Effects of elevated temperatures on mechanical properties of concrete containing haematite evaluated using fuzzy logic model

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Concretes containing different proportions of haematite (15, 30, 45 and 60%) were fabricated and subjected to elevated temperatures (25, 200, 400, 600 and 800°C). The cement content and water/cement ratio were 450 kg m^{-3} and 0·38 respectively. The compressive strength and elasticity modulus of concretes were determined according to ASTM C39 and ASTM C469. A rule based Mamdani type fuzzy logic model for predicting the compressive strengths and elasticity modules of concretes containing haematite has been developed. The inputs were haematite content (%), exposure time (h) and temperature T (°C); the outputs were compressive strength and compressive elasticity modulus. It is shown that all the results of the model for elasticity modulus and compressive strength were in good correlation with the experimental results for all data sets.

Keywords: Concrete, Haematite, Fuzzy logic

Introduction

Polymer and organic concretes are often used construction materials for many applications, such as building structures and bridges.[1–5] Moreover, concrete is considered to be an excellent and versatile shielding material widely used for shielding nuclear power plants, particle accelerators, research reactors, laboratory hot cells and medical facilities.[6] Very extensive literature on concretes includes a number of reviews.[7–12] Concrete generally provides adequate fire resistance for most applications. However, the strength and durability properties of concrete are significantly affected when subjected to elevated temperatures due to chemical and physical changes.[13–18]

In previous studies, radiation attenuation of concrete containing haematite[19] and the protective effect of concrete produced with haematite on rats[20] and also the effects of haematite on the physical and mechanical[21] and some durability properties of concrete[22] were investigated. However, limited studies have been reported about predicting the effect of elevated temperature on the properties of concrete. In particular, no study has been carried out to utilise a computing technique in modelling the behaviour of concrete containing haematite subjected to elevated temperatures.

Concrete may be considered as a three-phase composite consisting of hardened cement paste, aggregate and interfacial zone between the hardened cement paste and the aggregate. As the compressive strength of concrete is mainly dependent on the adhesion between two main phases, failures happen within the hardened cement paste and/or along the interfacial zone. Therefore, attention should be paid to the effect of aggregate type on interface bonding,[23,24] which applies to high temperatures also. Strength degradation of concretes with different aggregates under high temperatures varies because of the mineral structures of the aggregates.[25] When exposed to temperatures >300°C, evaporation of the bound water increases the deterioration of concrete and causes a decrease in compressive strength.[14] When temperatures exceed 400°C, calcium silica hydrates (C–S–Hs) undergo degradation, and the strength of concrete decreases rapidly; at 900°C, the structure of C–S–Hs disintegrates.[26] Thus, the critical exposure temperature range is 400–800°C in terms of compressive strength loss. Most of the original strength is lost between 600 and 800°C.[27]

One of the objectives of this work, after gathering experimental data, is the development of a model with predictive capabilities. Such a model would significantly reduce further experimental work and save money and time in the design of composite materials.

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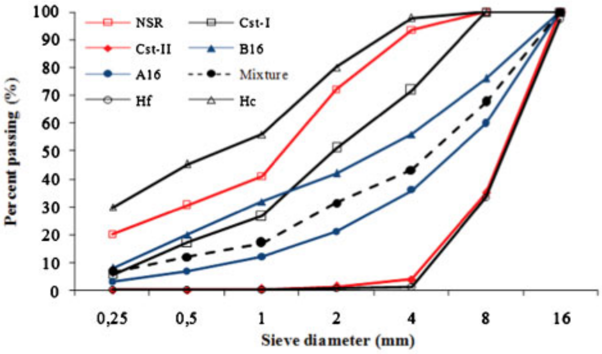
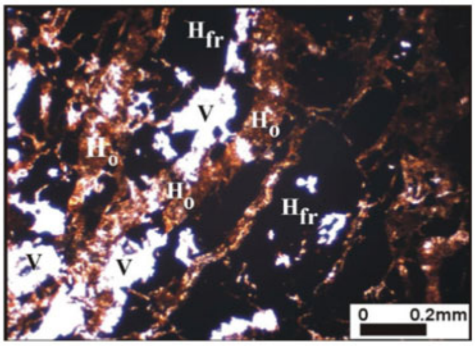


1 Gradations of aggregates



2 Mineralogical structure of haematite

Different problems in engineering require different approaches.[28–30] Thus, artificial intelligence has been extensively used in civil engineering applications such as construction management, building materials, hydraulic, geotechnical and transportation engineering, etc.[31,32] One of the popular artificial intelligence methods is fuzzy logic (FL). Fuzzy inference systems (FISs) have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems and computer vision. Because of its multidisciplinary nature, FISs are associated with a number of names, such as fuzzy rule based systems, fuzzy expert systems, fuzzy modelling, fuzzy associative memory, FL controllers and simply (and ambiguously) fuzzy systems.[30]

Researchers can implement two types of FISs in the MATLAB FL Toolbox: Mamdani type and Sugeno type. On the basis of our experimental data, we have developed a rule based Mamdani type FL model that was developed to predict the compressive strength and compressive elasticity modules of concrete containing haematite under elevated temperatures.

Experimental

Aggregates

Plain concrete (PC) was produced using limestone based aggregates with three different grain sizes: crushed stone (CSt-I), natural river stone (NRS) and crushed stone II (CSt-II). The maximum aggregate size selected had 16 mm diameter. Results of sieve analysis of fine and coarse aggregates used are presented in Fig. 1. A16 and B16 are grading limits for the mixture. The mixing ratios of CSt-I, NRS and CSt-II were 25, 25 and 50% respectively.

The pure form of haematite we have used is a natural red rock that contains iron oxide, has Mohs hardness between 5·5 and 6·5 and has specific gravity between 4·9 and 5·5 g cm^{-3}. However, the physical properties of rocks in which haematite is the main constituent may vary considerably; the specific gravity of haematite ores can range between 3·2 and 4·3. Some ores are soft and produce dust in the course of being handled, which would make them a poor aggregate for heavy concrete. Haematite particles tend to be flaky, which is undesirable with regard to the workability of concrete.[6] The mineralogical structure of haematite is presented in Fig. 2. As seen, haematite consists of two zones, oxide (H_o) and fresh (H_{fr}). Voids (V) have appeared during the formation of haematite.

