the compressive strength of the concrete. In this context, the nanoparticle quantity holds substantial influence on the compressive strength of concrete reinforced with magnesium oxide nanoparticles compared to other factors. Consequently, it has been excluded from the proposed relationship. The static parameters associated with the proposed model are presented in Table 7. Notably, the table demonstrates a robust correlation (0.95876 for training data and 0.99589 for test data) between the outcomes derived from the model and the laboratory results, affirming the model's accuracy. Additionally, the error percentage of the proposed model for all data is noted to be 3.5061%.

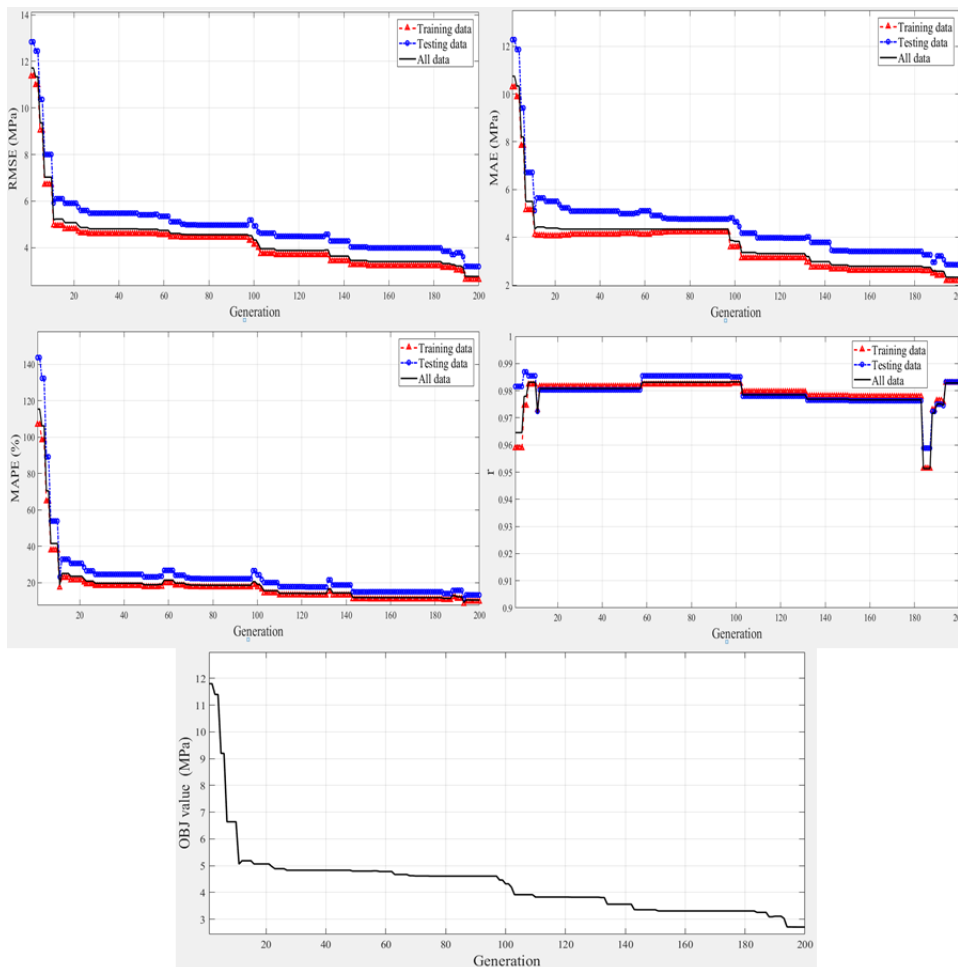


Figure 10. Static parameters related to the compressive strength model of concrete reinforced with magnesium oxide nanoparticles

