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Prediction of the Bond Strength between Ultra-High Performance Concrete and Normal Strength Concrete

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Abstract: ***How to extend the service life of existing damaged (environmental corrosion) concrete structures has become a hot issue in the field of structural engineering. Using ultra-high performance concrete (UHPC) as the repair material of normal strength concrete (NSC), the interface bonding performance of UHPC-NSC has a significant effect on the overall force of the repaired component. In this paper, combined with the relevant experiments carried out by relevant scholars at home and abroad on the interface adhesion performance of UHPC-NSC, the effects of UHPC-NSC age, surface treatment of NSC matrix, moisture content of NSC matrix, strength of NSC matrix and UHPC curing method on the interfacial bonding strength of UHPC-NSC were analyzed. In addition, the dataset of UHPC-NSC interfacial shear strength under oblique shear test conditions was collected, and the interface bond strength of UHPC-NSC was predicted by artificial neural network (ANN) training, and the predicted value of oblique shear strength was in good agreement with the experimental value.***

Keywords: Ultra-high performance concrete, Normal strength concrete, Interface bond strength, Artificial neural networks**.**

1. Introduction

In recent years, the performance deterioration of reinforced concrete structures under the effect of environmental corrosion has been a severe challenge in the field of structural engineering. Ultra-high performance concrete (UHPC), as a novel construction material, has exhibited promising application prospects in the repair and reinforcement projects of normal strength concrete (NSC) due to its outstanding mechanical properties and durability.

Relevant research findings indicate that the mechanical performance of the repaired UHPC-NSC structure is highly correlated with the interface bonding performance of UHPC-NSC. Good interface bonding performance is a prerequisite for ensuring the collaborative work of composite or reinforced components and determines the safety and durability of the repaired structure. This paper mainly collates and statistically analyzes the latest research achievements in the aspect of interface bonding performance of published UHPC-NSC. Based on the collected oblique shear test database, artificial neural network (ANN) is utilized to train the data set and predict the oblique shear strength of the interface, which can provide certain references for future related research works.

2. Loading Method for Interfacial Bond Performance test

2.1 Direct Shear Test

The research on the interfacial bonding performance of UHPC-NSC mainly adopts test methods such as single-sided direct shear, double-sided direct shear, L-shaped direct shear, and inclined shear [1]. The commonly used loading test specimens are depicted in Figure 1.

During the loading process of specimens in single-sided direct shear, it is prone to be influenced by the eccentric additional bending moment and edge effect, resulting in inaccurate test results. To mitigate the impact of the eccentric additional bending moment, Guan et al. [2] designed an L-shaped shear test. The L-shaped shear can largely avoid the additional bending moment generated by eccentric loading; however, it causes stress concentration at the corner during the loading process, thereby leading to the fracture of the component.

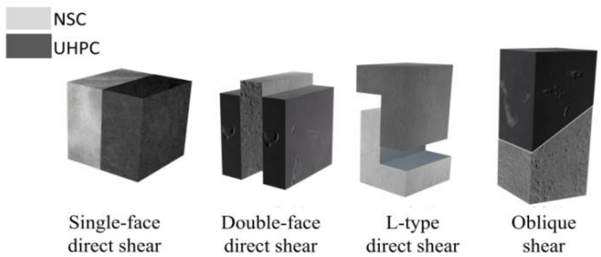


Figure 1: Schematic diagram of the commonly used test specimen in shear tests

To solve the aforementioned problems, Momayez et al. [3] put forward a double-sided shear scheme and utilized this test method to investigate the influence of the surface roughness of concrete on the interfacial bond strength. The test results indicated that the relationship between the interfacial roughness and the bond strength was positively correlated, and the discreteness of the test results was relatively small.

2.2 Oblique Shear Test

The oblique shear test commonly employs rectangular or cylindrical specimens and is generally utilized to test the interfacial bond strength under shear and normal pressure conditions. The inclined interface of the specimens forms an angle with respect to the vertical axis. Existing relevant studies suggest that the optimal inclination angle is within the range of 20 to 40 degrees.

Carbonell et al. [4] investigated whether the interfacial shear strength in the oblique shear test was correlated with the inclination angle, with a focus on the effects of different interface inclination angles (55 and 70 degrees) on the interfacial shear strength and failure mode. The test results demonstrated that only the specimen with an interface inclination angle of 70 underwent interfacial failure, while the remaining two groups of specimens experienced base failure. Hence, different interface inclination angles can result in different failure modes, and selecting an appropriate interface inclination angle can more rationally reflect the interfacial bond strength in the oblique shear test.

