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Analysis of the superplasticizer demand using computer simulation

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Abstract. The merits of self-consolidating concrete (SCC) such as high deformability, excellent resistance to segregation, and usability without applying vibration is highly common. To gain an environment-friendly approach or improving SCC properties, cement in SCC can be partially replaced with other materials. However, identifying the most effective parameters on the Superplasticizer demand (SP demand) of SSC would not be easy after the replacement. The main aim of this study is to identify the most influencing approaches on SP demand prediction. Hence, five different approaches in SP demand prediction, including Jring test, V funnel test, Ubox test, 3-min slump value, and 50-min slump value have been considered. Then, different models of an artificial intelligence approach are developed and the most influential one in an accurate SP demand prediction was determined. In comparison with other methods, it was indicated that in estimating the SP demand, V-funnel can be a better technique because of producing the lowest RMSE.

Keywords: ANFIS; prediction; self consolidating concrete; superplasticizer demand

1. Introduction

In recent decades, extensive investigations have been performed on different structural elements (Shariati *et al.* 2020c, d, e, Toghroli *et al.* 2020b, Jahandari *et al.* 2021). Researchers have tried to improve the properties of concrete structures using innovative approaches (Shariati 2013, Shariati *et al.* 2020l, r, Naderipour *et al.* 2021b). After water, concrete is the second most used material in the world, which has been examined under various conditions (Shariati *et al.* 2012c, d, 2014a, 2016, Shariati 2014, Armaghani *et al.* 2019). Few studies have been recently carried out on pozzolan to obtain the relationship between the mixing percentage of cement and water. According to ASTM (C618), pozzolan is defined as silica or silica material, which is not sticky, but in mixing cement with water and cement is adhesive (Xu *et al.* 2020a, b, Zhang *et al.* 2021b, Zhao *et al.* 2021a). This paper aims to achieve a suitable cement replacement and optimize the environmental issues and increase the properties such as hardened concrete, fresh concrete and durability (Shah *et al.* 2016a, Nosrati *et al.* 2018, Toghroli *et al.* 2018b, Nilashi *et al.* 2019, Shariati *et al.* 2019g). Hence, cement was partially replaced with pumice, pozzolan, slag, silica fume, and fly ash (Jitchaiyaphum *et al.* 2013, Rukzon *et al.* 2013, Shariati 2020, Shariati *et al.* 2020q, Rajaei *et al.* 2021). Previous studies have been conducted on the properties of concrete containing fly ash, silica fume and slag (Malhotra 1999, Shariati *et al.* 2011b, Dehwah 2012, Shariati *et al.* 2012b, Shariati *et al.* 2013, Li *et al.* 2019). Natural pumice pozzolan means that there is no need for applying chemical properties and minerals, and it is employed directly (Arabnejad Khanouki *et al.* 2016, Chen *et al.* 2019, Sajedi *et al.* 2019, Suhatril *et al.* 2019, Razavian *et al.* 2020, Toghroli *et al.* 2020a, Mehrabi *et al.* 2021). Pumice is a kind of volcanic product, which is mostly made of silica and alumina while its components are similar to bubbles with a large inner surface (Hossain 2005, Jaturapitakkul *et al.* 2011, Boroujerdnia *et al.* 2019, Rezania *et al.* 2021). The physical and chemical properties of pumice could lead to perfect durability and strength. Pumice improves both concrete durability (Hossain *et al.* 2006) and shows excellent resistance against sulfate attacks (Aydin *et al.* 2007, Huang *et al.* 2020a, Xu *et al.* 2021a, Zhang *et al.* 2021a). In addition to improving the mechanical properties of concrete including initial strength (Bınıci *et al.* 2012), it could be produced by pumice with high strength and low weight in comparison with cement which has lower weight and density (Beggas *et al.* 2013, Jahandari 2015, Shah *et al.* 2016b, Shariati *et al.* 2020j, Yazdani *et al.* 2020). Slag is a mineral product that is chemically similar to cement (Boukendakdji *et al.* 2012, Huang *et al.* 2020b, Xu *et al.* 2021b). There are several types of slag, which are generally divided into two main categories: (1) crystallized slag, and (2) granulated blast furnace slag. About 600 million tons of slag are produced across the world, in which around 430 million tons are molten slag and 170 million tons are crystallized slag (Vejmelková *et al.* 2011, Hosseinpour *et al.* 2018, Kamyab *et al.* 2018, Safa *et al.* 2019, Naghipour *et al.* 2020b, Shariati *et al.* 2020k). Crystallized slag is provided in two ways of rapid and slow cooling, which are considered in material aggregate group. Furnace Slag is a