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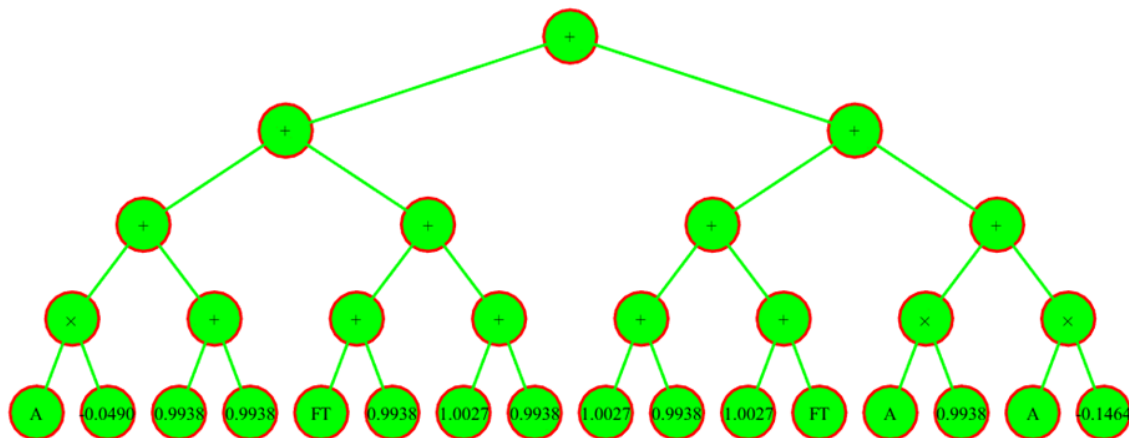


Figure 11. The final tree structure related to the compressive strength model of concrete reinforced with magnesium oxide nanoparticles

Table 7. Values of static parameters of compressive strength model of concrete reinforced with MgO nanoparticles

	RMSE (MPa)	MAE(MPa)	MAPE (%)	R	OBJ(MPa)
Training data	1.5624	1.2685	3.5972	0.95876	
Test data	0.9235	0.8126	2.1136	0.99589	1.1365
Total data	1.4892	1.1206	3.3691	0.98935	

6. Conclusions

This study employed a systematic experimental approach to investigate the influence of magnesium oxide nanoparticles (MGO) on the permeability and mechanical properties of concrete. Unidirectional compression tests and splitting tensile tests were performed to assess the compressive and tensile strengths, respectively, of concrete specimens containing varying MGO content (0%, 0.1%, 0.5%, 1.0%, and 1.5% by weight of cement) at two curing ages: 7 and 28 days. Additionally, assessments were made regarding water permeability and absorption. The findings regarding the mechanical resistance of concrete samples revealed an enhancement in both compressive and tensile strength with increasing nanoparticle substitution, up to a certain threshold. However, substituting a high percentage of magnesium oxide nanoparticles had a detrimental effect on the mechanical properties of concrete, likely due to the elevated surface energy of the nanoparticles leading to the formation of low-strength aggregates within the concrete matrix. Specifically, the increase in

compressive strength of concrete samples containing 1% magnesium oxide nanoparticles at 7 and 28 days of age was noted to be 20% and 16%, respectively, while the corresponding increase in tensile strength was 39% and 22%, respectively. Subsequently, to predict the mechanical properties of concrete, a combined approach utilizing neural networks and genetic algorithms was employed. Remarkably, a robust correlation (0.95876 for training data and 0.99589 for test data) was observed between the outcomes obtained from the model and the laboratory results, underscoring the accuracy of the model. Furthermore, the error percentage of the proposed model for all data was calculated to be 3.3691%.

7. References

– Esmaili, J., V. Romouzi, J. Kasaei, and K. Andalibi, An investigation of durability and the mechanical properties of ultra-high performance concrete (UHPC) modified with economical graphene oxide nano-sheets. *Journal of Building Engineering*, 2023. 80: p. 107908.

