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Optimum usage of waste marble powder to reduce use of cement toward eco-friendly concrete

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ABSTRACT

In this study, waste marble powder (WMP) was used to replace cement of concrete in specific amounts. To accomplish this aim, WMP was replaced at 10%, 20%, 30%, and 40% of the cement weight, and a reference concrete sample without WMP (REF) was created to compare the compressive strength, splitting tensile strength, and flexural strength. The replacement of WMP at 10%, 20%, 30%, and 40% of the cement weight resulted in 5.7%, 21.7%, 38.1%, and 43.6% decreases in the compressive strength compared with REF. Furthermore, the splitting tensile strength results commonly followed the same trend as the compressive strength. However, WMP at 10%, 20%, 30%, and 40% led to 5.3%, 8.6%, 19.4%, and 26.7% decreases in the flexural strength compared with REF. In addition, three different calculations, ranging from simple to complex, were proposed to compute mechanical resistances of concrete with WMP. These proposed calculations for practical applications were validated using values from the literature and the implications obtained from the current research. While the simple calculations were based on the strength of REF and the WMP percentages, the complex calculations were dependent on the design of the concrete mixture, age of the samples, and the WMP percentages. For the complex calculations, the ANN approach was used with the help of the coefficient of determination (R^2) for the K-fold cross validation method. All the proposed methods provided high accurate estimation to predict the properties of concrete with WMP. Based on the studies, utilizing 10% WMP as the replacement of cement is recommended to obtain the optimum benefits considering both mechanical and environmental aspects. Moreover, scanning electron

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microscope (SEM) and energy dispersive X-ray (EDX) analyses were then conducted to observe the interaction of WMP in concrete. According to the SEM analyses, some pores were detected and the interfacial transition zone was observed in the reaction zone. On the other hand, based on the EDX analyses, the presence of WMP in concrete was manifested by the presence of high levels of calcium.

1. Introduction

Currently, concrete is a commonly used building material and lots of improvement still are performed [1–5]. According to a report from the ISO/TC071 strategic business plan, approximately 32 billion tons of concrete were produced in 2020, with the volume expected to increase further [6]. The selection of concrete mixing materials and mixing percentages, and their environmental influences and mechanical performances are all important research topics for the construction industry. Portland cement concrete is the most widely utilized binder material, from small buildings to skyscrapers, dams, airports, and nuclear power plants [7].

One of the main reasons of global warming is thought to be limestone calcination from the production of Portland cement, the primary binding material of concrete, and carbon dioxide released into the atmosphere [8–11]. In fact, it accounts for 11% of all CO_2 emitted into the atmosphere [12,13]. Researchers have been gaining attention to reduce use of cement with employing alternative methods [14–17]. Moreover, the utilization of waste materials instead of raw materials is the current trend [18–22]. For concrete production, the use of waste materials can be categorized as the replacement of cement [23,24], replacement of aggregate [25–29], and additives [30–32].

Marble has been one of the most popular building and decorating materials since ancient times. It is utilized for both structural and aesthetic reasons [33–37]. Application of waste materials to enhance the properties of other materials like soil has also been reported in the literature [38]. Furthermore, the high energy consumption during the processing of marble rocks is characterized as a negative impact on the environmental pollution caused by waste marble powder (WMP) [39–41]. Processing of pozzolanic material improving the strength properties of blended concrete was reported by [42]. A high percentage of WMP is released during the cutting and shaping of marble in extensive applications [43–45]. This waste is estimated to weigh 200 million tons globally [39]. The proper disposal of marble wastes will provide important protection for critical areas such as air, soil, water, and environment [46,47].

Aliabdo et al. [46] observed the probability of utilizing WMP in cement and concrete manufacture. In their study, firstly, the belongings of cement modified with WMP (cement with WMP additive) were investigated, and in the second part, the belongings of concrete containing WMP as the cement substitute and sand substitute (cement addition) were examined. It was found that the usage of WMP in concrete as the cement or sand replacement (cement addition) improved both mechanical and physical properties of concrete particularly with lower water–cement ratio. Ashish [48] evaluated the probability of WMP as the partial replacement of sand and cement. For this purpose, concrete was blended with WMP at proportions of 0%, 10%, and 15% by weight. It was concluded that the mechanical and durability features might be attained consuming 20% WMP. Seghir et al. [49] also investigated the probability of utilizing WMP as a partial cement substitution in air-cured mortar. Three changed stages of the cement replacement were assessed such as 5%, 10%, and 15% by the cement weight. The results pointed out that replacing cement with WMP influenced the physical and mechanical characteristics of air-cured mortar.

Khan et al. [50] assessed WMP blended concrete with the objective of WMP organization and recognized the optimal machine learning technique. For this aim, a methodology was made to custom WMP with changed quantities in concrete. The compressive strength of WMP blended concrete was estimated in view of limited combination amounts with limited input considerations. WMP blended concrete having 10% WMP (as a substitute) was suggested to be recycled as a construction material. Ashish [51] studied the probability of consuming WMP better with cementitious additives. The concrete samples containing WMP up to 15% replacement of sand and 10% additional cementitious material (silica fume/metakaolin) as the replacement of cement were assessed. Finally, 10% cement was swapped with silica fume or metakaolin in concrete prepared with WMP, which improved the strength.

If WMP, created during the processing of marble rocks, is substituted for cement in certain percentages and used as a binding material, cement production which causes environmental threat can be reduced. WMP provides significant benefits for the strength development of cement-based composite concrete due to the presence of alumina, silica, lime, and iron oxide [52–54]. In addition, owing to its microstructure, WMP fills the small pores and improves the mechanical performance of concrete because of its calcium silicate hydrate (C–S–H) reaction [55,56].

The WMP addition rate and what it replaces are critical for improving concrete properties such as the mechanical performance, workability, and setting time. Aliabdo et al. [46]

discovered that the application of 0.4 water/WMP (W/WMP) and WMP as 10% substitute for cement improved the compressive strength, but 0.5 W/WMP decreased the compressive strength. Moreover, Ergun [57] resulted that the contribution of WMP to the compressive strength improvement was limited to 7.5% cement change, and higher percentages negatively affected the compressive strength. Aruntas et al. [58] obtained the maximum compressive strength at 5% replacement of Portland cement with WMP from the replacement rates of 2.5–10%. Similarly Kum et al. [59], conducted experimental research and revealed that 5% substitute of cement with WMP improved the concrete strength by 42 N/mm^2. Khodabakhshian et al. [55,56] studied the influence of 5%, 10%, and 20% WMP and found that only 5% substitute of cement with WMP enhanced the compressive strength, while 10% slightly reduced the compressive strength. An experimental research was also done by [60,61]. They reported that the use of WMP as 10% substitute for cement increased the flexural strength. Furthermore, Shukla et al. [62] stated that the strength properties were improved as the percentage of WMP in the samples was improved. According to them, it met the compressive strength and splitting tensile strength standards.

Aside from the expected mechanical performance of concrete, the properties such as the workability and slump during preparation are also important. These properties differ depending on the powders and chemicals used in concrete. Aydin and Arel [63] explained that as the WMP percentage enhanced, the slump flow of the reduced mixtures increased. Elfaki [64] conducted a slump test to approximate the workability of concrete using a similar mix. It was concluded that increasing the workability of concrete with WMP affects the rate of flow. Sharma et al. [65] indicated that when WMP was changed by 20% of cement, the largest slump value was 120 mm. Karakurt and Dumangöz [66] elaborated that slump test implications ranged from 550 mm to 720 mm with 10–30% WMP. Li et al. [67] mentioned that the gauged rate of flow of mortar mixes varied between 202 mm and 300 mm.

Although several research studies on this subject have been conducted, as stated above, there are some variances in the literature. As a result, there is still a requirement to investigate the performance of concrete via incomplete exchange of WMP and its best quantity. In order to accomplish this objective, exploratory research has been carried out on several test materials and extensive research findings have been collected from the literature. Based on the findings of this investigational research, analytical models have been proposed through different approaches to predict the capacities.

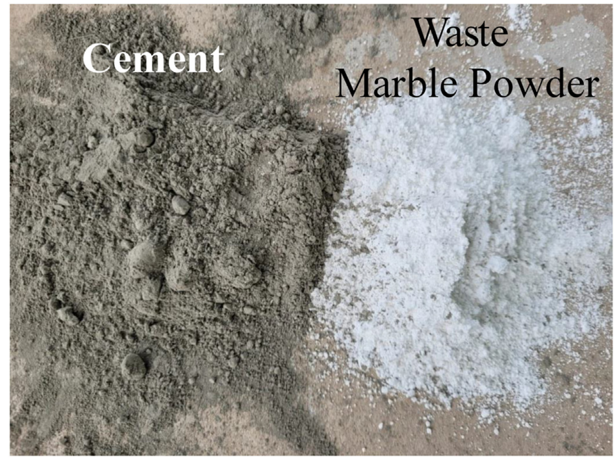


Fig. 1 – Cement and WMP used in this research.

2. Experimental program

WMP influences on cement were studied in both the fresh and hardened properties. The workability and slump were addressed with regard to the fresh properties. Mechanical tests were performed to determine the hardened properties. WMP was utilized to replace some percentages of cement. WMP was used in increments of 10%, 20%, 40%, and 50%. Fig. 1 depicts used cement and WMP.

Portland CEM 32.5 was used as cement. Fine to coarse aggregate percentages were considered constant in the design mix. The water–binder ratio (W/B) was set to 0.5. Binder was the combination of cement and WMP. Table 1 summarizes the design of concrete mixture.

Slump values for each mixture are displayed in Fig. 2. The addition of WMP had no negative impact on the workability. On the contrary, the reference concrete sample without WMP (REF) had the lowest slump value. Using WMP in cement improved the slump value. This was happened as a result of high-water absorption of WMP. Moreover, the binder effect was less in WMP compared with cement. These results are similar to the results in the literature [68].