3. Factors Affecting the Bond Strength of the UHPC-NSC Interface

The shear strength at the UHPC-NSC interface is affected by Some factors. Current relevant research results indicate that factors such as the age of UHPC, the curing mode of the UHPC interface, the surface treatment approach of NSC, the moisture degree of NSC, and the strength of the existing NSC substrate all have a notable influence on the bond strength.

3.1 The Age of UHPC and the Strength of NSC

The research results of Zhang et al. [5] indicated that the interfacial bond strength of UHPC-NSC increased with the increase of the curing age of UHPC, reaching the peak at 28 days. Zhang et al. [6] discovered that the interfacial shear strengths of UHPC-NSC at the ages of 3 days and 7 days reached 88.4% and 93.1% of the shear strength at 180 days, respectively. During the period from 7 to 28 days, the interfacial shear strength increased by only 4.2%. It is illustrated that the interfacial shear strength of UHPC-NSC grew rapidly in the first 7 days and tended to stabilize after 7 days.

The strength of the existing NSC is also a major factor influencing the interface bonding performance of UHPC-NSC [5]. Zhang et al. [6] verified through loading methods such as direct shear, oblique shear, and splitting whether the strength of the existing concrete would have an impact on the interface bond strength of UHPC-NSC. The test results demonstrated that the interface bond strength of UHPC-NSC increased as the strength of the existing NSC matrix increased. Furthermore, the research by Bonaldo [7] et al. discovered that the strength of the NSC matrix could also be enhanced by means of an interface agent. The influence of the strength of the NSC matrix and the age of UHPC on the interface shear strength is depicted in Figure 2. It can be observed that both the strength of the existing concrete and the age of UHPC have a positive reinforcing effect on the interface shear strength, and when the age exceeds 7 days, the interface shear strength is essentially stable.

3.2 The Curing Method of UHPC

Zhang et al. [6] discovered that the bond strength of the specimens after 28 days of curing at room temperature basically reached the peak. The interfacial bond strength of the specimens subjected to steam curing at 60° C for 72 hours was slightly lower than that of the specimens cured at room temperature or was essentially the same. High-temperature steam curing can enhance the mechanical properties of UHPC; however, after steam curing at 90° C for 48 hours, the interfacial bond strength of the specimens decreased significantly. This is attributed to the negligible deformation of UHPC with time under high-temperature curing conditions, which implies a rapid increase in the differential shrinkage between the NSC substrate and the UHPC layer, thereby causing a rapid rise in the interfacial shear stress induced by shrinkage before the interfacial bond strength attains its maximum value. Chen et al. [8] found that the interfacial bond strength between UHPC and NSC initially increased and then decreased as the curing temperature rose. This is because when the temperature is moderate, it enables adequate hydration of UHPC, strengthening the bonding capacity with the NSC matrix. When the temperature is excessively high, it leads to an increase in internal pores within UHPC, thereby reducing the interfacial bonding performance.

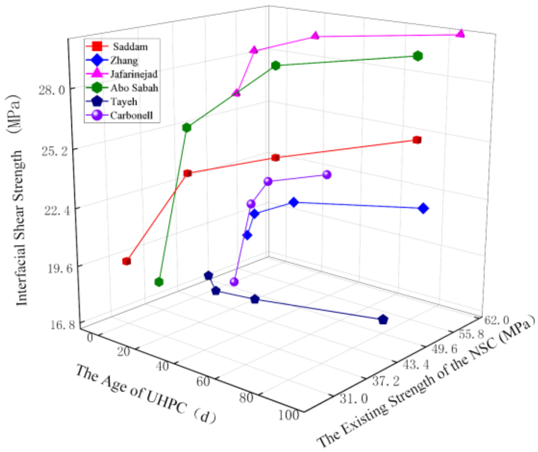


Figure 2: Effect of UHPC age and NSC matrix strength on the interfacial shear strength

3.3 The Degree of Surface Moistening of NSC

The degree of wetness of the NSC matrix can influence the interfacial bond strength of UHPC-NSC. Fully moistening the NSC substrate can significantly enhance the interfacial bond strength. Semendry et al. [9] investigated the effect of the degree of wetness of the NSC matrix on the interfacial strength, as shown in Figure 3. It can be observed that, under the condition of the same interfacial roughness, appropriately moistening the surface of the NSC matrix is conducive to increasing the interfacial shear strength. This is because the dry surface of the NSC matrix absorbs the water within UHPC, affecting the degree of the hydration reaction of UHPC and thereby weakening the interfacial bonding performance between UHPC and NSC.