- Esmaeili, J., S.P. Khoshkanabi, K. Andalibi, and J. Kasaei. An innovative method for improving the cyclic performance of concrete beams retrofitted with prefabricated basalt-textile-reinforced ultra-high performance concrete. in *Structures*. 2023. Elsevier.
- Esmaeili, J., K. Andalibi, O. Gencel, F.K. Maleki, and V.A. Maleki, Pull-out and bond-slip performance of steel fibers with various ends shapes embedded in polymer-modified concrete. *Construction and Building Materials*, 2021. 271: p. 121531.
- Esmaeili, J. and K. Andalibi, Investigation of the effects of nano-silica on the properties of concrete in comparison with micro-silica. *International Journal of Nano Dimension*, 2013. 3(4): p. 321-328.
- Minaei, M., M. Rezaee, and V. Arab Maleki, Vibration analysis of viscoelastic carbon nanotube under electromagnetic fields based on the nonlocal Timoshenko beam theory. *Iranian Journal of Mechanical Engineering Transactions of ISME*, 2021. 23(2): p. 176-198.
- Vahidi Pashaki, P., M. Pouya, and V.A. Maleki, High-speed cryogenic machining of the carbon nanotube reinforced nanocomposites: Finite element analysis and simulation. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 2018. 232(11): p. 1927-1936.
- Alizadeh, M.H., M. Ajri, and V.A. Maleki, Mechanical properties prediction of ductile iron with spherical graphite using multi-scale finite element model. *Physica Scripta*, 2023. 98(12): p. 125270.
- Hoseinzadeh, M., R. Pilafkan, and V.A. Maleki, Size-dependent linear and nonlinear vibration of functionally graded CNT reinforced imperfect microplates submerged in fluid medium. *Ocean Engineering*, 2023. 268: p. 113257.
- Maleki, F.K., M.K. Nasution, M.S. Gok, and V.A. Maleki, An experimental investigation on mechanical properties of Fe₂O₃ microparticles reinforced polypropylene. *Journal of Materials Research and Technology*, 2022. 16: p. 229-237.
- Pourreza, T., A. Alijani, V.A. Maleki, and A. Kazemi, The effect of magnetic field on buckling and nonlinear vibrations of Graphene nanosheets based on nonlocal elasticity theory. *International Journal of Nano Dimension*, 2022. 13(1): p. 54-70.
- Sabet, A.B., S.A.H. Hashemi, R. Farokhzad, and A. Delnavaz, Synergic effect of defects on carbon nanoparticles under interaction with calcium silicate hydrate composites. *Applied Surface Science*, 2023. 622: p. 156712.
- Ahmad, J. and Z. Zhou, Properties of concrete with addition carbon nanotubes: a review. *Construction and Building Materials*, 2023. 393: p. 132066.
- Jiao, H., Y. Wang, L. Li, K. Arif, F. Farooq, and A. Alaskar, A novel approach in forecasting compressive strength of concrete with carbon nanotubes as nanomaterials. *Materials Today Communications*, 2023. 35: p. 106335.
- Huseien, G.F., A review on concrete composites modified with nanoparticles. *Journal of Composites Science*, 2023. 7(2): p. 67.
- Wang, C., M. Zhang, Q. Wang, J. Dai, T. Luo, W. Pei, A. Melnikov, and Z. Zhang, Research on the influencing mechanism of nano-silica on concrete performances based on multi-scale experiments and micro-scale numerical

Experimental Investigation and Numerical Analysis of the Effect of Magnesium Oxide Nanoparticles on the Mechanical Properties of Roadway Concrete

simulation. *Construction and Building Materials*, 2022. 318: p. 125873.

– Xu, Z., Y. Ji, J. Zhang, Z. Zhang, Q. Xue, and F. Gao, Mechanism of nano-SiO₂ internal generation for modification of cement-based materials. *Journal of Building Engineering*, 2023. 76: p. 107247.

– Naderi, M., A. Saberi Vaezaneh, and M. Parhizkari, The effect of different temperature cycles on permeability and surface resistance of concretes containing permeability reducing materials. *Amirkabir Journal of Civil Engineering*, 2023. 55(9): p. 1845-1862.

– Li, C., G. Li, D. Chen, K. Gao, Y. Mao, S. Fan, L. Tang, and H. Jia, Influencing mechanism of nano-Al₂O₃ on concrete performance based on multi-scale experiments. *Construction and Building Materials*, 2023. 384: p. 131402.

– Tangtakabi, A., M.H. Ramesht, A. Golsoorat Pahlaviani, and T. Pourrostam, Optimum use of microsilica in reducing corrosion reinforcing steel of marine concrete structures. *Amirkabir Journal of Civil Engineering*, 2022. 54(8): p. 2953-2968.