Table 1 – Design of concrete mixture.

Sample	WMP (%)	Cement (kg/m^3)	WMP (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	W/B
M0	0	435	0	870	870	0.50
M10	10	392	44	870	870	0.50
M20	20	348	87	870	870	0.50
M30	30	305	131	870	870	0.50
M40	40	261	174	870	870	0.50

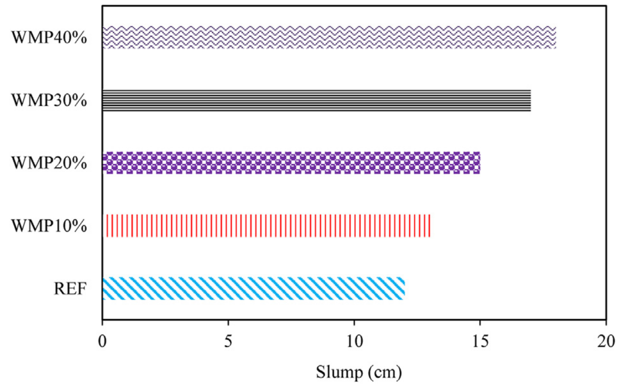


Fig. 2 – Results of slump tests.

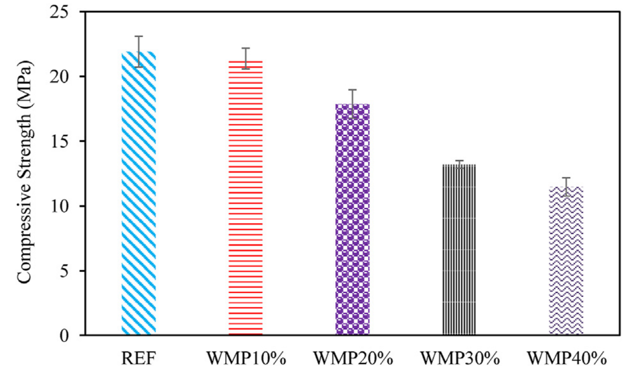


Fig. 4 – Results of compressive strength tests.

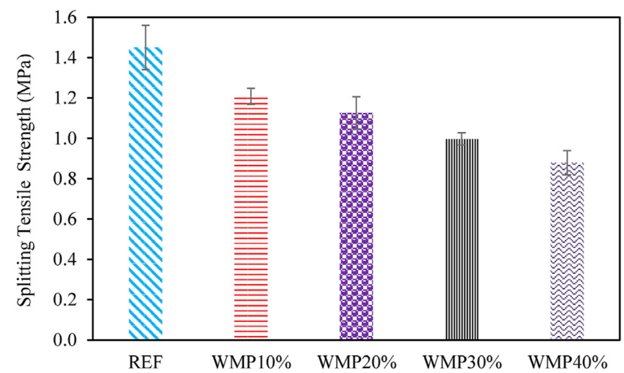


Fig. 5 – Results of splitting tensile strength tests.

3. Experimental results and discussion

The goal of this study was to conduct a thorough examination of various productivity-based concrete structures using varying amounts of WMP as the cement replacement. In this study, the following tests were performed (Fig. 3).

3.1. *Investigation of compressive strength*

In this section, the compressive strength tests of the samples are explained. The compressive strength tests were done following ASTM C39/C39M. The cube samples had dimensions of 150 × 150 × 150 mm. Three samples were manufactured for each type and a total of 15 samples were tested. Fig. 4 demonstrates the results of the compressive strength tests at 28 days for the mixtures. As can be seen from the figure, 10%, 20%, 30%, and 40% of cement was replaced with WMP (WMP10%, WMP20%, WMP30%, and WMP40%); this predisposition was inverted as the graded replacement of cement with WMP. The tests implications showed that WMP led to an important decrease in the compressive strength of concrete. The compressive strength of concrete with WMP10%, WMP20%, WMP30%, WMP40%, was 5.7%, 21.7%, 38.1%, and 43.6% lower than that of REF, respectively. As a conclusion, it was witnessed that when WMP was expended instead of cement, a remarkable reduction in the compressive strength was obtained compared with REF.

3.2. *Investigation of splitting tensile strength*

The assessment of the comparative splitting tensile strength of the several combinations is illustrated in Fig. 5. According to the figure, the implications of the splitting tensile strength

a) Compressive strength test b) Splitting tensile strength test c) Flexural strength test

Fig. 3 – Testing of mechanical properties of WMP blended concrete.

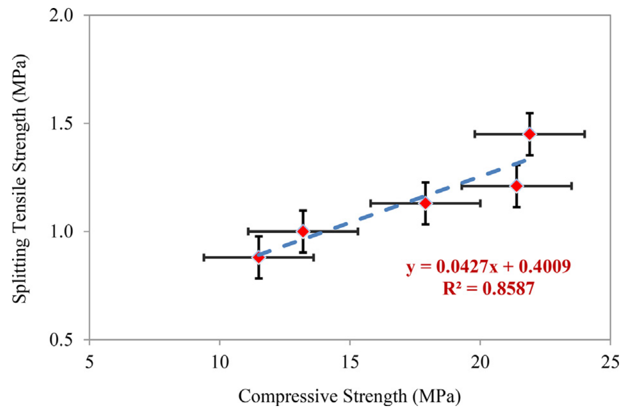


Fig. 6 – Results of splitting tensile strength tests versus compressive strength tests.

tests usually followed the same tend as the compressive strength, which was presented in the above section. The replacement of WMP at 10%, 20%, 30%, and 40% of cement resulted in 16.7%, 22.4%, 31.3%, and 39.4% decreases in the splitting tensile strength, respectively, compared with REF. The relationship of the obtained compressive strengths with the splitting tensile strengths is provided in Fig. 6. Based on the figure, a smooth relation between the compressive strengths and splitting tensile strengths is seen. Moreover, the line in the figure describes a strong connection to the compressive strength compared with the splitting tensile strength, with an R^2 value of more than 85%.

3.3. *Investigation of flexural strength*

The obtained averages of the flexural strength exchanged amid 6.0 MPa and 8.2 MPa. The outcomes of the flexural strength of the samples are depicted in Fig. 7. With the addition of 10%, 20%, 30%, and 40% WMP as the replacement of the cement weight, the reduction in the flexural strength was noticed to be 5.3%, 8.6%, 19.4%, and 26.7%, respectively, compared with REF (8.2 MPa). After 20% replacement of cement with WMP, a considerable reduction in the flexural strength was found. This issue might be due to a reduction in the quantity of accessible cement ingredients. It is indicated in Fig. 8 that a straight-line association exists between the flexural strength of the samples and WMP percentages.

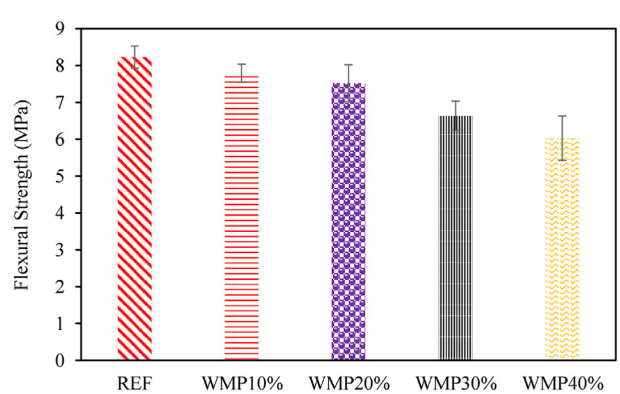


Fig 7 – Results of flexural strength tests.

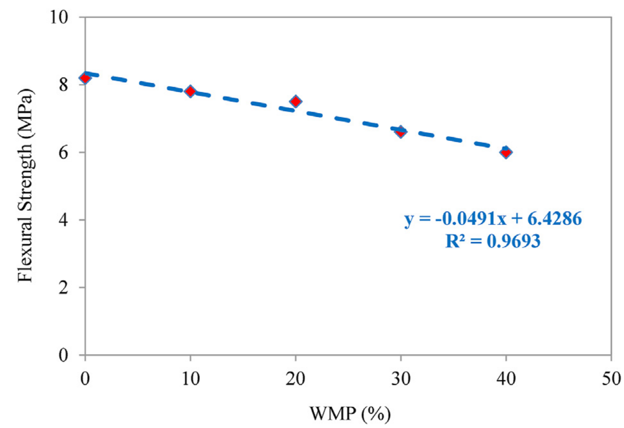


Fig 8 – Effect of WMP on flexural strength.

4. Modeling using artificial neural network

Since, it is newly blended concrete, the estimation of concrete strength from the mix ingredients requires a lot of time, consumption of natural resource materials, and lots of manpower. Therefore, it is necessary to estimate the mechanical properties of concrete with the help of a technique as artificial neural network (ANN), which has several advantages as discussed in the earlier studies [69,70]. In order to quantify the mechanical properties, the mix proportions of blended concrete are required, which are collected from the literature.

Because of the ability of ANNs to model complex nonlinear systems, they have widely been used in a variety of engineering applications. ANNs are a type of computational model inspired by the structure and function of the human brain. They are made up of interconnected nodes called “neurons” that can learn to perform tasks by adjusting the strength of their connections called “synapses” based on input–output pairs [71].

4.1. *Literature studies*

From the literature [46,48,51,57,72–83], the data were assembled for modeling from which they were separated for input and output variables. The input variables used in this study are cement (kg/m^3), WMP (kg/m^3), water (kg/m^3), fine aggregate (kg/m^3), coarse aggregate (kg/m^3), superplasticizer (kg/m^3), and age of samples (days), while the output variables are the compressive strength (MPa), splitting tensile strength (MPa), and flexural strength (MPa). To predict the compressive strength, splitting tensile strength, and flexural strength of WMP blended concrete, 307, 169, and 233 data points were collected from the literature, respectively. Maximum and minimum values used for the prediction of the data from the literature are summarized in Table 2. For this aim, 70% of the data were used for training and 30% of the data were utilized for testing in this study.