3.4 The Surface Treatment Approaches of NSC

Zhang et al. [6] discovered that the roughness of the NSC matrix surface constitutes a crucial factor influencing the interface strength of UHPC-NSC. The impact of the NSC interface treatment methods on the interface bonding strength is depicted in Figure 4. Some researchers have investigated the influence of different interface treatment approaches on the interface bonding strength. In the inclined shear tests, compared to the untreated smooth surface, the interface bonding strengths after wire brush and sandblasting treatments were enhanced by 45.4% and 91.3% respectively. Relevant research findings indicate that when the metric indicator of roughness, namely the average sand filling depth, lies within the range of 2.11 - 6.01, a greater UHPC-NSC interface bonding strength can be attained.

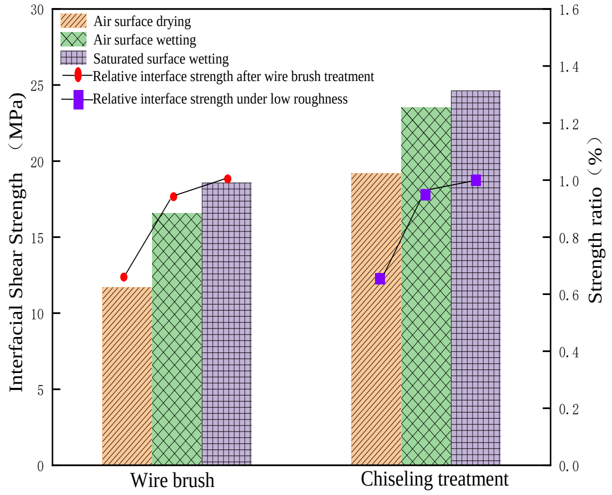


Figure 3: The Influence of the Moisture Degree of the NSC Matrix on the Interface Strength [6]

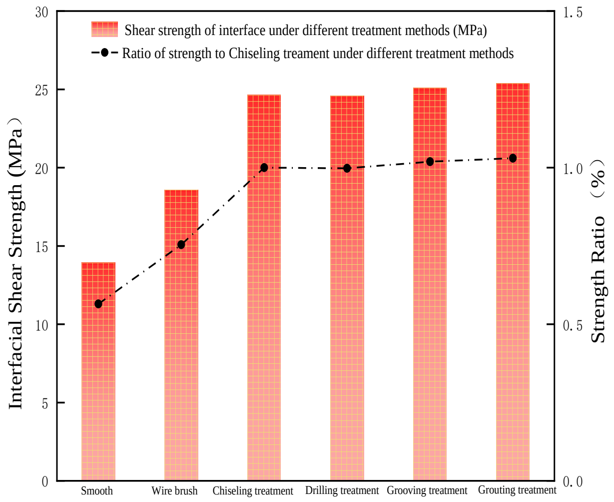


Figure 4: Shows the effect of NSC interface treatment on interface strength [6]

4. Prediction of UHPC-NSC Bond Strength Using Artificial Neural Networks

Artificial neural networks are a type of machine learning method that employs decision-layer networks for data analysis. They consist of a series of processing elements, known as neurons, which are interconnected by synaptic weights. The common architecture of artificial neural networks encompasses an input layer (introducing data into the artificial neural network), a hidden layer (processing data), and an output layer (producing results). In this prediction, the input layer comprises five factors, namely the age of UHPC, the interface curing method of UHPC, the surface treatment method of NSC, the moisture degree of NSC, and the strength of the existing NSC substrate.

4.1 Data Collection and Training of Artificial Neural Network Model

To achieve the prediction of the interface bond strength of UHPC-NSC under the oblique shear test, this article collected 100 sets of data from relevant literature for the training of the interface strength prediction model. The data samples were categorized in proportions of 70%, 15%, and 15%, namely, 70% of the data was utilized for model training, 15% of the data was employed for testing, and 15% of the data was used for validation. The database and the determination methods of each influencing factor are presented in Table 1.

