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Prediction of Flexural Strength of Portland–Composite Cement Mortars Substituting Metakaolin Using Fuzzy Logic

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ABSTRACT

In this study, Fuzzy Logic models have been introduced to predict flexural strength values of cement mortars. For this purpose, reference cement mortar containing only Portland–composite cement, and mixtures having metakaolin replacing 5, 10, 15 and 20% by weight of the Portland–composite cement were produced. The mortars' flexural strength values were established at 2, 7, 28 and 56-day with standard cement test. In addition, Fuzzy Logic prediction models were created by using fuzzy triangular number coefficients and Gauss membership function to predict flexural strength of cement mortars. Subsequently, experimental with fuzzy results are compared. Accordingly, the correlation coefficient of flexural strength of cement mortars for fuzzy triangular number coefficients and Gauss membership function were found 0.84 and 0.87, respectively. These results show that between experimental and fuzzy results are a good harmony, and can be successfully applied in civil engineering applications.

Metakaolin İkameli Portland Kompoze Çimento Harçlarının Eğilme Dayanımının Bulanık Mantık Yaklaşımıyla Tahmin Edilmesi

ÖZET

Bu çalışmada, çimento harçlarının eğilme dayanım değerlerini tahmin etmek için Bulanık Mantık tahmin modelleri geliştirilmiştir. Bu amaçla, referans ve %5, 10, 15 ve 20 oranında metakaolin ikameli çimento harçları üretilmiştir. Üretilen bu harçların eğilme dayanım değerleri 2, 7, 28 ve 56. günlerde standart çimento deneyleri ile tespit edilmiştir. Ayrıca, çimento harçlarının eğilme dayanımlarını tahmin etmek için üçgen bulanık sayı katsayıları ve Gauss üyelik fonksiyonu kullanılarak, Bulanık Mantık tahmin modelleri oluşturulmuştur. Deneysel sonuçlar Bulanık Mantık sonuçlarıyla karşılaştırılmıştır. Sonuç olarak, bulanık üçgen sayı katsayıları ve Gauss üyelik fonksiyonu için çimento harçlarının eğilme mukavemeti korelasyon katsayıları sırasıyla 0,84 ve 0,87 olarak bulunmuştur. Bu sonuçlar, test sonuçları ile bulanık sonuçlar arasında iyi bir uyum olduğunu ve inşaat mühendisliği uygulamalarında başarıyla uygulanabileceğini göstermektedir.

I. INTRODUCTION

In the last few decade, advancements on cement and concrete industry lead to the utilization of supplementary cementitious materials (SCMs). Commonly utilized SCMs are fly ash, silica fume, rice husk ash, blast furnace slag, zeolite, trass, diatomite in Portland cement (PC) have attracted very high interest [1–6]. Recently, Metakaolin (MK) is receiving a lot of attention, and is commonly used as popular SCMs in cement and concrete.

MK is an ultra-fine pozzolan and anhydrous aluminosilicate material. MK is produced by controlled calcination of kaolin clay at 650–800 °C to destroy the crystalline structure and remove off chemically bound water [7, 8]. Specific surface area of MK is almost from 10 to 25 m^2/g, and particles size is usually in the range of 2–10 μm [8]. MK has high pozzolanic reactivity, surface area and other excellent properties, and has attracted considerable attentions of a large number of scientists because of these features [9–12]. With the use of MK, mechanical characteristics of concrete, including modulus of elasticity, they observed that both flexural, splitting tensile and compressive strengths have been improved significantly [13–16]. Inclusion of MK in concrete not only improves the mechanical properties of concrete, but also improves its durability properties [17-20].

