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A Predictive Model for the Strength of a Novel Geopolymer Construction Material Produced by Autoclaved Aerated Concrete Waste

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Abstract: Carbon dioxide emission and consumption of large amounts of natural resources are the environmental hazards observed in the production process of various commonly used construction materials, like Portland cement and clay bricks. Also, debris from the demolition of old buildings and disposing of the waste of construction material factories also cause environmental pollution. Producing environmentally friendly geopolymer materials with recycling construction wastes containing aluminosilicate resources and alkaline activators could be an effective method for reduction of environmental hazards. This paper is an innovative feasibility study of geopolymer material production using the waste autoclaved aerated concrete (AAC) powder. Here, a mix of AAC powder together with activator solution containing sodium hydroxide and sodium silicate at different concentrations was used to prepare the geopolymer mortar samples. The specimens were oven-cured at different temperatures. The effects of sodium hydroxide concentration and curing temperature on the compressive, tensile, and flexural strengths, as well as water absorption of the samples, were investigated. The main contribution of this study is the feasibility of the successful fabrication of geopolymer material based on AAC waste powder with desirable mechanical properties. Namely, the compressive strength of the base AAC blocks used here was 3 MPa and the maximum strength of the produced geopolymer material using the AAC powder was about 21 MPa. The test results were used to develop a model to predict the compressive strength of the proposed geopolymer AAC material to the effective parameters by Gene Expression Programming. The model predictions were confirmed using an extra series of test results implemented by the authors.

Keywords: Recycling and reuse of materials, Autoclaved Aerated Concrete (AAC), geopolymers, compressive strength, construction

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Nomenclature	
AAC	autoclaved aerated concrete
Na_2O	sodium oxide
NaOH	sodium hydroxide
Na_2SiO_3	sodium silicate
SEM	scanning electron microscopy
SiO_2	silica
W1	dry weight of the sample
W2	wet weight of the sample
XRD	x-ray diffraction
X_{norm}	normalized values of GEP parameter
X_{min}	minimum values of GEP parameter
X_{max}	maximum values of GEP parameter
d0	molarity or concentration of sodium hydroxide solution in GEP model
d1	ratio of sodium silicate to sodium hydroxide in GEP model
d2	sieve number in GEP model
d3	oven curing temperature in GEP model

1. Introduction

The production process of various widely used construction materials, such as cement and bricks, leads to numerous environmental hazards such as carbon dioxide emission and the consumption of large amounts of natural resources. On the other hand, disposing of debris from the demolition of old buildings in nature and the waste produced in construction material factories also result in environmental pollution. Today, solid waste management has become one of the most important environmental concerns in the world. Recycling these waste materials are a solution to deal with such environmental issues (Malayali et al. 2022). The geopolymerisation process is a rather new technique that has helped to reduce the consumption of Portland cement in the construction industry. According to the reports, replacing ordinary Portland concrete with geopolymer concrete could reduce carbon dioxide emission about 80 to 90% (Duxson et al. 2007; Pacheco-Torgal et al. 2008a, b; Van Deventer et al. 2010). Carbon dioxide emission is 5-6 times lower for geopolymer concrete production in compare to ordinary cement-based concrete (Davidovits 2002).

Geopolymer is a rather novel binder material used in concrete and other construction applications. Geopolymeric materials are produced by activating aluminosilicate (precursor material) using an alkaline solution (activator) that creates a polymer chain and a ring structure through a rapid chemical process (Sumajouw & Rangan 2006; Park & Kang 2006). These materials can be made from a wide range of aluminosilicates with varying proportions of aluminium and silicon. The activator materials are mostly sodium and potassium hydroxides, and sodium silicate (Provis & van-Deventer 2009; Heath et al. 2013).

Geopolymer technology has attracted the attention of many researchers because of its advantages over Portland cement concretes, such as optimal initial compressive strength, low permeability, good chemical resistance, and fire resistance (Khale & Chaudhary 2007; Rajini & Rao 2014; Hu et al. 2014; Deb et al. 2014; Singh et al. 2015). However, the geopolymerisation largely depends on different factors such as the type of alkaline activator, alkali solution concentration, sodium silicate to solution ratio, and curing temperature, which all can affect the cost and product characteristics (Kejkar et al. 2020).