Table 1 Physical and mechanical properties of aggregates

Aggregate codes	Specific gravity/g cm^{-3}	Water absorption/%	Loose unit mass/g cm^{-3}
CSt-I	2·61	2·91	1·91
NRS	2·63	3·13	1·83
CSt-II	2·70	0·83	1·68
H_f	3·75	2·35	1·96
H_c	4·00	1·27	1·73

Haematite was prepared as an aggregate by crushing and grounding the ore in a laboratory mill and then sorting it via sieves into two groups of coarse (H_c) and fine (H_f) aggregates. Specific gravity, water absorption and loose unit weight were determined according to ASTM C127, ASTM C128 and ASTM C129 standards. The properties of aggregates used are presented in Table 1. The chemical composition of haematite used is presented in Table 2.

Cement

The cement used in all concrete mixtures was Portland cement CEM I 42·5R. The physical and mechanical properties as well as the results of chemical analysis of cement are presented in Tables 3 and 4 respectively.

Superplasticiser (SP)

An SP based on a modified polycarboxylic ether was employed to obtain a satisfactory workability for the mixes. It has a specific gravity of 1·08, pH 5·7 and solid content of 40%.

Mix proportions

Mixtures of concrete containing different haematite proportions and PC were made. Heavyweight concrete for radiation shielding can be made using the American Concrete Institute method of absolute volumes developed for normal concrete. That method is generally accepted and is considered to be more convenient for heavyweight concrete,[6] and we have applied it.

After extensive trials, the water/cement ratio and the cement content were settled as 0·38 and 450 kg m^{-3} for all mixtures. In heavy concrete, the cement content is generally quite high, >350 kg m^{-3}. This helps to improve the shielding characteristics of the concrete because of the high bound water content of the paste.[34]

The haematite aggregate was replaced with limestone based aggregates at 15% (H15), 30% (H30), 45% (H45) and 60% (H60) ratios. The weights of materials used in

Table 2 Chemical composition of haematite/wt-%

Fe_2O_3	MnO	MgO	TiO_2	Al_2O_3	CaO	SiO_2	LOI*
81·13	0·14	1·55	0·03	0·57	4·8	4·2	5·82

*Loss of ignition=mass loss in a sample heated to 950°C.

the mix design to obtain 1 m^3 of concrete are presented in Table 5.

Mixing, curing and testing specimens

The procedure for mixing heavy concrete is similar to that for conventional concrete. In a typical mixing procedure, the materials were placed in a mixer with capacity of 56 dm^3 in the following sequence: first course aggregates, fine aggregates followed by cement, initially dry material mixed for 1 min and finally addition of 80% water. After 1·5 min of mixing, the rest of the mixing water was added. All batches were mixed for a total time of 5 min; in order to prevent fresh concrete from segregation, the mixing duration was kept as short as possible. Then, all concrete specimens were cast in moulds. After 24 h, the specimens were demoulded and then cured in lime saturated water at 20 ± 2°C temperature for 28 days before testing. It is well recognised that adequate curing of concrete is very important not only to achieve the desired compressive strength but also to make durable concrete. Curing was performed according to ASTM C511.

After the mixing procedure was completed, three specimens made from each concrete mixture were fabricated for each test. Cubic specimens with $150 \times 150 \times 150$ mm were used for compressive strength testing. Cylindrical specimens with 150 mm diameter and 300 mm height were used for compressive elasticity modulus testing. Compressive strength and elasticity modulus were determined according to ASTM C39 and ASTM C469.

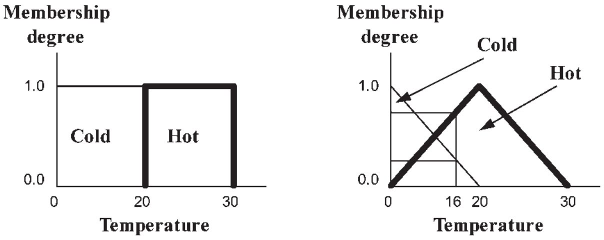
In order to assess the effect of elevated temperatures on the properties of hardened concrete containing haematite, measurements of the mechanical properties of test specimens were made shortly before and after heating, when specimens were cooled down to laboratory temperature.

For heating exposure, a big furnace chamber with maximum temperature of 1500°C was used. Samples were placed unloaded in the cooled furnace chamber, and the temperature was increased at the rate of 10°C min^{-1}. After a predefined period (1, 2 and 3 h), the furnace was switched off, and the specimens were removed from the furnace using a long clamping arm. Specimens were left to cool for water cooling and air cooling. Then, the specimens were subjected to testing.

Fuzzy logic (FL)

Fuzzy logic theory

Fuzzy logic was used for the first time in 1965 by Zadeh.[35] He developed a new approach instead of Aristotelean logic, which contains two definite possibilities only (1 or 0). By contrast, FL provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria rather than the presence of random variables.[35–38]



3 Example for Aristotelean logic (left) and FL approaches (right)

The FL approach can simply be explained by an example: The temperature of 16°C is cold according to Aristotelean logic shown in Fig. 3 (left). On the other hand, in the FL approach, it cannot be said exactly to be cold or hot for 16°C, as shown in Fig. 3 (right), because the value of 16°C has a membership degree in both cold and hot levels. Thus, the FL approach shown in Fig. 3 (right) is a suitable structure accepted as plausible by the human brain.

