Experimental investigation and numerical analysis of the effect of zinc oxide nanoparticles on the permeability of concrete in hydraulic channels

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ABSTRACT

Concrete is a fundamental building material widely employed in various construction projects, particularly in ensuring the structural integrity of hydraulic channels against water and chemical infiltration. In this study, we investigate, for the first time, the impact of zinc oxide nanoparticles on the permeability and mechanical properties of concrete through experimental and laboratory analyses. Uniaxial compressive tests were conducted to determine the compressive and tensile strength of concrete specimens containing zinc oxide nanoparticles at concentrations of 0%, 0.1%, 0.5%, 1.0%, and 1.5% at 7 and 28 days of age. Additionally, permeability and water absorption rates were assessed. The findings reveal that the mechanical strength of concrete increases with the addition of nanoparticles up to a certain threshold. Remarkably, at a nanoparticle concentration of 0.1%, the permeability of concrete decreased by 97% compared to the control sample. This enhancement can be attributed to the ability of nanomaterials to enhance mechanical strength by fostering a denser and less porous microstructure in the mortar-concrete matrix. Furthermore, behavioral models were developed utilizing genetic algorithm programming to depict the time-dependent properties of concrete specimens incorporating nanoparticles under various compressive and tensile conditions at different ages. Consequently, this study endeavors to predict the concrete mix design incorporating nanoparticles using neural networks in conjunction with the genetic algorithm approach. The aim of this modeling is to demonstrate the accuracy of neural networks in forecasting the compressive, tensile, and permeability properties of concrete with varying proportions of zinc oxide nanoparticles.

KEYWORDS

Zinc oxide nanoparticles, Concrete permeability, Genetic algorithm, Compressive strength, Neural network.

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1. Introduction

The advancement of nanotechnology has spurred engineers and researchers to develop more effective methods for incorporating nanomaterials into concrete, aiming to enhance the stability and lifespan of structures by improving concrete's efficiency and resistance to penetration [1-5]. The use of nanoparticles has seen significant growth across various engineering disciplines in recent years [6-8]. One notable application is the reinforcement of concrete, where nanoparticles significantly influence its mechanical behavior due to their exceptional properties [9-11]. Studies indicate that the incorporation of various nanoparticles, such as ZrO_2, Fe_3O_4, TiO_2, and Al_2O_3, markedly enhances the mechanical properties and durability of concrete [12]. These findings underscore the potential of nanotechnology to revolutionize concrete performance, contributing to more resilient and long-lasting structural applications.

Prediction of concrete properties is of great importance as a key and influential parameter in the useful depth of a concrete structure [13]. Zhang et al. [14, 15] introduced a hybrid neural network designed to predict the pore pressure and temperature of fire-exposed concrete, a critical factor in preventing explosive spalling. In a comparative study, Bescopelni et al. [16] evaluated the performance of three machine learning algorithms—CatBoost, k-nearest neighbor, and support vector regression—in predicting the compressive strength of concrete. Meanwhile, Miri et al. [17] explored the impact of wollastonite nanoparticles on the mechanical properties of concrete, assessing their effect on durability and resistance to water penetration across different ages through the creation of concrete samples.

Although extensive research has examined the impact of various nanoparticles on concrete's mechanical properties and permeability, the effects of zinc oxide (ZnO) nanoparticles remain underexplored. This study addresses this gap by substituting ZnO nanoparticles for cement in concrete mixes and evaluating their influence on mechanical resistance at different ages using standardized tests. Additionally, scanning electron microscope (SEM) images are employed to analyze the microstructural arrangement of the nanoparticles within the concrete. The innovative aspect of this research lies in its focus on the permeability of hydraulic structures when incorporating ZnO nanoparticles. Different water-to-cement ratios are used to determine the optimal nanoparticle percentage for enhancing mechanical properties. Given the complexity of concrete behavior and mix design, neural networks coupled with genetic algorithms are utilized to predict the optimal mix, aiming to reduce costs and save time in large-scale projects. Input parameters for the model include weights of coarse and fine aggregates, water, cement, water-cement ratio, nanoparticle percentage, and other additives.