To get an optimized combination of datasets for training and testing purposes, the data were divided into the number of data subsets [84]. In the present study, the K-fold cross validation, the number of datasets (collected), was divided into ten subsets, which were employed for training and

Table 2 – Minimum and maximum values of variables used for ANN analysis to determine mechanical properties of WMP blended concrete.

Minimum or Maximum	Cement (kg/m^3)	WMP (kg/m^3)	Water (kg/m^3)	Natural Fine Aggregate (kg/m^3)	Natural Coarse Aggregate (kg/m^3)	Superplastizer (kg/m^3)	Age of Testing (Days)	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)
Minimum	564.3	164	200	858	1382.5	20.5	360	72.31	–	–
Maximum	256	0	120	579.15	948	0	3	14.31	–	–
Minimum	445.58	164	200	858	1310	–	360	–	6.19	–
Maximum	256	0	120	580	948	–	7	–	2.08	–
Minimum	564.3	164	197	858	1382.5	–	360	–	–	8.85
Maximum	256	0	120	579.15	948	–	3	–	–	2

testing of the data. As discussed earlier, number of used training datasets was 7 and number of used testing datasets was 3. For optimizing the combination of the datasets, the K-fold cross validation (K = 10) was utilized at different combinations.

4.2. *Algorithm and normalization techniques*

The Levenberg–Marquardt (LM) algorithm can be used to train ANNs to approximate concrete properties, such as the compressive strength, splitting tensile strength, and workability, based on the input variables such as combination percentages, curing conditions, and additives. ANNs can also be employed to optimize the design of concrete to achieve desired properties, while minimizing costs and environmental impact [85]. The data are preprocessed using normalization methods prior to prediction. Normalization techniques must be utilized in the data preparation stage of machine learning. Using these techniques, data are transformed into a form that machine learning programs can easily process.

Normalization can enhance the performance of machine learning models by lowering the impact of outliers, accelerating convergence, and reducing overfitting. Eq. (1) presents the normalization method used in this modeling. The scaling technique has been recommended in the literature [86].

$$X_N = \left\{ \left[\frac{2(X - X_{min})}{(X_{Max} - X_{Min})} \right] - 1 \right\} \tag{1}$$

The feedforward propagation method and mean square performance error were both employed in this study. A hyperparameter is the number of "epochs" used by the learning algorithm to cycle through the entire training example. The coefficient of determination, also known as R^2, is a statistical measure that represents the percentage of the variance in the dependent variable, which the independent variable (s) explains. In the regression analysis, it is frequently used to determine the strength of the relationship among the independent and dependent variables. The coefficient of determination has a value between 0 and 1, with higher values indicating a stronger relationship among the variables. A value of 0 signifies that the independent variable (s) accounts for none of the variance observed in the dependent variable, providing no explanatory power. On the other hand, a value of 1 implies that the independent variable (s) completely explains the variance in the dependent variable, demonstrating a perfect relationship between the variables [87].

Weights are assumed for each used variable, and bias values are assumed for every layer in the ANN model by tool. Depending on the transfer function (based on algorithm) utilized in the prediction, the value of trigonometric function chosen is Tanh in this study. Similar prediction of the output variables employing the input variables has been reported in the literature [88]. Hence, the equations developed in the present study has a trigonometric value in the prediction of the mechanical properties of WMP blended concrete.

4.3. *Predicted compressive strength*

The use of ANNs for predicting the compressive strength of concrete involves training a network with a set of input–output

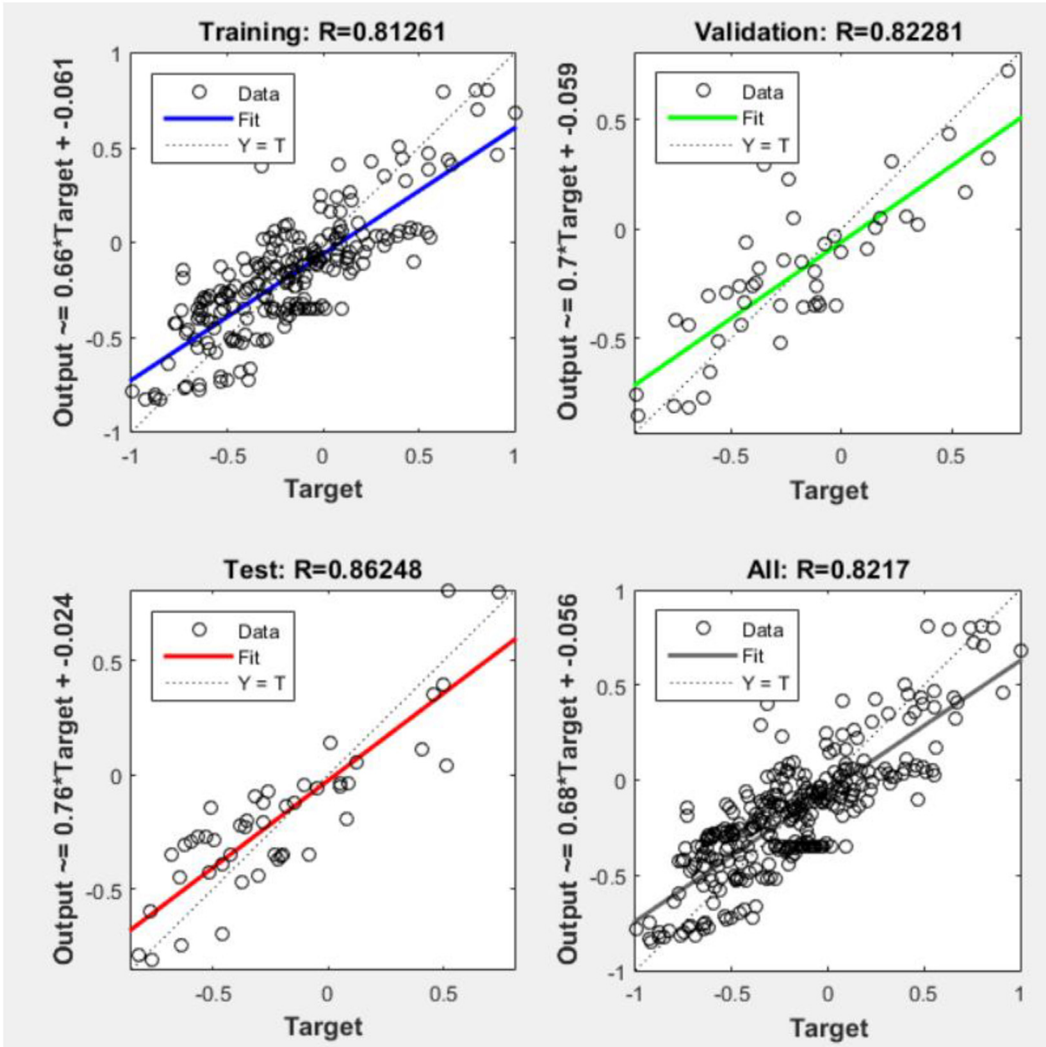


Fig. 9 – Prediction of compressive strength.

data, where the input variables include information on the percentages of combination, curing conditions, and age of concrete, and the output variable is the compressive strength of concrete. Once the network is trained, it can be used to approximate the compressive strength of concrete based on new input data. Several studies have been conducted on the use of ANNs for predicting the compressive strength of concrete. For example, Gholampour et al. [89] utilized an ANN model for the approximation of the compressive strength of self-compacting concrete based on the input variables such as the water–cement ratio, fine aggregate-to-total aggregate percentage, and superplasticizer content. Also, Shah et al. [90] developed an ANN model to predict the compressive strength of concrete incorporating waste glass powder and waste tire rubber.

In the proposed ANN models, a two-layer network structure was chosen, consisting of one input layer and one output layer. The input layer featured two neurons, while the hidden layer also contained two neurons, and the output layer had a single neuron. A non-linear (TANSIG) transfer function was employed for both the input and output layers, enabling the model to effectively capture complex relationships between the input and output variables. The prediction of the compressive strength of concrete using the LM algorithm with the help of ANN is shown in Fig. 9.

The optimized K-fold cross validation method demonstrated K = 1 had R^2 value as 0.72 (average of training and testing), which is noted from Fig. 10. To predict the compressive strength of WMP blended concrete, Eq. (4) was derived with the help of ANN using the LM algorithm. Eqs. (2) and (3) were used to develop Eq. (4). These equations were utilized to obtain the constants and compressive strength using the data without normalization.

$$A_1 = -0.7642[\mathrm{Tanh}\{(-0.019C) - (0.0153WMP) - (0.0024W) - (0.0015FA) + (0.0024CA) - (0.0006A) + 7.80955\} - 0.9538] \tag{2}$$

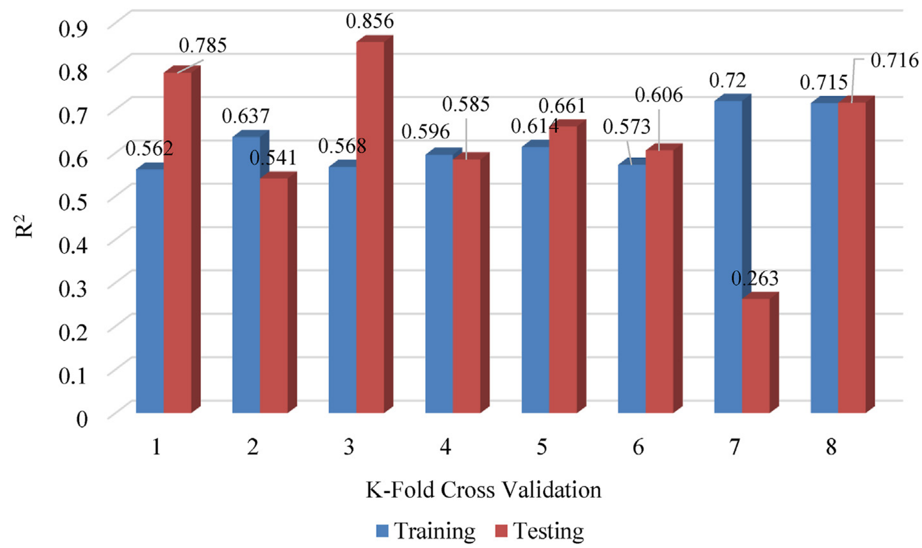


Fig. 10 – Performance of K-fold cross validation (K = 1) method for compressive strength.

$$A_2 = -0.5315[\text{Tanh}\{(0.01697C) + (0.01946WMP) + (0.12998W) + (0.02007FA) + (0.0101CA) - (0.1341A) - 31.2057\} - 21.909] \quad (3)$$

$$CS = \text{Tanh}\ (A_1 + A_2 - 0.1435) \quad (4)$$

where,

A_1 and A_2 are constants.