In the Aristotelean logic, all systems such as mathematic or stochastic have three components. These are input, system behaviour and output. The difference of the FL approach from the Aristotelian logic is that the FL approach divides the system behaviour into four parts, as follows:

(i) fuzzification, which converts each input data into degrees of membership by a lookup in one or more of several membership functions; for our study, *see* Figs. 4 and 5

(ii) fuzzy rule base, which contains rules that include all possible fuzzy relationships between input and outputs using the IF–THEN format; for this study, *see* Table 6

Table 5 Mix proportions in mass/kg m^{-3}

	PC	H15	H30	H45	H60
Cement	450	450	450	450	450
Water	171	171	171	171	171
SP	4·5	4·5	4·5	4·5	4·5
CSt-I	428	364	300	235	171
NRS	431	367	302	237	173
CSt-II	885	752	620	487	354
H_f	0	184	369	553	738
H_c	0	197	393	590	787

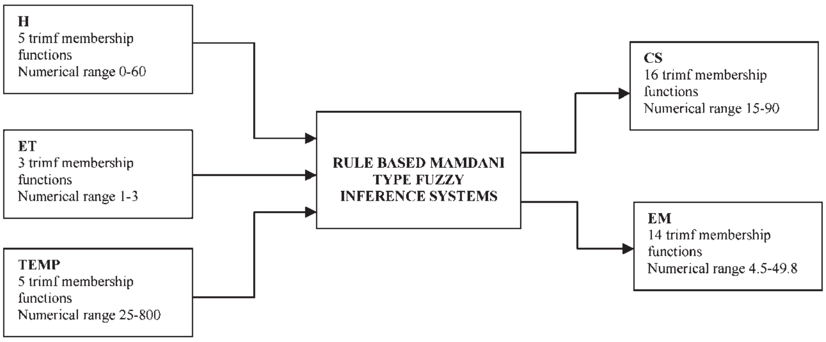
Table 3 Physical and mechanical properties of Portland cement

Compressive strength/MPa			Flexural strength/MPa			Initial setting time/min	Final setting time/min	Le Chatelier/mm	Specific gravity/g cm^{-3}	Blaine/cm^2 g^{-1}
2 Days	7 Days	28 Days	2 Days	7 Days	28 Days	175	260	1	2·92	3671
28·6	45·5	59·5	4·7	6·9	8·5					

Table 4 Chemical analysis of Portland cement, wt-%

Total SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl	LOI*	Free CaO	Total admixture
20·23	5·73	2·65	61·63	2·25	2·65	0	2·9	2·2	4·9

*Loss of ignition.



4 General structure of model

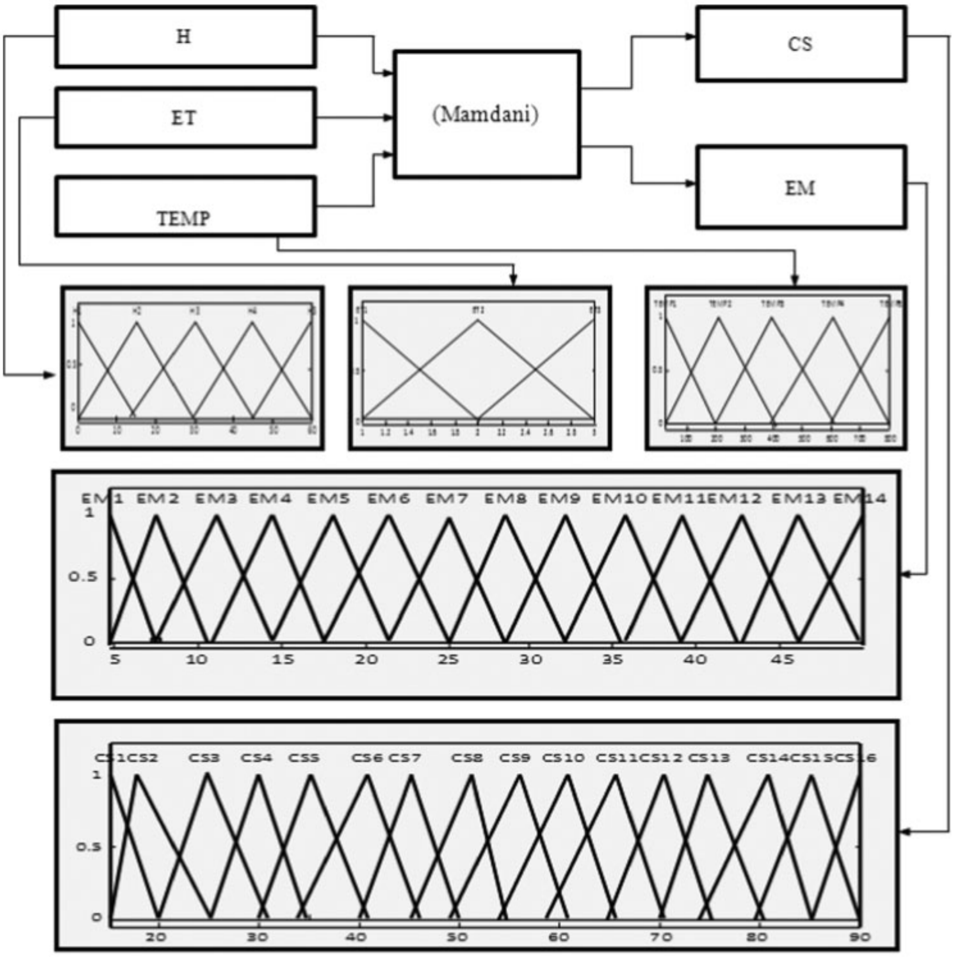
(iii) fuzzy interference engine, which collects all fuzzy rules in the fuzzy rule base and learns how to transform a set of inputs to related outputs

(iv) defuzzification, which converts the resulting fuzzy outputs from a fuzzy interference engine to a number;[34,39] for this study, *see* Table 7.

