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Passer Journal

Passer 5 (Issue 1) (2023) 121-127

http://passer.garmian.edu.krd/

Strength Prediction of FRCM Confined Cylindrical Concrete Specimens by Artificial Neural Network

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Received 25 January 2023; revised 16 March 2023;
accepted 17 March 2023; available online 20 March 2023

DOI: 10.24271/PSR.2023.383129.1239

ABSTRACT

This paper presents developing a new model for predicting the strength capacity of cylindrical concrete specimens confined with Fiber-Reinforced Cementitious Matrix (FRCM) by using the artificial neural network (ANN) technique. For this purpose, a database of 127 reliable specimen results was assembled from the literature. The most sensitive parameters in the strength enhancement were used as input values for the development of the new model which sequentially are; the strength of unconfined concrete, the tensile strength of fabric meshes, the strength of the matrix, the mechanical reinforcement ratio, and the thickness of the matrix. The new model was trained, validated, and tested using MATLAB, which produced a model with a mean square error of 0.00105 and an R-value of 0.9921 that had excellent prediction capacity and high accuracy. Moreover, to evaluate the reliability and validity of the ANN simulated model, the new model was verified against other available models and design code equations in the literature by using different specimens than that used for model development. The new model showed excellent results compared to other models and demonstrated the least rate of average absolute error of about 9%. Finally, a parametric study was investigated to evaluate the effectiveness of sensitive variables on confinement efficiency. The outcomes demonstrated that the new model's predictions for all parameters and the physical performance of the test results were in good agreement.

Keywords: Fiber-reinforced cementitious matrix; Confined concrete; Artificial neural network; parametric study.

1. Introduction

Over the past few decades, several techniques for the repairing or restoring of deficient concrete members have been introduced, namely, lateral steel plate bonding, reinforced concrete jacketing by enlarging the concrete cross-sections, application of external post-tensioning steel straps, and using FRP wrapping. Among these methods, structural engineers have focused their emphasis mostly on FRP confinement. Consequently, numerous papers and research have been published on using FRP composites for the strengthening of structural elements. Nowadays, engineers and scientists agree that FRP confinement boosts concrete strength and decreases its deformability[1-3]. Conversely, the availability of epoxy resins (organic materials) as binders have led to several disadvantages, for instance, poor resistibility to high temperatures, irrelevance for damped areas, weak compatibility with concrete surfaces, and high cost.

As a result, to overcome the drawbacks mentioned above, during the last two decades strengthening of concrete elements by a new technique has been introduced, namely, Fiber-reinforced cementitious matrix (Fiber reinforced matrix). This technique which is also referred to as textile-reinforced concrete (TRC), or textile-reinforced mortar (TRM) has gained the attention of engineers and researchers. Basically, this confinement system consists of fabric mesh textiles (Carbon, basalt, PBO, glass, and steel) and a cementitious paste (inorganic mortar) as a binder agent (Fig. 1). Experimental compression tests of concrete columns confined with different fabric types, various bonding mortar types, and with various fiber mesh orientations showed that FRCM confinement considerably increased axial load capacity and reduces lateral deformation[4-6]. On the other hand, in terms of comparison between FRP and FRCM confinement, several researchers, based on their experimental results, reported that FRP confinement is more active in enhancing the strain behavior and compressive strength of concrete columns. This is explained by the strong epoxy adhesive that FRP wraps have with concrete surfaces[7-9]. However, the above-mentioned drawbacks of FRP confinement have led to the FRCM application.