Metakaolin is one of the aluminosilicate resources tested by Rovnaník (2010) who reported that the 28-day strength of geopolymer concrete cured at 10°C is slightly higher than that of geopolymer concrete cured at ambient temperature. In another experiment by Kumar & Kumar (2011) it was shown that an increased Silica to Aluminium ratio caused to increase in the compressive strength of geopolymer concrete up to a specific percentage. Bondar et al. (2011) indicated compressive strength did not necessarily enhance with increasing molar concentration of sodium hydroxide solution. Jaydeep and Chakravarthy (2013) showed that adding sodium silicate solution to sodium hydroxide, as an alkaline activator, would accelerate the reactions between the raw material and the solution. In a series of experiments by Deb et al. (2014) it was shown that with the change in the Sodium silicate to sodium hydroxide ratio, the compressive strength of geopolymer concrete and mortar did not vary significantly, but this affected the setting time duration. Sarker and Mcbeath (2015) observed that under the fire conditions, the fracture and cracking of geopolymer concrete were less than the ordinary cement-based concrete. Naskar and Chakraborty (2016) studied the effect of nanomaterials on the geopolymer concrete properties. Based on their observations, the geopolymer concrete containing 1% titanium dioxide showed a significant increase in compressive strength (Naskar & Chakraborty 2016).

Recently, Kheradmand et al. (2020) introduced the short polymer hybrid fibres (SPHF) to control the shrinkage cracking of geopolymer mortars. Chakkor et al. (2022) produced a sustainable recycled geopolymer composition using recycled fine aggregates and leftover industrial materials.

Since any aluminosilicate resources can be used to produce geopolymer materials, the authors proposed utilising the autoclaved aerated concrete (AAC), as a rich source of silica, to produce geopolymer material. AAC is a relatively

modern material with an acceptable density to strength ratio, thermal insulation properties, and many other advantages such as lightness, fire resistance and ease of cutting (Korniyenko et al. 2016; Winkels et al. 2018; Gyurkó et al. 2019). AAC was invented by a Swedish architect in 1924 and since then, it has been widely used in the United States and Europe (Saghi & Arefizadeh 2015). AAC is considered as an environmentally friendly construction material (Hammond & Jones 2008), the ingredients of which include cement, water, lime, silica-based materials (silica sand, ash, or silica fume), porosity-inducing materials (aluminium powder), and other additives (Sherin & Saurabh 2018). According to studies in Germany, the AAC waste is estimated at 2.5 million tons per year, and is likely to increase in the coming years (Kreft 2016; Hlawatsch et al. 2018). Therefore, AAC waste recycling ideas have considerable importance from an environmental perspective.

Few studies have been performed on the recycling AAC waste material. One of these ideas is the reusing AAC waste in the manufacturing of new AAC productions (Melichar et al. 2018; Hlawatsch et al. 2018). However, according to past studies, the use of AAC waste in producing new AAC materials, had some negative effects on the product's characteristics (Lam 2021). In a case study in the port of Antwerp in Belgium the recycling of AAC waste as a substitute for sand in the manufacture of concrete flooring was examined (Bergmans et al. 2015). Topcu and Sarıdemir (2007) investigated the possibility of utilising crushed autoclaved aerated concrete waste as the primary material in concrete production. Bisceglie et al. (2014) used AAC waste powder to make porous materials suitable for green roofing. Also, Fenyvesi and Jankus (2015) produced the lightweight concrete using AAC block wastes.

Aggregates obtained from crushed AAC were used to manufacture lightweight bitumen, lightweight blocks, and floorings in experiments performed in Germany (Hlawatsch et al. 2018). Coman et al. (2019) used the crushed AAC pieces along with polyester resin in the production of recycled materials. A mix design for the construction of AAC blocks was also proposed by Rafiza et al. (2019) in which recycled AAC powder was used. Gyurkó et al. (2019) investigated the possibility of utilising waste AAC aggregates to manufacture load-bearing and non-load-bearing construction materials. He et al. (2020) proved that AAC powder could be an alternative cementitious material in concrete production.