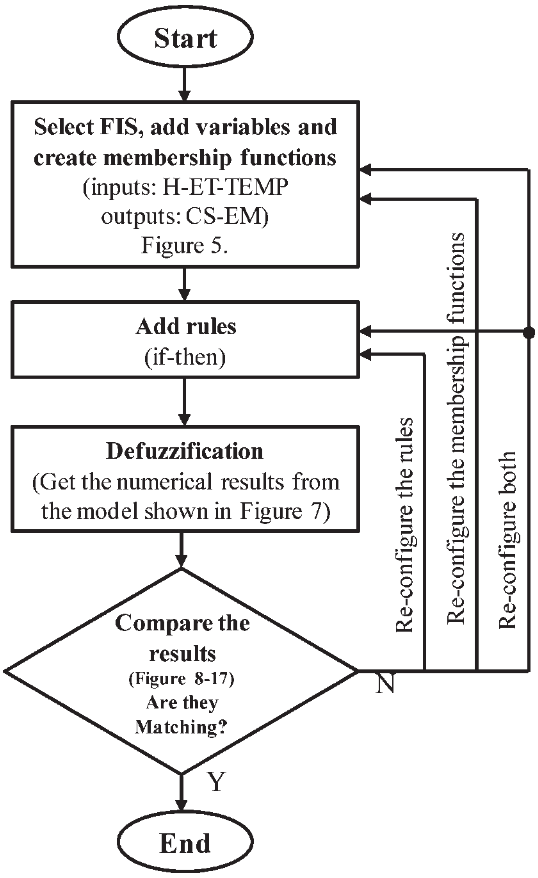
Reasons for using FL Toolbox

Fuzzy logic is one of the most popular artificial intelligent approaches. A large number of investigations pertain to the usability of rule based Mamdani type FL systems. If asked why use of this application, the general observations that are listed below would be written according to the MATLAB FL Toolbox user's guide.[40]

Let us discuss reasons for using FL. It is conceptually easy to understand; the mathematical concepts behind fuzzy reasoning are very simple. Fuzzy logic is a more intuitive approach without far reaching complexity. Fuzzy logic is flexible; with any given system, it is easy to layer on more functionality without starting again from the beginning. Fuzzy logic is tolerant of imprecise data; everything is imprecise if you look closely enough; more than that, most things are imprecise on careful inspection. Fuzzy reasoning builds this understanding into the process rather than tacking it onto the end. The FL can model non-linear functions of arbitrary complexity; one can create a fuzzy system to match any set of input–output data. This process is made particularly easy by adaptive techniques like Adaptive Neuro-Fuzzy Inference Systems, which are available in the FL Toolbox software. Fuzzy logic can be built on top of the experience of experts; in direct contrast to neural



5 Membership functions of inputs and outputs of model



6 Flow diagram for this study

networks, which take training data and generate opaque, impenetrable models, FL allows one to rely on the experience of people who already understand a given system. Fuzzy logic can be blended with conventional control techniques; fuzzy systems do not necessarily replace conventional control methods. In many cases, fuzzy systems augment them and simplify their implementation. Finally, FL is based on a natural language; the basis for FL is also the basis for human communication. Because FL is built on the structures of qualitative description used in everyday language, FL is claimed to be easy to use.[40]

Structure and parameters of developed FL model

The users of the MATLAB FL Toolbox can implement two types of FIS in the toolbox: Mamdani type and Sugeno type.

Table 6 Summary of fuzzy rules constructed in FL modelling

Rules		H		ET		TEMP		CS		EM
R1	if	H1	and	ET1	and	TEMP1	then	CS13	and	EM13
R2	if	H1	and	ET1	and	TEMP2	then	CS11	and	EM11
R3	if	H1	and	ET1	and	TEMP3	then	CS9	and	EM7
R4	if	H1	and	ET1	and	TEMP4	then	CS7	and	EM5
R5	if	H1	and	ET1	and	TEMP5	then	CS4	and	EM4
.	if	.	and		and	.	then		and	
.	if	.	and		and	.	then		and	
R74	if	H5	and	ET3	and	TEMP4	then	CS7	and	EM4
R75	if	H5	and	ET3	and	TEMP5	then	CS3	and	EM2