C: Denormalized cement content (kg/m^3).

WMP: Denormalized WMP content (kg/m^3).

W: Denormalized water content (kg/m^3).

FA: Denormalized fine aggregate content (kg/m^3).

CA: Denormalized coarse aggregate content (kg/m^3).

A: Denormalized age of sample (days).

CS: Denormalized compressive strength (MPa).

4.4. *Predicted splitting tensile strength*

Accurate prediction of the splitting tensile strength is essential for designing and constructing safe and reliable concrete structures. Akçaözoğlu et al. [91] developed an ANN model to approximate the splitting tensile strength of high-strength concrete using the input variables such as the compressive strength, water–cement ratio, and age of concrete. Similarly Gupta et al. [92] employed an ANN model to predict the splitting tensile strength of recycled aggregate concrete utilizing the input variables including the water–cement ratio, aggregate–cement ratio, and age of concrete. Hassanpour and Gholampour [93] established an ANN model to approximate the splitting tensile strength of concrete using the input variables such as the compressive strength, water–cement ratio, and curing time. Nagaraj et al. [94] developed an ANN model to predict the splitting tensile strength of high-performance concrete utilizing the input variables including the compressive strength, water–cement ratio, and curing time.

The prediction of the splitting tensile strength of concrete using the LM algorithm with the help of ANN is illustrated in Fig. 11. The performance of the model on the training, testing, validation, and overall is demonstrated in the figure.

To predict the splitting tensile strength of WMP blended concrete, the K-fold cross validation method was used, as presented in Fig. 12. To obtain the optimized result, K = 2 (R^2 = 0.903) was noted as the average of the training and testing results of ANN from Fig. 12. Denormalized data were employed for predicting the splitting tensile strength of concrete using Eq. (7) with the help of Eqs. (5) and (6). B_1 and B_2 are two constants utilized for the prediction of the denormalized splitting tensile strength (STS) of WMP blended concrete in MPa.

$$B_1 = -(0.503)\text{TanH}[\{((-0.1046C) - (0.0974WMP) - (0.1614W) - (0.0752FA) - (0.1155CA) - (0.001A)) + 282.358\}] \quad (5)$$

$$B_2 = 0.87545\ \text{TanH}[\{(0.00403C) - (0.0017WMP) - (0.0006W) + (0.00286FA) - (0.0002CA) + (0.0324A) - 1.30255\}] \quad (6)$$

$$STS = \text{Tanh}(B_1 + B_2 - 0.1038) \quad (7)$$

4.5. *Predicted flexural strength*

The flexural strength of concrete, also known as the modulus of rupture, is a critical mechanical property that measures its ability to resist bending stresses. Ganesan and Rajamane [95] developed an ANN model to approximate the flexural strength of high-strength concrete applying the input variables such as the compressive strength, water–cement ratio, and curing time. Gupta et al. [92] established an ANN model to predict the flexural strength of steel fiber-reinforced concrete using the input variables

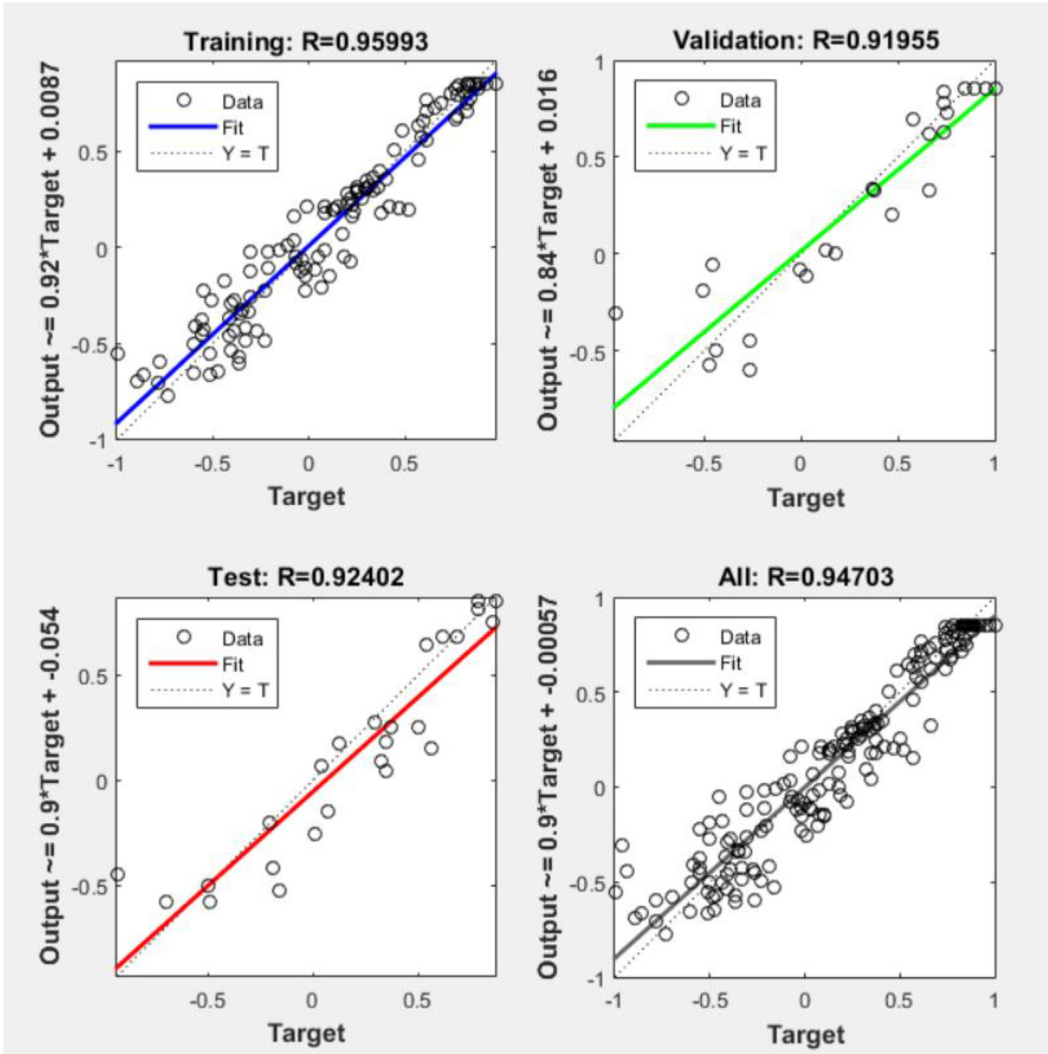


Fig. 11 — Prediction of splitting tensile strength.

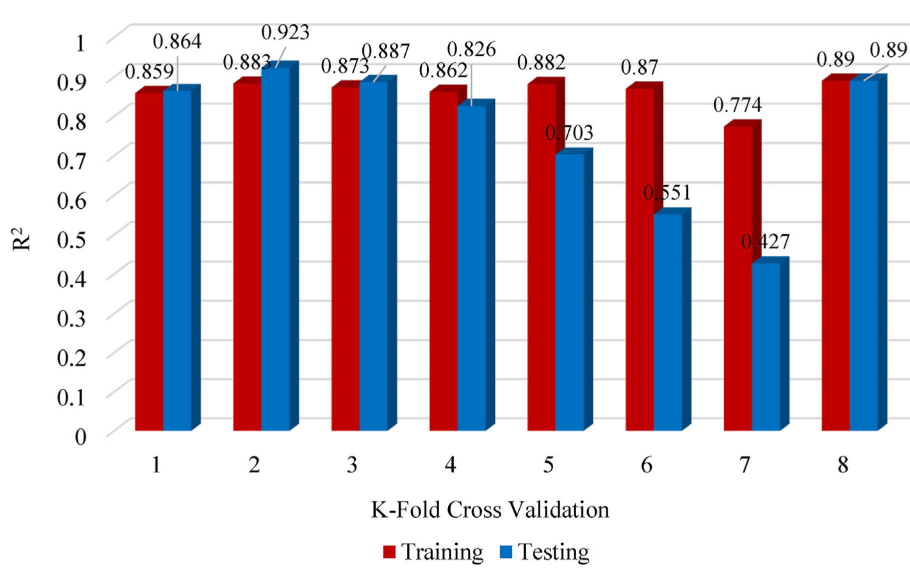


Fig. 12 — Performance of K-fold cross validation (K = 2) method for splitting tensile strength of concrete.