In general, literature reviews showed that in most studies, non-constructional and non-load-bearing materials had been produced using AAC wastes. Very limited studies were performed on the use of AAC wastes in the manufacture of load-bearing construction materials. Since AAC powder is a rich source of silica, in the present study, the possibility of producing load-bearing geopolymer materials was evaluated using a mix of AAC powder with an alkaline solution containing sodium hydroxide and sodium silicate. In practice, AAC or Hebelex blocks are widely used in construction in Iran (Hakiminejad et al. 2015). The effect of various parameters on the early-aged mechanical properties of geopolymer specimens were investigated. Considered factors included AAC powder particle size, the mass ratio of activator solution to AAC powder (activator to pozzolan ratio), the mass ratio of sodium silicate to sodium hydroxide in alkaline activator solution, concentration (molarity) of sodium hydroxide solution, and the curing temperature.

2. Materials and Methods

In In this study, six mix designs were introduced to prepare the geopolymer mortar specimens based on AAC waste powder. The mechanical properties (compressive, tensile, and flexural strength) of the samples were measured at the age of 3 and 7 days. Afterward, a series of specimens were prepared based on the mix designs with better resistance results to measure the water absorption. AAC powder passing the standard sieves No.100 (150 μm) and No.50 (300 μm) was used as the aluminosilicate source to make the geopolymer specimens. The total number the samples prepared and tested using AAC powder here, were 147 and 60 respectively made of the AAC powder passing the sieves No.50 and No.100. The AAC block pieces used in this study (**Fig.1**) were the waste of the production line of Aran Polymer Concrete Factory in Shahid Salimi industrial complex of Tabriz (Azershahr, East Azerbaijan province in Iran). To prepare the alkaline activator solution, the drinking water of Bonab city (East Azerbaijan) together with the 99% sodium hydroxide of Color Pars Tabriz Company were used here. Utilised 43%-liquid industrial sodium silicate (Na_2SiO_3) was a combination of 10.75% sodium oxide (Na_2O), and 32.25% silica (SiO_2). The sodium silicate, which is known as water glass in Iran, was prepared from Alvand Silicate Company in Tabriz.

Fig. 1 - AAC block wastes used in this study; (a) AAC pieces; (b) AAC powder

The mixture proportioning of geopolymer mortar samples made based on the AAC waste powder is presented in Table 1. These samples were examined in compressive strength testing (according to BS EN, 12390-3 (2009)). The geopolymer mortar samples were tested to determine the water absorption, by 5-hour boiling method (according to ASTM C67/C67M (2018)), and also half-hour surface water absorption method (according to INBC-Part 9 (2014)). The mix designs of these samples are provided in **Table 2**. In **Tables 1** and **2**, molarity refers to the molar concentration of sodium hydroxide solution, WG/NaOH refers to the sodium silicate to sodium hydroxide ratio, and Alkaline/Powder refers to the mass ratio of activator solution (containing sodium hydroxide and sodium silicate) to ACC waste powder. In the mix designs' naming, the left number indicates the concentration of sodium hydroxide, and the right number shows the sodium silicate to sodium hydroxide ratio (e.g., G10-1 refers to the geopolymer composition with 10 M sodium hydroxide and the mass ratio of sodium silicate to sodium hydroxide of 1).