Several studies[4, 6, 10] based on their limited test results, using the regression analysis technique, all developed their design-oriented model for forecasting the maximum strength and strain behavior of FRCM-confined concrete samples. On the other hand, Ombres

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Peer-reviewed under the responsibility of the University of Garmian.

and Mazzuca[11] used 152 specimens to investigate the efficiency of a relevant mechanical and geometrical property on the performance of FRCM-wrapped circular concrete specimens. Then, they established an empirical model utilizing the regression analysis technique to forecast the strength capacity and strain of the FRCM-confined specimens. Part of their collected specimens was wrapped with inclined FRCM layers (30◦ and 45◦), which, based on some recent researchers[12, 13] this form of confinement is not efficient as perpendicular (90◦) FRCM confinement over the axis of specimens. Therefore, in this study, only the specimens wrapped with (90◦) FRCM layers are considered. Recently, Cascardi et al[14] developed a new model based on 231 circular and quadratic/rectangular cross-section concrete specimens confined with FRCM assembled from various sources in the literature. They adapted multiple regression analysis techniques to explain the interactions between mortars and fibers to enhance the strength capacity of internal concrete, and they also proposed a new predictive model. Moreover, they reported that circular and rectangular section behavior is different under the confinement lateral load, as a result of the stress intensity at the edges of rectangular sections[6, 15]; so, it might be better to study each type of confinement separately. Therefore, for the development of the current model, only circular specimens are considered. Regarding the design guidelines and regulations, ACI Committee 549[16] can be considered the first guideline to address the FRCM strengthening method and propose a design equation.

Figure 1: Application of fabric impregnated by cementitious matrix[9].

Over the past few decades, the use of artificial neural networks (ANN) in structural engineering has been the subject of extensive research, among these applications, numerous ANN models have been developed to forecast the maximum strength capacity of confined concrete specimens with various materials. Studies[16-19] have developed ANN models to forecast the strength and behavior of FRP-wrapped concrete members.

Experimental results showed the good efficiency of FRCM confinement of concrete columns in increasing the axial load capacity; therefore, proposing predictive models to predict the confined concrete strength is crucial and structural application demand. On the other hand, the available predictive equations were proposed based on regression analysis which was developed based on a database that includes specimens wrapped with inclined FRCM layers as well as containing both rectangular and circular concrete specimens. Consequently, the current study tries to contribute to developing a predictive model by using an artificial neural network, as a new technique in this specific area, for FRCM-confined cylindrical concrete specimens with perpendicular wraps only. Therefore, based on 119 assembled specimens from various literature sources, a new ANN model was trained, validated, and tested depending on the selection of the most sensitive parameters. Moreover, a parametric study was investigated to evaluate the effectiveness of sensitive parameters on confinement efficiency. Finally, the ANN model was verified against two available models and one standard equation by using eight specimens other than that used to develop the model.

2. FRCM Confinement Application and Mechanism

In their review of the failure modes, Koutas et al. and Awani et al[20, 21] condensed the FRCM-confined concrete failure modes into two primary modes. Firstly, a failure approach because of the debonding at the end of the overlap. This approach of failure usually occurs at the fabric-matrix surface which may occur due to the poor tensile strength of the mortar, short overlap length, or low impregnation of the mortar into the mesh in situations of the high density of the mesh[4, 22]. The second mode is the rupture of the jacket when the textile reaches its tensile strength due to the hoop stress. This type of failure may be brought on by the longitudinal steel buckling in reinforced concrete column specimens or lateral dilation of the confined concrete[8, 23, 24]. The second type of failure occurs more frequently in fibers with low tensile strength. Concrete specimens confined with glass fibers showed fiber rupture failure, according to Bournas et al[8]. Meanwhile, for similar specimens confined with carbon fiber, different failure modes have been observed. Moreover, another failure mode observed by Ombres and Verre[12] was due to internal concrete crushing; typically, this failure mode could occur when the specimens are confined by a high amount of FRCM (two layers and more).

Many studies[7, 8, 25, 26] examined the efficiency of different types of mortars, as a binder agent on the failure mechanism. They claimed that the jacket fracturing is the cause of failure for higher-strength mortars. While for mortars with lower strength, the reported failure mode is caused by debonding at the end of the overlaps. On the other hand, the overlap length should also be adequate to increase the strength of confinement; according to Yin et al[27], prolonging the overlap may result in an increase in the strength enhancement.