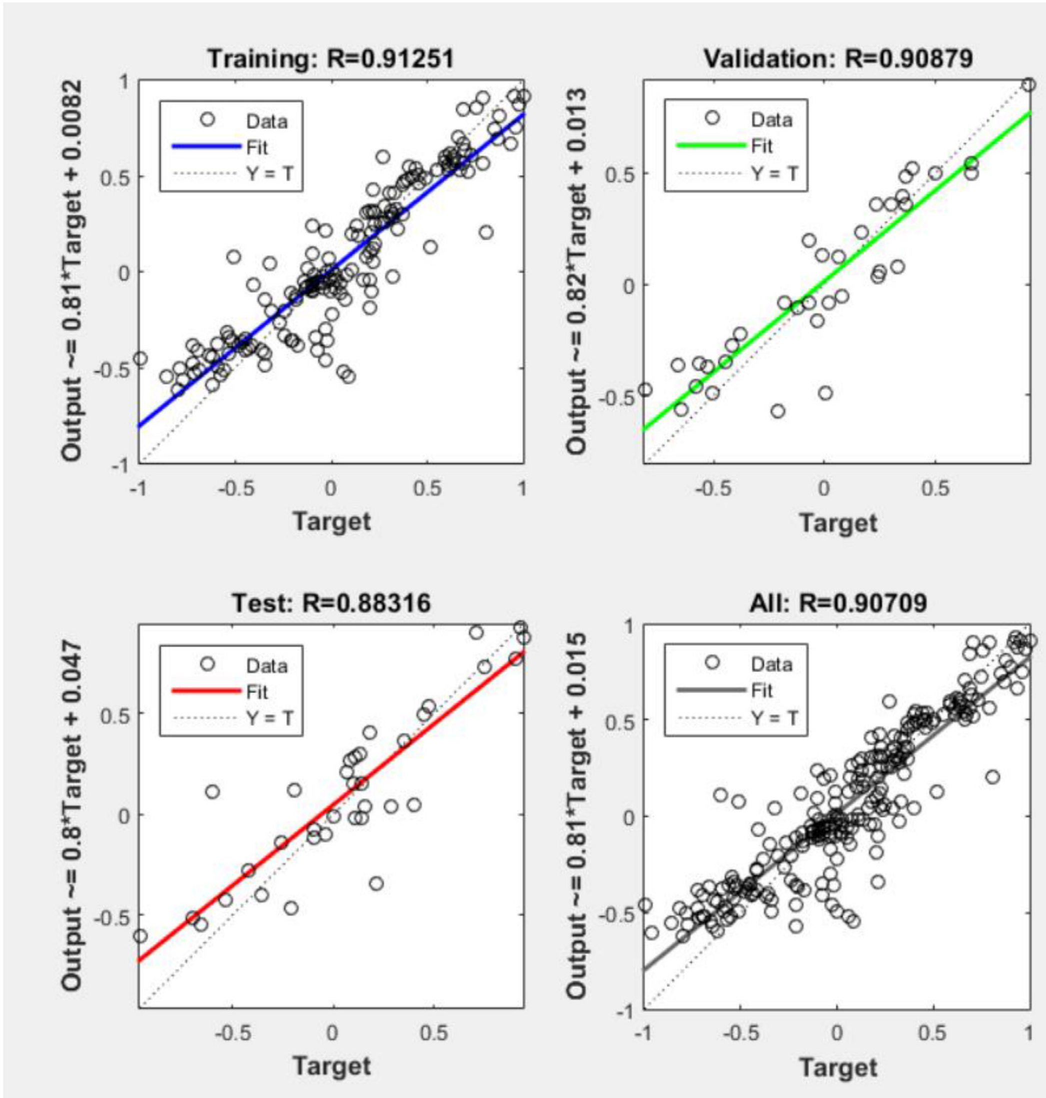


Fig. 13 – Prediction of flexural strength.

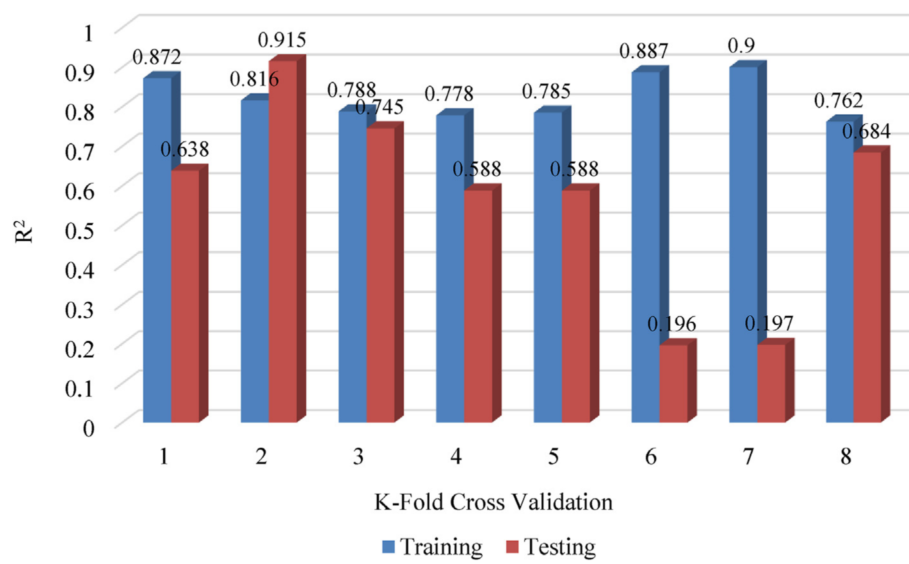


Fig. 14 – Performance of K-fold cross validation (K = 2) method for flexural strength of concrete.

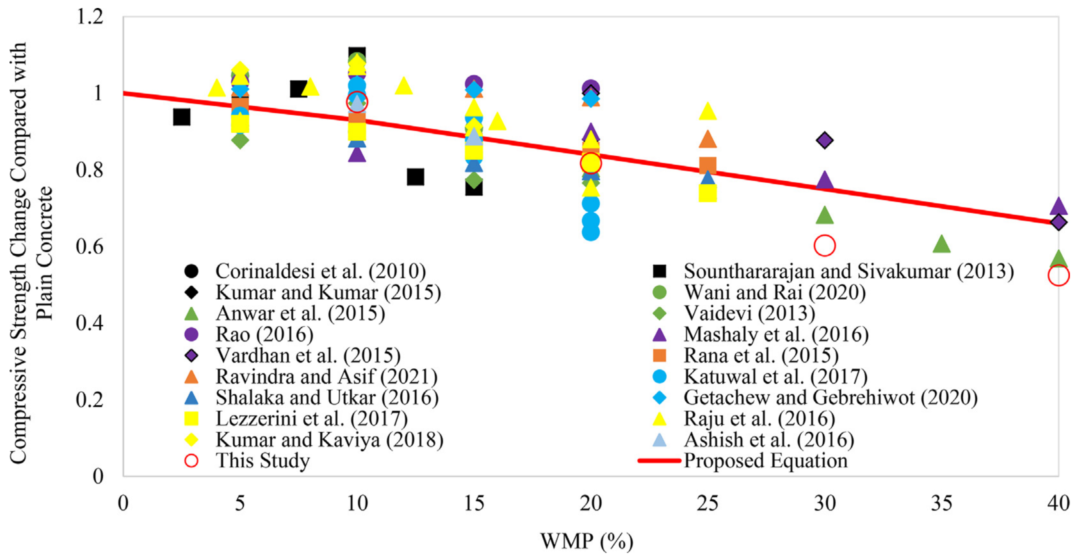


Fig. 15 – Compressive strength variation against WMP.

including the water–cement ratio, fiber content, and curing time. Sivanandan and Sivapriya [96] employed an ANN model to approximate the flexural strength of concrete utilizing the input parameters such as the water–cement ratio, curing time, and coarse aggregate content. Shahsavari et al. [97] used ANNs for the approximation of the flexural strength of fiber-reinforced concrete based on the input variables such as the fiber content, aspect ratio, and curing age. The prediction of the flexural strength of WMP blended concrete is displayed in Fig. 13.

Fig. 14 indicates how the K-fold cross validation (K = 2) was utilized to predict the flexural strength of WMP blended concrete. To obtain the optimized result, K = 2 (R^2 = 0.915) was achieved as the average of the training and testing results of ANN from Fig. 14. Denormalized data were used to approximate the flexural strength of concrete using Eq. (10) with the assistance of Eqs. (8) and (9). The constants, C_1 and C_2, were employed for the approximation of the denormalized flexural strength (FS) of WMP blended concrete in MPa.

$$C_1 = (-53.388)\mathrm{TanH}\,[(0.00546C) + (0.00589MP) - (0.0132W) + (0.00472FA) + (0.00567CA) - (0.0019A) - 10.3643] \quad (8)$$

$$C_2 = (-50.811)\mathrm{TanH}\,[(-0.006C) - (0.0064MP) + (0.01438W) - (0.0051FA) - (0.0062CA) + (0.00199A) + 11.30304] \quad (9)$$

$$FS = \mathrm{Tanh}(C_1 + C_2 - 1.0778) \quad (10)$$

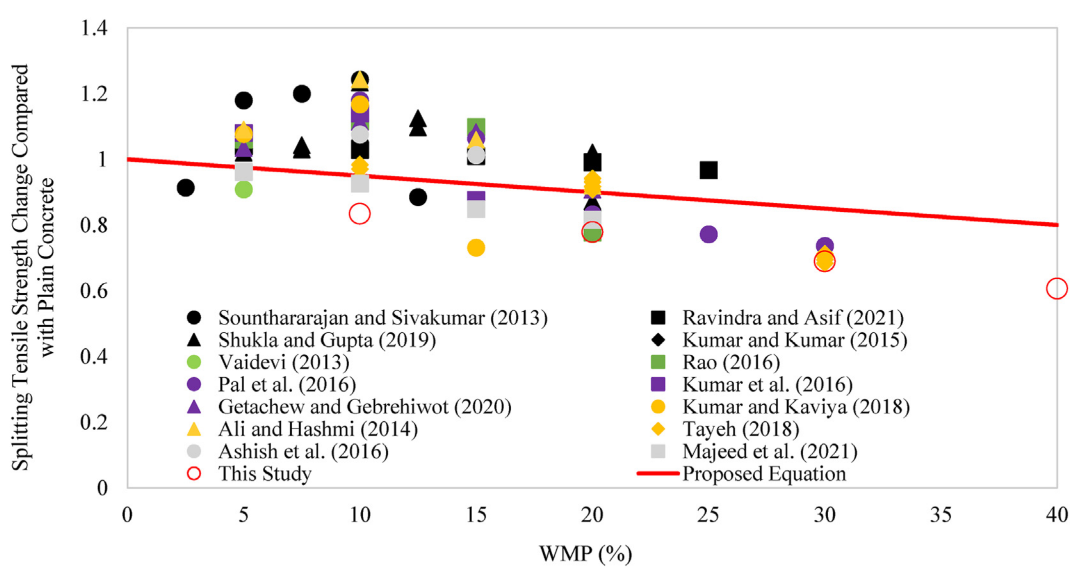


Fig. 16 – Splitting tensile strength variation against WMP.