Table 1 - Geopolymer mortar mix designs based on AAC waste powder with 5x5x5 cm cube samples for compressive strength test

Number of samples	Alkaline/ Powder	Weight of the components (g)			WG/ NaOH	Molarity	Name of mix design	No.
		sodium silicate	NaOH	AAC powder				
AAC powder passing sieve No.100								
2*5	0.93	300	300	650	1	4	G4-1	1
2*5	0.93	400	200	650	2	4	G4-2	2
2*5	0.93	300	300	650	1	8	G8-1	3
2*5	0.93	400	200	650	2	8	G8-2	4
2*5	0.93	300	300	650	1	12	G12-1	5
2*5	0.93	400	200	650	2	12	G12-2	6
AAC powder passing sieve No.50								
3*2	1	325	325	650	1	4	G4-1	1
3*2	1	434	216	650	2	4	G4-2	2
3*2	1	325	325	650	1	6	G6-1	3
3*2	1	434	216	650	2	6	G6-2	4
3*2	1	325	325	650	1	8	G8-1	5
3*3	1	434	216	650	2	8	G8-2	6
3*2	1	325	325	650	1	10	G10-1	7
3*2	1	434	216	650	2	10	G10-2	8
3*2	1	325	325	650	1	12	G12-1	9
3*2	1	434	216	650	2	12	G12-2	10
3*2	1	325	325	650	1	14	G14-1	11
3*2	1	434	216	650	2	14	G14-2	12

Table 2 - Mix designs of geopolymer mortar with 5×5×5 cm cube samples for water absorption test (AAC powder passing the sieve No.50)

Number of samples	Alkaline/ Powder	Weight of the components (g)			WG/ NaOH	Molarity	Name of mix design	No.
		sodium silicate	NaOH	AAC powder				
10	1	300	150	450	2	8	G8-2	1
25	1	900	450	1350	2	8	G8-2	2

For tensile strength testing (according to ASTM C307-03 (2012)), the briquette specimens of geopolymer mortar were prepared, and for flexural strength tests (3-point loading method according to ASTM C78-02 (2002)), the prismatic specimens with dimensions of 16×4×4 cm were prepared according to the mix designs shown in **Table 3**.

Table 3 - Mix designs of geopolymer samples for tensile and flexural testing (curing at 80°C and AAC powder passing the sieve No.50)

Number of samples	Alkaline/ Powder	Weight of the components (g)			WG/ NaOH	Molarity	Name of mix design	No.
		sodium silicate	NaOH	AAC powder				
tensile testing of briquette samples (ASTM C307-03, 2012)								
20	1	440	150	450	2	8	G8-2	1
flexural testing of prismatic samples (ASTM C.78-02, 2002)								
20	1	1320	660	1980	2	8	G8-2	2

In this study, preparation, curing, and testing procedures of AAC-based geopolymer specimens were carried out using the equipment available in Concrete and Soil Mechanics Laboratory of the University of Bonab. The equipment included stone crusher, vibrating sieve, oven, hydraulic compression testing machine, flexural and tensile strength test device, and freeze/thaw machine. For samples preparing, firstly, the required alkaline solution was made using sodium hydroxide solution at six different concentrations of 4, 6, 8, 10, 12, and 14 M with two mass ratios of sodium silicate to sodium hydroxide of 1 and 2. Due to the strong alkaline properties of the solution, it should be prepared considering all the safety regulations. The resulted solution was then gently mixed with AAC powder for 5 minutes. After complete mixing, the materials were poured into the molds with desired dimensions, and after smoothing the surface, they were placed on a vibrating device. Finally, samples were cured at 40, 60, and 80°C in the oven for 3 days. Various stages of fabrication, curing, and testing of the samples are shown in **Fig.2**

