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BOND STRENGTH PREDICTION OF UHPC–NSC INTERFACE

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The application of ultra-high-performance concrete (UHPC) on top of normal-strength concrete (NSC) is a practical rehabilitation approach to maintaining degraded and damaged concrete members. However, a successful repair operation and consequent adequate performance are very much dependent on the ability of the interface between UHPC and NSC to present a superior performance of bonding under various surface conditions. Consequently, predicting the strength of the bond at the interface joining the existing NSC and the newly placed overlaying UHPC – with sufficient certainty – has become a vital and required step in assessing and maintaining UHPC rehabilitated NSC structural elements. In this work, Artificial Neural Network (ANN as well as Gene Expression Programming (GEP methods are utilized to predict the bond strength between the overlaying UHPC and the substrate NSC using a comprehensive database set consisting of 264 experimental data points gathered from the literature. A parametric ANN analysis is performed to examine and assess the effect of each parameter on the interfacial bond strength. The following five factors are identified as key parameters through the GEP and ANN analyses: curing method, age of UHPC, the compressive strength of NSC, interfacial surface treatment, and moisture conditions. The developed ANN and GEP models have good accuracy and closer predictions of the bond strength of the slant shear test and the splitting tensile strength with root mean square error (RMSE) values of 5.0, 4.3, and coefficient of variation (COV) values of 37%, 24%, respectively.

Keywords: UHPC, bond strength equation, ANN, GEP

1 INTRODUCTION

Preventing infrastructure deterioration from exposure to aggressive environmental factors and higher applied loads is a real challenge to civil engineers nowadays. Providing a strong and durable material overlay over the degraded existing construction material has been recognized as a practical and cost-effective rehabilitation and repair scheme [1-2]. The utilization of ultra-high-performance concrete (UHPC) as an overlaying material on top of existing degraded normal strength concrete (NSC) is considered in the current study. Concrete infrastructures may be exposed to several harsh circumstances over their life spans that might lead to degradation and eventually full deterioration of their building material. The degree of deterioration in concrete structures is assessed by observing the severity of cracking, spalling, and disintegration [3]. In addition, the primary reason for concrete deterioration is reinforcing steel corrosion. Other possible damage indicators include delamination of concrete cover or coating/overlay materials in rehabilitated structures. Therefore, concrete repair methods and materials are vital since it depends on the availability of repair material and the construction timeframe [4].

UHPC is considered as a refined cement-based composite material that exhibits increased tensile and compressive strengths and exceptional fatigue and impact resistance [5]. UHPC generally exhibits above 120MPa in compressive strength, up to 50MPa in flexural strength, and over 5 MPa in tensile strength [6]. Compared with NSC, UHPC typically contains water-reducing admixtures and steel fibers embedded to achieve the required high strength. It includes no coarse aggregates, has a maximum of 600 μm grain size, and less than 0.2 water-to-cement ratios [7]. In addition, using silica fume in UHPC increases the strength by enhancing the quality of the interfacial transition zone (ITZ) between the aggregate and surrounding matrix, and removing large calcium-hydroxide (CH) crystals through increasing the pozzolanic reaction. Additionally, the fineness of silica fume particles can fill the spaces between small and large particles to replace entrapped water, and thus contributing to the fluidity of fresh concrete [8].

Recently, the application of UHPC on top of existing NSC has evolved into a common rehabilitation practice for deteriorated concrete members. Advantages include savings in both labor costs and construction time. Rehabilitation using UHPC is a modern technique used prevalently, resulting in low permeability as well as reliable mechanical properties [1, 9-10]. UHPC achieves the required strength with a minimum water content using water-reducing admixtures that provide adequate viscoelasticity and freeze-thaw resistance [5]. Generally, structural rehabilitation techniques show failures at specific limits or thresholds. Through careful examination and comparison between the different mechanical behaviors and material properties of UHPC and NSC, the interface line is considered a weak zone that might develop cracks due to the loss of interface bonding [10].

Evaluating the interface bonding strength between NSC and the overlaying UHPC can be conducted using the splitting tensile and slant shear tests, as depicted in Figure 1 [5]. According to Zhang et al. [1], the UHPC-NSC interfacial bond strength gain shows rapid progress at the beginning, with a peak on the 28th day. However, bond strength exhibits a minor decrease versus age after 28 days of about 1.5-2.7%, resulting from an increase in long-term shrinkage of UHPC, which has a negative effect on the bond capacity of the UHPC-NSC interface.

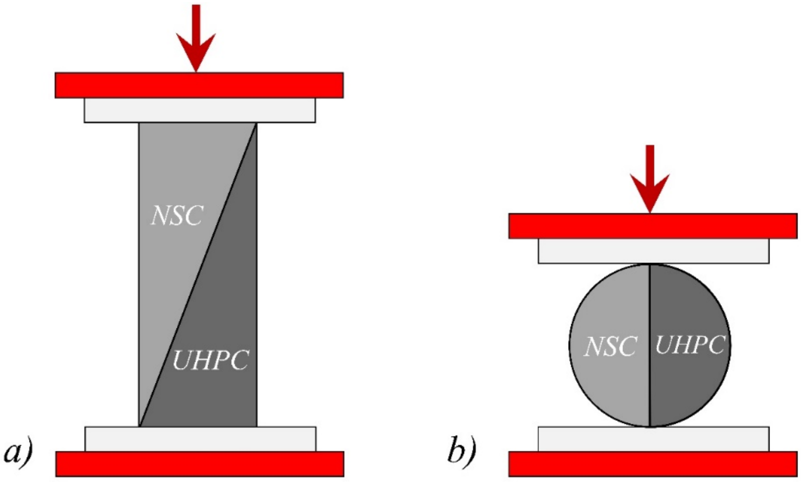


Figure 1: Slant shear test (a) and splitting tensile test (b)