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fine aggregate and could be used as a cement replacement in concrete (Karimi *et al.* 2016, Khorramian *et al.* 2016, Khorami *et al.* 2017b, Afshar *et al.* 2020, Shariati *et al.* 2020p). Low heat in hydration, proper performance, resistance against sulfate and acid attack, resistance to abrasion and corrosion and reasonable price range (Boukendakdji *et al.* 2012, Mohammadhassani *et al.* 2014a, Tahmasbi *et al.* 2016, Li *et al.* 2019, Luo *et al.* 2019, Selvama *et al.* 2019) are the benefits of slag. Concrete has an outstanding compressive strength due to its dense and robust texture which has not experienced the local or distortional buckling or other accidental deformations along with the low flexural and torsional strength which made the concrete a useful material for columns as an axial structural elements (Sinaei *et al.* 2011, Jalali *et al.* 2012, Shahabi *et al.* 2016a, 2019c, Khorami *et al.* 2017a, Davoodnabi *et al.* 2019, Trung *et al.* 2019b, Xie *et al.* 2019). Also, Self-consolidating concrete is turned to a favorable construction material due to its impressive properties. There are several existing studies on the inclusion of pumice powder on the self-consolidating concrete mixtures (Arabnejad Khanouki *et al.* 2010, 2011, Shariati *et al.* 2012a, Ardalan *et al.* 2017, Ismail *et al.* 2018, Li *et al.* 2021b). Cement replacement additives in SCC lead to some change in fresh and mechanical properties (Sinaei *et al.* 2012, Khorramian *et al.* 2017, Toghroli *et al.* 2017, Milovancevic *et al.* 2019, Lin *et al.* 2021). It is obvious that these changes are seen in experiments; however, realizing the most influencing parameters might not be easy at all (Shariati *et al.* 2011c, Shariati *et al.* 2011d, 2021, Shah *et al.* 2015, Ziaei-Nia *et al.* 2018). To address this problem, the use of artificial intelligence (AI) tools could be helpful. Adaptive neuro-fuzzy inference system (ANFIS) as a hybrid intelligence system can learn and adapt automatically (Hamidian *et al.* 2011, Mohammadhassani *et al.* 2014b, Safa *et al.* 2016a, Shariati *et al.* 2018, 2019b, Mishra *et al.* 2021). Compared to other AI techniques, ANFIS has not required system parameters to be known, and its simpler solutions can be adopted for multivariable problems. In this study, cement in SCC was partially replaced with pumice, slag, and fly ash in the contents of 10 to 50% (as binary mix designs). Besides, silica fume was employed along with pumice in some specimens (as ternary mix designs), and several evaluations were conducted on the specimens. Compressive strength, slump flow, and electrical resistance were examined. According to the obtained results, the most effective parameters on the compressive strength of SCC were identified. For this purpose, several ANFIS models including seven models with separate inputs and 21 models with couple parameters were developed. Finally, the effect of input parameters, i.e., contents of slag, silica fume, pumice, fly ash, cement, coarse and fine aggregates were investigated. Various approaches were used by researchers for data analysis such as artificial neural networks (ANNs) (Daie *et al.* 2011, Mohammadhassani *et al.* 2014d, Nasrollahi *et al.* 2018, Paknahad *et al.* 2018), Finite element method (FEM) (Mahdi Shariati 2019, Taheri *et al.* 2019, Usefi *et al.* 2019, Davoodnabi *et al.* 2021, Nouri *et al.* 2021), and Finite strip method (Shariati *et al.* 2011a, 2015, Sharafi *et al.* 2018a, b, Shariat *et al.* 2018, Katebi *et al.* 2019). In general, FEM is performed by finite element analysis using ANSYS and ABAQUS. Also, new metaheuristics algorithms can be utilized in prediction and optimization of different characteristics of structural elements (Shariati *et al.* 2010, 2019f, 2020g, Shah *et al.* 2016c, Shahabi *et al.* 2016b, Heydari *et al.* 2018). Moreover, the tricky empirical experiments have always been a barrier in front of the new explorations; however, employing intelligence solutions are one of the practical ways to address these issues (Armaghani *et al.* 2020, Shariati *et al.* 2020a, b, f, h, i). Whereas, artificial intelligence techniques have been performed on a variety of experimental studies as a reliable tool not only for parameters' estimation, but also for prediction of crucial design characteristics (Shariati *et al.* 2012e, 2014b, 2017, Wei *et al.* 2018, Trung *et al.* 2019c, Naderipour *et al.* 2021a). Different kinds of algorithms have been introduced with their traits and advantages (Mohammadhassani *et al.* 2015, Mansouri *et al.* 2016, Sari *et al.* 2018, Ali Shariati 2019). Using relevant algorithms in order to analytical assessment has been carried out on different types of studies (Shariati 2008, 2019a, Shahabi *et al.* 2016c, Chahnasir *et al.* 2018, Zandi *et al.* 2018, Katebi *et al.* 2019, Mansouri *et al.* 2019, Naghipour *et al.* 2020a). Therefore, AI techniques are widely applied to solve the nonlinear relationships between input and output variables (Toghroli *et al.* 2018a, Huang *et al.* 2021a, b, Jiao *et al.* 2021, Ma *et al.* 2021, Moradi *et al.* 2021, Zhao *et al.* 2021b). The main purpose of this paper is to avoid the high nonlinearity of mathematical methods employing soft computing technique, which does not require the knowledge of internal system and can provide a compact solution for multi-variable problems. Therefore, a reliable database has been employed from strong experimental studies (Ardalan *et al.* 2017, Chuanhua Xu 2019, Shariati *et al.* 2019g). Accordingly, ANFIS has been practiced to determine the most dominant parameters for SP demand forecast. ANFIS is a subset of AI techniques that integrates the capability of neural networks and fuzzy systems.

