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Fuzzy logic for prediction water absorption of lightweight geopolymers produced from waste materials

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Abstract

In the present work, water absorption of lightweight geopolymers produced by fine fly ash and rice husk bark ash together with palm oil clinker (POC) aggregates has been investigated experimentally and modeled by fuzzy logic. Different specimens made from a mixture of fine fly ash and rice husk bark ash with and without POC were subjected to water absorption tests at 2, 7 and 28 days of curing. The specimens were oven cured for 36 h at 80 °C and then cured at room temperature until 2, 7 and 28 days. The results showed that high amount of POC particles improve the percentage of water absorption at the early age of curing. In addition the ratio of ‘‘the percentage of water absorption’’ to ‘‘weight’’ of the POC-contained specimens at all ages of curing was much higher than that of POC-free specimens which make them suitable for lightweight applications. To build the model, training, validating and testing using experimental results from 144 specimens were conducted. The used data in the fuzzy model are arranged in a format of six input parameters that cover the quantity of fine POC particles, the quantity of coarse POC particles, the quantity of FA + RHBA mixture, the ratio of alkali activator to ashes mixture, the age of curing and the test trial number. According to these input parameters, the water absorption of each specimen was predicted. The training, validating and testing results in the fuzzy model have shown a strong potential for predicting the water absorption of the geopolymer specimens.

Keywords: Geopolymer; Water absorption; Ashes mixture; Palm oil clinker; Fuzzy logic

1. Introduction

Geopolymer, an inorganic material, which was developed by Davidovits, contains both silica and alumina as a binder to produce geopolymer. Various alkali activators also play a major role in producing geopolymers by dissolving silica and alumina from the raw material and forming aluminosilicate structures. Geopolymer has been used for various works such as for sculpture, building, repairing, and restoration. Numerous research publications relating to geopolymers have been released, with some reporting on chemical composition aspects or reaction processes while others present results relating to mechanical properties and durability [1].

Several waste materials containing silica and alumina sources like fly ashes could be used as a source material to produce geopolymer because of their suitable chemical composition along with favorable size and shape [2,3]. Fly ash is a solid, fine-grained material resulting from the combustion of pulverized coal in power station furnaces. The material is collected in mechanical or electrostatic separators. The term fly ash is not applied to the residue extracted from the bottom of boilers. Fly ashes capable of reacting with $Ca(OH)_2$ at room temperature can act as pozzolanic materials. Their pozzolanic activity is attributable to the presence of SiO_2 and Al_2O_3 in amorphous form. Fly ashes are particularly rich in SiO_2, Al_2O_3 and Fe_2O_3, and also contain other oxides such as CaO, MgO, MnO, TiO_2, Na_2O, K_2O and SO_3. Fly Ash with a high content of CaO (15–40%) may be regarded as potentially hydraulic and capable of causing unsoundness in mortars and concrete [4].

One of the suitable silica-reach source is rice husk–bark ash (RHBA) which is a solid waste generated by biomass power plants using rice husk and eucalyptus bark as fuel. The power plant company providing RHBA for this research reported that about 450 tons/day of RHBA are produced and discarded. The major chemical constituent of RHBA is SiO_2 (about 75%) [5,6]. Therefore, blending FA and RHBA can adjust the ratio of Si/Al as required.

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In the previous work [7], the properties of geopolymeric specimens with seeded FA and RHBA was studied. It was shown that the finer ashes particle results in higher compressive strength. In addition, that mixture contained the SiO_2/Al_2O_3 ratio equal to approximately 3 had the best properties. In the present work, experiments were conducted to decrease the weight of the produced specimens using lightweight aggregates. Palm oil clinker (POC) is a by-product in the incineration of Palm Oil Shell. It is a light solid fibrous material which when crushed has the potential to be used as aggregate in lightweight concrete. The density and the strength of POC falls within the requirements of the structural lightweight concrete. This is anticipated to grow further with the global increase in vegetable oil demand. However, it is also the main contributor to the nation's pollution problem, which includes the annual production of 2.6 million tons of solid waste in the form of oil palm shells [8].

