Fuzzy logic model for investigating the effect of steel fibers on mechanical properties of concrete

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Abstract

This study aimed to use fuzzy logic model to predict various mechanical properties such as compressive strength, flexural strength and post-peak deformation of steel-fiber reinforced concrete. For this purpose, five different dosages of steel fibers (10 kg/m³, 12.5 kg/m³, 15 kg/m³, 17.5 kg/m³ and 20 kg/m³) were used in the mix design. A total of 3 specimens (cylinders and beams) were casted for each fiber dosage and experimentally tested. The experimental results were compared with the simulated results obtained from fuzzy model using fuzzy logic toolbox provided in MATLAB®. It was found that the addition of steel fibers improved the flexural strength and post-peak deformation capability of test specimens by almost 12% and 20% respectively. The compressive strength of specimens also increased by 9.15%, when the amount of steel fibers was increased from 10 to 20 kg/m³. Overall, the compressive strength reduced with the addition of fibers as compared to specimens with no fibers. Similarly, it was also observed that fuzzy model can predict the study parameters within acceptable accuracy and the percentage difference between the simulated and experimental values was below 7.5%.

Keywords Concrete · Steel fibers · Fuzzy logic application · Flexural strength

1 Introduction

Concrete is recognized for its widespread use and durability. It has applications in almost every infrastructure like rigid pavements, the structural components of buildings and bridges and even, concrete made pipes which are used for the conveyance of sewage. Concrete is very strong in compression but, in most of the cases, its ability to resist tension and flexural loadings is challenged [2, 3]. To overcome the weakness of concrete in tension, mild-steel reinforcement is used. However, the trend is now changing and efforts have been made by various researchers like [1–3], by incorporating different types of fibers like steel fibers, glass fibers, polypropylene fibers and their combination, to improve the tensile and flexural strength of concrete.

Efforts have been made to study the impact of steel fibers on the compressive strength of specimens through various studies [1, 4, 5]. For example, the study conducted by Yoo and Yoon [5], showed that the incorporation of steel fibers did not improve the compressive strength of concrete considerably. For example, the compressive strength obtained for control and specimen with a reinforcement ratio of 1.5% was 201 MPa and 211 MPa respectively. Similarly, Wu et al. [4] also observed that the amount of steel fibers made negligible improvements in the compressive strength of specimens. According to experimental results, the compressive strength only improved by 12% for a steel fibers dosage of 0.9%. Similar results were reported by Lee et al. [6], in which the incorporation of steel fibers did not improve the compressive strength of concrete specimens considerably.

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In contrast, it has been observed that the addition of steel fibers has major positive impact on the flexural strength of specimens [1, 2, 7, 8]. The experimental program carried-out by Yoo et al. [9], involved testing of full-scale beam specimens. It was observed that the addition of steel fibers enabled the specimens to take more flexural load and ensured high post-peak stiffness. The flexural strength increased by almost 20% as compared to specimens without steel fibers. During testing of specimen under flexural load, it was observed that the specimen showed a ductile failure mode due to bridging of cracks by steel fibers. Lee et al. [6] made an attempt to study the impact of increasing amounts of steel fibers on the flexural and compressive strength of specimens. The results revealed that the addition of fibers improved the equivalent flexural strength ratio, which is the ratio of first peak strength and energy absorption capacity of specimen. The overall flexure strength improved by about 22% as compared to specimens without steel fibers.

According to [10] and [11], fuzzy logic is very user-friendly and its rules can be very easily written depending on experience. Fuzzy logic modelling allows us to write the relationship between input(s) and output(s) verbally. In fact, Fuzzy logic can be very useful, if the relationship between the input and output is fuzzy. Various researchers [11–13], have used fuzzy logic and neural networking to predict various properties of concrete like compressive strength, flexural strength and the impact of various types of additives like fly ash and low lime concretes. For example Saridemir Mustafa [12], studied the impact of adding metakaolin on the compressive strength of cement mortars. The results were also simulated on Fuzzy logic and artificial neural networking. It was found that fuzzy logic can successfully predict the compressive strength of test specimens. Statistical analysis of data gave a root mean square (RMS) value of 0.28. Artificial neural networking also produced acceptable results with RMS value of 1.79. The obtained slope and intercept values for fuzzy model were 0.9764 and 0.5842 respectively. Thamma and Barai [14], used gene expression programming to simulate the effect of Blaine and Alkalies on the compressive strength of cement mortar. It was found that gene expression programming can successfully predict the compressive strength of cement mortar with RMS value of 1.4956. Similarly, another study was conducted by Bekir and Mustafa [13], which involved predicting the compressive strength of concrete using fuzzy logic and artificial neural networking. The obtained RMS value was 2.02 and the linear fit of equation give a slope and intercept value equal to 0.9824 and 0.6354 respectively. According to them, the statistical analysis of results concluded that the results produced by both models were not only satisfactory, but also reliable.