The possibility of bond breakage at the UHPC–NSC interface line increases with the application of heavier loads. To understand such a complex behavior at the UHPC-NSC interface line, Du et al. (2021) developed artificial neural network (ANN) models using a database of 563 and 338 specimens for the splitting tensile and slant shear tests, respectively. ANN models were developed using the compressive strengths of the UHPC and NSC materials, normal stress, and interfacial surface roughness. The results demonstrated higher interfacial bond strength when the NSC was cast before UHPC. The model resulted in moderate accuracy with a Coefficient of Variation (COV) of 34% [11].

Valikhani et al. (2020) conducted shear tests on 30 specimens with different cases, including roughness degrees, mechanical connectors, as well as bonding agents. The failure mode was transferred to the underlying concrete substrate from the UHPC repair material when adequate roughening of the interfacial surface – with or without mechanical connectors – had been performed. This indicates increased bond strength between the two material layers compared to interfaces without preparation [12].

Valikhani et al. (2020) and Zhang et al. (2020) concluded that the utilization of a bonding agent adversely affected the strength of the bond between the two materials, especially on surfaces of low roughness. On the contrary, the use of a bonding agent might enhance bonding on smooth surfaces [12, 1]. Moreover, Carbonell et al. (2014) reported that having the concrete substrate surface sufficiently saturated with moisture resulted in a higher cohesive force between the UHPC overlay and NSC substrate during the time period of moist curing [8]. In addition, some researchers proved that the bond strength reached its peak when the substrate surface was sandblasted [12-13]. Abo Sabah et al. (2019) concluded that the bond strength was even maximized using sandblasting as a surface treatment method [14], while Jafarinejad et al. (2019) reported that the wire brushing method has a negligible effect on the interfacial bond strength [14].

Research available in the literature that studied the strength of the bond between UHPC and NSC concluded that the strength of the bond is affected by a number of factors, including surface treatment of the interface [1,9,12,14], NSC compressive strength [1,11], age of the UHPC [1,9], curing method of the UHPC [1,11], and moisture conditions of the interface [1,8]. This study aims to accurately predict the bond strength at the interface between NSC and UHPC through models obtained by applying Artificial Neural Network (ANN) and Gene Expression Programming (GEP). The key parameters – substantially affecting the interface bond strength – taken into consideration in this study are based on the outcomes of previous studies available in the literature. These five key parameters are the curing method, the UHPC age, the compressive strength of NSC, interfacial surface treatment, and moisture conditions.

2 EXPERIMENTAL DATABASE

A worldwide database consisting of 264 samples for both slant-shear and splitting tensile tests carried out by many researchers has been gathered from the literature and used to train the ANN and GEP models. The details of these samples are shown in Tables 1 and 2. In these two tables, for the surface treatment column: 1 refers to sandblasting, 2 refers to a grooved surface, 3 refers to a low rough surface, 4 refers to wire brush, 5 refers to drill holes, 6 refers to a rough surface, 7 refers to the brushed surface, 8 refers to as cast surface, and 9 refers to a smooth surface. For the curing method column: 1 refers to normal curing, and 2 refers to steam curing. For the NSC moisture conditions: 1 refers to air dry surface (ASD), 2 refers to saturated surface dry (SSD), and 3 refers to saturated surface wet (SSW).

Table 1: Experimental input for the slant shear tests used in the ANN and GEP models

Reference	Number of Samples	Surface Treatment	NSC f_c' (MPa)	Age of UHPC (days)	P (kN)	Curing Method UHPC	NSC Moisture Condition	Bond Strengt (MPa)
Tayeh et al. (2012) [16]	44	2–6	45	3–28	140.27–370.06	2	2	7.01–18.5

Reference	Number of Samples	Surface Treatment	NSC f_c' (MPa)	Age of UHPC (days)	P (kN)	Curing Method UHPC	NSC Moisture Condition	Bond Strengt (MPa)
Baharuddin et al. (2016) [13]	15	1	40	28	70–110	1	1–3	1.19–3.5
Jafarinejad et al. (2019) [14]	7	2–6	51–57.4	3–28	230–588	1	2	11.5–29.4
Abo Sabah et al. (2019) [15]	18	4, 6	39.9–50.76	7–90	382–824	2	2	19.1–41.2
Carbonell et al. (2014) [9]	16	4–7	44.5–56.8	2–8	68–434	1	1	3.4–21.7
Abo Sabah et al. (2019) [17]	6	4, 8	39.9–51.16	7–90	465.4–722.6	2	2	23.27–36.13
Zhang et al. (2020) [1]	26	1–7	31.9–53	3–180	203–439.8	1 , 2	1–3	10.15–21.99

Table 2: Experimental input for the splitting tensile tests used in the ANN and GEP models