Table 1: Database of the Training Model

DL	SR (MPa)	AR (d)	CM	ST	MC	RI (MPa)	ND
[10]	45	3-28	2	1-6	2	7.01-18.19	45
[11]	26-59	28	1	2	1-2	7.21-17.06	6
[12]	39.9-50.76	7-90	2	6	2	19.1-41.2	18
[13]	40	28	1	1	1-2	1.35-3.34	15
[4]	44.5-55.9	2-8	1	6	1	3.4-21.7	16

Notes: DL denotes the source of the cited data, AR denotes the age of the UHPC, identified according to the actual age of maintenance, SR denotes the strength class of the NSC, identified according to the actual strength of the substrate, CM denotes the method of maintenance of the UHPC, which is divided into normal and water vapor maintenance, identified as 1 and 2, MC denotes the moisture content of the interface, which was dried in the laboratory for more than 7 days, and the surface was moistened by sprinkling with water and wiped dry,. and NSC substrates kept in water for 24 hours removed and wiped dry. Coded as 1, 2, and 3, respectively, ST denotes NSC surface treatments, identified as smooth, wire brush treated, drilled, sandblasted, and grooved, identified as 1 through 6, respectively, RI denotes the range of interfacial bond strengths, and ND denotes the number of respective data from the data source literature.

As depicted in Figure 5, this architecture is designated as ANN5-11-1. The first digit indicates the quantity of input nodes, the second digit represents the number of neurons in the hidden layer, and the third digit signifies the number of output nodes. In this simulation, a single hidden layer with eleven neurons is employed.

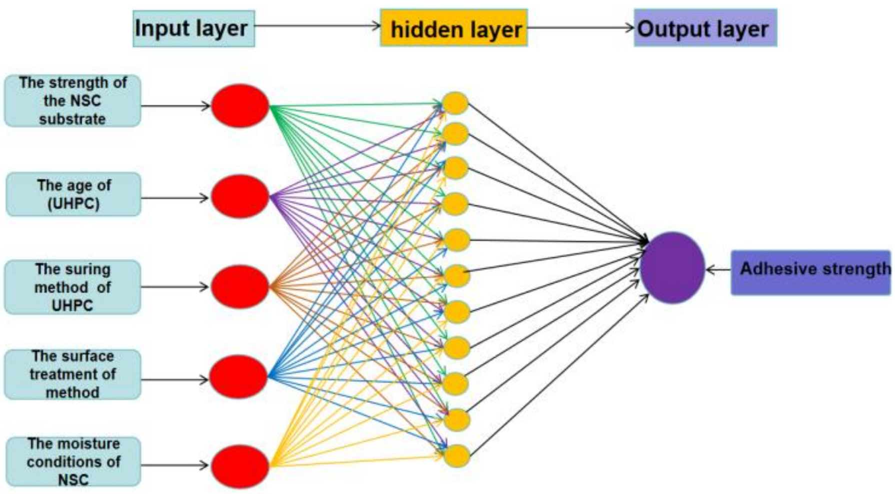


Figure 5: Artificial Neural Network Architecture Diagram

Figure 6 presents the training iteration processes of three training networks of the artificial neural network (ANN). Among them, the blue line represents the training iteration of the neural network, the green line represents the validation iteration of the neural network, and the red line represents the testing iteration of the neural network. It can be observed that as the training proceeds, all three lines exhibit a downward trend, and the mean squared error (MSE) gradually decreases, indicating that the ANN network has accomplished the training process very well. Figure 7 provides the range of errors produced by the three training sets during the training process. The data indicates that the errors generated by the three training sets are concentrated between -1.588 and 4.056.

It can be observed from Figure 8 that the R values of the training set, validation set, test set, and overall data set are 0.92652, 0.85918, 0.824941, and 0.88995, respectively. The regression of the validation set is the best, and the R values of the training set, test set, and overall set are all above 0.8, suggesting that the learning and prediction of the artificial neural network are relatively accurate.