Several works have addressed utilizing of computer-aided prediction of engineering properties including those done by the authors [9]. Over the last two decades, a different modeling method based on fuzzy logic (FL) has become popular and has been used by many researchers for a variety of engineering applications. Fuzzy control theory can be applied on linear and nonlinear systems. It does not need to handle the tedious mathematical models of controlled body. It needs only to set a simple controlling method based on engineering experience. Therefore, it is particularly useful in complicated structural control system. The water absorption of geopolymers can be calculated using the models built with FL. It is convenient and easy to use these models for numerical experiments to review the effects of each variable on the water absorption values [10,11].

As authors' knowledge, there are no works on utilizing a mixture of FA, RHBA and POC to produce lightweight geopolymers. In addition, since the concept of geopolymers is somewhat new and there are few works on their properties, application of computer programs like FL to predict their properties is rarely reported. The aim of this study is to investigate the water absorption of lightweight geopolymers experimentally and presenting suitable model based on FL to predict their water absorption. Fine FA and RHBA were mixed by different amount of POC and subjected to water absorption tests. As indicated in the previous work [7], the advantage of using a mixture of ashes is to control the SiO_2/Al_2O_3 ratio to achieve a suitable combination of waste materials result in higher strengths. Properties of the produced specimens were investigated after specific times of curing. Totally 144 data of water absorption tests in different conditions were collected, trained, validated and tested by means of FL. The obtained results have been compared by experimental ones to evaluate the software power for predicting the water absorption of the geopolymer specimens.

2. Experimental procedure

The cementitious materials used in this work were FA and RHBA. Their chemical composition has been illustrated in Table 1. In addition, Fig. 1 shows SEM micrograph of the cementitious materials, respectively. The as-received ashes were sieved and the particles passing the finesses of 33 μm were grinded using Los Angeles mill 180 min. The average particle size obtained for FA was 3 μm with the BET specific surface of 38.9 m^2/g. The average particle size obtained for RHBA was 7 μm with the BET specific surface of 33.1 m^2/g. Fig. 2 shows the particle size distribution of the two produced samples.

Table 1
Chemical composition of FA, RHBA and WG (wt%).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	Na_2O	Loss on ignition
FA	35.2	23.2	12.4	20.0	2.36	0.36	0.24
RHBA	81.4	0.40	0.12	3.23	0.85	–	3.55
WG	34.2	–	–	–	–	13.1	–

POC particles less than 7 mm and 7–18 mm size were used as fine and coarse aggregate. The density of fine and coarse POC was 1015 and 693 kg/m^3 respectively.

Sodium silicate solution or water glass (WG) and sodium hydroxide (NaOH) were used as the solution part of the mixture. WG was used without following modification, but the sodium hydroxide was diluted to different concentrations before using. The chemical composition of the utilized WG is also given in Table 1.

Totally 2 series of geopolymer specimens each contain different mixture of FA, RHBA and POC as illustrated in

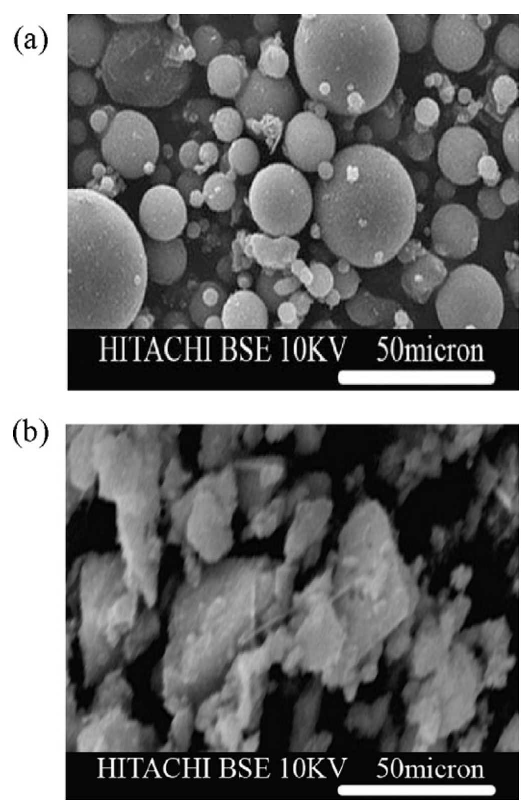

Fig. 1. SEM micrograph of (a) FA and (b) RHBA used in this study.