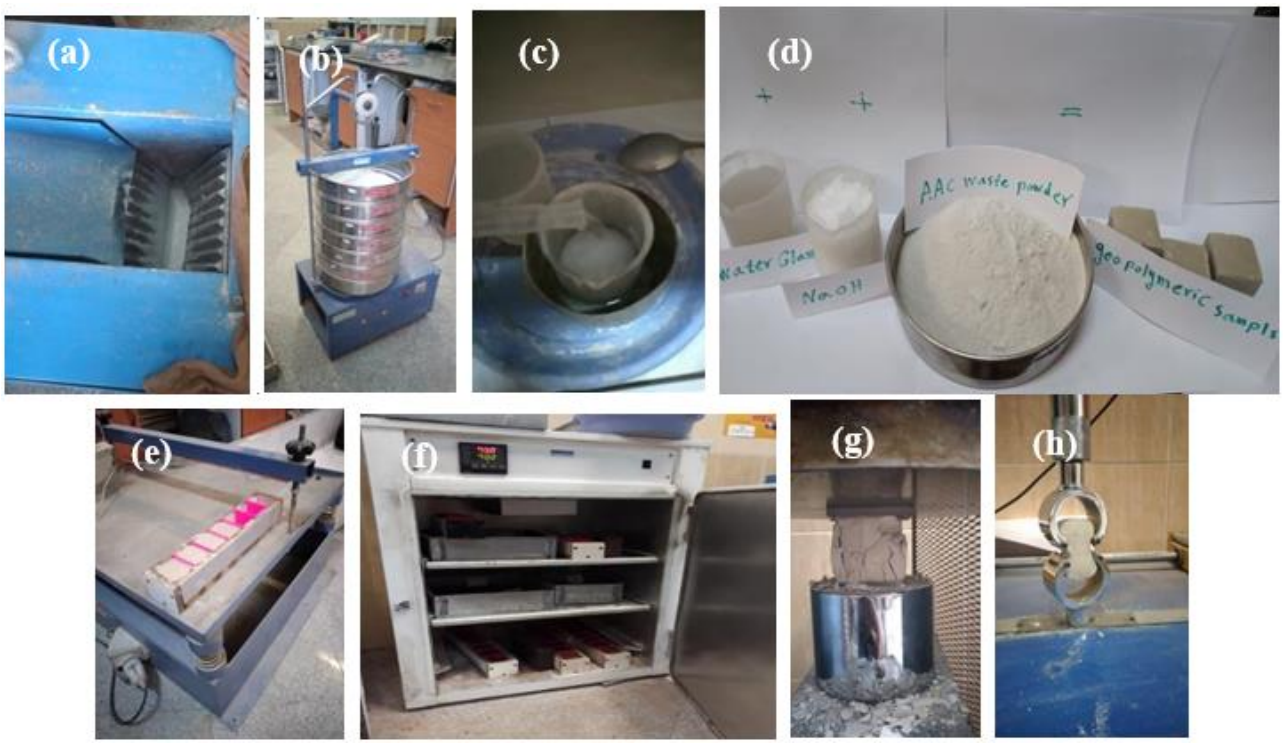

Fig. 2- Experimental procedure steps; (a) AAC crushing; (b) AAC powder sieving; (c) alkaline solution preparing; (d) mixing the solution with AAC powder; (e) casting; (f) oven-curing; (g) compressive testing; (h) briquette testing; (i) flexural testing; (j) immersion water absorption testing; (k) boiling water absorption testing

To measure the water absorption and durability of geopolymer mortar, after 3-day oven-curing (at 80°C), the water absorption was calculated according to Eq.1. Two testing methods of 5-hour boiling, and 30-minute immersing of the samples in the water were applied to find the water absorption. Afterward, the samples were placed again in the oven at 110°C for 24 hours. Then, on the seventh day, the compressive strength was measured.

$$water\ absorption=\frac{W2-W1}{W1}\times 100 \quad (1)$$

In Eq.1, W1 is dry weight, and W2 is wet weight of the sample.

2.1 XRD and SEM Analysis

X-ray diffraction (XRD) analysis is used to study the crystallographic structure of the materials. Also, the scanning electron microscopy (SEM) test is one of the best methods to perform chemical analysis, determination of compositions, surface properties, and high magnification imaging of the sample's topography. Here, XRD analysis and SEM scanning were performed on the utilised AAC waste and prepared geopolymer samples in Taban Bimogastar Laboratory in Tehran.

3. Results and Discussion

3.1 AAC Compressive Strength

The AAC solid pieces used in this study were tested according to ASTM C495 (2012) regulation to determine its compressive strength. The considered AAC material was the production of Aran Polymer Concrete Factory in Shahid Salimi industrial complex of Tabriz which its main contents are summarized in Table 4. According to the results the average strength of the specimens was 3 MPa.