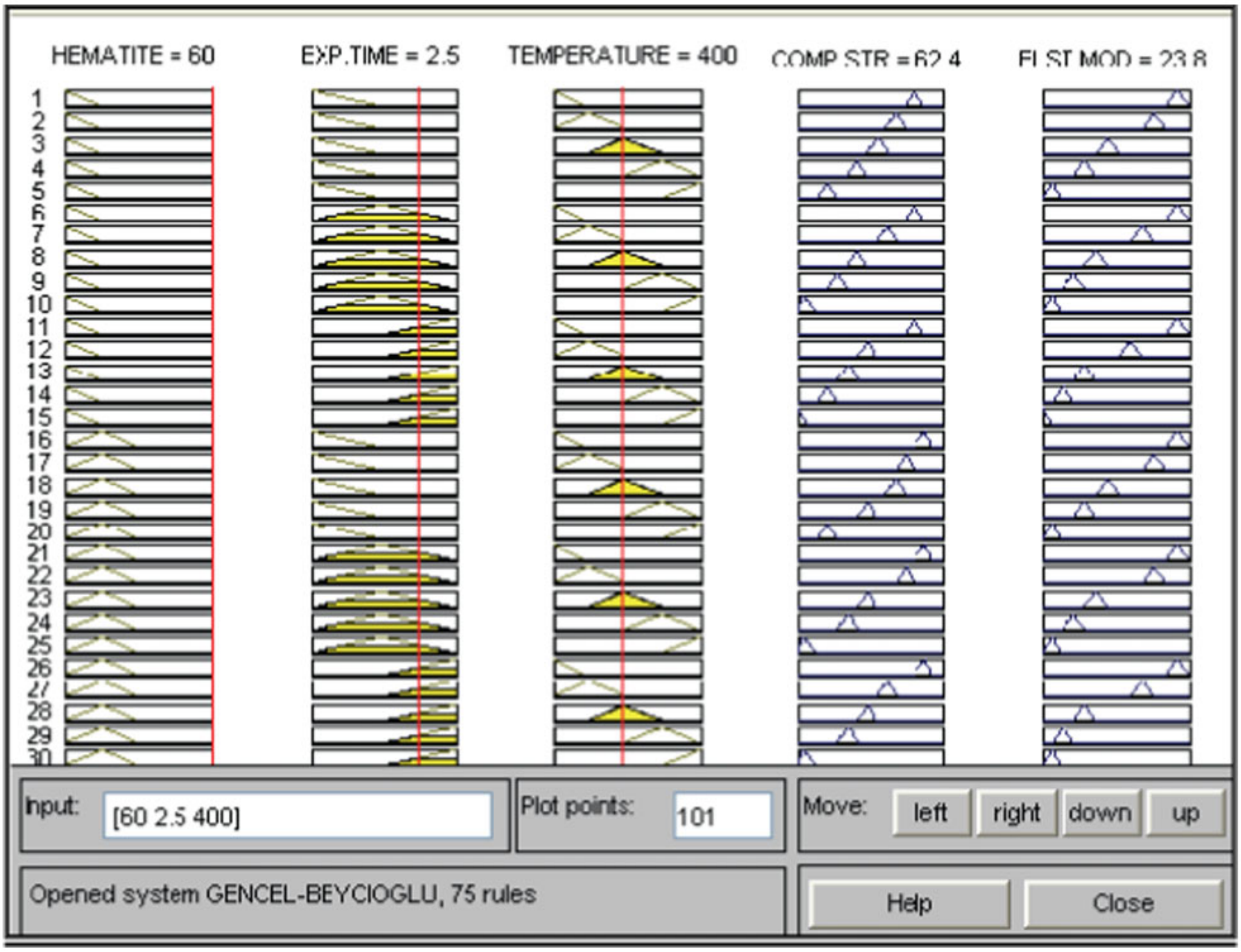
Mamdani type FIS is widely accepted for capturing expert knowledge. It allows us to describe the expertise in a more intuitive, more human-like manner. However, Mamdani type FIS entails a substantial computational burden. On the other hand, Sugeno type FIS is computationally efficient and works well with optimisation and adaptive techniques, which makes it very attractive in control problems, particularly for dynamic non-linear systems. These adaptive techniques can be used to customise the membership functions so that the fuzzy system best models the data. The most fundamental difference between the Mamdani and the Sugeno type FIS is the way the crisp output is generated from the fuzzy inputs. While the Mamdani type FIS uses the technique of defuzzification of a fuzzy output, the Sugeno type FIS uses weighted average to compute the crisp output. The expressive power and interpretability of Mamdani output is lost in the Sugeno FIS since the consequences of the rules are not fuzzy. On the other hand, Sugeno has a shorter processing time since the weighted averages replace the time consuming defuzzification process. Owing to the interpretable and intuitive nature of the rule base, the Mamdani type FIS is widely used in particular for decision support application. In terms of use, the Mamdani FIS is more widely used, mostly because it provides reasonable results with a relatively simple structure and also due to the intuitive and interpretable nature of the rule base.[41–43]

We have developed a rule based Mamdani type FL model using the FL Toolbox in MATLAB to predict the compressive strength and elasticity modulus of concretes. The model has three inputs and two outputs. The inputs were haematite ratio, exposure time and temperature. The outputs were compressive strength and elasticity modulus.

We have prepared a flow diagram to display all stages of the modelling, presented in Fig. 6. In the figure, FIS is a fuzzy interference system, H is the haematite content (%), ET is the exposure time (hours), T is the temperature (°C), CS is the compressive strength (MPa) and EM is the elasticity modulus (GPa). The general structure of the developed model is displayed in Fig. 4.

Table 7 Statistics of CS and EM estimation using FL

	Statistical parameters for comparison of the compressive strength values between EXP and FL		
SET	R^2	RMSE	MAE
SET I H0	0·99	1·17	0·89
SET II H15	0·99	1·18	1·03
SET III H30	0·99	1·37	1·19
SET IV H45	0·99	1·35	1·12
SET V H60	0·99	1·59	1·39
	Statistical parameters for comparison of the elasticity modulus values between EXP and FL		
SET	R^2	RMSE	MAE
SET I H0	0·98	0·88	0·74
SET II H15	0·99	0·74	0·62
SET III H30	0·97	1·18	0·96
SET IV H45	0·98	0·98	0·83
SET V H60	0·97	1·28	1·12



HEMATITE = 60
EXP.TIME = 2.5
TEMPERATURE = 400
COMP STR = 62.4
ELST MOD = 23.8

Input: [60 2.5 400]

Plot points: 101

Opened system GENCEL-BEYCIOGLU, 75 rules

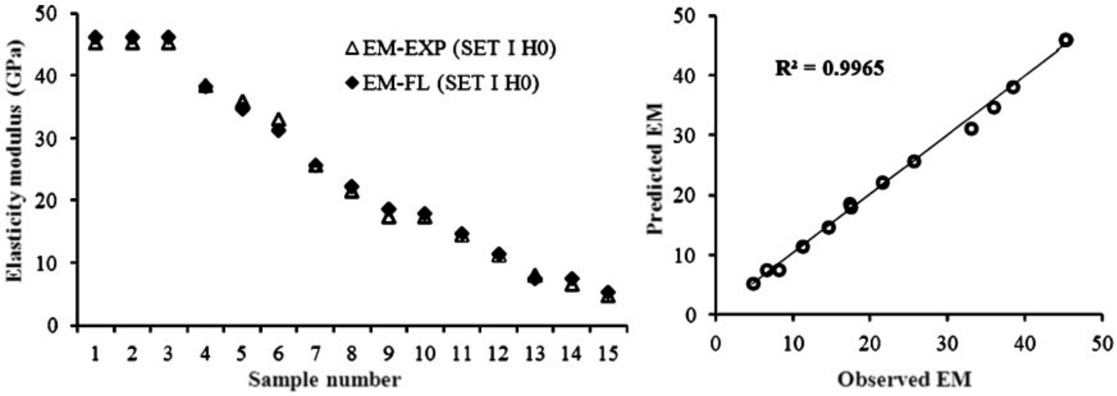
7 **Defuzzification monitor of model**

In the model, the membership functions for H, ET, TEMP, CS and EM were selected 5–3–5–16–14 respectively, as seen in Fig. 5. The numerical ranges are 0–60 for H, 1–3 for ET, 25–800 for TEMP, 15–90 for CS and 4·5–49·8 for EM.