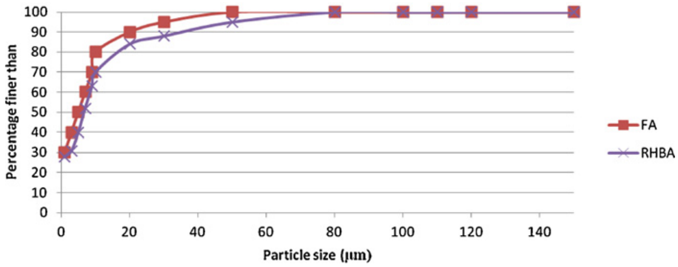

Fig. 2. Particle size distribution pattern of the different ashes used in this study.

Table 2 were prepared for the tests. The mixture of FA to RHBA had a constant ratio of 70:30 and a bulk density of 2318 kg/m^3 to achieve SiO_2/Al_2O_3 ration equal to approximately 3 [7]. The mixed alkali activator of sodium silicate solution and sodium hydroxide was used. Sodium hydroxide was diluted by tap water to have concentrations of 12 M since this concentration was found to produce the best properties [7]. The solution was left under ambient conditions until the excess heat had completely dissipated to avoid accelerating the setting of the geopolymeric specimens. The sodium silicate solution without preparation was mixed with the sodium hydroxide solution. The ratio of the sodium silicate solution to sodium hydroxide solution was 2.5 by weight for all mixtures because this ratio demonstrated the best properties for fly ash-based geopolymer [12,13]. For all samples, the mass ratio of alkali activator to FA–RHA mixture was 0.4. Pastes were mixed by shaking for 5–10 min to give complete homogenization. The mixtures were cast in ø30 mm × 60 mm polypropylene cylinders. The mixing was done in an air-conditioned room at approximately 25 °C. The molds were half-filled, vibrated for 45 s, filled to the top, again vibrated for 45 s, and sealed with the lid. The mixtures were then precured for 24 h at room temperature (this precuring time has been found to be beneficial to strength development and hence improved properties [14]). Precuring time before application of heat induces significant dissolution of silica and alumina from fly ash and formation of a continuous matrix phase, increasing, therefore, the homogeneity of the geopolymeric materials [14,15]. After the precuring process, the samples and molds were placed in a water bath to prevent moisture loss and the carbonation of the surface. The batches were put in the oven at the elevated temperatures of 80 °C for 36 h. Again this temperature and time was found to have the best effect on the properties of the specimens [7]. The percentage of water absorption results of the produced specimens were measured on the cylindrical samples at 2, 7 and 28 days of curing (including oven curing). Three tests were carried out on each mixture and the average values were reported.

To prepare the water absorption testing specimens, 1 cm from the top and bottom of the samples from each mixture were removed to avoid any effects caused by surface paste. Hence, the samples having ø30 mm × 40 mm were used as representative specimens for each mixture. Non-shrinking epoxy resin was cast around all specimens with a thickness of 25 mm to prevent water leakage. These specimens were installed in housing cells to test their water permeability. In this work, to evaluate the water permeability of the specimens, percentage of water absorption is an evaluation of the pore volume or porosity of concrete after hardening, which is occupied by water in saturated state. Water absorption values of the samples were measured in accordance to the ASTM C 642 [16] after 7 and 28 days of moisture curing adapted to the method done for concrete specimen.

3. Experimental results and discussion

The percentage of water absorption of the produced specimens has been illustrated in Table 3 for 2, 7 and 28 days of curing. On the whole, samples made with the fine RHBA and FA particles (C0 series) have shown higher percentage of water absorption at 2 days of curing. This may be

Table 2
Mixture proportioning of the utilized FA, RHBA and POC to produce geopolymeric specimens.