Table 4 - Life contents of AAC block mixture with density of 500 kg/m^3

Row materials	Contents (kg/m^3)
Silica sand	350
lime	100
cement	25
aluminium powder	0.5
water	330

3.2 Early-Age Compressive Strength of The Geopolymer Material

Section The results of the 3-day compressive strength of geopolymer material specimens prepared with AAC powder passing through the standard sieve No.100 with curing at 40°C are presented in **Fig.3**. These results are

obtained from the mean compressive strength of the three test specimens made from each sample type. It is observed that the highest 3-day compressive strength, which is 11 MPa, was obtained for 4M sodium hydroxide solution with the sodium silicate to sodium hydroxide ratio of 2 (i.e., G 4-2). Also, the lowest compressive strength (5 MPa) was obtained at a concentration of 8M for sodium hydroxide and the sodium silicate to sodium hydroxide ratio of 1 (i.e., G 8-1). In general, the compressive strength of geopolymer samples made with sodium silicate to sodium hydroxide ratio of 2 was higher than those with a ratio of 1.

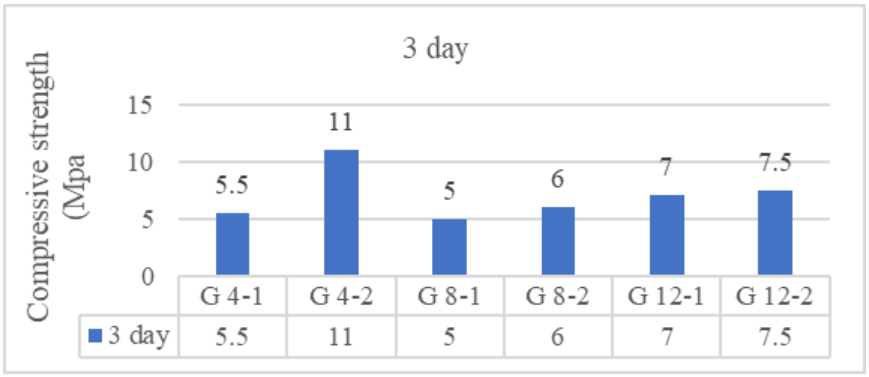

Fig. 3 - Three-day compressive strength of geopolymer mortar with AAC powder passing the sieve No.100 (curing at 40°C)

The mean results of the 3-day compressive strength of geopolymer mortar samples prepared with AAC powder passing through the sieve No.100 with curing at 60 and 80°C are presented in **Fig.s 4** and **5**, respectively. It can be observed that, for curing at 60°C, the highest 3-day compressive strength was 11 MPa that was obtained for the sample G12 (sodium hydroxide concentration of 12 M). The lowest 3-day compressive strength was 5.3 MPa that was also recorded for the G-8-1 sample. Also, similar to curing at 40°C, the compressive strength with sodium silicate to sodium hydroxide ratio of 2 was higher than the compressive strength of the samples with the ratio of 1. On the other hand, in curing at 80°C, the highest 3-day compressive strength was 21 MPa that was obtained for G8-2 (concentration of 2 M for sodium hydroxide solution with sodium silicate to sodium hydroxide ratio of 2). And, the lowest 3-day compressive strength was 2 MPa that was obtained for the G 4-1 sample.

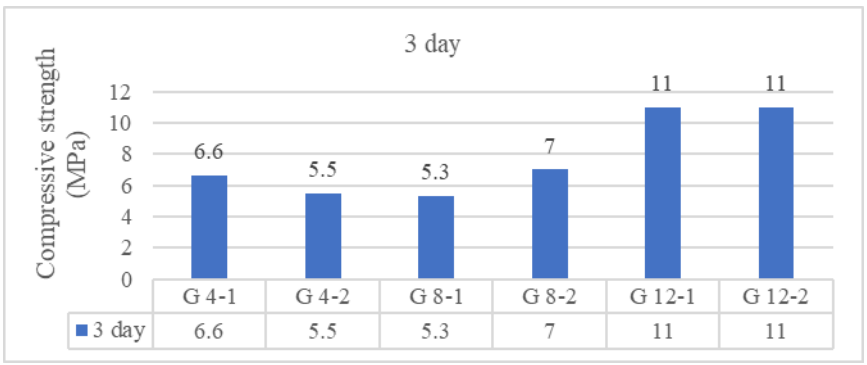

Fig. 4 - Three-day compressive strength of geopolymer mortar with AAC powder passing sieve No.100 (curing at 60°C)