3. Efficient Parameters on Confinement and Experimental Database

The most critical variables that contribute to the strength improvement of FRCM-wrapped concrete samples can be classified as unconfined concrete-related parameters, fabric (Textile) related, and mortar-related variables. These variables include; the diameter of the specimens, the number of FRCM laps, the strength of the fabric meshes, the thickness and strength of binder mortar, and the strength of unconfined concrete. It is agreed by almost all researchers that axial load capacity and deformation capacity increase as the number of layers increases., but it is not proportional. The strength of unconfined concrete (f'_{co}) also significantly affects the confinement efficiency, for lower-strength concrete the confinement effectiveness increases compared to higher values of f'_{co}[7, 11, 23, 28]. The flexural and compressive strength of the binder mortar also influences the confinement effectiveness and failure modes. For higher-strength mortars, the failure mode will be due to the fracture of fabrics rather than debonding failure[4, 29]. However, ACI Committee 549[16] equation conservatively neglected the contribution of mortar to strength enhancement and it limited the ultimate axial strain to 0.01 to limit the concrete cracks that result in the loss of concrete integrity.

Besides, Fabric type also influences the efficiency of the confinement process, Bournas et al[30] examined the efficiency of two different fabric types, namely, carbon-FRCM and glass-FRCM. About strength and strain capacity development, almost both fiber types presented the same behavior. However, regarding the failure manner, the confined concrete with a glass-FRCM jacket failed according to the jacket rupture because of the low tensile strength of the glass fibers. Statistical analysis was performed to find the correlation coefficient for the selected parameters with the confined compressive strength, as shown in Fig. 2. It is clear that the most sensitive parameters based on the Pearson correlation coefficient in sequence are; the unconfined concrete strength f'_{co}, the ultimate tensile strength of fabrics f_{fab}, the strength of mortar f_{mat}, the mechanical reinforcement ratio of the wrapped scheme $\rho_f E_f$, and the thickness of matrix t_{mat}.

To achieve the aim of this paper, an intensive review of the currently available literature was conducted, and 127 specimens were assembled from twelve reliable published papers[4–6, 9, 10, 13, 23, 25, 26, 29, 31, 32].

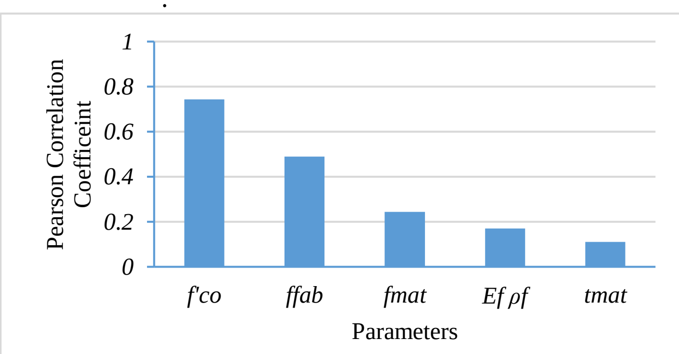

Figure 3: Pearson correlation coefficient of selected parameters with the *f'cc*.

4. Artificial Neural Network Overview

ANN technique simulates the mechanism of the human brain. Generally, ANN comprises three main parts, namely, an input unit, hidden layers, and an output unit (Fig. 3). ANN receives input data from the external world, mathematically this data is noted as x(n), in which "n" represents the number of inputs. The input value is multiplied by its corresponding weights, then all weighted data will be summed up inside the hidden layers and summed with bias values. Finally, the data is passed through a particular activation function and as a result, the output value (f) will be achieved (Eq. 1).

$$f = \sum_{i=1}^{n} x_i w_i + b \quad (1)$$

5. Neural Network Modelling

The performance of ANN models is mainly affected by two crucial factors, namely, the input variables and the structure of the model. Therefore, based on reviewing the available literature critically, input variables were selected as unconfined concrete strength f'_{co} strength of mortar f_{mat} and thickness of matrix t_{mat}, the ultimate tensile strength of fabrics f_{fab} and mechanical reinforcement ratio of the wrapped scheme $\rho_f E_f$ where E_f is the modulus of elasticity of fabrics and $\rho_f=4nt/D$, n is the number of