Sample designation	Volume fraction of fine + coarse POC in geopolymeric specimens (%)	Weight percent of fine POC in aggregate mixture (wt%)	Weight percent of coarse POC in aggregate mixture (wt%)	Density of the specimen (kg/m^3)
C0 (control)	0	0	0	2318.0
fPOC30-1	5	30	70	2248.0
fPOC30-2	10	30	70	2178.0
fPOC30-3	20	30	70	2038.1
fPOC30-4	40	30	70	1758.2
fPOC30-5	50	30	70	1618.2
fPOC50-1	5	50	50	2244.8
fPOC50-2	10	50	50	2171.6
fPOC50-3	20	50	50	2025.2
fPOC50-4	40	50	50	1732.4
fPOC50-5	50	50	50	1586.0
fPOC70-1	5	70	30	2241.6
fPOC70-2	10	70	30	2165.2
fPOC70-3	20	70	30	2012.3
fPOC70-4	40	70	30	1724.3
fPOC70-5	50	70	30	1573.0

Ashes mixture contains 70 wt% FA and 30 wt% RHBA.
Alkali activator (WG + NaOH) wt% to FA–RHBA wt% mixture ratio is 0.4.

Table 3
Percentage of water absorption of the geopolymeric specimens (wt%).

Specimen designation	2 days	7 days	28 days
C0 (control)	1.42	0.90	0.72
fPOC30-1	1.25	0.89	0.81
fPOC30-2	1.23	0.88	0.81
fPOC30-3	1.20	0.88	0.82
fPOC30-4	1.16	0.87	0.82
fPOC30-5	1.14	0.86	0.83
fPOC50-1	1.21	0.88	0.79
fPOC50-2	1.17	0.87	0.80
fPOC50-3	1.15	0.86	0.80
fPOC50-4	1.10	0.86	0.81
fPOC50-5	1.08	0.85	0.82
fPOC70-1	1.15	0.86	0.79
fPOC70-2	1.12	0.85	0.79
fPOC70-3	1.08	0.84	0.80
fPOC70-4	1.06	0.83	0.80
fPOC70-5	1.01	0.83	0.81

Ashes mixture contains 70 wt% FA and 30 wt% RHBA.
Alkali activator (WG + NaOH) wt% to FA–RHBA wt% mixture ratio is 0.4.

attributed to the fact that the nature of ashes particles is hygroscopic [17]. In the early age of curing, the pozzolanic activity of fine ashes particles results in more water consumption in C0 series with respect to POC-contained series (i.e. all of the specimens except C0 series) because the amount of ashes in C0 series is higher than the other series. The percentage of water absorption at 7 days of curing for C0 series specimen is also higher than the other series. However, the differences between the obtained values are not high; it may be due to the proceeding of the reaction and more gel formation at 7 days of curing. After that, at 28 days of curing, the percentage of water absorption of C0 series specimens became smaller than the POC-contained series specimens. This may be due to completion of aluminosilicate formation in C0 series and hence, the absorption of water is no longer required by the geopolymeric paste. Although this completion is occurred in the other series because of the similar composition of the geopolymeric paste in the all specimens, the greater water absorption in POC-contained series may be due to the larger volume of pores in the POC–gel interface. This is in contrast with C0 series in which the production of more compacted specimens due to presence of finer FA and RHBA particles rather than POC particles occurred. Fine particles are capable to fill the vacancies and produce more densified specimens which make them stronger to the applied loads. This has been confirmed in some works done on concrete specimens [17], but as the authors' knowledge, there are no reports which confirm this matter in geopolymers except the previous work [7].

The best point of view for using POC particles is its low density with respect to the ashes mixture. Fig. 3a and b respectively shows the 2 and 28 days P/W for all geopolymeric specimens. From Fig. 3a it is obvious that when the weight is a critical factor for designing an structure, regardless of strength of the produced specimens which may be low because of the presence of POC particles and early age of curing, the higher POC particles (more than 20%) results in the much higher P/W ratio and hence makes it suitable for lightweight application.