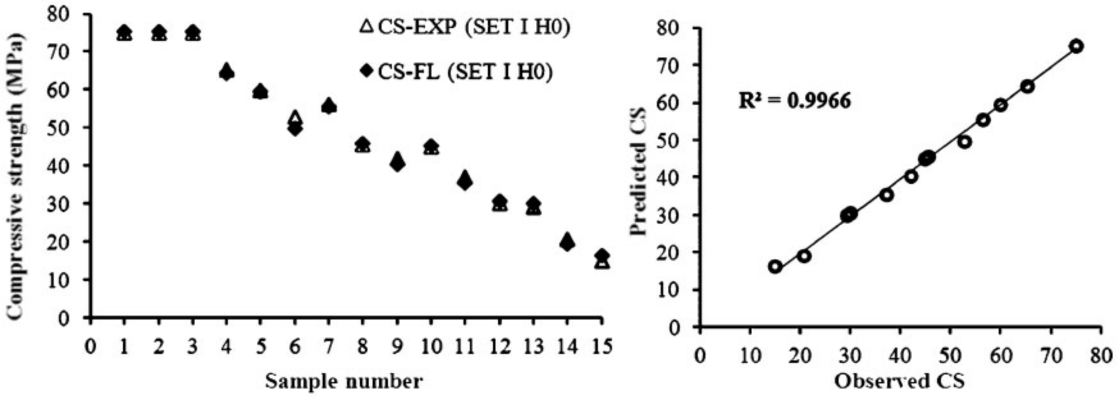
In Fig. 5, *x* axes show the numerical range, and y axes show the membership degree for each fuzzy set. The membership degree quantifies the grade of membership of the element to the fuzzy set. The value '0' means that is not a member of the fuzzy set; the value '1' means that is fully a member of the fuzzy set. The values between '0' and '1' characterise fuzzy members, which belong to the fuzzy set only partially, which is an important advantage of the fuzzy set approach.

A fuzzy model uses rules that are linguistic if–then statements involving fuzzy sets, FL and fuzzy inference. We formulated 75 rules after determining membership functions using experimental results and experiences. Some of the rules are shown in Table 6.

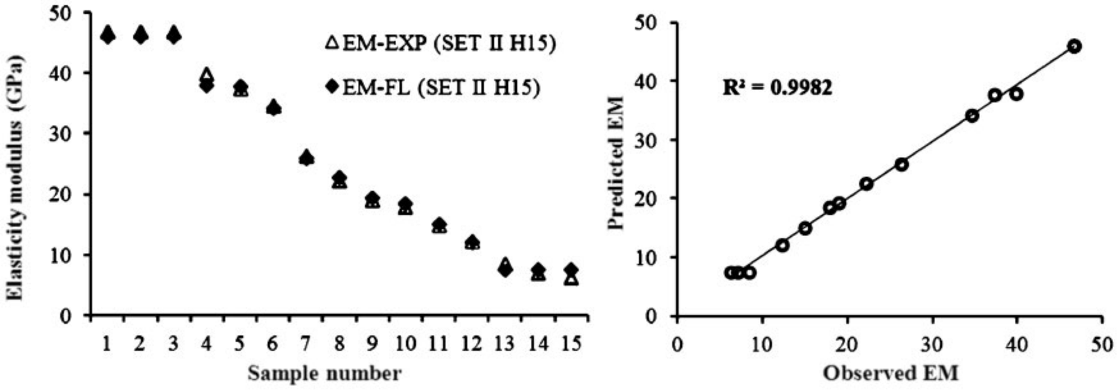
To obtain numeric output values (CS and EM), defuzzification was performed by a centroid of area method. This method is also known as centre of gravity or centre of area defuzzification. This is the most commonly used technique and believed to be very



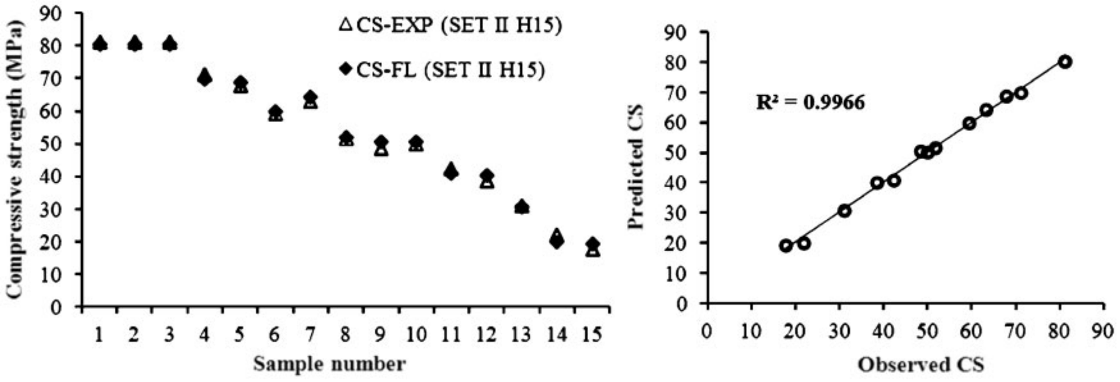
8 **Matching figure of results of EM for SET I H0 (FL versus EXP)**