Reference	Number of Samples	Surface Treatment	NSC f_c' (MPa)	Age of UHPC (days)	P (kN)	Curing Method UHPC	NSC Moisture Condition	Bond Strength (MPa)
Tayeh et al. (2012) [16]	45	2–6	45	3–28	10–130.5	2	2	7.01–18.5
Baharuddin et al. (2016) [13]	15	1	40	28	10–65	1	1–3	1.19–3.5
Abo Sabah et al. (2019) [15]	18	4, 6	39.9–50.76	7–90	128.84–278.78	2	2	11.5–29.4
Carbonell et al. (2014) [8]	20	1–9	53.7–59.4	186–298	87.96–207.34	1	1	19.1–41.2
Hong and Kang (2015)[18]	4	1 – 7	19.3	7	30.16–46.8	1	2	3.4 – 21.7
Abo Sabah et al. (2019) [17]	6	4, 8	39.9 – 51.16	7–90	141.37–267.98	2	2	23.27–36.13
Zhang et al.(2020) [1]	26	1 – 7	31.9 – 53	3–180	69.11–128.18	1, 2	1–3	10.15–21.99

3 MACHINE LEARNING MODELS: ANN AND GEP

Generally, ANN is considered a multiple layer framework with three fundamental layers: a fee (input) layer, one or multiple hidden layers, and a target (output) layer. Each layer is made up of several neurons (processing stations) that are fully tethered to the neurons in the following layer in order to replicate the human nervous system, as shown in Figure 2 [19]. Each signal travels through neurons from one layer to the next, passing through processing units. In this study, five neurons make up the input layer that represents the key parameters that affect the interfacial bond strength: the curing method, UHPC age, NSC compressive strength, interfacial surface treatment, and moisture conditions. The output layer consists of one neuron which represents the bond strength between NSC and UHPC. This study uses only two hidden layers to develop simple models. Bayesian regularization training algorithms are used to calibrate the neuron's weight. Training and testing sub-sets were created by randomly dividing the collected database, in which 85 percent of the data were set for training and 15% for testing. Several iterations were performed to train the prediction models in the training phase. The model keeps running till the error (root-mean-square error (RMSE)) converges. Based on the results of the slant shear and tensile splitting tests, two models for predicting the interfacial bond strength were developed in this work.

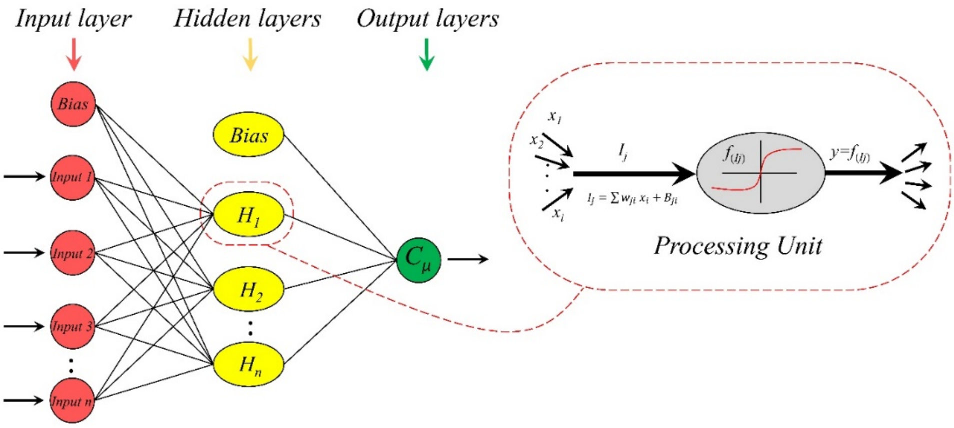
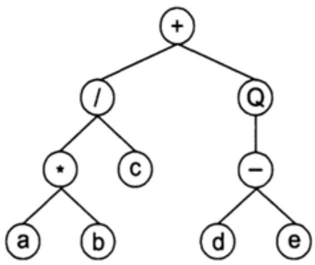


Figure 2. Artificial Neural Network layers

On the other hand, GEP algorithms mimic Darwin's theory of evolution in constructing the optimal solution. GEP models use chromosomes consisting of given strings of symbols (genes) that represent a possible solution to the problem, where mathematical functions resulting with least fitness to the output are excluded, while functions with high fitness are allowed to seed. An expression tree and mathematical function are represented for the predictive model, as shown in Figure 3. Two GEP models are developed to study the interfacial bond strength for both slant and splitting tests. The same dataset used to develop the ANN models was used for developing the GEP models. The collected database was again randomly divided into sub-sets for training and testing, where 88% of the collected data were used for training while 12% was used for testing. Two GEP models were developed for slant and splitting tests. The parameters selected to construct the GEP model are shown in Table 3. These iterations were evaluated based on the average tested-to-predicted ratio, the coefficient of variation (COV), and RMSE. Similar to the ANN models, the GEP models keep running until the most accurate prediction model is obtained.



$$\frac{a.b}{c} + \sqrt{d - e}$$

Figure 3. The mathematical expressions corresponding to each Tree expression

Table 3: Parameters selected in the GEP model

Model Parameter	Value Selected
Measured variable (Bond strength)	1
Feed (Independent) variables	4
Genes	2,3
Function set	$-, +, \times, \div, Sin, \sqrt{}$
Head size	5,6
The function linking ETs	Addition

4 RESULTS AND DISCUSSION

ANN and GEP techniques were used to obtain the best models to predict the interfacial bond strength between the overlaying UHPC and the NSC substrate. GEP is utilized to develop an empirical equation that is utilized to assess the strength of the bond between UHPC and NSC. Both models are supplied by five inputs (given): the curing method, UHPC age, the NSC compressive strength, moisture condition, and interfacial surface treatment to predict the bond strength. A comparison between the GEP and ANN models in terms of COV and RMSE for both slant shear and splitting tests, respectively, is shown in Figures 4 and 5. The proposed ANN and GEP models closely match the experimental data. It is observed that the GEP models are more accurate than the ANN models. As demonstrated by the statistical evaluation, and compared to the other models discussed previously, the proposed models are more accurate at predicting the bond strength. This sheds light on the gains obtained by investing in the use of machine learning techniques with large experimental datasets. It also indicates that the two machine learning techniques used in this study were able to learn and identify the target (interfacial bond strength).