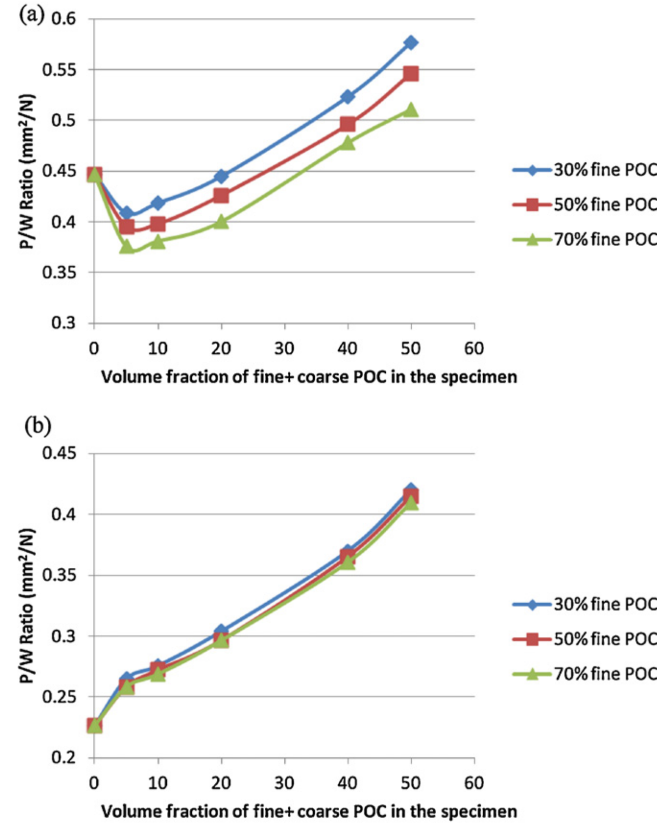

Fig. 3. The percentage to water absorption to weight (P/W) ratio for (a) 2 and (b) 28 days of curing.

For 28 days of curing (Fig. 3b), this value (P/W) for POC-contained specimens is always higher that C0 series specimen which make it suitable for lightweight applications.

4. Architecture of fuzzy logic

Fuzzy set theory was developed by Lotfi Zadeh in 1965 to deal with the imprecision and uncertainty that is often present in real world applications [18]. In 1974 Mamdani [19], by applying Zadeh's theories of linguistic approach and fuzzy inference, successfully used the 'IF-THEN' rule on the automatic operating control of steam generator. It does not need to handle the tedious mathematical models of controlled body. It needs only to set a simple controlling method based on engineering experience. Therefore, it is particularly useful in complicated structural control system. Since is does not involve complicated mathematical calculations and time of system delay is reduced in process of operations, lowering its impact on the controlling effects can be expected. Furthermore, since the fuzzy control method is easy to comprehend and to amend, it can be adjusted according to the actual situation. It effectiveness is therefore confirmed. Now, fuzzy control has become most successfully in application of fuzzy theory.

In this part of study, the developed fuzzy logic-based model was applied to predict the geopolymers' water absorption data obtained from experiments. The fuzzy rules were written for this purpose. It can be seen from Fig. 4 that we devised the