SCMs in cement and concrete industry are commonly used because of the technical, economic and ecological advantages. In this industry, it causes losses in both time and financial costs for preparing the cement mortars and concretes by using various additives. By using various calculation methods, these losses are eliminated. While some researchers prefer statistical methods, other researchers prefer the expert systems. Both Adaptive Neuro-Fuzzy Inference System, and Artificial Neural Networks, have become popular, and have been used via many scholer to solve different problems in civil engineering applications (21-28). On the other hand, recent experimental civil engineering studies exploit fuzzy logic models, and the results have achieved satisfying accuracy performance. Fuzzy logic is an artificial intelligence model, which enable computers to make accurate decisions. In terms of the model, input values are fuzzified among 0 and 1 in continuous form. In order to set decision hallmarks, it is necessary to form rule tables [29]. Nowadays, fuzzy logic has been applied to scientific fields of construction widely. Gulbandilar and Kocak studied the analysis of the cements, which are procurred by substituting PC with different ratios of silica fume and fly ash on setting times. Their predictions are provided by using fuzzy logic. According to the results, they introduced fuzzy logic approaches that establish correlation among cement's setting time, the silica fume and fly ash [30]. Tanyildizi investigated a fuzzy logic model during the analysis of lightweight concrete and bond strength. He found that experimental results are effective. They introduced that fuzzy logic can be utilized during bonding strength estimation of concrete with lightweight feature [31]. Demir devised fuzzy modeling to determine the elasticity of concrete. The results indicated that there is a good correlation between the chemical tests and computer based fuzzy logic results [32]. Güler et al. investigated another fuzzy model to assess high strength concrete under uni-axial loading. They indicated that test data cannot be easily defined mathematically, whereas a fuzzy approach enables to define the data more accurately. They also stated that the fuzzy logic predicted lab tests accurately [33].

This study researches the flexural strength of the cements formed with the substitution of MK at different rates on days of 2, 7, 28 and 56. Assessed fuzzy logic based flexural strength prediction results of were compared to the reference values of cement mortars.

II. MATERIALS AND METHODS

We utilize CEM II/B-M (V-L) 42.5 R type Portland–composite cement, metakaolin (MK), aggregate and water. We purveyed Portland–composite cement (PCC), produced in Mersin Cement Factory, and it is used as reference. MK was supplied from the Micron's Company (Turkey). We ensured that CEN standard aggregate conforms TS EN 196–1 [34] and were used during mortar specimens preparation.

We utilize tap water from Mersin province. Chemical and physical specifications of the PCC and MK are given in Table 1.

Table 1. Chemical and physical features of PCC and MK.

Materials	PCC	MK
Chemical composition, wt.%		
SiO_2	21.59	58.25
Al_2O_3	6.14	20.03
Fe_2O_3	3.14	0.46
CaO	59.56	9.71
MgO	2.6	1.54
SO_3	2.95	1.58
Na_2O	0.31	0.24
K_2O	1.03	0.92
Reactive CaO	0.60	-
Physical specifications		
Residue on 45- µm sieve, %	2.0	1.00
Blaine, cm^2/g	3670	9180
Specific gravity, g/cm^3	3.06	2.59

In this study, five different cements are used. The produced cement names are given in Table 2.

Table 2. Chemical and physical specifications of PCC and MK.

Number	Type of cement	Names of Cement
1	PCC (CEM II/B-M (V-L) 42.5 R)	R
2	MK replaced cement, 5%	MK1
3	MK replaced cement, 10%	MK2
4	MK replaced cement, 15%	MK3
5	MK replaced cement, 20%	MK4

We evaluated the specific gravity, surface areas, particle size and chemical analysis of PCC and MK by Hosokowa-Alpine Air Jet Sieve 200 LS-N, Toni Technik 6565 Blaine, Quantachrome MVP–3 and ARL 8680 S X–ray diffraction, respectively. During the mortar specimen mix preparation, a mix was designated as 6/2/1 contains 6 parts of standard sand (1350 g), 2 parts of cement (450 g) and 1 part of water (225 g) in accordance with TS EN 196–1 [34]. After mix phase, the mixtures were cast into 40x40x160 mm size three–section rectangular prism mold. Afterwards, mixtures were put into the chamber. We set humidity to 90%. On the other hand, 20±1°C temperature is ensured. Processed molds were taken out after 24 hours. Specimens were cured in the water with 20±1 °C. Samples were taken from the pool at 2, 7, 28 and 56-day, and tested to determine flexural strength in accordance with TS EN 196-1 [34].