As evident from literature review, different researchers used fuzzy logic modelling for predicting mechanical properties of concrete like compressive and flexural strength by adding different types of admixtures/fibers. In this study, fuzzy logic model was used to predict post-peak deformation capability of test specimens in addition to other mechanical properties such as compressive and flexural strength. In previous studies, fuzzy model was mostly based on experimental data of other researchers. This study involved casting and testing of specimens followed by their modelling in fuzzy logic.

The objective of this experimental study is to evaluate the impact of locally available steel fibers on the mechanical properties of concrete such as compressive strength, flexural strength and post-peak deformation. For this purpose, five different amounts of steel fibers 10 kg/m³, 12.5 kg/m³, 15 kg/m³, 17.5 kg/m³ and 20 kg/m³ were used, respectively. The amount of steel fibers added is also expressed in terms volume of concrete which are 0.13%, 0.16%, 0.24%, 0.42% and 0.84%, respectively. The impact of steel fibers on the afore-mentioned mechanical properties is also predicted by fuzzy logic algorithm. Finally, the experimental results were compared with the simulated data.

2 Experimental program

In this study, ordinary Portland cement conforming to ASTM C150 [15], fine and coarse aggregates conforming to ASTM C33 [16], were utilized. Similarly, locally available binding wire, which is made up of mild steel and commonly used for binding reinforcement in Reinforced Concrete buildings, was used in the mix. The length and diameter of steel fibers was 30 mm and 0.2 mm respectively.

Several problems like clumping of fibers and their non-uniform distribution are associated, if proper care is not taken during mixing of materials as reported by [17, 18]. For this reason, first, small amounts of fibers were added to coarse aggregate and mixed until the desired quantity was added. The process was followed with the addition of fine aggregate, cement and water. The gradation curves of fine and coarse aggregates is shown in Fig. 2. It is important to note that proper mixing was carried-out following the addition of each material. The mix design adopted for this study is shown in Table 1. Two types of specimens were casted i.e. cylinders and beams as shown in Fig. 1. The cylinders had

Table 1 Mix proportions

W/C ratio	Unit weight (kg/m ³)			
	Water	Cement	Fine aggregate	Coarse aggregate
0.40	180	450	900	1800

Fig. 1 Test specimens **Fig. 2** Sieve analysis of fine and coarse aggregates

length to diameter ratio equal to 2 (305 mm × 152 mm) as stated in ASTM C39 [19]. Similarly, the flexural strength was evaluated by casting beams having dimension 457 mm × 100 mm × 100 mm. Both beams and cylinders were casted for five different amounts of steel fibers designated as SF10, SF12.5, SF15, SF17.5, SF20, where SF stands for steel fibers respectively. A total of 15 beams and cylinders were casted (3 for each amount of steel fibers). The reported compressive and flexural strength values represent the average of 3 specimens being casted for each amount of fibers (SF10, SF12.5, SF15, SF17.5, SF20).

The compressive strength was determined with the help of Universal Testing Machine. Strain-gauges were wrapped around the specimens to record the load-deformation history of each specimen. Similarly, the flexural testing of beams was carried-out by Center Point Loading Method as specified by ASTM C293 [20]. According to this specification, the flexural strength of test specimen is given by:

$$\text{Flexure strength} = 3PL/2BH^2 \quad (1)$$

where P = load at failure, L = effective span of beam, B = width of beam, H = depth of beam.

It must be noted that for each amount of steel fibers, the average of three specimens was reported as the final result.

3 Fuzzy logic modelling

In this research study, fuzzy logic-based model was used to simulate the effect of amount of steel fibers on the mechanical properties of concrete i.e. compressive strength, flexural strength and post-peak deformation of test samples. Fuzzy rules were written for this purpose in fuzzy logic toolbox present in MATLAB®. Fuzzy logic deals with real world problems in a natural way, where the absence of sharply defined criteria becomes the cause of imprecision. It is very helpful in problems where linguistic uncertainties can play a role in the control mechanism of problem/study concerned [12]. Fuzzy logic was selected based on its ease to develop its rules, simulate the results in a short time and requires a smaller number of experimental data to develop a representative model of study variable [21]. Fuzzy logic has widely been used for modelling various engineering problems like mechanical properties of solder alloys, mechanical properties of concrete, traffic volumes and rainfall prediction models [11], [22].