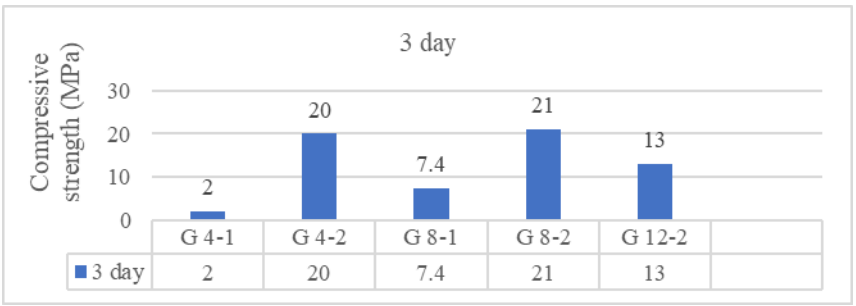

Fig. 5 - Three-day compressive strength of geopolymer mortar with AAC powder passing the sieve No.100 (curing at 80°C)

Comparing **Fig.**s **3** to **5** shows that the maximum compressive strength was the same for curing at 40 and 60°C (11 MPa), but this value had been increased significantly for a curing temperature of 80°C (i.e., 21-20 MPa). This phenomenon can result from the higher acceleration of the polymerisation process with the increase in the curing temperature, which is consistent with past studies (Rovnaník 2010; Jaydeep & Chakravarthy 2013).

In the following, the average 3-day compressive strength of geopolymer mortar samples prepared with AAC powder passing through the standard sieve No.50 in curing temperature of 60 and 80°C are shown in **Fig.**s **6** and **7**, respectively. It can be seen that, for both curing temperatures, the highest 3-day compressive strength was obtained in G-1-1 (11 MPa and 10 MPa, respectively). Also, for almost all mix designs, higher resistance was recorded for curing the samples at the higher temperature. The lowest compressive strength was 3 MPa that was obtained for G14-1 for curing at 60°C, and one of the lowest resistances (i.e., 5 MPa) was obtained for the same samples at 80°C curing temperature. However, the lowest resistance recorded for curing at 80°C was for G 4-1 (i.e., 4.3 MPa). Also, for most cases, the compressive strength of the samples with a sodium silicate to sodium hydroxide ratio of 2 was higher than those with a ratio of 1.

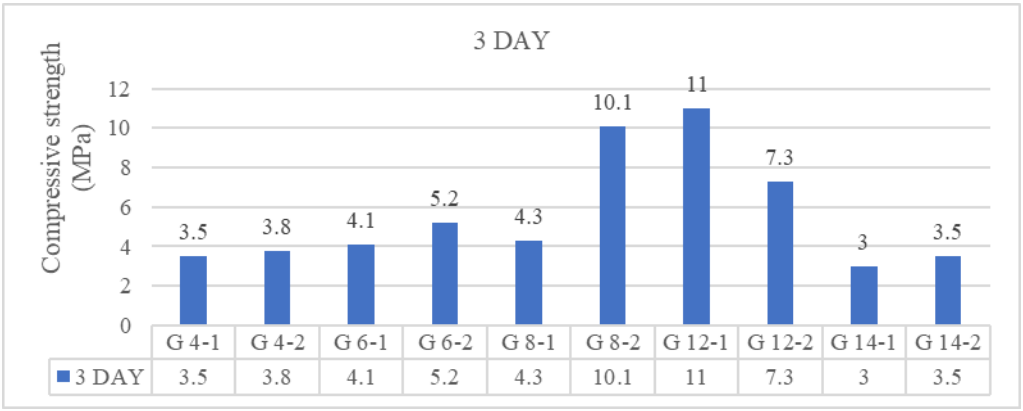

Fig. 6 - Three-day compressive strength of geopolymer mortar with AAC powder passing the sieve No.50 (curing at 60°C)