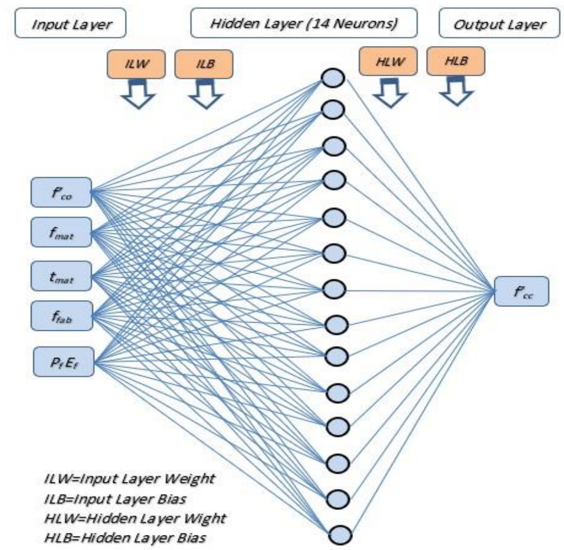

Figure 2: Architecture of the ANN.

layers, t is the thickness of fabrics and D is the diameter of specimens (Eq. 2). The fabric reinforcement ration, ρ_f, and the fabric modulus of elasticity, E_f, were considered together as one-parameter because their effects are interrelated and due to the large variability of E_f for various types of FRP materials[4,7,8]. For the sake of brevity, only the average, minimum, and maximum value of all the data is presented in (**Error! Reference source not found.**).

Table 1: Statistical analysis of input parameters.

Parameters	Maximum	Minimum	Average
f'_{co}	67.1	11.4	20.7
f_{mat} (MPa)	50	2.25	22.4
t_{mat} (mm)	90	1	11.4
f_{fab} (MPa)	5800	846	2751.9
$\rho_f E_f$	202.6	2.23	59.4
D (mm)	200	113	152
t (mm)	0.58	0.0455	0.1085
n	15	1	1.98

$$f'_{cc} = (f'_{c0}, f_{mat}, t_{mat}, f_{frp}, \rho_f E_f) \quad (2)$$

Where; f'_{cc} is the ultimate strength of confined concrete.

On the other hand, the architecture of the feed-forward backpropagated network is used. Five input layers are used which represents the above-mentioned parameters in Eq.2, and one output layer is expected which represents the ultimate strength f'_{cc}. For models that hold about some hundredweights, the Levenberg-Marquardt training function (trainlm) will possess the fastest convergence and the lower MSE values. Therefore, the current network "trainlm" function is utilized, and one hidden layer is adopted. Moreover, (Log-sigmoid) transfer function is utilized as the network is multilayer; therefore, all the data is normalized to the values between 0 and 1 by applying the equations (Eq.3).

$$x_{n,normalized} = \frac{(0.9-0.1)(x_n - x_{min})}{x_{max} - x_{min}} + 0.1 \qquad (3)$$

where x_n is any variable of the database, $x_{n,\ normalized}$ is the normalized variable, x_{min} and x_{max} is the minimum and maximum values of the data for the interested variable.

Moreover, another crucial issue of the structure of the ANN is the number of hidden neurons, since using too few neurons will result in underfitting, and using too many neurons will cause overfitting. Selecting the number of hidden neurons is a time-consuming procedure; herein, a trial and error-based technique is adopted to choose the most effective number of hidden neurons (n-values). Two parameters; named, correlation coefficient (R-values) and mean squared error (MSE) was adopted to select the best number of neurons. In this study, for each hidden neuron, ten trial and error tests are taken; then, the average values for MSE and R-values of these trials are presented in Fig. 4 and Fig.5. From both figures, it can be seen that the network with 14 neurons gives the lowest MSE values, and the highest R-values. Therefore, the 5-14-1 architecture is selected, the first digit "5" represents the number of input values, the second digit "14" demonstrates the number of hidden neurons and the last digit shows the output value, which is the ultimate strength of FRCM confined circular concrete specimens f'_{cc}