2. Experimental Methodology

2.1 Materials

A commercially available ASTM type II Portland cement with a specific density of 3160 kg/m3 and fineness of 290 m^2/kg and volcanic pumice have been used to carry out the experiments. Mixing coarse aggregates with a maximum size of 19 mm and density of 2.5 kg/cm^3, fine aggregates with Blain of 3.6 with specific density of 2.7 g/cm^3 and water absorption of 2.95%, have been considered. The employed water was drinking water, also LG superplasticizer based on carboxylate with a density of 1.07 g/cm^3 was applied to obtain a desirable efficiency and regulate the slump loss. As mentioned earlier, pozzolan pumice, fly ash, slag, and silica fume are the cement additives with different replacement percentages that are used with binary and ternary blends. Table 1 shows the chemical components of cement.

Table 1 The chemical components of Portland cement and other cementitious materials

Components (%)	Cement	FA	Pumice	Slag	SF
SiO_2	22.42	62.8	44.13	33.1	86.2
Al_2O_3	4.68	45.9	16.71	13.8	1.44
Fe_2O_3	3.68	0.92	1.72	3.12	0.2
CaO	63.25	2.60	11.09	40.7	3.06
MgO	3.63	1.40	1.95	8.70	1.32
SO_3	1.74	0.49	0.39	0.60	0.34
Specific gravity (kg/m^3)	3160	2200	2850	2850	2350
Blaine (m^2/kg)	290	260	320	445	20000

FA: Fly ash, SF: Silica fume

Table 2 Mix proportion of self-consolidating concrete

Cement material	(kg/m^3) powder					aggregate (kg/m^3)		
	Pumice	Silica Fume	Slag	Fly ash	OPC	gravel	sand	(kg/m^3) water
Control	-	-	-	-	500	1070	580	191
FA10	-	-	-	50	450	1063	590	191
FA20	-	-	-	100	400	1052	584	191
FA30	-	-	-	150	350	1040	578	191
FA40	-	-	-	200	300	1029	571	191
FA50	-	-	-	250	250	1017	565	191
Pu10	50	-	-	-	450	1072	595	191
Pu20	100	-	-	-	400	1069	594	191
Pu30	150	-	-	-	350	1066	592	191
Pu40	200	-	-	-	300	1063	590	191
Pu50	250	-	-	-	250	1060	589	191
Slg10	-	-	50	-	450	1072	595	191
Slg20	-	-	100	-	400	1069	594	191
Slg30	-	-	150	-	350	1066	592	191
Slg40	-	-	200	-	300	1063	590	191
Slg50	-	-	250	-	250	1069	580	191
Pu25- SF5	125	25	-	-	350	1063	590	191
Pu45- SF5	225	25	-	-	250	1057	587	191
Pu40- SF10	250	50	-	-	200	1051	584	191