III. FUZZY ALGORITHM FOR PREDICTION OF FLEXURAL STRENGTH

The fuzzy system used to predict flexural strengths was designed with MatLab Toolbox. For the fuzzy logic system, the weight percentage of MK as the first input and the time as the second input were used. We present the membership functions of the inputs in Figure 1.
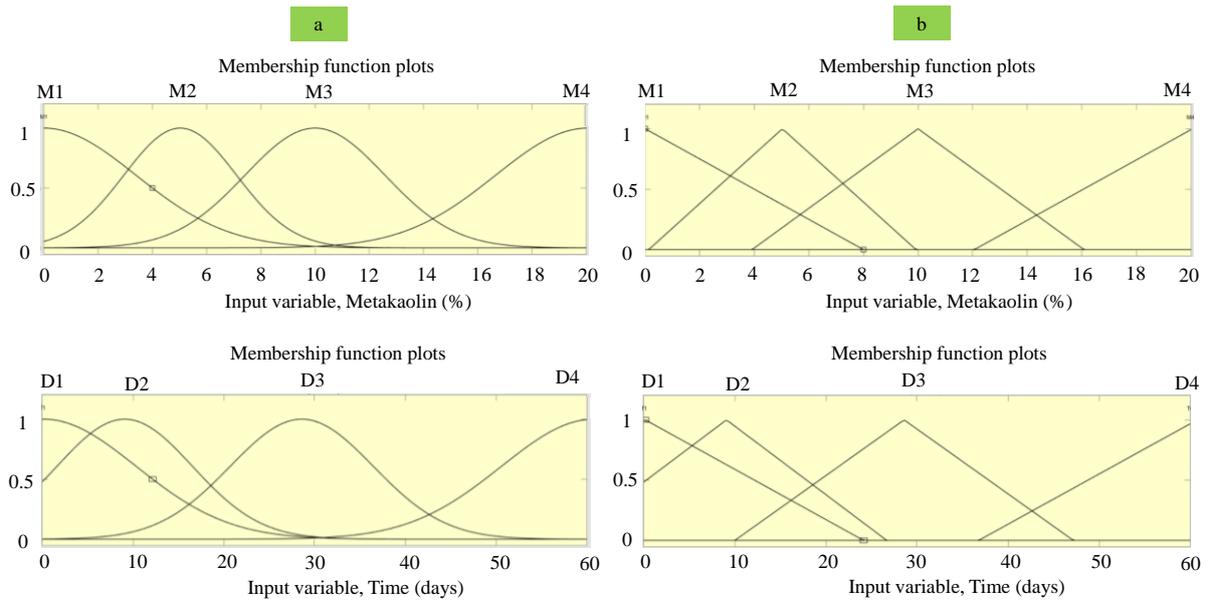
Figure 1. *Membership functions of input variables.*

In the models, Gauss (Figure 1a) and triangular (Figure 1b) membership functions are used. In the process, crisp input variables split into four for MK percentage ratios and time (days), respectively. Experimental results were taken into account when determining the shape and values of fuzzy sets. In calculation of membership degrees, for Gauss membership functions are used Equation 1.

$$\mu(x) = \exp\left(-\left(\frac{x-b}{\sigma}\right)^2\right) \tag{1}$$

In the relationship in equation 1, b is a model value (center), and σ is a range factor (width for $\mu(x) = 0.5$). When MK ratio is at least 20%, membership degree of M4 set becomes 1, and the membership degrees of other sets become 0. If the MK ratio is 15% and we set membership degrees of M1 and M2 as 0, membership degrees of sets M3 and M4 will be computed as 0.11 and 0.15, respectively.