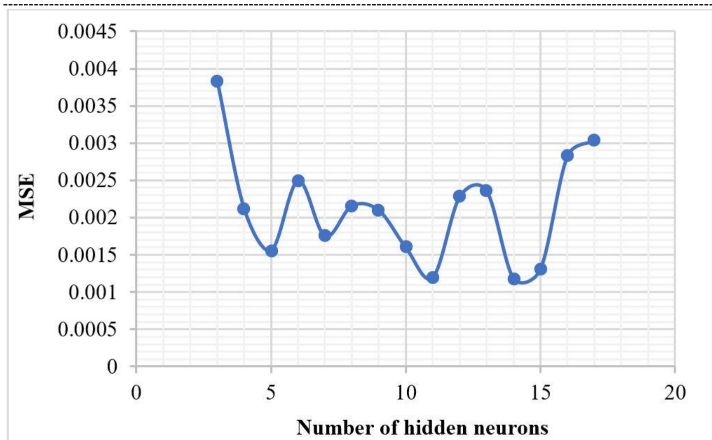

Figure 4: MSE versus the number of hidden neurons.

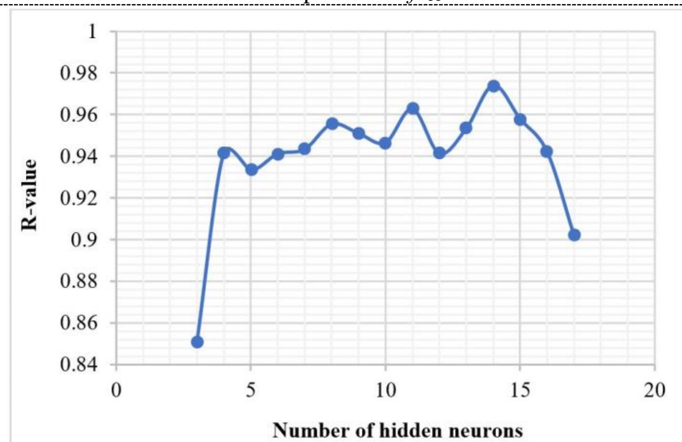

Figure 5: R-values versus the number of hidden neurons.

7. Parametric Study

In order to assess the efficiency of the new model and compare its results with the existing experimental studies, a parametric study is conducted for all input parameters, by using the ANN model.

Nearly all researchers in the literature concur that raising the fabric reinforcement ratio, particularly by raising the number of textile layers, results in an increase in final strength. However, as stated by Koutas et al.[21], once the layer numbers increased, the confinement efficiency will decrease, i.e., using axtra number of layers will not proportionally increase the strength capacity. In contrast, the ratio of tensile strength resisted by the extra layers is reduced relatively. Herein, the mechanical reinforcement ratio of the confinement system $\rho_f E_f$ is plotted against the predicted ultimate strength, and all other input parameters are kept constant at the average value (Fig. 6). As can be observed, the confinement efficiency is high for lower mechanical reinforcement ratio values; however, as much as $\rho_f E_f$ increases the strength enhancement rate decreases. This is due to the potential physical explanations that, for concrete confined with smaller FRCM layers under a monotonic load, the confinement process begins to activate earlier and tends to prevent internal concrete dilation laterally. However, for higher FRCM layers, the internal concrete might get crushed before the outside FRCM layers rupture. This prediction by the ANN model almost totally coordinates with all available test results in the literature.