2.2 Mix proportion

Fly ash, pumice, and slag binaries with replacement percentages of 10, 20, 30, 40 and 50 %, and water to cement ratio of 38% are considered in the first series of mix design. The second series consists of ternary mixtures of pumice and silica fume with the same water to cement ratio (Table 2). The content of cement replacements in all designs is 500 kg/m2. The replacement percentage of each material is indicated by its design name. Dry materials were firstly mixed, then water and superplasticizer were added. Mixing processing time was about 10 minutes and concrete was rested about 4 minutes after the first 3 minutes. Consequently, it was mixed in machine for 3 min. After 10 minutes, the slump flow experiment was carried out immediately.

2.3 Test specimens and test procedure

Each series of mix designs including 12 standard cube specimens with the size of 15 × 15 × 15 cm were molded 24h under laboratory condition after mixing process and applied in water tanks at an average temperature of 20°C. The slump flow was examined (according to ASTM C1611) to determine the fresh concrete workability in self-consolidating concrete at various intervals. In this experiment, the propagation of concrete after funnel removal is measured. Findings of slump flow analysis show the filling ability degree and SCC stability. Furthermore, the results of compressive strength were collected at 7, 28, and 90 days after mixing, according to ASTM C39. Moreover, after reaching target slump flow, V-funnel, J-ring and U-box self-compatibility experiments were performed on fresh

Fig. 1 J-ring test

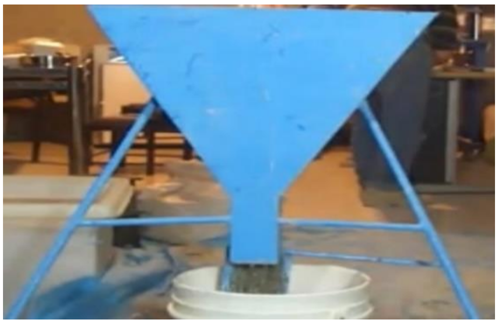

Fig. 2 V-funnel test

Fig. 3 U-box test

properties of each mix design according to EFNARC standards as below:

(a) The apparatus of the j-ring test consists of a round of rebars that bonded to a circular plate and made the j-ring cage. The j-ring value is the difference between the spread diameter of the concrete with and without the j-ring cage. A higher value of the j-ring test shows the higher segregation and lower flowability of the mix.

(b) The v-funnel test comprises a large vertical specific funnel with standard geometry. It is a simple test that measures the time that a sample takes to completely fall from the above of the funnel and expel from the bottom of the funnel. This time could be a suitable criterion for fluidity and rheology condition, in which higher time values are directly related to the lower viscosity and workability.

(c) The difference of concrete height in two chambers is measured using the U-box test. The device comprises a vessel that is divided by a middle wall into two compartments. An opening with a sliding gate is fitted between the two sections. The left hand section is filled with about 20 L of concrete, then the gate is lifted and the concrete flows upwards into the other section. The height of concrete in both sections is measured.

3. Tests results

3.1 Fresh concrete properties

In binary blends of pumice and slag, the slump flow drop is reduced as the replacement percentage increases. However, the downward curve trends of pumice and slag are entirely different. The growing trend of slump flow measurement in the 30th minute and replacement percentage of more than 20% could be seen in the mixture. This increment can be due to the physical characteristics of pumice particles. It appears that in the initial minutes, the mixed water can be absorbed by pumice particles, and then, it is returned to the mix. Unlike slag and pumice binaries, the opposite result is shown by fly ash. The slump flow increases as the fly ash replacement increases. This phenomenon can be attributed to the fine particles of fly ash compared to the size of cement, pumice, and slag aggregates which have more surface and result in a higher friction factor. A concrete mix is only can be considered as SCC when the necessities for segregation, filling and passing criteria are satisfied according to EFNARC.