2. Methodology

The zinc oxide nanoparticles used in this study were sourced from Mehrgan Shimi Company in Tehran. These nanoparticles were incorporated into the concrete samples in the form of a colloidal nano solution with a concentration of 1000 ppm, consisting of 0.1% nanoparticles and 99.9% water. The concrete samples were mixed according to ACI 211 regulations and by weight method. In this project, the grade of cement is 350 kg/m^3. 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/m^3. Table 1 shows the mixing plan of concrete samples with an approximate ratio of W/C=0.61. Figure 1 illustrates the failure states of both the standard and the tested samples. In this research, the tensile strength was determined using the Brazilian test method, which involves splitting the cylinder in half according to ASTM C496 standard. As shown in Figure 2, a supporting clamp was employed to correctly position the test sample and the support rod. This setup ensures that the support rod and the axis of the sample are aligned directly under the center of the spherical support block. This alignment is crucial for accurate and consistent application of tensile stress during the test.

Table 1. Mixing plan of concrete samples with 0.61 w/c

Quantities (kg/m^3)				
Nano	Cement	Sand	Gravel	Water
0	336	684	1155	205
0.35	335.65	684	1155	205
1.75	334.25	684	1155	205
3.5	332.50	684	1155	205
5.25	330.75	684	1155	205

(a) (b)

Figure 1 (a) cubic sample under compression test and (b) satisfactory state of rupture of the tested samples

Figure 2 Cylindrical sample in the splitting test

3. Results

Figure 3 presents the graph depicting changes in compressive strength relative to the percentage of zinc oxide nanoparticle replacement. In this graph, the horizontal axis represents the replacement percentage of nanoparticles, while the vertical axis indicates the average compressive strength in kilograms per square centimeter. The results demonstrate that the addition of zinc oxide nanoparticles enhances the compressive strength of the concrete. Specifically, concrete samples containing 1% zinc oxide nanoparticles exhibit a 20% increase in compressive strength at 7 days and a 16% increase at 28 days. This significant improvement highlights the effectiveness of zinc oxide nanoparticles in reinforcing concrete and enhancing its mechanical properties.

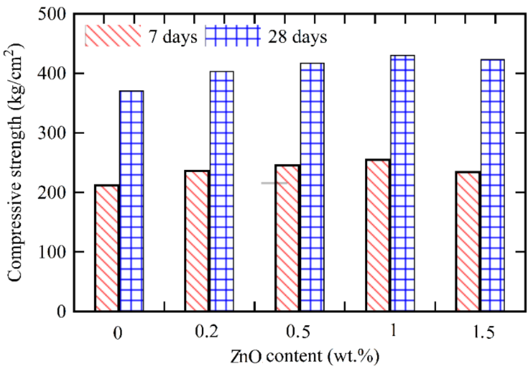
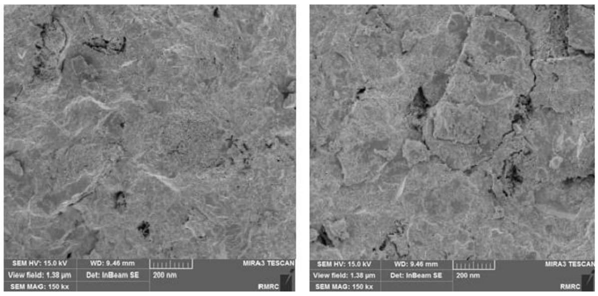


Figure 3 Compressive strength of concrete containing zinc oxide nanoparticles

Figure 4 reveals the presence of small voids in both pure concrete and concrete reinforced with 0.5% zinc oxide nanoparticles. In contrast, the sample containing 1% zinc oxide nanoparticles exhibits significantly fewer defects. This improved microstructure is attributed to the optimal distribution and interaction of the nanoparticles within the concrete matrix. The enhanced microstructure of the 1% zinc oxide nanoparticle sample correlates with the highest observed increase in compressive strength. Consequently, concrete modified with 1% zinc oxide nanoparticles demonstrates superior performance in terms of both microstructural integrity and compressive strength, making it the most suitable choice for enhanced concrete applications.