Note that Equation (1) is also utilized during fuzzification of days versus flexural strength. For instance, if the flexural strength is at 10-day, the membership degrees of D1, D2, D3 and D4 sets can be calculated 0.73, 1, 0.08 and 0, respectively.

For triangular membership functions are used equation 2. Equality is given 2;

$$\mu(x) = \begin{cases} 0 & \text{for} \quad x < a \\ \dfrac{x-a}{b-a} & \text{for} \quad a < x < b \\ \dfrac{c-x}{c-b} & \text{for} \quad b < x < c \\ 0 & \text{for} \quad c > 0 \end{cases} \tag{2}$$

In Equation (2), a, b and c denotes the crisp values of triangular membership function. For instance, when MK rate is at least 20 %, membership degree of M4 will be 1, whereas rest of the sets membership degrees will be 0. On the other hand, given that MK is 15 % and membership degrees of M1 and M4 sets are 0; we can compute membership degrees of sets M2 and M3 as 0.29 and 0.21, respectively.

Equation 2 is also utilized during computation and fuzzification of parameters: days versus flexural strength. As an example, given that flexural strength is observed as 10-day, the membership degree of D1, D2, D3 and D4 sets can be computed 0.60, 1, 0.00 and 0.00, respectively.

The membership functions of the output variable for Gauss (Figure 2-a) and triangular membership functions (Figure 2-b) were preferred triangle shapes. The shape of output membership functions has been determined taking into account the experimental results.
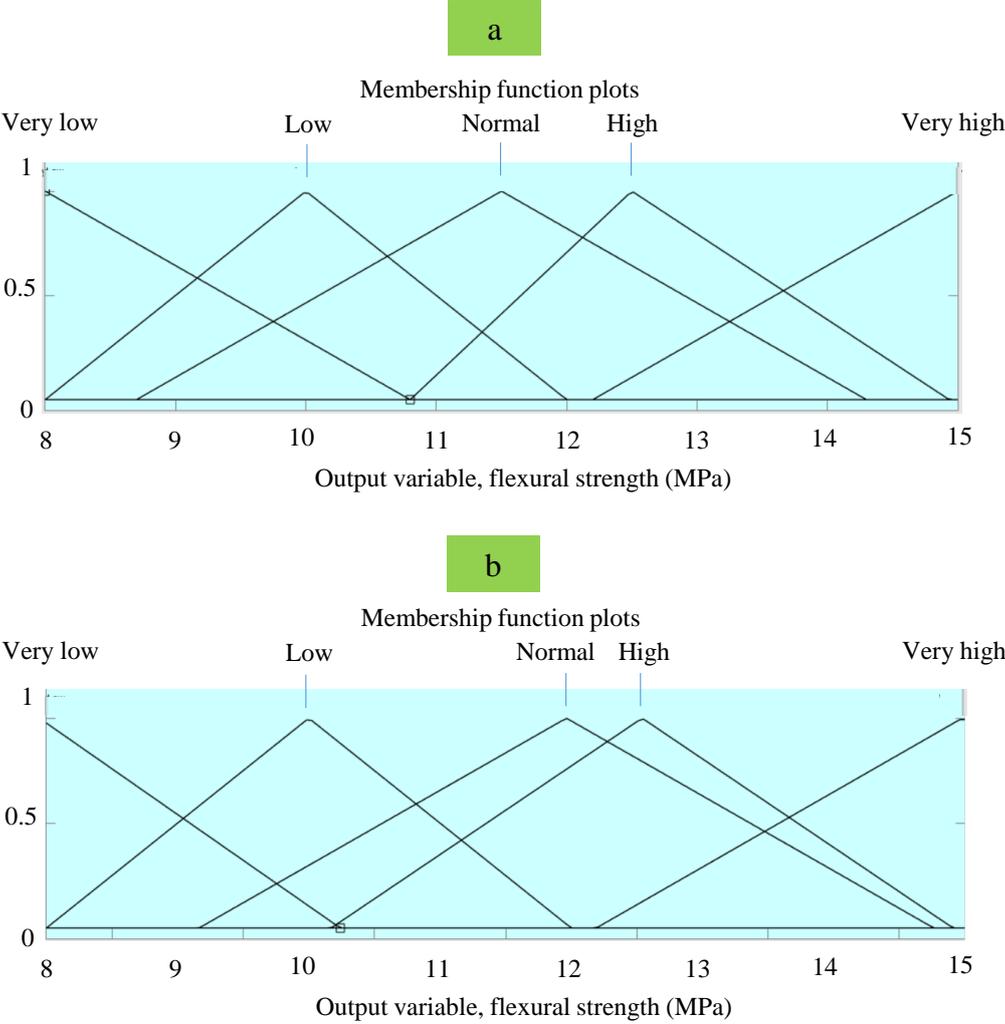