3.2 Superplasticizer consumption

A comparison of superplasticizer demand and slump loss between 10-50 minutes for all binaries is shown in Fig. 4. For better analysis, the relative numbers are used by converting all slump losses. Control sample for each binary is supposed 100%, and other mixing models proportioned based on own samples. Moreover, in 10th minute, to reach the 65±2 slump, the superplasticizer content is determined. According to the findings, more superplasticizer is used by binary pumice mixtures to reach a slump of 65 ±2, which have a less slump loss. As the replacement percentage increases, lower superplasticizer is consumed. As mentioned earlier, slag particles have little water absorption at the start of mixing process, making this mixture behavior very susceptible against superplasticizer. Therefore, concrete segregation happens once the small content of superplasticizer is added more than normal amount. But in general, it seems that slag shows better performance than the other two powders because of the superplasticizer consumption and the acceptable slump loss. However, the spherical shape of fly ash results in the lowest superplasticizer demand and the highest slump loss. Also, this feature leads to increasing fluidity of mixture and reducing intergranular fraction. Moreover, the lower superplasticizer consumption which leads to shorter preservation of slump flow is obtained (Ramachandran *et al.* 1996). Besides, a high percentage of alumina oxide in fly ash leads to decreasing the curing period, and thus, the loss of slump flow happens in a shorter time. This amount for slag and pumice powders is much lower as approved by findings. For a single slump flow, it was observed that pumice consumes more superplasticizer in binary mixtures compared to other used powders. It also increases as the

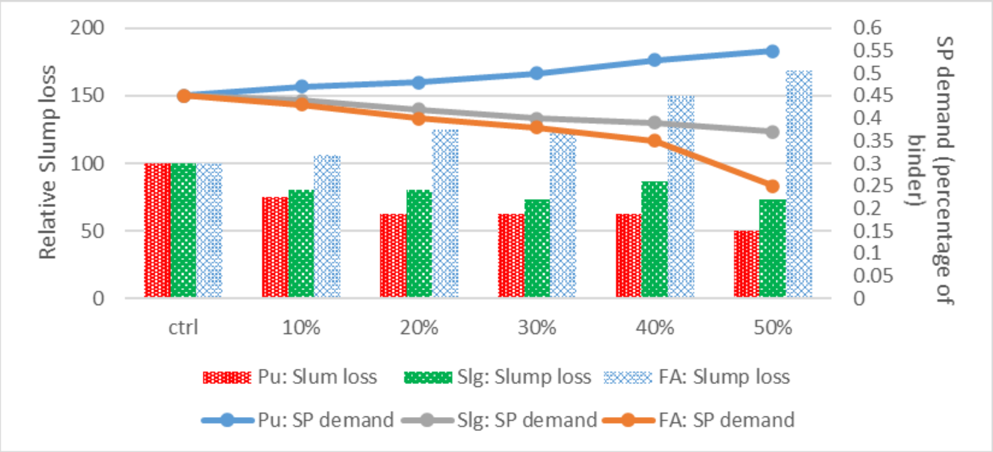

Fig. 4 Superplasticizer consumption and slump flow loss in the range of 10-50 minutes for binary designs

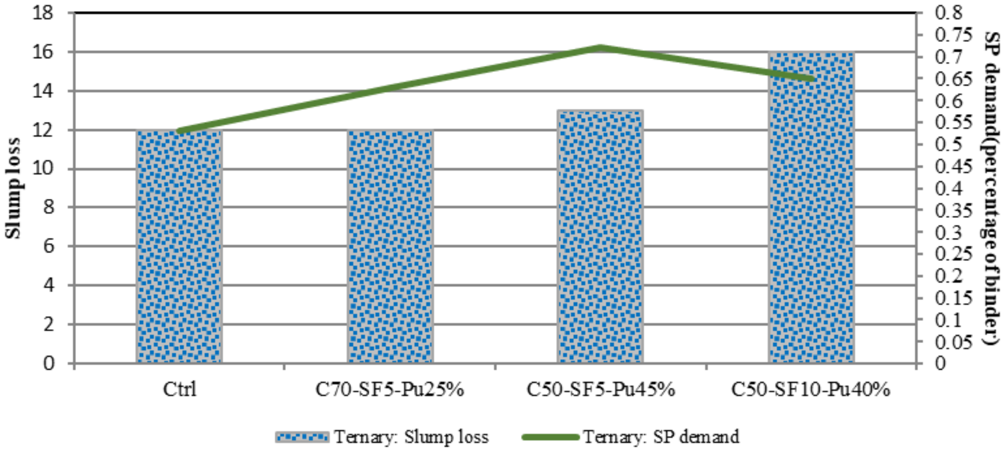

Fig. 5 Superplasticizer consumption and slump flow loss in the range of 10-50 minutes for ternary designs