(a) (b)

Figure 4 SEM image of the failed surfaces of the concrete compression sample containing different amounts of nano zinc oxide (a) 0 wt.%, (b) 0.5 wt%

The proposed tree structure of the compressive strength model for concrete reinforced with zinc oxide nanoparticles is illustrated in Figure 5. In this model, "FT" represents the amount of nanoparticles incorporated into the concrete, while "A" denotes the age of the concrete. This hierarchical structure is designed to systematically evaluate the influence of varying nanoparticle concentrations and the curing period on the compressive strength of the concrete. By incorporating these key parameters, the model provides a comprehensive framework for predicting the performance and optimizing the mix design of nanoparticle-reinforced concrete.

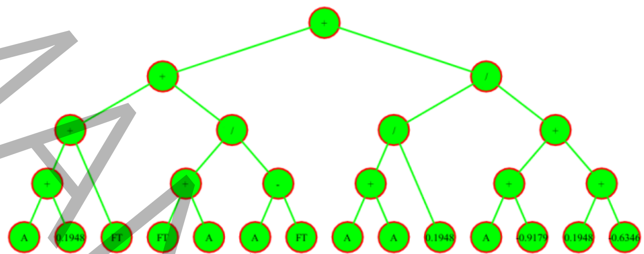


Figure 5 The final tree structure related to the compressive strength model of concrete reinforced with zinc oxide nanoparticles

After the implementation of the genetic programming algorithm, the mathematical relationship related to the test tree for the compressive strength of concrete reinforced with zinc oxide nanoparticles is obtained as follows:

$$f_c' = 0.1099\text{A} + 22.8912\text{FT} + \frac{0.5528\text{A}}{0.2321\text{FT} + 1} + 21.82 \qquad (1)$$

where FT and A represent the amount of nanoparticles and the age of concrete, respectively. As it is known in this relation, the amount of nanoparticles in comparison with other factors has a great effect on the compressive strength of concrete reinforced with zinc oxide nanoparticles in such a way that it has been removed from the proposed relationship. The static parameters related to the proposed model are given in Table 2. As it is clear in the table, there is a very good correlation (0.9837 for training data and 0.9990 for test data) between the results obtained from the model and the laboratory results, which proves the accuracy of the model. Also, the error percentage of the proposed model for all data is 3.5061%.

Table 2 Static parameters of the compressive strength model of concrete with ZnO nanoparticles

	RMSE (MPa)	MAE (MPa)	MAPE (%)	R
Training data	1.562	1.2685	3.597	0.9587
Test data	0.923	0.8126	2.113	0.9958
Total data	1.489	1.1206	3.369	0.9893

4. Conclusion

This research experimentally investigated the effect of zinc oxide nanoparticles on the permeability and mechanical properties of concrete. One-way compressive tests and Brazilian split tests were conducted to assess the compressive and tensile strength of concrete containing various amounts of zinc oxide nanoparticles (ranging from 0% to 1.5%) at 7 and 28 days of age. Additionally, water permeability and absorption were examined.

The findings reveal that increasing the amount of zinc oxide nanoparticles initially enhances both the compressive and tensile strength of the concrete samples. Specifically, at 1% zinc oxide nanoparticles, compressive strength increased by 20% at 7 days and 16% at 28 days, while tensile strength increased by 39% at 7 days and 22% at 28 days. However, substituting a higher percentage of zinc oxide nanoparticles adversely affects the mechanical properties of the concrete. To predict the mechanical properties of the concrete, a hybrid model combining neural networks and genetic algorithms was employed. The model demonstrated a strong correlation between predicted and experimental results, with correlation coefficients of 0.9837 for training data and 0.9990 for test data, and an overall error percentage of 3.5061%. These results validate the model's accuracy and its potential for optimizing concrete mix designs incorporating zinc oxide nanoparticles.

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