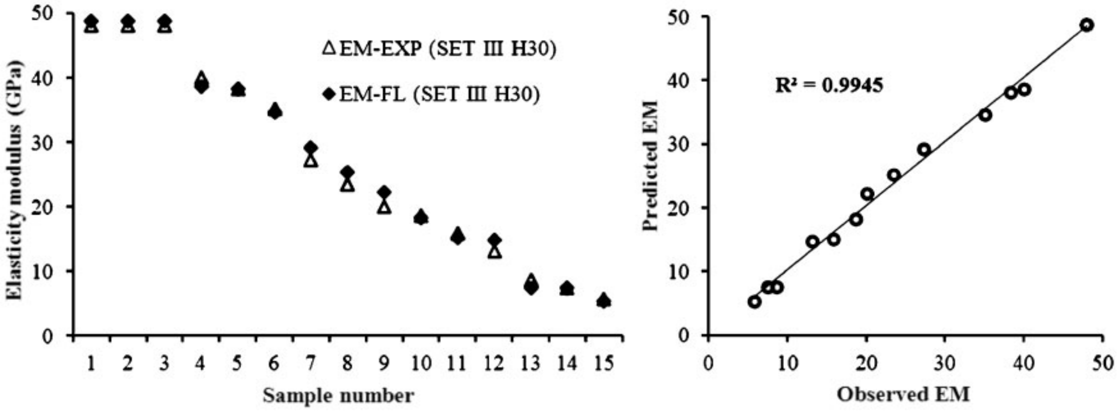
9 Matching figure of results of CS for SET I H0 (FL versus EXP)



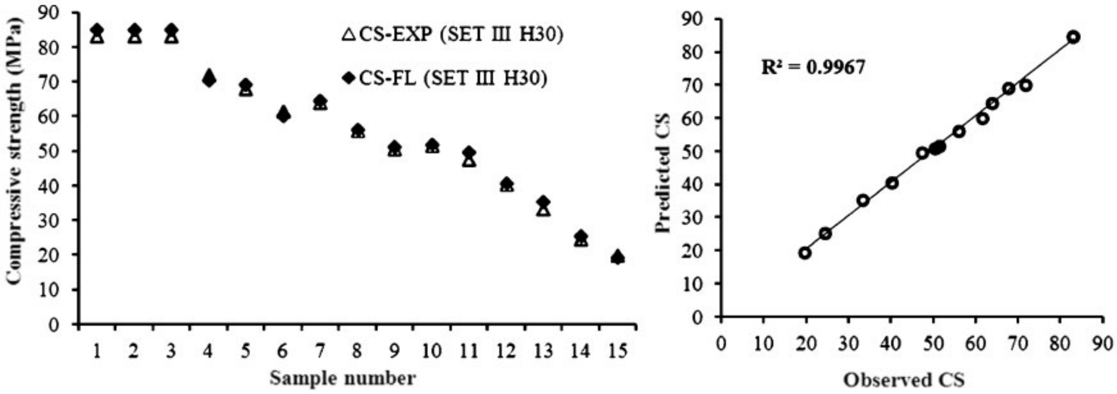
10 Matching figure of results of EM for SET II H15 (FL versus EXP)



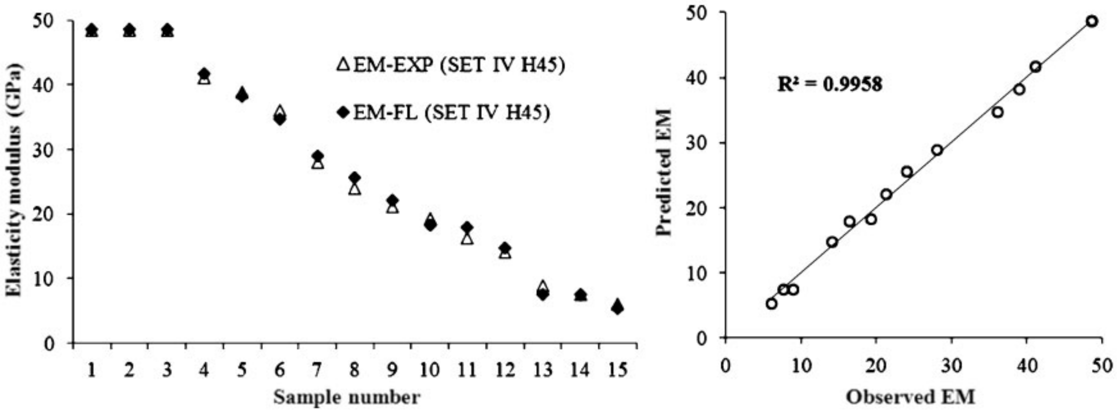
11 Matching figure of results of CS for SET II H15 (FL versus EXP)



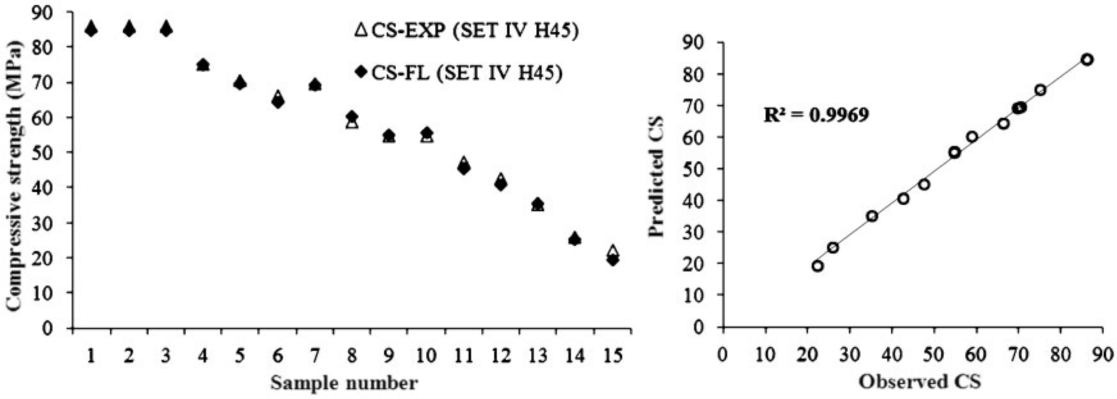
12 Matching figure of results of EM for SET III H30 (FL versus EXP)