Figure 2. *Fuzzy subset membership functions according to flexural strength.*

The fundamental design pattern of fuzzy based decision-making is its rule-base. In other words, the computer input these rules as basis to decision setting. For his goal, field experts are referenced during matrice generation. In this context, firstly, rule matrices have been generated for the flexural strength of cement mortars by taking into account the professional experiences and experimental results and shown in Table 3 [35].

Table 3. *Rule base of flexural strengths (MPa).*

	M1	M2	M3	M4
D1	Low	Very Low	Low	Low
D2	Very Low	Low	Very Low	Very Low
D3	High	High	Normal	Normal
D4	High	Very High	Very High	High

Here, a total of 16 "If-then" relationships were obtained for the input variables of the flexural strength of cement mortars. Some of them are exemplified below.

If (time is D1) and (metakaolin is M1) than (flexural strengths is Low)

If (time is D2) and (metakaolin is M2) than (flexural strengths is Very Low)

If (time is D3) and (metakaolin is M3) than (flexural strengths is Normal)

If (time is D3) and (metakaolin is M4) than (flexural strengths is *High*)

If (time is D4) and (metakaolin is M3) than (flexural strengths is Very *High*)

As denoted, relationships are linked with the conjunction "and", on the assumption that the inputs of "If-then" relations are considered. In a logical relationship, while assigning membership degrees to output sets, the combination of "and" assigns minimum input membership degrees. Based on the relationship, "max-min inference" can be employed during fuzzy inference. In order to introduce defuzzification, in the last phase of fuzzification, we chose eighted average technique. Overall, the method is introduced by the equation 3 as shown below;

$$x^* = \frac{\sum_{i=1}^{n} \mu_i(x).x_i}{\sum_{i=1}^{n} \mu_i(x)} \tag{3}$$

In the relationship in equation 3, x^*, μ_i and x_i show defuzzification output value, the membership, each rule's output degree, and each rule's weighted average, accordingly [35, 36].

IV. RESULTS AND DISCUSSION

We depict the flexural strengths and corresponding fuzzy logic performances of cement mortar specimens at 2, 7, 28 and 56-day in Table 4, 5, 6 and 7 as follows:

Table 4. Cement mortars' flexural strengths at 2-day (MPa).

Number of samples	Cements				
	R	MK1	MK2	MK3	MK4
1	8.6	9.0	8.7	9.1	8.7
2	8.9	9.4	8.3	8.1	8.6
3	8.8	8.7	8.5	8.7	8.3
Average	**8.8**	**9.0**	**8.5**	**8.6**	**8.6**
Index,%	100.0	102.3	96.6	97.7	97.7
Predicts with fuzzy logic, Gauss	**9.24**	**9.09**	**9.50**	**9.30**	**9.24**
Predicts with fuzzy logic, triangler	**9.25**	**9.07**	**9.53**	**9.38**	**9.25**

Table 5. Cement mortars' flexural strengths at 7-day (MPa).