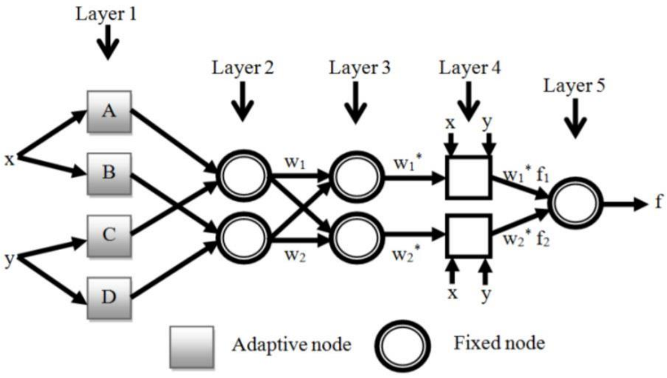

Fig. 6 The structure of ANIFS

replacement increased; however, leads to lower slump flow. On the other hand, once the silica fume is added to the blend, the slump loss is achieved during the time, without a considerable influence on the initial slump and amount of initial utilized superplasticizer. Therefore, in the ternary mixtures of pumice and silica fume, a more superplasticizer is required for a mixture incorporating pumice with a higher replacement percentage, and the slump loss decreases. However, a mixture with higher amounts of silica fume shows the opposite performance. According to Fig. 5, these findings are in close agreement with the obtained measurements. It was found that an inverse relationship is observed between the value of superplasticizer demand and the slump flow loss. It was also indicated that in binary mixtures, 30% replacement of pumice and slag is highly cost-effective and reasonable. In the case of ternary designs, 45% replacement for pumice with 5% for silica fume can be favorable for requirements of mixing design.

4. ANFIS methodology

Artificial intelligence (AI) as a novel approach has been developed widely in recent years (Shariati *et al.* 2018, 2019d, e, 2020n, Maslahati Roudi *et al.* 2018). In fact, AI has many applications in different fields, especially in civil engineering (Safa *et al.* 2020, Shariati *et al.* 2020m, o, Li *et al.* 2021a). The ability of AI algorithms has been proven in numerous papers (Mohammadhassani *et al.* 2014c, Safa *et al.* 2016b, Qi *et al.* 2019, Trung *et al.* 2019a). ANFIS is a fuzzy inference system implemented in the frame work of adaptive networks (Jang 1993, Mohammadhassani *et al.* 2013, Toghroli *et al.* 2014a, 2016). ANFIS network has five layers (Fig. 6). The central core is a fuzzy inference system. The first layer receives inputs (x and y in Fig. 6) and converts them to fuzzy values by membership functions (Toghroli *et al.* 2014b, Ali 2015, Hamdia *et al.* 2015, Sadeghipour Chahnasir *et al.* 2018, Sedghi *et al.* 2018a, b, Shariati *et al.* 2019h). The rule base includes two fuzzy IF-THEN rules of Takagi and Sugeno's type:

Rule 1: if x is A_1 and y is B_1, then $f_1 = p_1 x + q_1 y + r_1$,

Rule 2: if x is A_2 and y is B_2, then $f_2 = p_2 x + q_2 y + r_2$,

In the first layer, each node is chosen as an adaptive node with a node function,

$$O_i^1 = \mu A_i(x) \tag{1}$$

where A_i is a linguistic label, and O_i^1 is the membership function of A_i. Bell-shaped membership function is commonly selected due to having the highest capacity for the regression of nonlinear data (Sari, Suhatril et al., 2019). This function with the maximum value of 1 and minimum value of 0 is described by:

$$\mu(x) = bell(x; a_i, b_i, c_i) = \frac{1}{1 + \left[\left(\frac{x - c_i}{a_i}\right)^2\right]^{b_i}}$$

where $\{a_i, b_i, c_i, d_i\}$ is the parameters set and x is the input. The parameters of this layer are known as *premise parameters*.

The incoming signals are multiplied using the second layer and their product are sent to the next layer. For example:

$$w_i = \mu A_i(x) \times \mu B_i(y), \quad i = 1,2. \tag{2}$$

Every output of the nodes exhibits the firing strength of a rule.