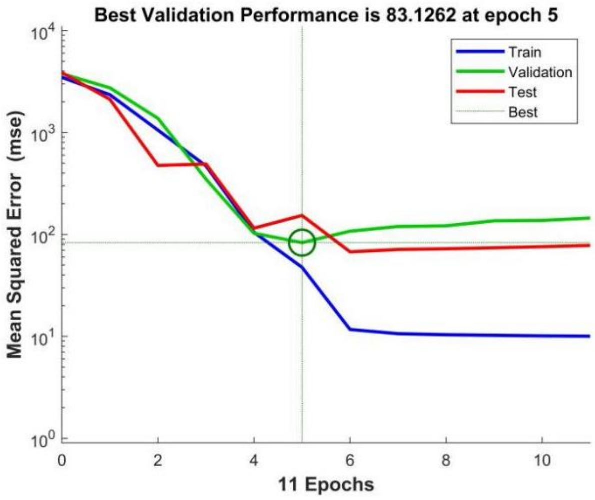


Figure 6: Training Process

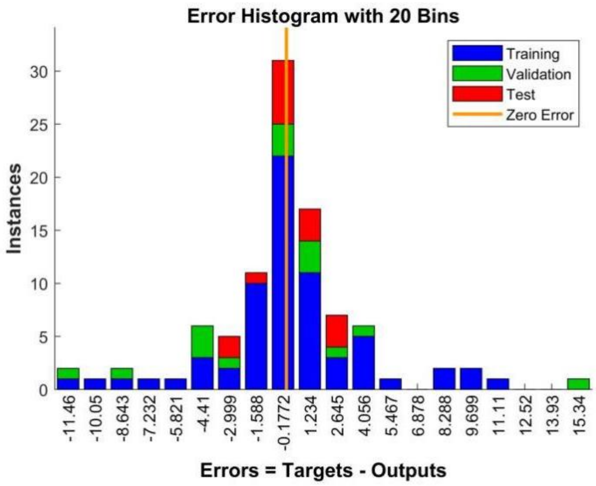


Figure 7: Error Histogram

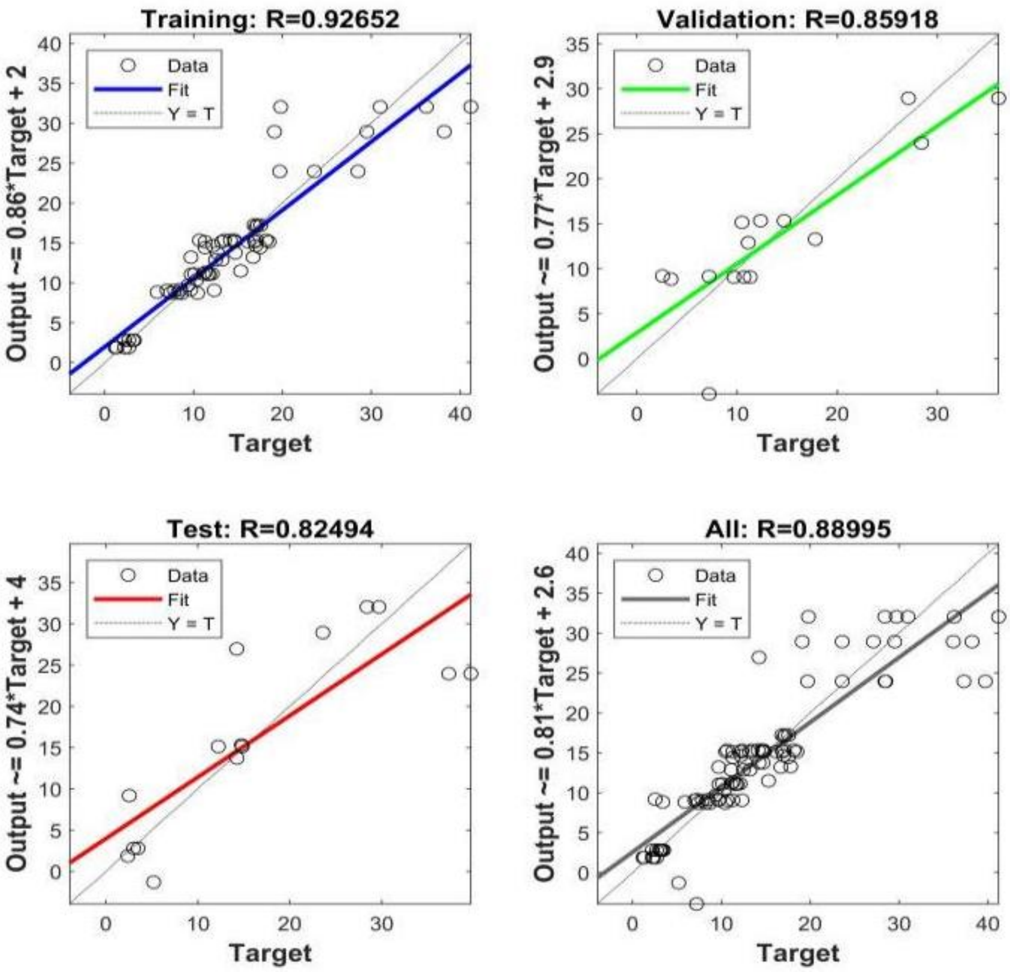


Figure 8: Linear Fitting of the Training Set and Data Regression

4.2 Prediction of UHPC-NSC Bond Strength Using Artificial Neural Networks

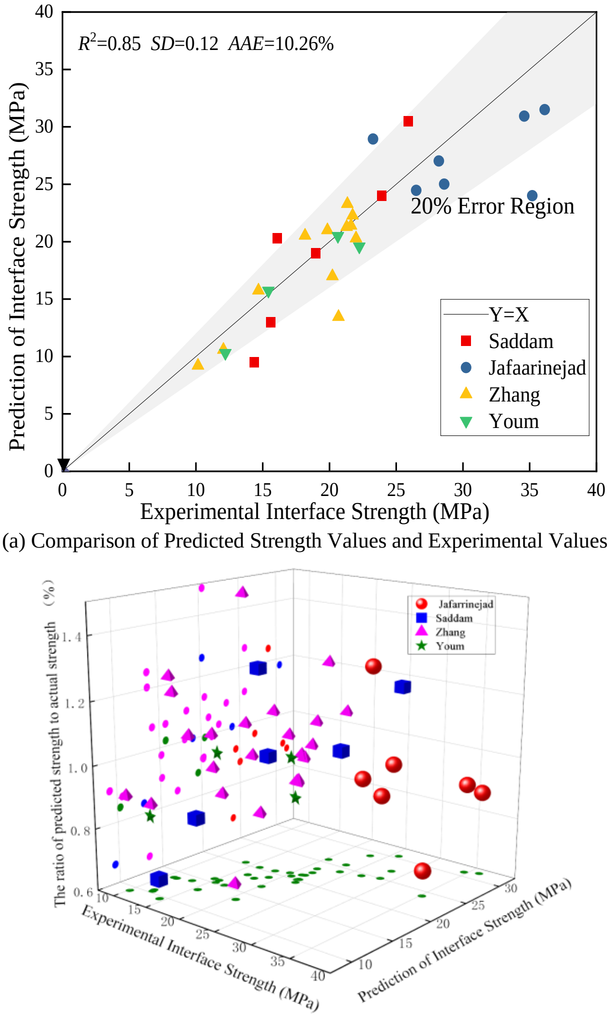
The dataset for this prediction is composed of 43 data points, as presented in Table 2.

Table 2: Prediction Database

DL	SR (MPa)	AR (d)	CM	STd	MC	RI (MPa)
[14]	51-57.4	3-28	1	1-6	2	11.5-29.4
[15]	40-51	7-90	2	6	2	23.9-36.13
[16]	20-30	28	1-2	1，5	2	12.2-22.24

Notes: The identification rules of each variable are identical to those in Table 1.

By utilizing the training model, the five influencing factors were separately input into the code of the artificial neural network model. The comparisons between the experimental values and the predicted values of the interface shear strength obtained from the training are presented in Figure 9. The predicted values are in good agreement with the experimental values, suggesting that the training model based on the artificial neural network can conduct relatively accurate predictions of the interface strength of UHPC-NSC.



(a) Comparison of Predicted Strength Values and Experimental Values

(b) Comparative Analysis of the Three-Dimensional Spatial Distribution of Predicted Strength Values and Test Values

Figure 9: Comparison of Predicted Interface Strength and Experimental Value

5. Conclusion

This article mainly integrates the relevant published literature regarding the interface bonding performance of UHPC-NSC and summarizes the major factors influencing the interface bonding performance of UHPC-NSC. Based on the collected dataset of oblique shear tests, the artificial neural network (ANN) is employed to train the dataset and predict the oblique shear strength of the interface. The principal conclusions are as follows,

(1) The roughness, degree of wetting and strength of the NSC substrate surface are the main factors affecting the bonding strength at the UHPC-NSC interface.

(2) The interface bond strength of UHPC-NSC increases with the curing age of UHPC and generally stabilizes after 28 days.

(3) An artificial neural network (ANN) is utilized to train the dataset and predict the diagonal shear strength at the UHPC-NSC interface, and the predicted and experimental values are in good agreement.

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