Number of samples	Cements				
	R	MK1	MK2	MK3	MK4
1	10.8	11.0	10.4	11.2	10.2
2	10.8	9.8	10.6	10.3	9.6
3	10.57	10.0	10.19	10.44	10.27
Average	**10.7**	**10.3**	**10.4**	**10.6**	**10.0**
Index,%	100.0	96.3	97.2	99.1	93.5
Predicts with fuzzy logic, Gauss	**9.13**	**9.19**	**9.50**	**9.30**	**9.13**
Predicts with fuzzy logic, triangler	**9.19**	**9.25**	**9.63**	**9.52**	**9.18**

Table 6. *Cement mortars' flexural strengths at 28-day (MPa).*

Number of samples	Cements				
	R	MK1	MK2	MK3	MK4
1	12.7	12.0	11.1	11.6	11.9
2	12.5	12.9	10.9	11.5	11.9
3	12.7	13.2	12.2	12.2	12.1
Average	**12.6**	**12.7**	**11.4**	**11.7**	**11.9**
Index,%	100.0	100.8	90.5	92.9	94.4
Predicts with fuzzy logic, Gauss	**12.00**	**11.90**	**11.50**	**11.50**	**11.50**
Predicts with fuzzy logic, triangler	**11.90**	**11.80**	**11.00**	**11.00**	**11.00**

Table 7. *Cement mortars' flexural strengths at 56-day (MPa).*

Number of samples	Cements				
	R	MK1	MK2	MK3	MK4
1	14.1	14.2	14.5	14.0	13.3
2	12.7	14.3	13.0	13.1	13.1
3	13.9	13.6	14.6	13.6	12.1
Average	**13.6**	**14.0**	**14.0**	**13.6**	**12.8**
Index,%	100.0	102.9	102.9	100.0	94.1
Predicts with fuzzy logic, Gauss	**12.00**	**11.90**	**11.50**	**11.50**	**11.50**
Predicts with fuzzy logic, triangler	**12.00**	**12.80**	**13.50**	**12.10**	**12.00**

Results concretely denotes that flexural strengths of the mortar samples depend on hardening time, curing conditions, specific surface areas, particle size and substitution rate. When we compare results and reference mortar samples we observe the following evaluations as follows:

Given that 5% MK substitution to PCC, we observed that flexural strengths of the mortar specimens rise 2.3% at 2-day, 0.8% at 28-day and 2.9% at 56-day. Meanwhile, same environment lead to decrease by 3.7% when 7-day passed. Given that 10% MK replacement to PCC is ensured, flexural strength of the mortar specimens dwindle 3.4% at 2-day, 2.8% at 7-day and 9.5% at 28-day; whereas, it rised 2.9% at 56-day. On the assumption that 15% MK replacement to PCC is provided, the flexural strength of the mortar specimens dwindle 2.3% at 2-day, 0.9% at 7-day, 7.1% at 28-day and 0.0% at 56-day. Finally, given that 20% MK substitution to PCC is ensured, the flexural strength of the mortar specimens decreased by 2.3% at 2-day, 6.5% at 7-day, 7.1% at 28-day and 5.9% at 56-day (Table 4-7).