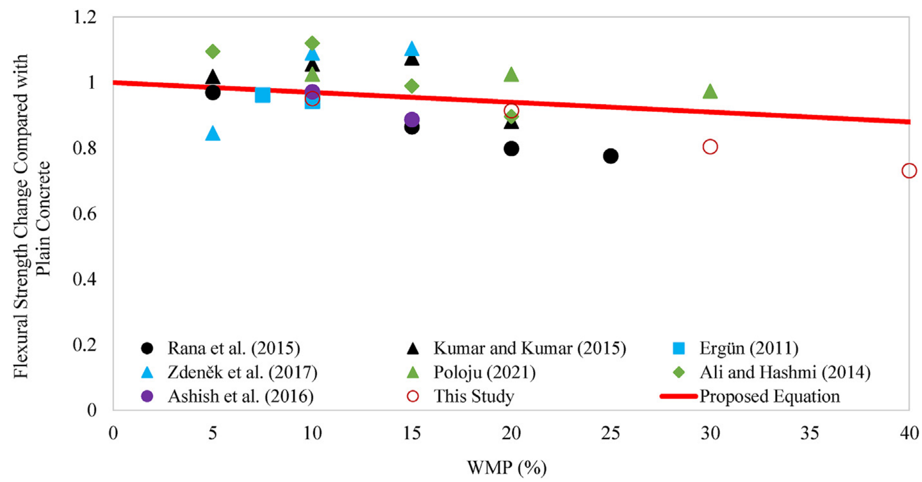


Fig. 17 – Flexural strength variation against WMP.

5. Assessment of capacities with simple calculations

The influence of WMP on production properties has been investigated by some researchers [35,73,73,75,83,98–116]. These studies have demonstrated the utilization of WMP in civil engineering applications. As a result, there has been a research need to develop empirical models for the mechanical properties of concrete produced using WMP. Variations of the compressive strength, splitting tensile strength, and flexural strength for plain concrete and WMP blended concrete were compiled from the previously mentioned studies. The plain concrete strengths were the primary determinants of the measured strength values of WMP blended concrete. These are depicted in Figs. 15–17 as the utilization of the WMP percentages for three different strength cases.

A design expression was proposed to approximate the compressive strength, splitting tensile strength, and flexural strength by taking into account findings of the current study and previous studies as follows:

$$f = [1 + c_1 \times (WMP)] \times f' \tag{11}$$

where f is the strength value to be considered, c_1 is the coefficient based on Table 3 for f_c: compressive strength, f_t: splitting tensile strength, and f_f: flexural strength, $0<WMP<40$, and f' is the strength value of plain concrete.

According to Eq. (11), the mechanical properties of WMP blended concrete were presented as a function of the quantity of WMP. These values can simply be used in the proposed phases.

Table 3 – Constants for Eq. (11).

Strength Values, f	c_1
f_c	−0.009
f_t	−0.005
f_f	−0.003

To predict the performance of WMP blended concrete, ACI 318 and Eurocode 2 (EC2) were selected to approximate the splitting tensile strength and compressive strength values. ACI 318 proposes the following equations.

$$f_f = 0.62\sqrt{f'_c} \tag{12}$$

$$f_t = 0.56\sqrt{f'_c} \tag{13}$$

where f_f and f_t are the flexural and splitting tensile strengths, respectively, and f'_c is the compressive strength after 28 days of curing. Moreover, EC2 proposes the equations below.

$$f_{ctm,fl} = \max\left(\left(1.6 - \frac{h}{1000}\right)f_{ctm}\right) \tag{14}$$

$$f_{ctm,sp} = 2.12\ln\left(1 + \left(\frac{f_{cm,cyl}}{10}\right)\right) \Big/ 0.9 \tag{15}$$

In the above equation, $f_{ctm,fl}$ is the flexural strength and h is the height of the sample. Additionally, f_{ctm} is the mean of the flexural strength reaching $0.3(f_{ck})^{2/3}$, where f_{ck} is the experimental value attained for the compressive strength minus 8 MPa. The splitting tensile strength ($f_{ctm,sp}$) is estimated from the tests values of the cylinder compressive strength ($f_{cm,cyl}$). Furthermore, Singh et al. [76] proposed the correlation between the compressive and flexural strengths of the sample (Eq. (16)) and also between the compressive and splitting tensile strengths of the sample (Eq. (17)).

$$f_f = 0.1362 f_c + 2.3589 \tag{16}$$

$$f_t = 0.0738 f_c + 2.7378 \tag{17}$$

Eqs. (18) and (19) are suitable proposed equations for the flexural strength and splitting tensile strength, respectively, taking into account WMP as the partial replacement of cement. It is witnessed that the proposed equations estimated the strengths with good accuracy (Figs. 18 and 19).

$$f_f = 0.2 f_c + 3.5 \tag{18}$$

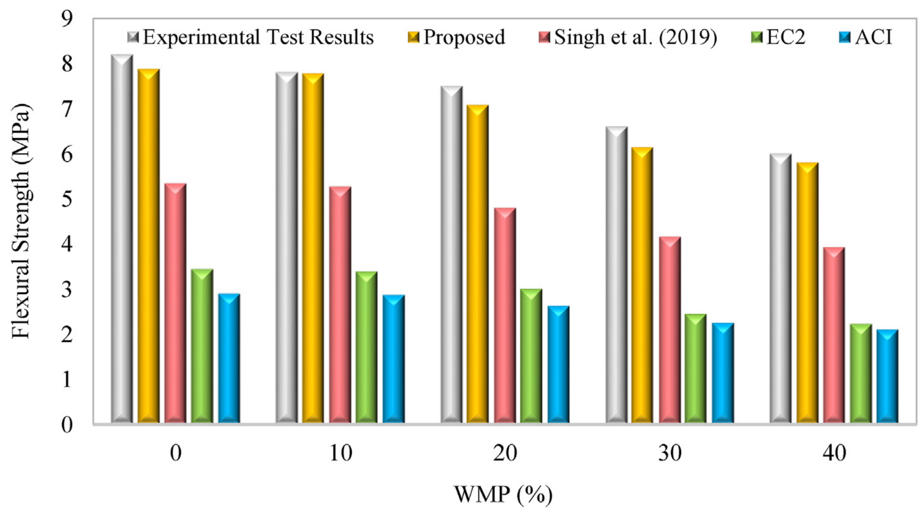


Fig 18 – Comparison of flexural strengths using different codes and proposed equation.

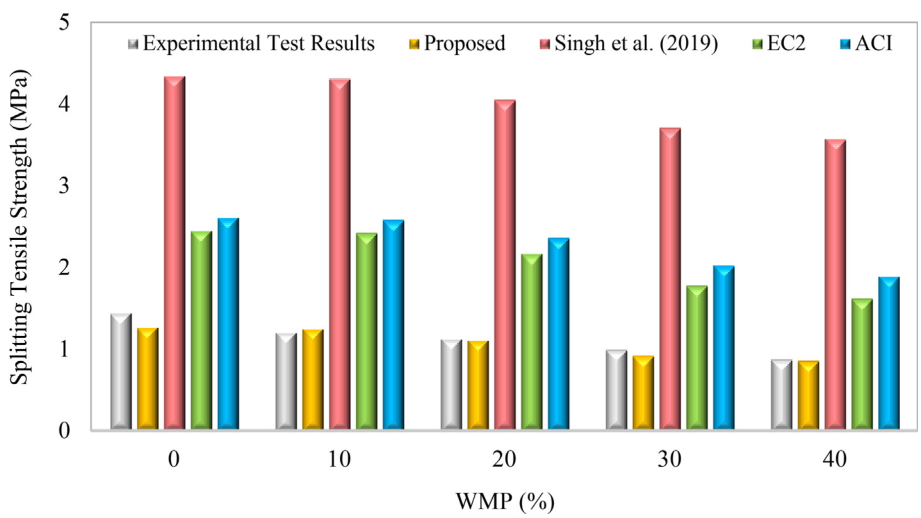


Fig 19 – Comparison of splitting tensile strengths using different codes and proposed equation.