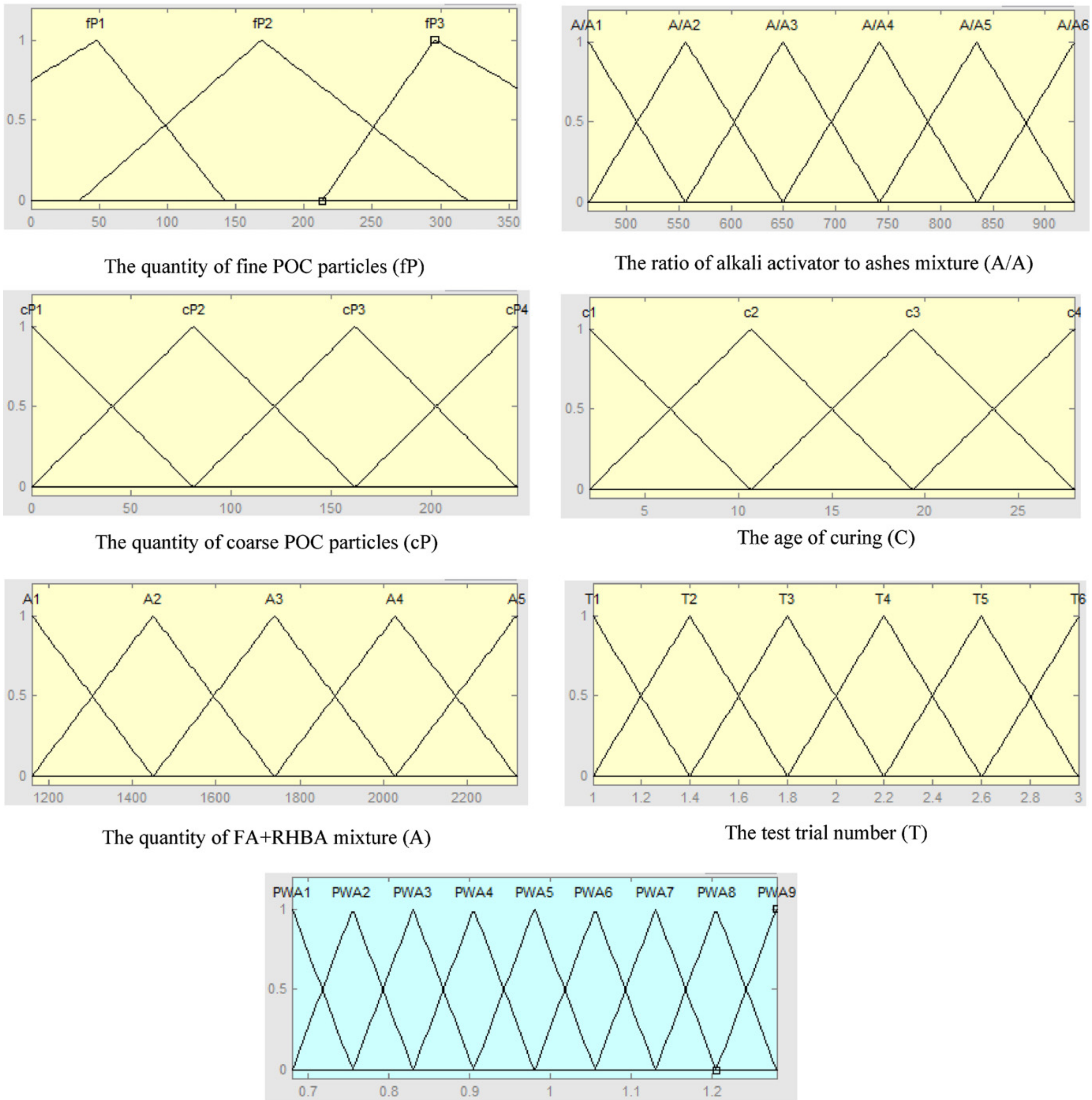

Fig. 4. Block diagram used for fuzzy modeling.

fuzzy logic-based algorithm model by using the FL toolbox in MATLAB.

The FL model had six input parameters and one output parameters. The parameters including the quantity of fine POC particles (fP), the quantity of coarse POC particles (cP), the quantity of FA + RHBA mixture (A), the ratio of alkali activator to ashes mixture (A/A), the age of curing (C) and the test trial number (T) were set as input data. The value for output layer was percentage of water absorption (PWA). Membership functions for input and output parameters used for fuzzy modeling are given in Fig. 4. The choice of the membership functions is based on the experiences gained, and their base values are selected so that they are concentrated on more sensitive regions. From the experiments, totally 144 data were achieved and used as target. The input and target values have been given in Table 3. From the total 144 data, 102 data were randomly selected for training set, 21 for validating set and the other 21 data were used for testing set. The fuzzy rules were written for predict the Charpy impact energy. These rules are obtained as in the following:

Table 4
Data sets for comparison of experimental results with tested and validated results predicted from the FL model.