The third layer is the rule layer. In this layer, the ratio of i^{th}node firing strength of rule to those of other nodes is calculated. This means that:

$$w_i^* = \frac{w_i}{w_1 + w_2} \qquad i = 1,2. \tag{3}$$

The outcomes w_i^* are known as *normalized firing strength.*

The fourth layer is deffuzification layer, in which every node has a node function as below:

$$O_i^4 = w_i^* f_i = w_i^*(p_i x + q_i y + r_i) \tag{4}$$

where $w_i^*$is the output of third layer and $\{p_i, q_i, r_i\}$ are the parameters of this layer known as *consequent parameters*.

The 5th layer is the output layer, in which the overall output is calculated through summing all the incoming signals as follows:

$$O_1^5 = f = \sum_i w_i^* f_i \tag{5}$$

In the current process, between the actual value and output, a threshold is established. Then, using the least-squares approach, the consequent parameters are achieved, and the error for each data is determined. If this value is larger than the considered threshold, the premise parameters are updated utilizing gradient decent method. This process continues until the error becomes less than the threshold. Since the parameters are achieved by two algorithms (i.e. least squares and gradient descent algorithm) simultaneously, the employed algorithm in this process is recognized as a hybrid algorithm.

4.1 Performance evaluation

The performance of models is examined through different indicators including determination coefficient (R^2), root mean squared error (RMSE) and Pearson correlation coefficient (r), which are shown as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{6}$$

$$r = \frac{n\left(\sum_{i=1}^{n} O_i \cdot P_i\right) - \left(\sum_{i=1}^{n} O_i\right) \cdot \left(\sum_{i=1}^{n} P_i\right)}{\sqrt{\left(n\sum_{i=1}^{n} O_i^2 - \left(\sum_{i=1}^{n} O_i\right)^2\right) \cdot \left(n\sum_{i=1}^{n} {P_i}^2 - \left(\sum_{i=1}^{n} P_i\right)^2\right)}} \tag{7}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - \overline{O_i}\right) \cdot \left(P_i - \overline{P_i}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - \overline{O_i}\right) \cdot \sum_{i=1}^{n}\left(P_i - \overline{P_i}\right)} \tag{8}$$

where P_i and O_i are the predicted and observed variables and *n* is the total number of considered data, respectively.

4.2 Statistical data

The used data in this investigation was obtained from the conducted tests on the specimens. Totally, a data base containing 26 data sets was collected. The data of Jring, Ubox, and V funnel tests, slump values in 3-th minute and 50-th minute have been considered as the inputs of models, and SP demand as output. Some details of the dataset are shown in Table 3 and the employed statistical data in ANFIS models are indicated in Table 4.

4.3 Models development

In order to identify the most effective parameters on SP demand. 5 ANFIS models were developed to evaluate the impact of each input variable on the output separately. In addition to parameter identification, SP demand was also predicated by another ANFIS model. Considering the number of data and in order to avoid the overfitting, 85% of inputs was randomly devoted to the training phase of

Table 3 Output and input variables detail

Inputs and outputs	Variables	Minimum	Maximum	Mean Value	Standard Deviation
Input 1	Jring	0.70	6.15	2.71	1.44
Input 2	Ubox	0.50	25.00	4.12	5.19
Input 3	V funnel	5.00	60.00	8.73	10.58
Input 4	3-min Slump	41.00	66.00	52.85	6.72
Input 5	50-min Slump	43.00	62.00	55.81	4.49
Output	SP Demand	0.25	2.22	0.61	0.37

Table 4 Statistical data

Input 1 Jring	Input 2 Ubox	Input 3 V funnel	Input 4 3-min Slump	Input 5 50-min Slump	Output SP Demand
1	0.5	5	52	58	0.45
1	1	5	66	59	0.47
2	1	5	46	58	0.48
2	1.5	7	55	62	0.5
3	2	8	52	60	0.53
3	2.5	9	55	60	0.55
1	0.5	5	52	58	0.45
1	1	5	66	59	0.43
1	1	5	46	58	0.4
2	1.5	7	55	62	0.38
3	2	7	52	60	0.35
3	2	8	55	55	0.25
0.7	3	6	42	50	0.58
5	12	9	55	55	0.57
2.25	8	8	55	55	0.55
2.5	4	10	58	56	0.53
2	3	7	66	50	0.51
3.15	5.5	7	58	56	0.5
4.25	4	5	53	52	0.53
3.05	10	5	46	52	0.63
3.1	1	6	53	52	0.72
3.28	7	5	44	49	0.65
2.75	2	6	53	59	0.6
3.65	2	7	41	57	0.95
5.75	4	10	52	56	1.14
6.15	25	60	46	43	2.22

models and the remaining 15% to testing phase. All the codes were developed in MATLAB environment and available functions of MATLAB software were used in developing process.