$$f_t = 0.04 f_c + 0.4 \quad (19)$$

6. Microstructural analysis

6.1. Scanning electron microscope analysis

Scanning electron microscope (SEM) analysis was done to observe the internal interaction of the WMP blended concrete samples. The SEM images consist of 500-fold enlarged shapes that highlight the binding of WMP and cement together. The WMP hydration is similar to the cement hydration [117]. Fig. 20(a) displays that WMP blended concrete results in a good bonding in the general view. Fig. 20(b) illustrates WMP and cement via 250 magnitudes. The particles that make up WMP are in the form of a visible, spherical, and amorphous cavity of various sizes, ranging from ultra-fine micrometers [118]. It is seen in Fig. 20(c and d) that the WMP shape is spherical or very close to spherical. In Portland cement, ettringite may occur due to the early phase hydration [119,120]. Ettringite formation is observed in Fig. 20(c and d). WMP, which is a rich source of calcium, is formed as cemented bioclastic because it is activated by different chemicals owing to metaphoric deposits [121]. It is displayed in Fig. 20(e and f) that there are pores and separations owing to the expansion. Fig. 20(g) shows the formation of C–S–H in the form of limestone [122]. C–S–H formation in concrete is a chemical reaction that takes place during the hardening of concrete, which is formed by mixing cement, water, and aggregates. C–S–H compounds are the main components that reduce the durability and porosity of concrete. C–S–H compounds ensure the longevity and durability of concrete [123,124]. In general, the absence of cracks indicates that the mixing was done well and that the bonding among the materials was good. However, the interfacial transition zone (ITZ) seen in Fig. 20(h) signifies that it is prone to cracking when under high stress. In concrete, an ITZ is formed where two different elements are joined. These elements may have different chemical and structural properties [125]. ITZ is

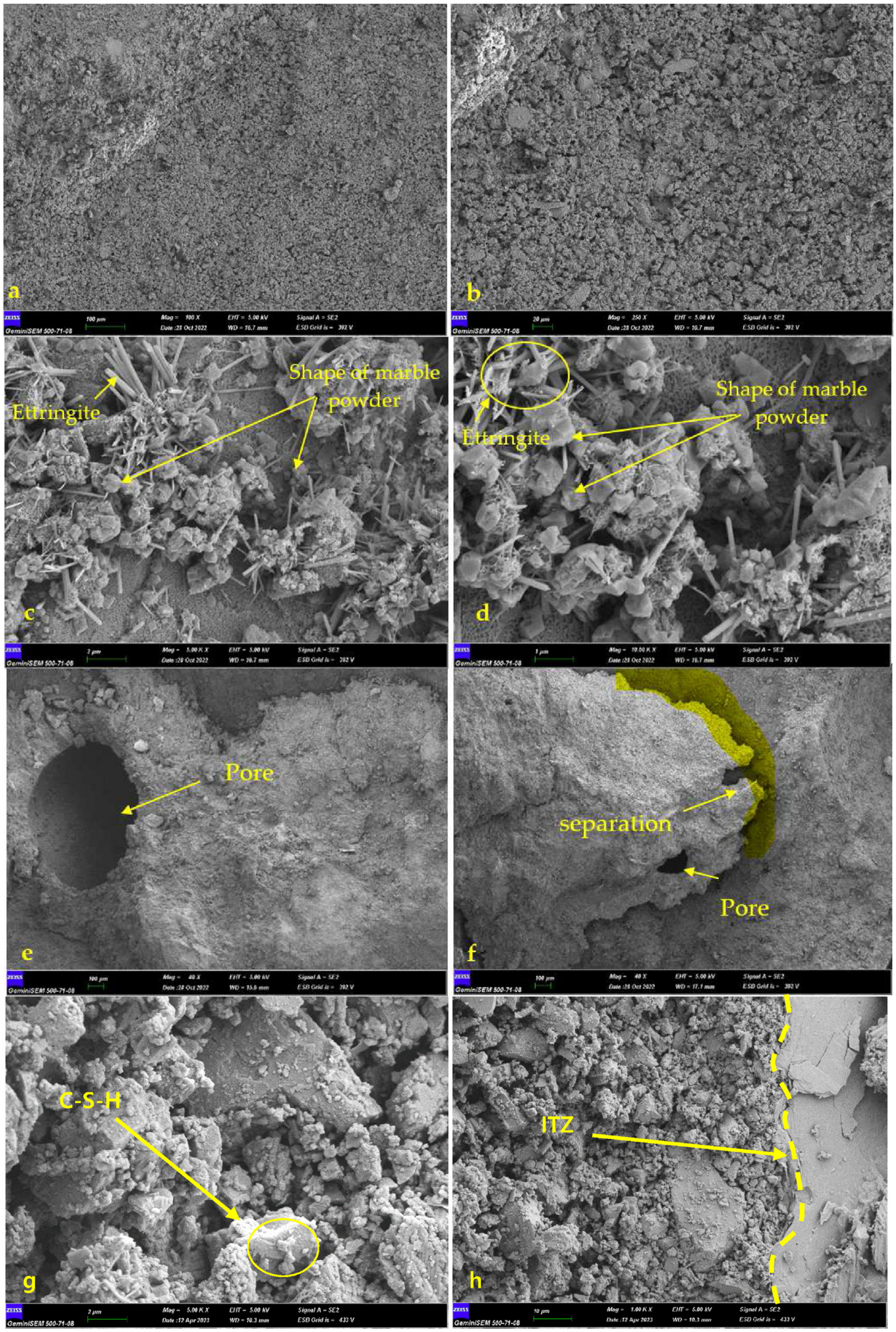


Fig. 20 – SEM analysis.

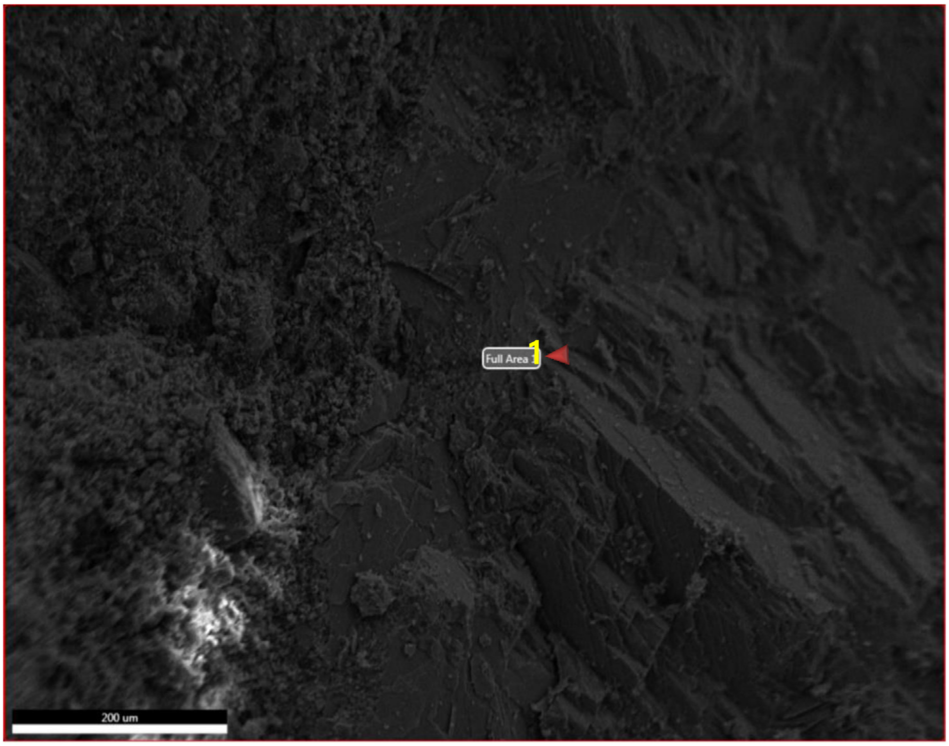


Fig. 21 – EDX analysis, area 1.

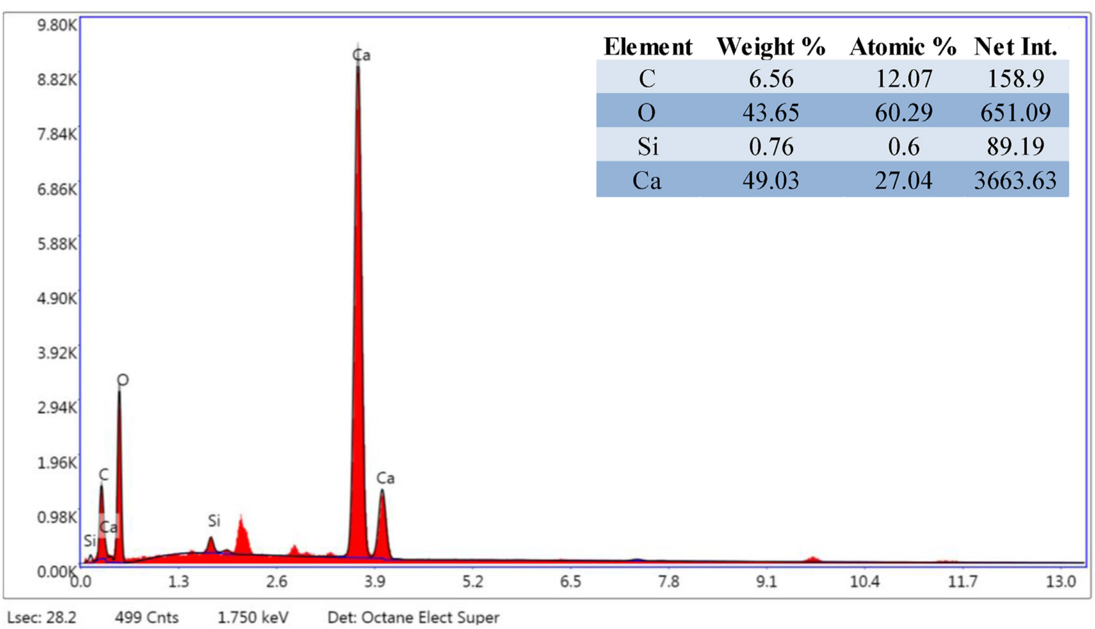


Fig. 22 – EDX analysis results from area 1.

important for the durability of reinforced concrete structures, and the strength of this zone ensures the longevity of the structures [126]. ITZ may occur more in pasty areas [127]. Therefore, ITZ can be reduced by better mixing and homogeneous distribution.