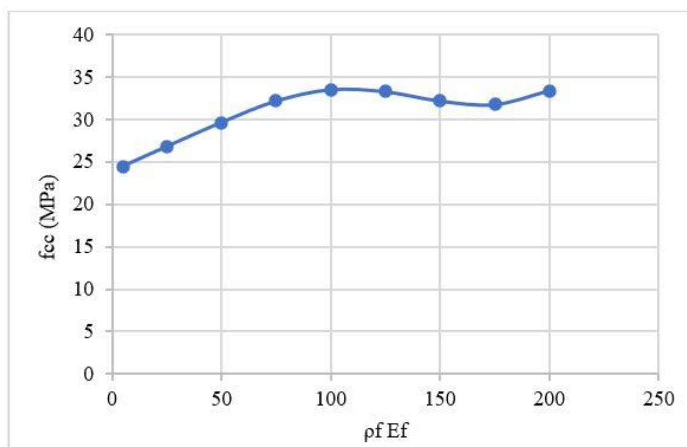

Figure 6: $\rho f E f$ *vs.* $f'cc$ for the selected specimens.

On the other hand, researchers in[6, 7, 11, 23], based on their experimental test results, they reported that the confinement effectiveness increases for lower f'_{co}. Similarly, the ANN model presented almost the same outcomes. As shown in Fig.7, for a specimen with unconfined concrete strength of 12MPa, the ultimate strength is 22.1 MPa, i.e., the strength enhancement rate (f'_{cc}/f'_{co}) is around 1.84. On the other hand, for the largest unconfined concrete strength f'_{co}=65 MPa, the strength improvement rate decreased to around 1.15. However, this change in strength enhancement ratio is not linear, as for a sample with a medium unconfined concrete strength of 42.5 MPa is around 1.36. Moreover, regarding the thickness of binder mortar, according to the author's knowledge, not a single experimental study investigated the efficiency of mortar thickness. Nevertheless, in this study based on the ANN model, the increment of mortar thickness on the efficiency of strength enhancement was investigated. As can be noted from Fig. 8, increasing the mortar thickness from 10mm to around 60mm will result in a strength increase. While increasing mortar thickness for more than 60mm, the confinement strength remains nearly constant. This behavior is rational and in agreement with the physical mechanism and indicates that the effectiveness of t_{mat} is reduced by increasing its value. Finally, for the last two parameters, namely, the compressive strength of the mortar, and tensile strength of the textile, a clear statement about the efficiency of these two parameters could not be found in the literature. Herein, by utilizing the developed ANN model their effectiveness on confinement is investigated. From Fig.9, it can be found that by increasing the f_{fab} to about 2500MPa, the confinement strength increased. While, higher values do not have a positive effect on confinement strength, where the trend line declined for higher values of about (4000-5000) MPa. This may be attributed to the very high tensile strength of the textile does not contribute effectively to increasing the confinement strength. In addition to the limitation of experimental data with a high tensile strength of the textile to train the ANN model and yield a more efficient model. Fig.10 presents the response of mortar compressive strength to confinement strength. It is clear that increasing the mortar compressive strength up to about 37MPa, does not have a significant effect on confinement strength. The confinement strength dramatically increased as mortar compressive strength values rose.

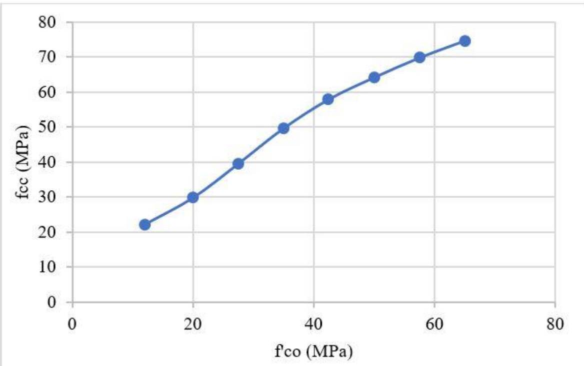

Figure 7: *f'co vs. f'cc* for the selected specimens.