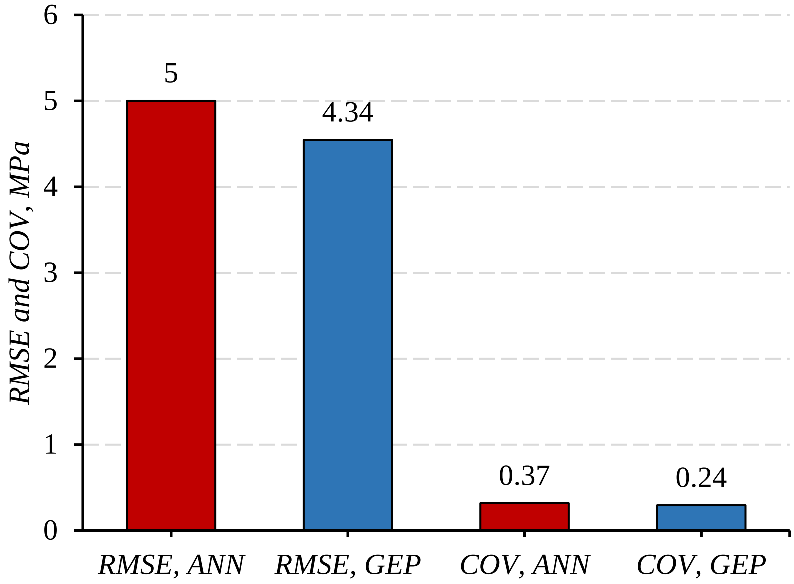


Figure 4: Correlation values comparison between ANN and GEP models for slant shear test

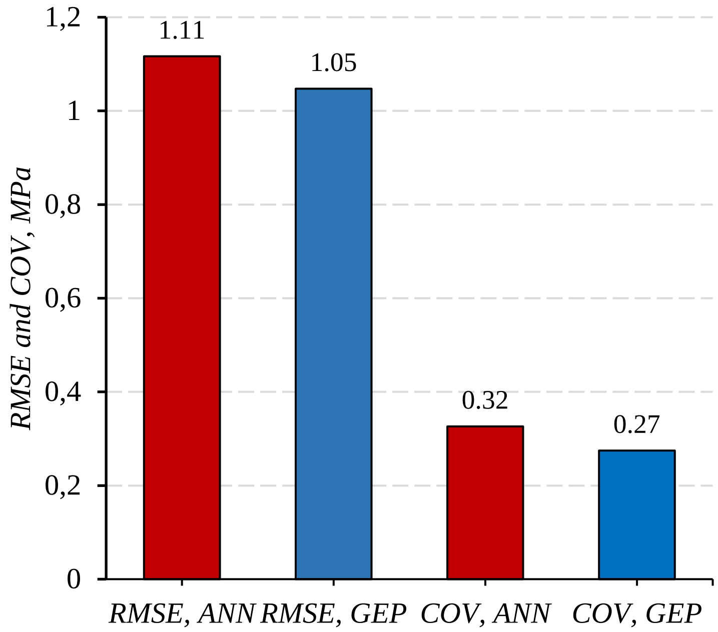


Figure 5: Correlation values comparison between ANN and GEP models for tensile splitting test

4.1 ANN Models Results

The accuracy of the chosen ANN models developed in this study is appraised and compared using the coefficient of determination (R^2). Figure 6 compares the predicted interfacial bond strength values with the experimental dataset gathered from the literature for the slant shear test. The predicted bond strength has a value of R^2 equal to 0.835. The performance of the splitting tensile strength model against the experimental dataset is shown in Figure 7, with a value for R^2 equal to 0.798. It can be seen from these figures that the proposed ANN models can provide accurate predictions for the interfacial bond strength when compared to the respective experimental datasets.