When the SEM results are summarized, first, it is concluded that WMP provides a good bonding with cement. It is revealed that WMP contributes to the early phase formation and the formation of ettringite. The absence of cracks uncovered that the mixture and proportions are good. ITZ, which

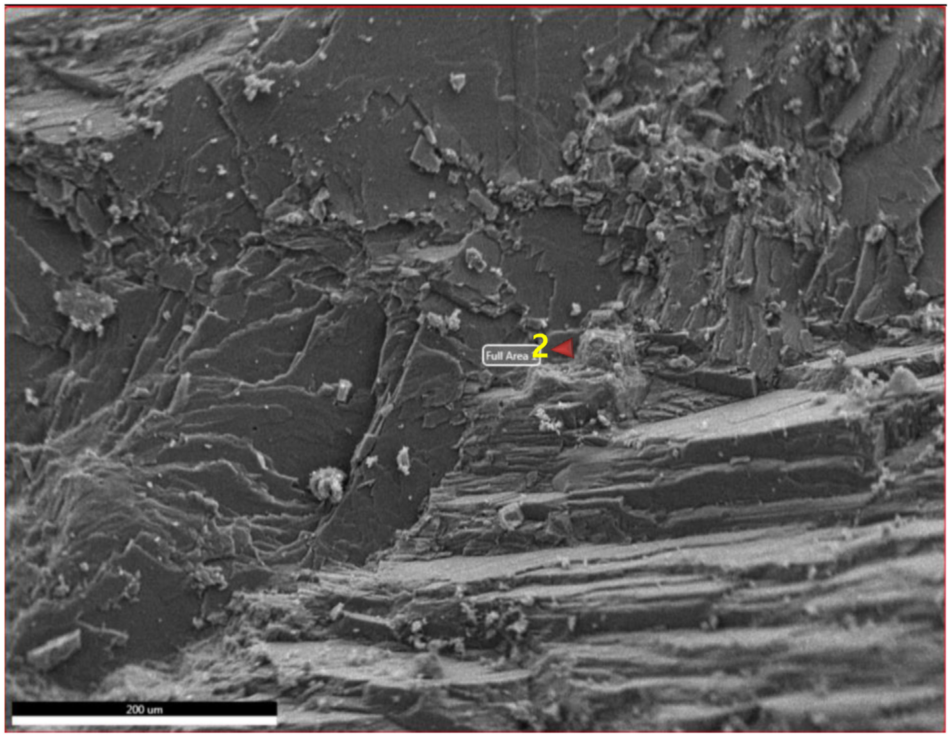
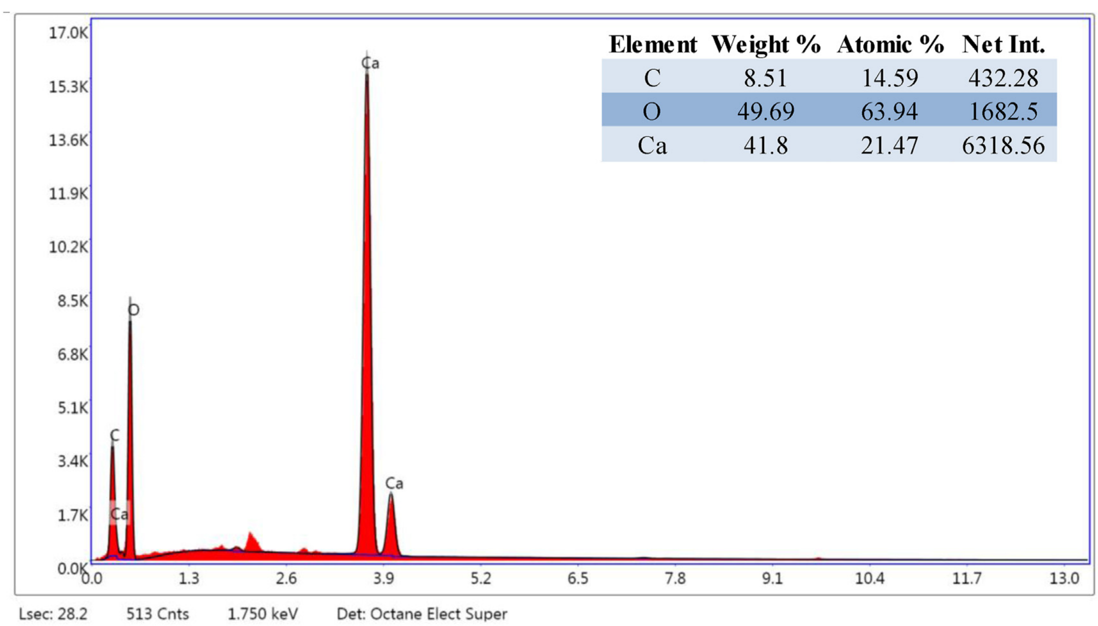


Fig. 23 – EDX analysis, area 2.



Element	Weight %	Atomic %	Net Int.
C	8.51	14.59	432.28
O	49.69	63.94	1682.5
Ca	41.8	21.47	6318.56

Fig. 24 – EDX analysis results from area 2.

is formed by the mixture of different chemical elements, is clearly seen and is a positive development in terms of the concrete strength.

6.2. *Energy dispersive X-ray analysis*

Energy dispersive X-ray (EDX) is an analysis technique chosen to define the chemical composition of a material. This technique works by collecting characteristic radiation from samples that have been excited with X-rays. EDX is a valuable technique that is widely used for understanding, especially in the characterization of complex composite materials such as concrete. Determination of chemicals and additive percentages in concrete with the EDX analysis is effective in determining performance such as the durability and strength. In the EDX technique, X-rays are utilized to determine the elements in the sample and emissions occur. With EDX, an electron beam is sent to a sample and this beam analyzes the atoms in the sample by excitation. Thanks to this excitation, atoms lose energy by emitting X-rays. These emissions create an energy spectrum and might be used to define the chemical composition of the sample [128–131].

In this study, the percentage and influences of WMP and chemical composition in concrete were tried to be determined by the EDX analysis from two different locations. According to the micro-morphology and EDX analysis in Fig. 21, it can be observed that the distribution of WMP in concrete is homogeneous and provides a tight bond.

The chemical compositions in the analyzed sample and the obtained results are depicted in Fig. 22. Carbon (C), oxygen (O), silicon (Si), and calcium (Ca) elements were determined for the full area. The figure provides information on EDX testing as a random spot. It is known that there is a high amount of Ca in WMP [132]. The results demonstrate that there are 49.03% Ca and 43.65% O concentrations. It is seen that this percentage makes a positive contribution to the concrete hydration. In addition, although C and Si percentages are not high, they are necessary elements for the formation of concrete.

In the image taken from another area in Fig. 23, it is clear that WMP has a homogeneous distribution and is a good binding material in concrete. The increase in the Ca concentration creates a density in the porosity of the internal structure, and its influence on the mechanical performance has also been expressed in previous studies [133,134].

In Fig. 24, the percentages of the chemical components in concrete are given. In this region, the high rate of Ca and O is noteworthy. The C percentage is seen at a lower level. The results indicate that the distribution is homogeneous.

In summary, the EDX analysis displays the effect of homogeneous distribution of WMP, which is a rich source of Ca, in cementitious concrete. It is witnessed that the presence of Si detected in addition to the high rate of Ca makes a good contribution for the formation of concrete.

7. Conclusions

The influences of dissimilar assemblies-based peculiarities of cement with different quantities of WMP as the cement replacement were investigated in this study. These percentages of the replacement were selected to be 10%, 20%, 30%, and 40%. The hardened and fresh conditions were compared. SEM and EDX were also completed to correlate the strength changes obtained from this research. Finally, helpful equations for predicting the compressive, splitting tensile, and flexural strengths of WMP blended concrete were achieved. The outcomes of this study can be summarized as follow:

- The experiments revealed that as results of the cement replacement with WMP, a reduction in the compressive strength was detected. The WMP replacement at 10%, 20%, 30%, and 40% of cement led to 5.7%, 21.7%, 38.1%, and 43.6% decreases in the compressive strength compared with REF. These reductions in the strength were primarily caused by the exchange of Portland cement by the WMP addition, which caused dilution.
- The implications of the splitting tensile strength frequently followed the same trend as the compressive strength. The splitting tensile strength at 10% WMP replacement was only 16.7% smaller than REF.
- When cement was replaced with WMP, the flexural strength decreased to a certain rate of WMP. It was discovered that 10%, 20%, 30%, and 40% WMP resulted in 5.3%, 8.6%, 19.4%, and 26.7% reductions in the flexural strength in comparison with REF (8.2 MPa).
- According to the SEM examinations, pores and separations caused by the expansion were detected. The EDX analysis revealed the effect of homogeneous distribution of WMP in concrete and the presence of Si with high rate of Ca.
- Furthermore, the established empirical equations of this study for the compressive, splitting tensile, and flexural strengths are relatively common, and they can be applied to WMP blended concrete. Correlations among the compressive and flexural strengths as well as the compressive and splitting tensile strengths were proposed. In addition to these simple calculations which are only based on the WMP percentage, more advanced calculations were proposed utilizing ANN.
- Using ANN, the capacities of WMP blended concrete were estimated with the help of the ingredients percentages. Statistical assessment was performed employing the coefficient of determination (R^2) for the K-fold cross validation method.
- In this research, it was also found that 10% WMP can be utilized as the replacement of cement for the optimum strength and cost. The cost of WMP is less than cement. As a result, it would support to decrease the cost of concrete while also assisting us in developing green and eco-friendly concrete.
- This area needs further research to address literature shortages on the performance of reused resources expended in concrete, including this material, to improve the perception of both researchers and practitioners working in this field.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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