The phase name	Number of set	The quantity of fine POC particles (fP) (kg/m^3)	The quantity of coarse POC particles (cP) (kg/m^3)	The quantity of FA + RHBA mixture (A) (kg/m^3)	The ratio of alkali activator to ashes mixture (A/A)	The age of curing (C) (day)	The test trial number (T)	Water absorption values obtained from experiments (%)	Water absorption values predicted by FL model (%)
Validating	14	25.40	17.30	2202.1	880.8	2	2	0.88	0.93
	16	35.50	10.40	2202.1	880.8	2	1	0.81	0.81
	33	101.5	69.30	1854.4	741.8	2	3	0.85	0.86
	41	203.0	138.6	1390.8	556.3	2	2	0.80	0.83
	51	253.8	173.3	1159.0	463.6	2	3	0.81	0.83
	53	355.3	104.0	1159.0	463.6	2	2	0.78	0.83
	57	15.20	24.30	2202.1	880.8	7	3	1.28	1.19
	59	25.40	17.30	2202.1	880.8	7	2	0.88	0.85
	60	25.40	17.30	2202.1	880.8	7	3	0.85	0.88
	66	30.50	48.50	2086.2	834.5	7	3	1.26	1.32
	67	50.80	34.70	2086.2	834.5	7	1	0.87	0.90
	75	60.90	97.00	1854.4	741.8	7	3	1.19	1.14
	78	101.5	69.30	1854.4	741.8	7	3	0.84	0.82
	92	152.3	242.6	1159.0	463.6	7	2	1.05	1.14
	94	253.8	173.3	1159.0	463.6	7	1	0.85	0.86
	97	355.3	104.0	1159.0	463.6	7	1	0.82	0.82
	108	35.50	10.40	2202.1	880.8	28	3	0.75	0.79
	121	101.5	69.30	1854.4	741.8	28	1	0.84	0.83
	139	253.8	173.3	1159.0	463.6	28	1	0.83	0.82
	140	253.8	173.3	1159.0	463.6	28	2	0.76	0.80
	144	355.3	104.0	1159.0	463.6	28	3	0.89	0.79
Testing	23	50.80	34.70	2086.2	834.5	2	2	0.84	0.87
	24	50.80	34.70	2086.2	834.5	2	3	0.89	0.87
	29	60.90	97.00	1854.4	741.8	2	2	1.15	1.17
	32	101.5	69.30	1854.4	741.8	2	2	0.80	0.82
	46	152.3	242.6	1159.0	463.6	2	1	1.14	1.12
	49	253.8	173.3	1159.0	463.6	2	1	0.86	0.83
	54	355.3	104.0	1159.0	463.6	2	3	0.80	0.84
	63	35.50	10.40	2202.1	880.8	7	3	0.83	0.73
	91	152.3	242.6	1159.0	463.6	7	1	1.08	1.11
	95	253.8	173.3	1159.0	463.6	7	2	0.86	0.87
	101	15.20	24.30	2202.1	880.8	28	2	1.13	1.05
	103	25.40	17.30	2202.1	880.8	28	1	0.86	0.88
	105	25.40	17.30	2202.1	880.8	28	3	0.89	0.90
	111	30.50	48.50	2086.2	834.5	28	3	1.15	1.19
	113	50.80	34.70	2086.2	834.5	28	2	0.83	0.82
	117	71.10	20.80	2086.2	834.5	28	3	0.75	0.81
	119	60.90	97.00	1854.4	741.8	28	2	1.05	1.03
	123	101.5	69.30	1854.4	741.8	28	3	0.86	0.76
	127	121.8	194.0	1390.8	556.3	28	1	1.06	1.05
	131	203.0	138.6	1390.8	556.3	28	2	0.81	0.79
	138	152.3	242.6	1159.0	463.6	28	3	0.95	0.95

R_i: (fP is fP_j) and (cP is cP_k) and (A is A_m) and (A/A is A/A_n) and (C is C_k) and (T is T_n) THEN (PWA is PWA_p) $i = 1,\ldots, 2$, $j = 1,\ldots, 3$, $k = 1,\ldots, 4$, $m = 1,\ldots, 5$, $n = 1,\ldots, 6$, $p = 1,\ldots, 9$.

The assignment of initial related parameters may also influence the performance of the FL to a great extent. However, there is no well defined rule or procedure to have an optimal architecture and parameter settings where the trial and error method still remains valid. This process is very time consuming [20–23]. In this study the MATLAB FL toolbox is used for FL applications. To overcome optimization difficulty, a program has been developed in MATLAB which handles the trial and error process automatically [20–23]. The program tries various numbers of parameters for the algorithm when the highest RMSE (Root Mean Squared Error) of the testing set, as the training of the testing set is achieved [20–23].

5. Predicted results and discussion

In this study, the error arose during the training, validating and testing in FL model can be expressed as absolute fraction of variance (R^2) which are calculated by Eq. (1) [24]:

$$R^2 = 1 - \left(\frac{\Sigma_i (t_i - o_i)^2}{\Sigma_i (o_i)^2} \right) \tag{1}$$

where t is the target value and o the output value.