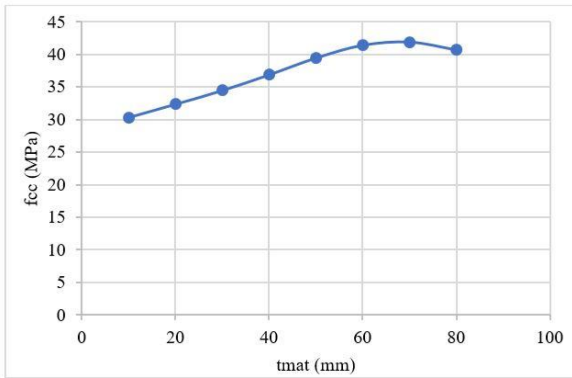

Figure 8: *tmat vs. f'cc* for the selected specimens.

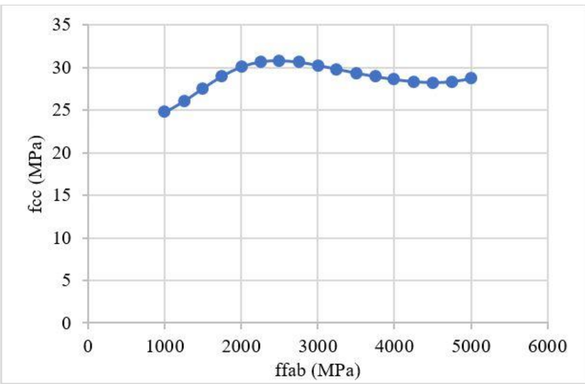

Figure 9: *ffab vs. f'cc* for the selected specimens.

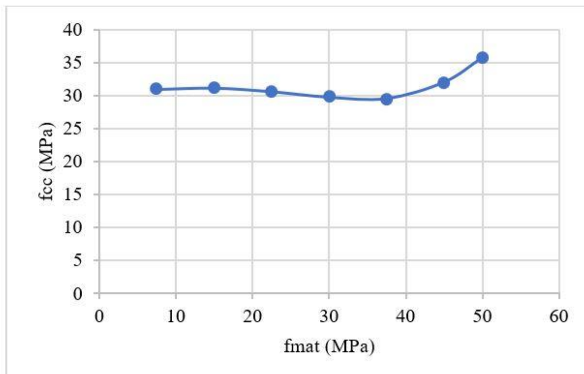

Figure 10: *fmat vs. f'cc* for the selected specimens.

8. Validation of The New Model

Appropriate to verify the accurateness and applicability of the new ANN simulated model, the new model is compared with two well-known equations from the literature (Ombres 2014, Ombres and Mazzuca 2016)[6, 11] and a proposed equation by ACI Committee 549[16]. Eight samples are assembled at random from diverse literature sources, besides the ones used to create the model. By using these samples, the validity of the new model is verified against above–mentioned models in Table 2.

Table 2: Models from the literature.

Models	Expressions
ACI Committee 549 (2013)	$\frac{f'_{cc}}{f'_{c0}} = 1 + 3.1\left(\frac{f_{lu}}{f'_{c0}}\right)$
(Ombres 2014)	$\frac{f'_{cc}}{f'_{c0}} = 1 + 5.268\left(\frac{f_{lu}}{f'_{c0}}\right)$
(Ombres and Mazzuca 2016)	$\frac{f'_{cc}}{f'_{c0}} = 1 + 0.913\left(\frac{f_{lu}}{f'_{c0}}\right)^{0.5}$

From Fig. 11, it is clear that the new ANN simulated model has the least percentage of average absolute error (AAE), about 9%. On the other hand, AAE for the other three models is relatively larger. AAE for the proposed model by Ombres and Mazzuca[11] Ombres[6] and ACI 549-13[16] equation is 17.4%, 90.4% and 51.7%, respectively. This may be attributed to the powerful and high ability of ANN in developing predictive models compared to other empirical or semi-empirical models. In Fig. 12, the percentage of errors for all specimens from the ANN simulated model is presented with the verifications against other models in Table.