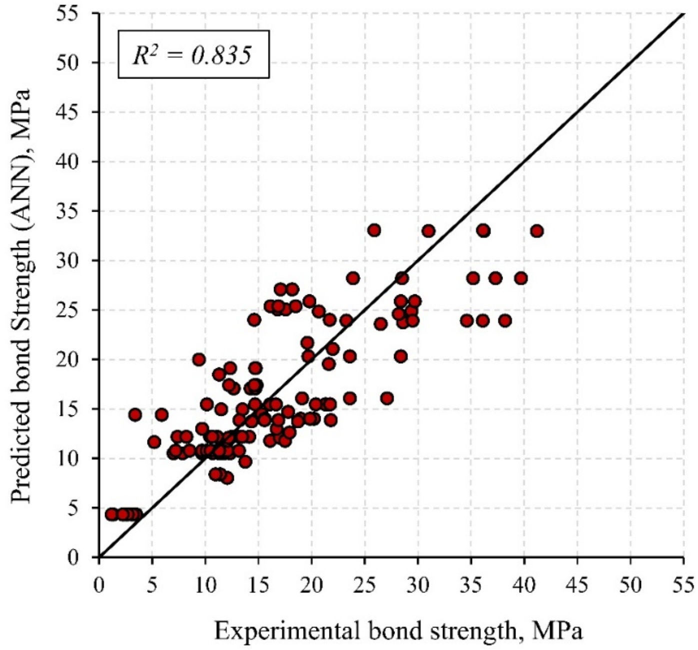


Figure 6: ANN model performance for slant shear test results

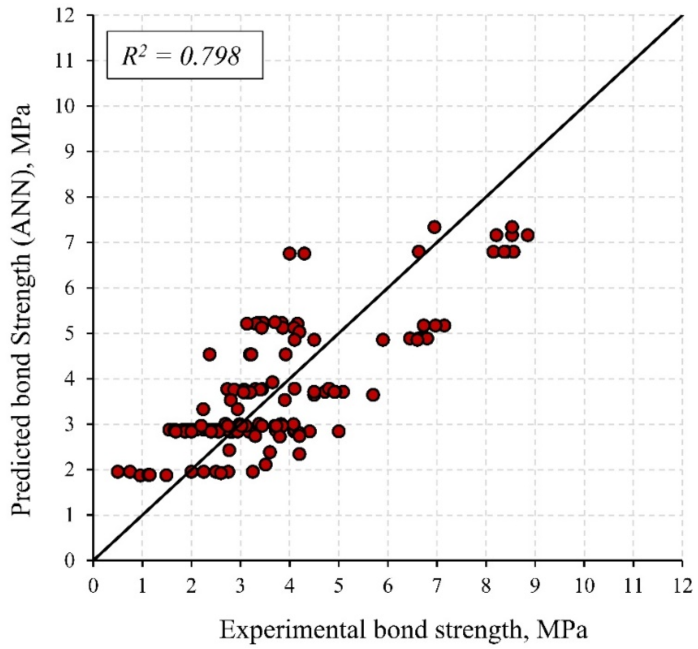


Figure 7: ANN model performance for splitting tensile strength results

4.2 GEP Models Results

The results of the developed GEP models for the slant shear and splitting tensile strength tests are presented in Figures 8 and 9, respectively. The GEP model developed resulted in an R^2 of 0.9 for the slant shear test and an R^2 of 0.87 for the splitting tensile strength test. Therefore, the proposed GEP models are more accurate when compared to the ANN models in predicting interfacial bond strength. The ETs form was used to present both GEP models, as shown in Figures 10 and 11. In the presented ET, d_0, d_1, and d_2, represent the interfacial surface treatment, the compressive strength of NSC, and the age of UHPC, respectively. Both slant shear and splitting models are respectively rewritten in equations form as follows in Eq1 and Eq2:

$$\tau_u = \frac{NSC}{SC+1.2} - \frac{SC^{SC}}{NSC-12.7} + \sqrt{0.75(UHPC)+0.13(SC^{cure})-1} \quad \text{(Slant Shear)} \quad (1)$$

$$\tau_u = \sqrt{UHPC} - \sin(-3.47NSC) - 3.44SC - \frac{7.6SC}{NSC-9}SC^{1.94} + 26.1 \quad \text{(Splitting Tensile)} \quad (2)$$

where τ_u is the interfacial bond strength (MPa), SC is the surface condition (substitute 1 for sandblasting, 2 for grooved surfaces, 3 for as-cast surface, and 4 for smooth surfaces); NSC represents the NSC compressive strength (MPa), UHPC is the UHPC age (days). For the curing method type (cure): 1 refers to normal curing and 2 refers to steam curing. Angle θ is in radians when calculating $\sin(\theta)$. It should be noted that the ranges of applicability of these equations are stated in Tables 1 and 2, based on the data set used to train the GEP models.