All of the results obtained from experimental studies and predicted by using the training, validating and testing results of FL model are given in Fig. 5a–c, respectively. The linear least square fit line, its equation and the R^2 values were shown in these figures for the training, validating and testing data. Also, inputs values and experimental results with validating and testing results obtained from FL model were given in Table 4. As it is visible in Fig. 5, the values obtained from the training and testing in FL model are very close to the experimental results. The result of testing phase in Fig. 5 shows that the FL model is capable of generalizing between input and output variables with reasonably good predictions.

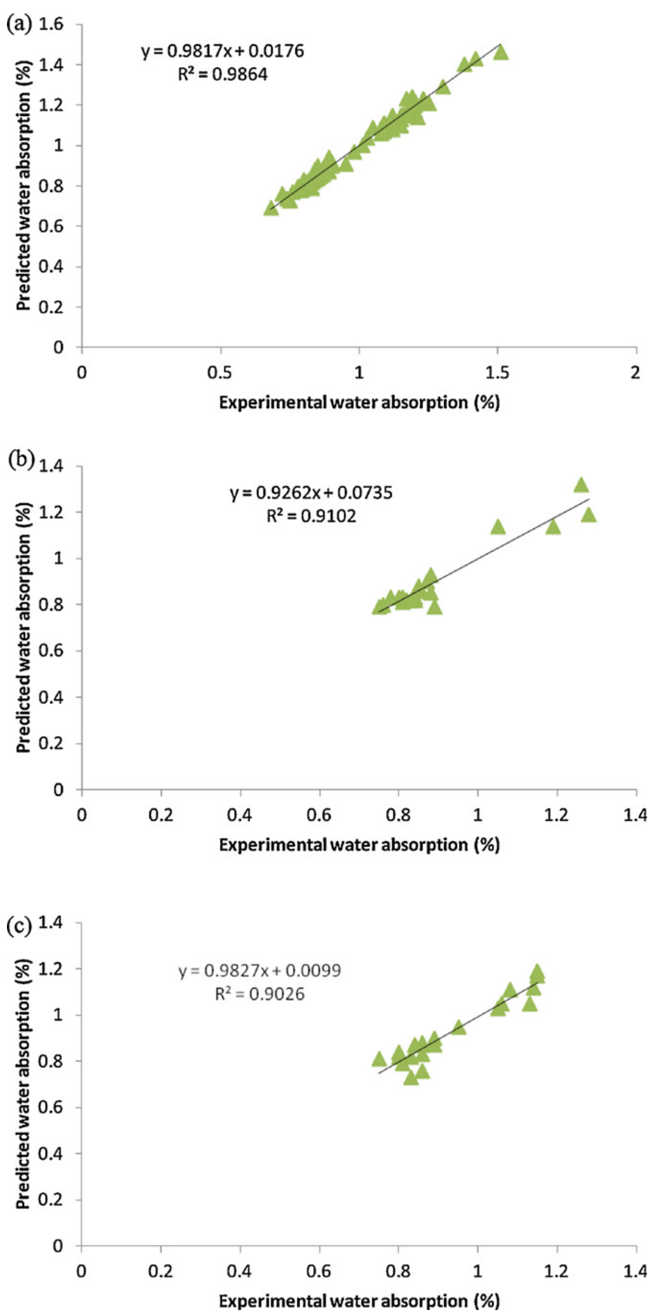

Fig. 5. The correlation of the measured and predicted water absorption values of geopolymers in (a) training, (b) validating and (c) testing phase for FL models.

The performance of the FL model is shown in Fig. 5. The value of R^2 is 0.9864 for training set and 0.9026 for testing set in the FL model. All of R^2 values show that the proposed FL model is suitable and can predict the water absorption values very close to the experimental values.

6. Conclusions

Utilizing POC particles in the geopolymeric specimens increase water absorption at later age of curing. However, using the POC particles results in a good resistance to water absorption with respect to the POC-free specimens at early ages which make them suitable for lightweight applications. The term ‘‘percentage of water absorption’’ to ‘‘weight’’ ratio for the specimens with more than 20% POC particles is much higher than POC-free specimens at early age of curing. At later ages of curing (28 days), this ratio for all of the POC-contained specimens is much higher than that of POC-free specimen. FL can be an alternative approach for the evaluation of the effect of seeded mixture of FA and RHBA on water absorption values of geopolymer specimens. The terms of R^2 showed that FL models are capable to predict suitable results for water absorption values of geopolymer specimens.

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