Figure 3 depicts the workflow of proposed model. The model takes-in the amount of steel fibers as input, which is transformed into fuzzy plane. Base rules are written which determines the study's outputs based on centroid method, and Mamdani method is used for defuzzification.

3.1 Membership functions

The numerical model had one input 'amount of steel fibers' and three outputs 'compressive strength, flexural strength and post-peak deformation'. The membership functions (MFs) for both the input and output are shown in Figs. 5 and 6. According to [23], the construction of membership functions requires experience to place the base values in

Fig. 3 Workflow of fuzzy logic-based simulation **Fig. 4** A generalized triangular membership function [24]

more sensitive regions. According to [24], triangular MFs give better results and, are most widely used. Triangular MFs can be mathematically and graphically interpreted as

shown in Fig. 4 and Eq. 2 [24]. Therefore, this study used the same for both input and output parameters.

$$T_n F(x; a, m, b) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{m-a}, & a < x \leq m \\ \frac{b-x}{b-m}, & m < x < b \\ 0, & x \geq b \end{cases} \quad (2)$$

3.2 Fuzzy sets

During the model development, the input parameter 'amount of steel fibers' was divided into eleven fuzzy sets. These are VVL (very very low), VL (very low), L (low), VVM (very very moderate), VM (very moderate), M (moderate), MH (moderate high), H (high), VH (very high), VVH (very very high), and EH (extremely high).

Fig. 5 Membership function for input

Fig. 6 Membership function for outputs

M (moderate), MH (moderately high), H (high), VH (very high), VVH (very very high), EH (extremely high). In the same manner, the output parameters 'compressive strength, flexural strength and post-peak deformation' were divided into eleven fuzzy sets such as VVL (very very low), VL (very low), L (low), VVM (very very

moderate), VM (very moderate), M (moderate), MH (moderately high), H (high), VH (very high), VVH (very very high), EH (extremely high).

Table 2 Fuzzy rule base for the input and outputs

Rules	Input	Output		
	Amount of steel fibers	Flexural strength	Post-peak deformation	Compressive strength
R1	VVL	VVL	VVL	VVL
R2	VL	VL	VL	VL
R3	L	L	L	L
R4	VVM	VVM	VVM	VVM
R5	VM	VM	VM	VM
R6	M	M	M	M
R7	MH	MH	MH	MH
R8	H	H	H	H
R9	VH	VH	VH	VH
R10	VVH	VVH	VVH	VVH
R11	EH	EH	EH	EH

3.3 Fuzzy rule base

According to [25], fuzzy rule base is a set of verbal description which has a general form of “IF VA THEN VB”, where VA and VB are propositions containing linguistic variables. In order to simulate the impact of amount of steel fibers on the mechanical properties of concrete, the following fuzzy rule base for the proposed fuzzy sets were developed as shown in Table 2.

4 Results

Figure 7 shows the impact of amount of steel fibers on the post-peak deformation of test specimens. It can be observed from the figure that the deformation capacity of specimens increases with the amount of steel fibers. The deformation capacity is increased by almost 20% when the volume of steel fibers is increased from 0.13 to 0.84% (10–20 kg/m³).

Fig. 7 Effect of steel fibers on post-peak deformation of specimens **Fig. 8** Effect of steel fibers on flexural strength of specimens **Fig. 9** Effect of steel fibers on compressive strength of specimens

Similarly, the simulation shows that the amount of steel fibers improved the flexural capacity of test specimens as depicted in Fig. 7. By comparing specimen SF10 and SF20, it is observed that the flexural strength is increased by almost 12% (Fig. 8).

According to fuzzy logic predicted values of compressive strength for SF specimens, shown in Fig. 9, the compressive strength of specimens increased with the addition of steel fibers. When comparing SF specimens, SF20 had 9.15% higher compressive strength as compared to SF10. However, the experimental results showed that, the addition of steel fibers reduced the compressive strength of test specimens by almost 31%, as compared to specimens without steel fibers (control group).

5 Discussions

The experimental study revealed that the addition of steel fibers improved the post-peak deformation capacity of test specimens by taking load even after yielding. This is due to the fact that steel fibers control the propagation of micro-cracks, helps the specimens to

Table 3 Comparison of results

Specimen type	Experimental results			Simulated results		
	Flexural strength (MPa)	Post-peak deformation (mm)	Compressive Strength (MPa)	Flexural strength (MPa)	Post-peak deformation (mm)	Compressive strength (MPa)
CG	7.20	0.33	28.00	–	–	–
SF10	5.69	1.57	18.97	5.69	1.56	19.04
SF12.5	5.73	1.59	19.53	5.73	1.64	19.39
SF15	5.74	1.60	20.58	5.74	1.725	19.88
SF17.5	6.23	1.80	20.62	6.23	1.81	20.30
SF20	6.34	1.88	20.72	6.34	1.89	20.65