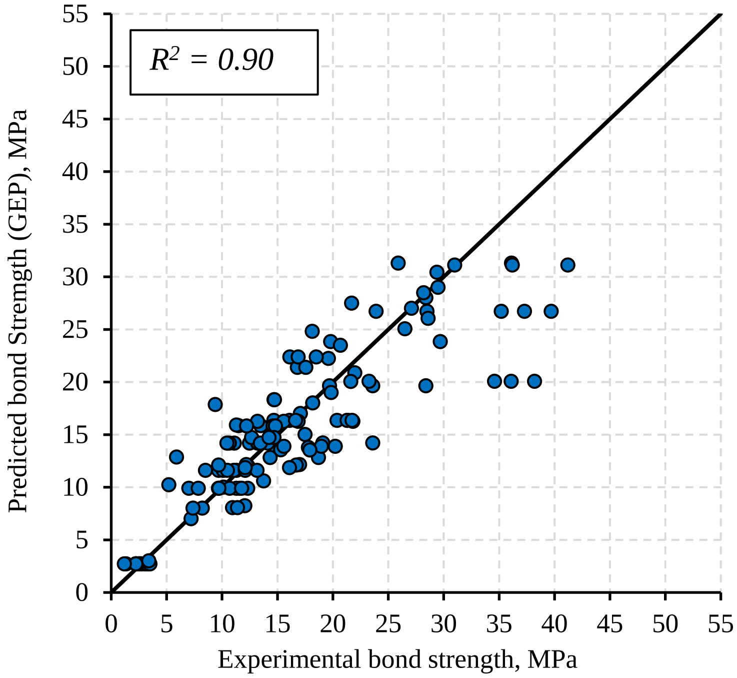


Figure 8: GEP model performance for slant shear test

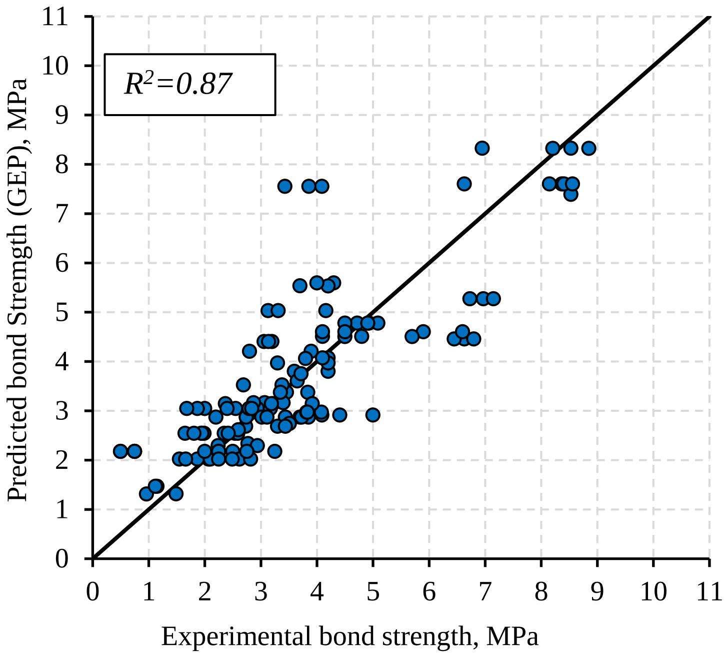


Figure 9: GEP model performance for splitting tensile strength

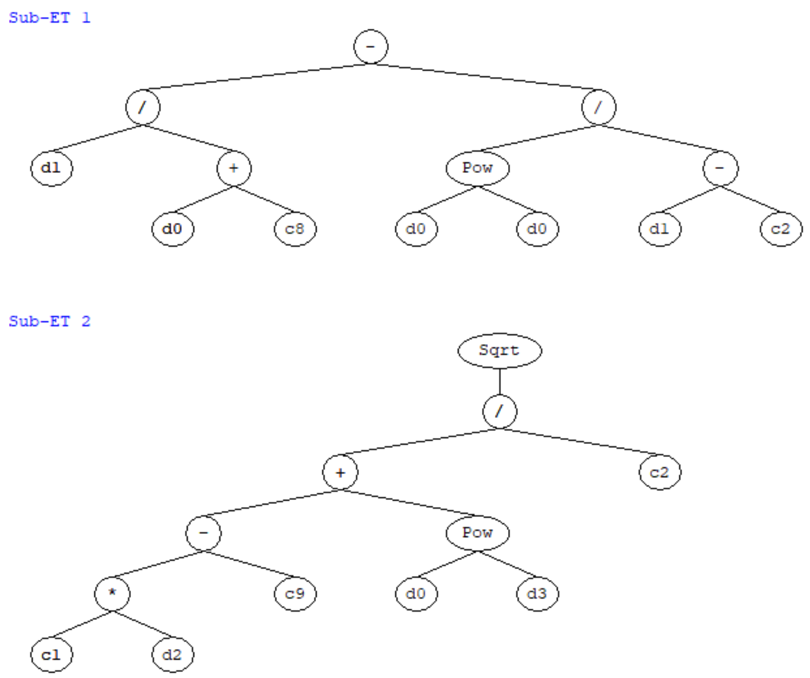


Figure 10: GEP model for slant shear test presented in ET format

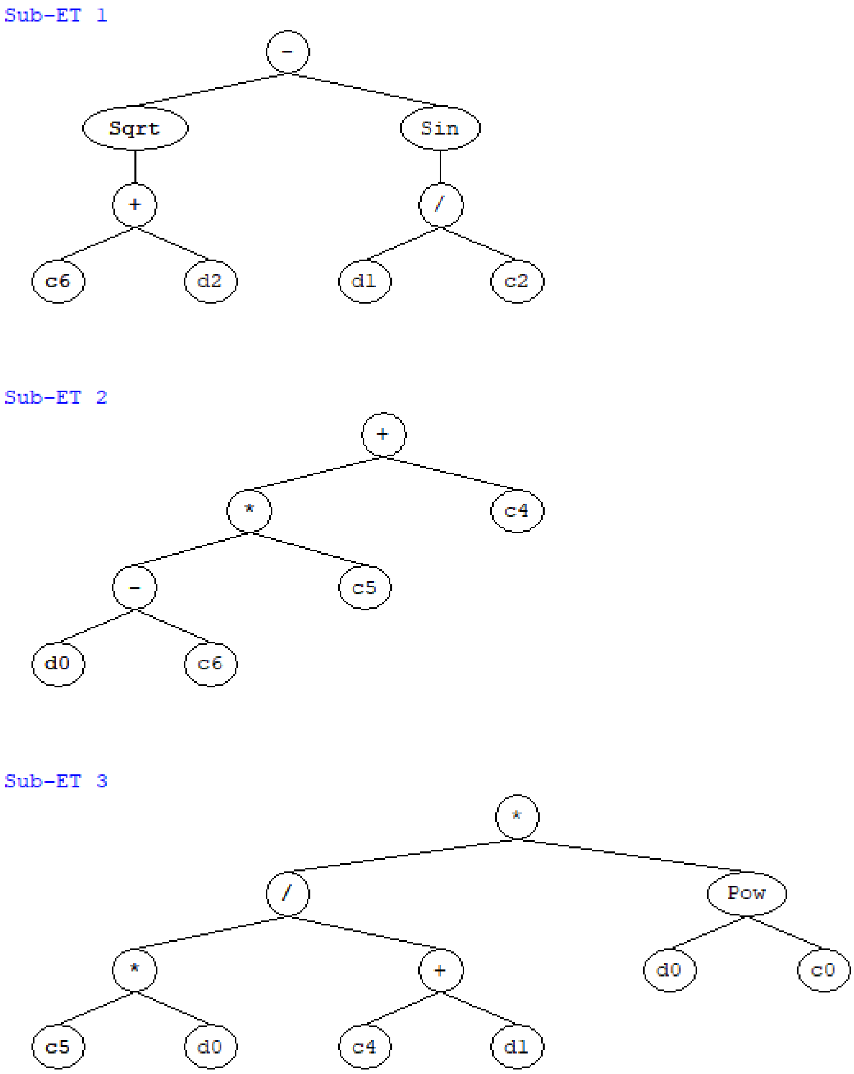


Figure 11: GEP model for splitting tensile strength presented in ET format

5 PARAMETRIC ANALYSIS USING ANN

The developed ANN models are utilized to perform a parametric analysis to determine the impact of each input variable on the target interfacial bond strength using the vast experimental database. The parametric analysis is carried out by keeping all variables fixed at average values and only varying the specific variable under consideration. The ANN model was selected for the parametric study because of the higher ability of the Bayesian algorithm for generalization and avoiding overfitting.

5.1 NSC Compressive Strength Effect

Figure 12 demonstrates the effect of varying the NSC compressive strength on the interfacial bond strength at various curing conditions. The age of UHPC and interfacial surface treatment were kept constant at average values during such analysis. The