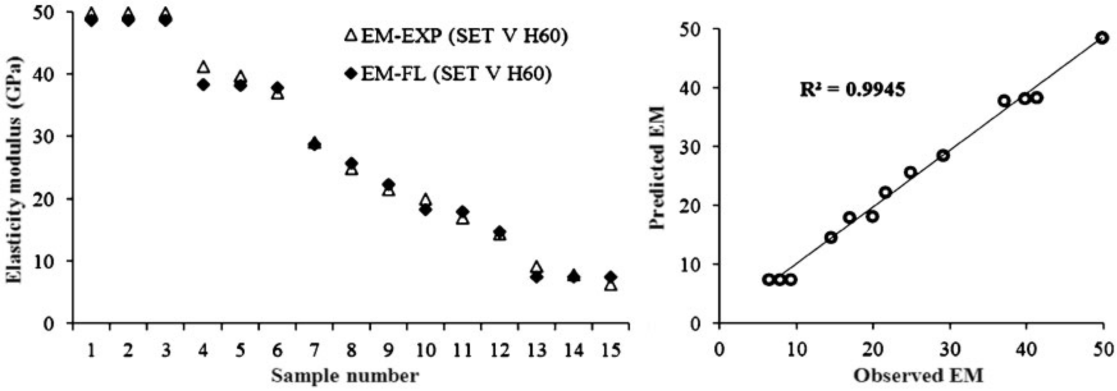
13 Matching figure of results of CS for SET III H30 (FL versus EXP)



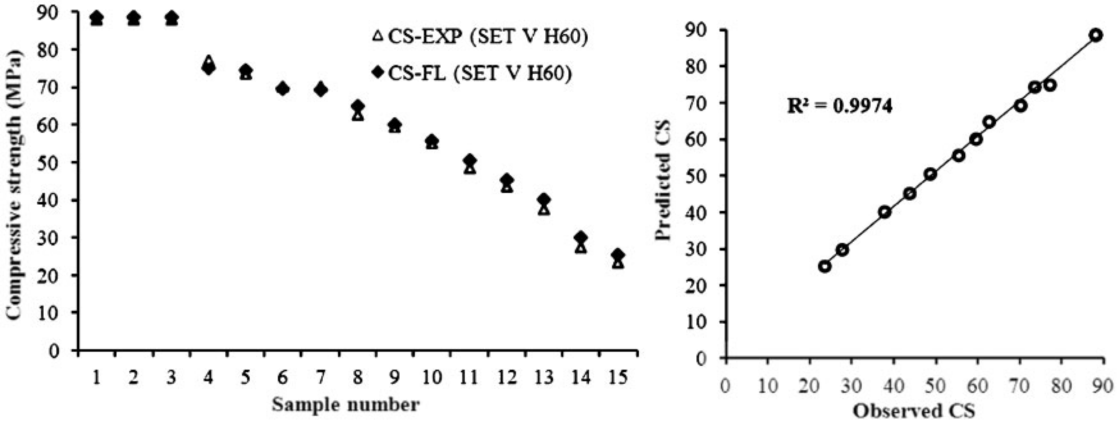
14 Matching figure of results of EM for SET IV H45 (FL versus EXP)



15 Matching figure of results of CS for SET IV H45 (FL versus EXP)



16 Matching figure of results of EM for SET V H60 (FL versus EXP)



17 Matching figure of results of CS for SET V H60 (FL versus EXP)

accurate. The centroid defuzzification technique can be expressed as follows

$$x^{*}=\frac{\int \mu i(x)x\mathrm{d}x}{\int \mu i(x)\mathrm{d}x} \tag{1}$$

where x^{*} is the defuzzified output, $\mu_{\mathrm{i}}(x)$ is the aggregated membership function and x is the output variable. As the final stage, after creating the model, the model results were obtained from the defuzzification monitor (Fig. 7).

Results and discussion

The values obtained from the model and experimental ones are divided into five groups (*see* Table 5) according to the haematite content to evaluate FL model predictability. The adequacy of the developed FL model was evaluated by considering three statistical evaluation criteria. These statistical parameters are coefficient of determination R^2, root mean square error (RMSE) and the mean absolute error (MAE) defined as follows

$$R^2=1-\left\{\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}}\left[Y_{\mathrm{i(m)}}-Y_{\mathrm{i(p)}}\right]^2}{\sum_{\mathrm{i}=1}^{\mathrm{N}}\left[Y_{\mathrm{i(m)}}-Y_{\mathrm{i(mean)}}\right]^2}\right\} \tag{2}$$

$$\mathrm{RMSE}=\left(\frac{1}{N}\right)^{1/2}\sum_{\mathrm{i}=1}^{\mathrm{N}}\left[Y_{\mathrm{i(m)}}-Y_{\mathrm{i(p)}}\right]^2 \tag{3}$$

$$\mathrm{MAE}=\frac{1}{N}\sum_{\mathrm{i}=1}^{\mathrm{N}}\left|Y_{\mathrm{i(m)}}-Y_{\mathrm{i(p)}}\right| \tag{4}$$

where m represents the measured values, p represents the predicted values, *mean* is the average of measured values and N is the number of datapoints. The statistical values of R^2, RMSE and MAE, including all the data sets, are given in Table 7. Matching figures were drawn for all groups to see the relationship between model and experimental results (Figs. 8–17).

Conclusions

We have developed a rule based Mamdani type FL model for calculation of the compressive strengths and elasticity modulus of concretes containing haematite under elevated temperature using appropriate experimental data. We have found the following.

1. Inclusion of haematite into concrete increases the compressive strength and elasticity modulus.
2. Concretes containing haematite survive better exposure to high temperatures than PC.
3. When the statistical results were evaluated for compressive strength in modelling, it was shown that all the results of the model are very close to the experimental results for all data sets.
4. When the statistical results were evaluated for elasticity modulus in modelling, it was shown that all the results of the model are very close to the experimental results for all data sets.
5. Rule based Mamdani type FL can be an alternative approach for the evaluation of the mechanical properties of concrete under elevated temperature. Our rule based Mamdani approach may be extended by adding other participants of concretes, such as water/cement ratio, pozzolan concentration and more.

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