Fig. 10 Correlation of measured and predicted deformation

take load even after yielding and ensures ductile failure of test specimens. Similar results were reported by [1, 26]. In their experiments, it was observed that the control specimens showed brittle failure while in steel fiber specimens, debonding of steel fibers from concrete matrix occurred very slowly and the failure of specimen was not sudden. According to their conclusions, the steel fibers act as anchors which slowed down the propagation of cracks and thus, ensured a ductile failure of specimen. The experimental results also support the simulation results as shown in Table 3 and gives a good fit with the simulation results as depicted in Fig. 10.

The flexure strength of specimens also increased with the addition of steel fibers. The reason being, perfect bonding between fibers and surrounding concrete matrix ensures efficient stress transfer and bridges the micro-cracks in tension region of flexural members thereby, increasing its capacity in flexural loading. It was also revealed that the SF specimens gives sufficient warning before failure (by undergoing large amount of deformation before failure). The experimental results are also in good agreement with the simulation results as shown in Table 3 (Fig. 11).

In contrast to flexure strength and post-peak deformation results of specimens, the addition of steel fibers

Fig. 11 Correlation of measured and predicted flexural strength **Fig. 12** Correlation of measured and predicted compressive strength

reduced the compressive strength of concrete specimens as compared to control group specimens. However, when the compressive strength results of SF specimens are compared, it is found that SF20 specimens has higher compressive strength as compared to other SF specimens as shown in Fig. 12. Similar results are reported by

Table 4 Percentage difference between experimental and simulation results

Specimen type	Flexural strength (%)	Post-peak deformation (%)	Compressive strength (%)
SF10	0.12	0.64	0.28
SF12.5	2.03	3.05	0.72
SF15	4.65	7.25	3.57
SF17.5	0.56	0.55	1.53
SF20	0.11	0.56	0.25

Falliano et al. [3], in which three different dosages of steel fibers 0.5%, 2% and 5% were incorporated. A higher compressive strength was observed for the mix having 5% steel fibers.

Table 4 depicts the percentage difference between the simulated and experimental results. It is evident that the percentage difference between the simulated and experimental values is less than 7.5%, and most of the values are below 1%. These results are in accordance with Tanyildizi [23]. According to Tanyildizi, if the percentage difference between simulated and experimental results is less than 10%, then the fuzzy model is reliable, and can be used to predict other values. Similarly, the correlation factor 'R2' was also determined between the measured and predicted values. The obtained R2 value for deformation capacity, flexural and compressive strength is 0.86, 0.83 and 0.85 respectively, which, again, shows that fuzzy model predicted the results close to experimental values. Bekir and Mustafa [13] obtained an R2 value of 0.99 using fuzzy logic modelling of compressive strength of concrete. Similarly, Mustafa Saridemir [12] obtained an R2 value of 0.96 for fuzzy logic modelling of flexural strength of concrete specimens having steel fibers. The reason for their higher R2 value is due to large number of data points being experimented and simulated, which allowed better training of fuzzy model for that particular study.

6 Conclusions

This study aimed to predicting the effect of locally available steel fibers on the mechanical properties such as compressive strength, flexural strength and post-peak deformation capability of concrete specimens using fuzzy logic. The simulation was carried-out in fuzzy logic toolbox provided in MATLAB® and its results were compared with the experimental findings. For this purpose, different volumes of steel fibers 0.13%, 0.16%, 0.24%, 0.42% and 0.84% (10 kg/m³, 12.5 kg/m³, 15 kg/m³, 17.5 kg/m³ and 20 kg/m³)

were assimilated in the mix design, and their mechanical properties were determined.

According to simulated results, the addition of steel fibers helped in improving the compressive strength, flexural strength and post-peak deformation capacity of test specimens. The experimental results also supported the findings of fuzzy logic. The compressive strength increased by almost 9.15%, when steel fibers were increased from 0.13 to 0.84%. However, experiments show that the compressive strength of specimens reduced with the addition of steel fibers as compared to specimens without steel fibers (control group).

Both the experimental and simulation results showed an increase in the flexural strength and post-peak deformation capacity of test samples by almost 2% and 20% respectively. The reason being, the incorporation of steel fibers bridges the cracked portions of specimens and, enables them to sustain more load before failure.

It is also concluded that fuzzy logic can predict the effect of steel fibers on the mechanical properties of concrete. The difference between the predicted and experimental values is less than 7.5%. The correlation factor 'R2' showed good agreement between the measured and predicted values.

Compliance with ethical standards

Conflict of interest None.

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