analysis revealed an increase in the interfacial bond strength as the NSC compressive strength increases. In addition, it can be seen that steam curing has a more pronounced effect on bond strength than normal curing. The effect significantly increases as the NSC compressive strength increases. Furthermore, unlike the splitting tensile strength, the slant shear test has a linear influence.

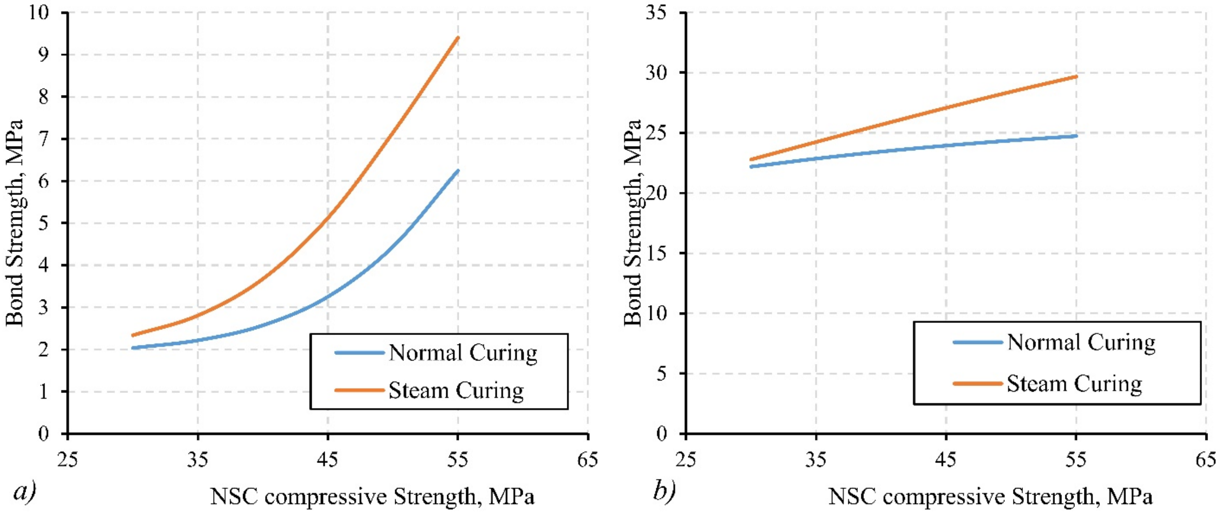


Figure 12: Effect of NSC compressive strength on the bond strength predicted at different curing conditions. (a) splitting tensile strength, (b) Slant shear test

5.2 UHPC Age

The impact on the interfacial bond strength resulting from changing the UHPC age at different curing conditions is shown in Figure 13. The NSC compressive strength and the interfacial surface treatment were kept constant at average values during such analysis. The figure shows a minimal impact of the UHPC age on the bond strength for the splitting tensile strength, while it shows a moderate impact in the slant shear test. It is observed that an increase in the UHPC age results in an increase in the interfacial bond strength. In general, the UHPC effect is considered small since the NCS controls the failure capacity.