– Wang, W., H. Kang, N. Li, J. Guo, D.Y. Girma, and Y. Liu, Experimental investigations on the mechanical and microscopic behavior of cement-treated clay modified by nano-MgO and fibers. *International Journal of Geomechanics*, 2022. 22(6): p. 04022059.

– Hay, R., N. Dung, A. Lesimple, C. Unluer, and K. Celik, Mechanical and microstructural changes in reactive magnesium oxide cement-based concrete mixes subjected to high temperatures. *Cement and Concrete Composites*, 2021. 118: p. 103955.

– Ye, Y., Y. Liu, T. Shi, Z. Hu, L. Zhong, H. Wang, and Y. Chen, Effect of nano-magnesium oxide on the expansion performance and hydration process of cement-based materials. *Materials*, 2021. 14(13): p. 3766.

– Esmaili, J., K. Andalibi, and O. Gencil, Mechanical characteristics of experimental multi-scale steel fiber reinforced polymer concrete and optimization by Taguchi methods. *Construction and Building Materials*, 2021. 313: p. 125500.

– Singh, P., A. Adebajo, N. Shafiq, S.N.A. Razak, V. Kumar, S.A. Farhan, I. Adebajo, A. Singh, S. Dixit, and S. Singh, Development of performance-based models for green concrete using multiple linear regression and artificial neural network. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 2023: p. 1-12.

– Paruthi, S., A.H. Khan, A. Kumar, F. Kumar, M.A. Hasan, H.M. Magbool, and M.S. Manzar, Sustainable cement replacement using waste eggshells: A review on mechanical properties of eggshell concrete and strength prediction using artificial neural network. *Case Studies in Construction Materials*, 2023. 18: p. e02160.

– Abellán García, J., J. Fernández Gómez, and N. Torres Castellanos, Properties prediction of environmentally friendly ultra-high-performance concrete using artificial neural networks. *European Journal of Environmental and Civil Engineering*, 2022. 26(6): p. 2319-2343.

– Zhang, Y., Z. Gao, X. Wang, and Q. Liu, Predicting the pore-pressure and temperature of fire-loaded concrete by a hybrid neural network. *International Journal of Computational Methods*, 2022. 19(08): p. 2142011.

- Miri, M., H. Beheshti Nezhad, and M. Jafari, Experimental Investigation on Mechanical Properties of Concrete Containing Nano Wollastonite and Modeling with GMDH-Type Neural Networks. *Amirkabir Journal of Science & Research (Civil & Environmental Engineering)*, 2014. 46(2): p. 49-51.
- Beskopylny, A.N., S.A. Stel'makh, E.M. Shcherban', L.R. Mailyan, B. Meskhi, I. Razveeva, A. Chernil'nik, and N. Beskopylny, Concrete strength prediction using machine learning methods CatBoost, k-nearest neighbors, support vector regression. *Applied Sciences*, 2022. 12(21): p. 10864.
- Ukrainczyk, N. and V. Ukrainczyk, A neural network method for analysing concrete durability. *Magazine of Concrete Research*, 2008. 60(7): p. 475-486.
- Nigam, M. and M. Verma, Effect of nano-silica on the fresh and mechanical properties of conventional concrete. *Forces in mechanics*, 2023. 10: p. 100165.
- International, A., Standard specification for mixing water used in the production of hydraulic cement concrete. 2022: ASTM International.
- ASTM, A., C33/C33M-16e1: Standard Specification for Concrete Aggregates. ASTM International, West Conshohocken, Pennsylvania, United States, 2016.
- Chen, Y., J. Liu, B. Feng, J. Wei, X. Tan, M. Zhang, and Z. Sun, Effect of Nano-MgO on the Durability of Cement-Based Materials. *Journal of Testing and Evaluation*, 2023. 51(2): p. 1181-1192.
- Moradpour, R., E. Taheri-Nassaj, T. Parhizkar, and M. Ghodsian, The effects of nanoscale expansive agents on the mechanical

properties of non-shrink cement-based composites: The influence of nano-MgO addition. *Composites Part B: Engineering*, 2013. 55: p. 193-202.