According to the findings obtained in the study, we observed a clear increase at 56-day, when compared to 2-day and 7-day, concerning with the relative flexural strength. Therefore we can cocnlude that there exists a clear increase, because of the pozzolanic reaction of MK. Flexural strengths, obtained from experimental and fuzzy predict results, of cement mortars at 2, 7, 28 and 56-day were given in Figure 3.
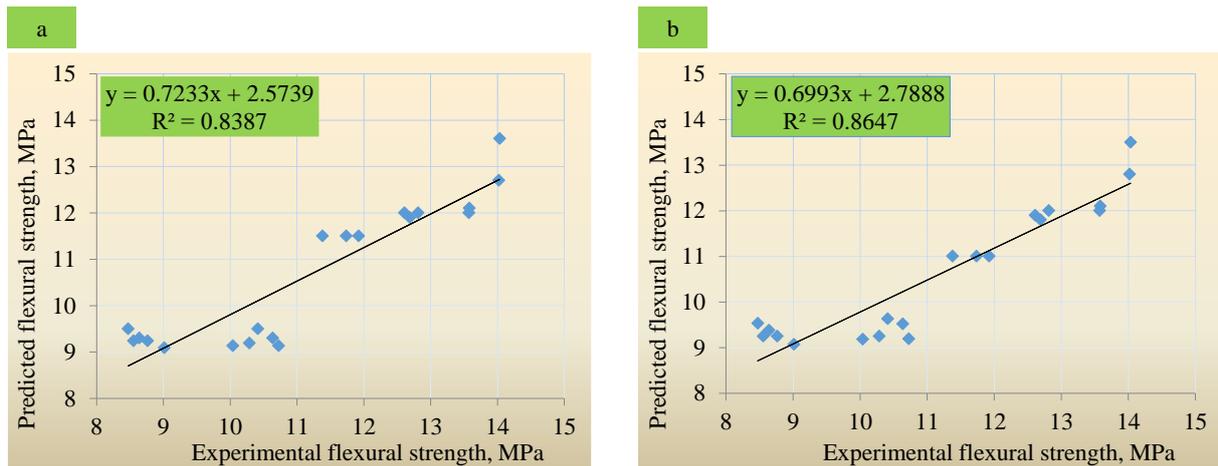
Figure 3. *Comparison of experimental and predicted values for flexural strengths.*

The linear least square fit line, its equation and the R2 values, for the experiments and the predictions made by the fuzzy logic (Gauss and triangler membership function) were shown in Figure 3. As a result, R2 for Gauss membership function in Figure 3-a is 0.84, and R2 for triangular fuzzy number coefficients in Figure 3-b is 0.87. As it is visible in Figure 3, the values obtained from fuzzy logic models are very close to the experimental results, and can generalize with reasonably good predictions.

V. CONCLUSION

This study analyzes the effects of MK addition to PCC on the flexural strengths. Furthermore, fuzzy logic based prediction models are presented that predicts the flexural strengths. Finally experimental results and computational predictions are evaluated.

Accordingly;

- The flexural strengths of the reference cement mortars (R) were obtained 8.8 MPa at 2-day, 10.7 MPa at 7-day, 12.6 MPa at 28-day and 13.6 MPa at 56-day.
- When MK is substituted into PCC in 5% ratio (MK1), the flexural strengths of the mortar were obtained 9.0 MPa at 2-day, 10.3 MPa at 7-day, 12.7 MPa at 28-day and 14.0 MPa at 56-day.
- When MK is substituted into PCC in 10% ratio (MK2), the flexural strengths of the mortar were obtained 8.5 MPa at 2-day, 10.4 MPa at 7-day, 11.4 MPa at 28-day and 14.0 MPa at 56-day.
- When MK is substituted into PCC in 15% ratio (MK3), the flexural strengths of the mortar were obtained 8.6 MPa at 2-day, 10.6 MPa at 7-day, 11.7 MPa at 28-day and 13.6 MPa at 56-day.
- When MK is substituted into PCC in 20% ratio (MK4), the flexural strengths of the mortar were obtained 8.6 MPa at 2-day, 10.0 MPa at 7-day, 11.9 MPa at 28-day and 12.8 MPa at 56-day.
- R2 for Gauss membership function is 0.84.
- R2 for triangular fuzzy number coefficients is 0.87.

According to the findings obtained in the study, at 56-day flexural strengths shows a clear improvement, Fundamental factor of the improvement is the pozzolanic reaction of the MK. As a result of the evaluation, we can conclude that MK affects the long–term cement mortars' flexural strength in a positive way. Furthermore, we can say that, between experimental and fuzzy results there is a good harmony, and Fuzzy Logic prediction models can be successfully applied in civil engineering applications.

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