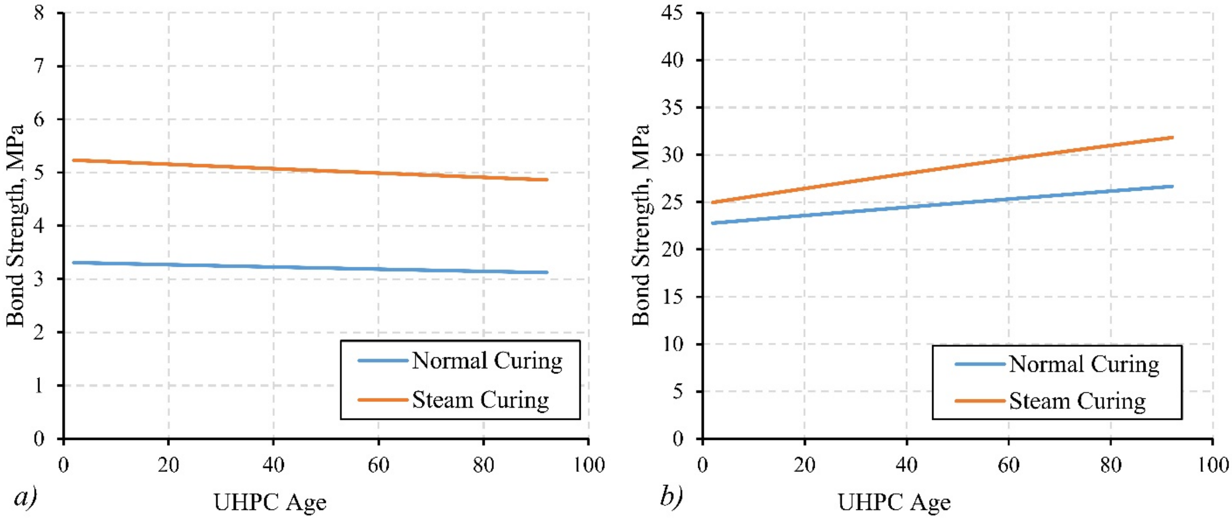


Figure 13: Effect of UHPC age on the predicted bond strength for different curing conditions. (a) splitting tensile strength, (b) Slant shear test

5.3 Effect of Surface Condition

Figure 14 demonstrates the impact of changing the surface condition on the bond strength at different curing conditions. During such analysis, the NSC compressive strength and the UHPC age were fixed at average values. It is noticed from Figure 14 that increasing the surface roughness of the NSC substrate leads to an increase in the interfacial bond strength. This figure also indicates that the curing conditions have a negligible effect on the interfacial bond strength in the case of the slant shear test. Weak bond strength resulted from a smooth surface, while the highest interfacial bond strength was obtained using a sandblasted surface.

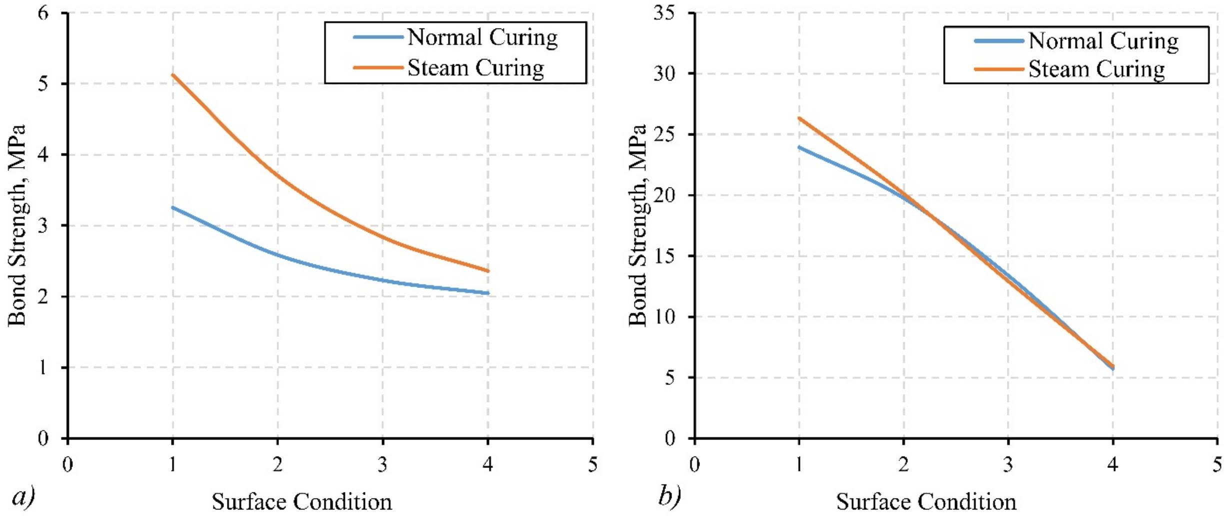


Figure 14: Effect of surface condition on the predicted bond strength for different curing conditions. (a) splitting tensile strength, (b) Slant shear test

6 SUMMARY AND CONCLUSIONS

The proposed ANN and GEP models are developed to estimate the strength of the bond between UHPC and NSC using a comprehensive database consisting of 264 experimental data points gathered from the literature. The newly proposed models predict the interfacial bond strength with good accuracy. A parametric ANN analysis is performed to examine and assess the individual effect on the performance of each of the key variables on the targeted interfacial bond strength. These five key factors used through the GEP and ANN analyses are the curing method, UHPC age, NSC compressive strength, interfacial surface treatment, and moisture conditions. Based on the results of this investigation, the following conclusions were drawn:

1) The developed ANN and GEP models have good accuracy and closer predictions of the bond strength of the slant shear test with RMSE of (5.0, 4.34) and COV (37%, and 24%), respectively.
2) For the splitting tensile strength, the proposed ANN and GEP models resulted in RMSE of (1.11, 1.05) and COV (32%, and 27%), respectively.
3) The newly proposed ANN and GEP models closely predict the bond strength and attain values of R^2 equal to (0.84, 0.9) respectively for the slant shear test and R^2 of (0.798, 0.87) for the splitting tensile strength.
4) From the parametric study results, it is seen that as the NSC compressive strength increases, the interfacial bond strength also increases. Steam curing has a larger effect on bond strength than normal curing. The effect significantly increases as the NSC compressive strength increases.
5) A minimal impact of the UHPC age on the bond strength for the splitting tensile strength was observed, while a remarkable effect was shown in the case of the slant shear test, where it was noted that an increase in the UHPC age resulted in an increase in the bond strength.
6) Increasing the surface roughness increases the bond strength in the slant shear and splitting tensile strength.
7) It was concluded that the curing conditions have a negligible impact on the bond strength in the case of the slant shear test.

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