4.4 Results and discussion

The impact of each input variable on the output variable can be seen through RMSE value. The model with the lowest value of RMSE in training phase demonstrates that it is better able to solely predict the output. All ANFIS models were run 3 times and the mean value of RMSEs in training and testing phase were recorded. Table 5 shows the obtained RMSE values. Based on table 5, the model number 3 is the most effective parameter on the output by having the lowest value of RMSE in training phase. In other words, V funnel test is the best indicator in SP demand prediction of SCC.

Fig. 7 shows the RMSE values for each model. Comparing the testing and training RMSEs in this figure, it can be concluded that the developed models have shown an appropriate performance, also overfitting has been avoided.

Table 5 Training and testing RMSEs of the input parameters

ANFIS model 1: in1 ⟶ trn = 0.131, tst = 0.177
ANFIS model 2: in2 ⟶ trn = 0.160, tst = 0.248
ANFIS model 3: in3 ⟶ trn = 0.126, tst = 0.165
ANFIS model 4: in4 ⟶ trn = 0.263, tst = 0.354
ANFIS model 5: in5 ⟶ trn = 0.140, tst = 0.277

Fig. 7 RMSE values in the training and testing phases

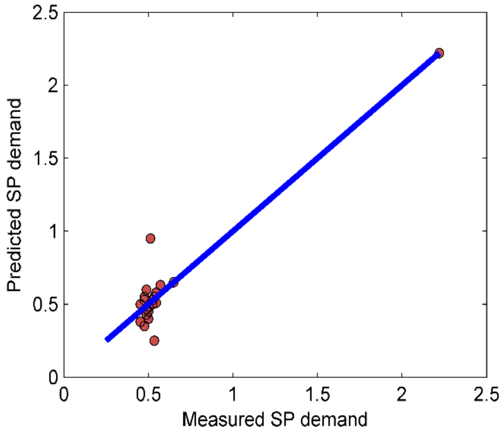

Fig. 8 Scatter diagram for predicting the required superplasticizer

Also, it can be observed that after model 3, model 1 (i.e. Jring test) shows the lowest training RMSE. Therefore, it is the second most effective parameter in SP demand prediction. The order and the efficiency of other inputs on SP demand value can also be observed in Fig. 7. Fig. 8 shows the scatter plot of the predicted results of SP demand. In this diagram, the values of RMSE, r, and R^2 are equal to 0.944, 0.892, and 0.125, respectively. It can be observed that using the ANFIS model is an appropriate technique in SP demand estimation.

5. Conclusions

Determining the SP demand is a challenging process because of many effective factors in the prediction process. This study used an artificial intelligence approach to overcome the problems in SP demand prediction. The results of various methods such as Jring, U-box, V funnel, 3-min slump, and 50-min slump were collected for the predicting the SP demand. ANFIS methodology has been used to select the most dominant approach in SP demand prediction. Five types of ANFIS models were used and the effect of each approach on the prediction of SP demand was evaluated. Also, an experimental program was carried out to investigate the possible incorporation of pumice powder as cement replacement in binary and ternary blended systems in SCC through its performance at fresh and hardened state in comparison with other common cementitious materials such as fly ash and slag. The following conclusions can be drawn:

- Pumice has a significant impact on the maintenance of SCC slump optimal performance, though superplasticizer demand of pumice powder is more than the other two powders.
- All the binary mixtures satisfies the limits for U-box and Vfunnel tests while most of them could not fulfill the EFNARC recommendation for J-ring test. On the other hand, the ternary blends of cement, pumice and silica fume yields satisfactory performance in all tests.
- Test results suggest that the amount of SP required for consistent improvement in the initial slump flow is directly related to the composition of concrete mixtures, while mixtures containing pumice need higher SP dosage than fly ash to reach the desired value.
- Comparing the developed ANFIS models, the corresponding model to V funnel test was led to the best RMSE value. This shows that V funnel test is one of the approaches in the SP demand prediction and it is more likely to culminate in an accurate prediction.

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