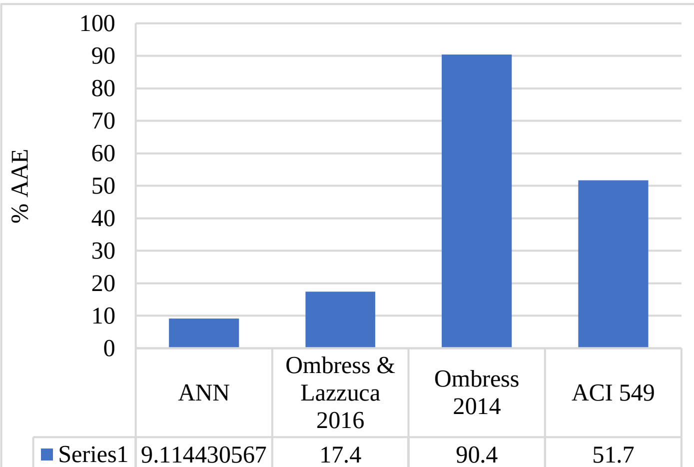

Figure 11: AAE of the new model compared to other models.

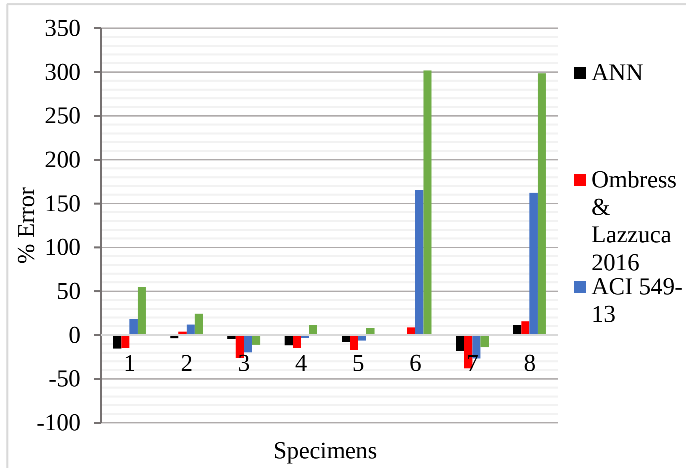

Figure 12: Percentage of error of specimens.

Conclusion

In this study, the efficiency of FRCM confinement on cylindrical concrete specimens was examined Based on physical considerations and available literature review, the most critical variables of the strength improvement were indicated. The statistical correlation coefficient indicated that the most sensitive parameters on FRCM confinement strength capacity in sequence are; the unconfined concrete strength, the ultimate tensile strength of fabrics, the strength of mortar, the mechanical reinforcement ratio of the wrapped scheme, and the thickness of matrix.

Using the ANN technique, a new simulated model was established by utilizing the (119) specimens collected from various sources of the literature. The architecture of the developed model was (5-14-1), was developed by following a new approach. The model showed efficient and excellent powerful in predicting the FRCM confinement strength as the MSE and R-value for the model were 0.00105 and 0.9921, respectively. These two parameters are good indicators that the new model trained well, and can be generalized over samples other than those used for the model development.

Moreover, to check the reliability of the new model, was verified against available models and guideline equations in the literature. In order to undertake the verification, different specimens (8 specimens) other than those used to construct the new model were used. The new model presented good results compared to others, as the percent of AAE (9%) by the new model was less than those by other models and guideline equation. Additionally, based on conducted the parametric study for evaluating the new model more deeply, the outcomes demonstrated that the new model's predictions for all sensitive parameters and the actual physical performance of the experimental test results were in good agreement. This confirms the high efficiency of the ANN-developed model which can be applied throughout the entire range of sensitive parameters with good results.

The literature review showed that there are limited studies on FRCM-confined concrete samples. Therefore, in the future, more experimental studies are required to investigate the strength and behavior of deficient columns strengthened by FRCM confinement. Moreover, collecting databases to develop predictive models for reinforced concrete columns confined by FRCM wraps is another research area for future studies.

Conflict of interests

None

Author contribution

Ghazi Bahroz Jumaa: Literature review, data collection, data analysis, modeling, writing, reviewing, and editing.

Funding declaration

This paper did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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