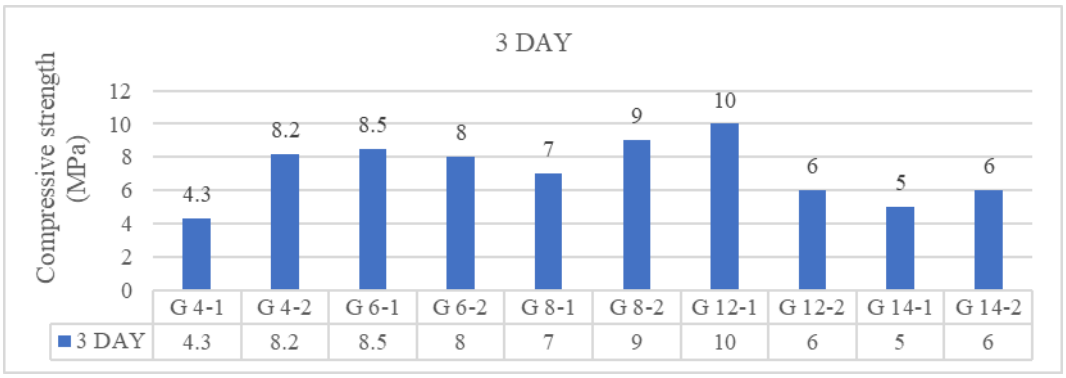

Fig. 7 - Three-day compressive strength of geopolymer mortar with AAC powder passing the sieve No.50 (curing at 80°C)

Comparison of the compressive strength of the specimens prepared using AAC powder passing the standard sieve No.100 (**Fig.**s **3** to **5**) with samples made of AAC powder passing the sieve No.50 (**Fig.**s **6** and **7**) indicated that, for most mix designs, higher compressive strengths were obtained using finer aluminosilicate resources (i.e., for sieve No.100). For example, the G 4-2 specimen cured at 80°C, in the case with finer AAC powder, had a 144% higher compressive strength than the one made with coarser AAC powder. At 60°C, this increase is 45% for G 4-2 mix design. However, in a few numbers of G 4-1 and G 8-2 specimens, the compressive strength had reduced with using the finer AAC powder. This may be due to human mistakes in the manufacturing, curing or testing procedures.

Table 5 shows the densities and the compressive strength to density ratios of the specimens. According to Table 5, under different curing temperatures, and using AAC powder passing through sieves No.50 & 100, one can determine which mix design had the highest strength to density ratio. For example, it can be observed that for sample G 4-2, the highest strength to density ratio is equal to 0.01389 in the case of using AAC powder passing through sieve No.100 and curing at 80°C. The lower ratio indicates the lower efficiency of the mix design.

Table 5 - Compressive strength to density ratios of geopolymer mortar samples

compressive strength/density (*10^-3)	Compressive strength (MPa)	density (kg/m^3)	Alkaline/powder	mix design	No.
5*5*5 cm cube samples, AAC powder passing the sieve No.100, curing at 40°C					
5.29	5.5	1040	0.93	G 4-1	1
8.59	11	1280	0.93	G 4-2	2
4.46	5	1120	0.93	G 8-1	3
5	6	1200	0.93	G 8-2	4
6.25	7	1120	0.93	G 12-1	5
5.96	7.5	1280	0.93	G 12-2	6
5*5*5 cm cube samples, AAC powder passing the sieve No.100, curing at 60°C					
5.16	6.6	1280	0.93	G 4-1	7
4.04	5.5	1360	0.93	G 4-2	8
3.9	5.3	1360	0.93	G 8-1	9
4.86	7	1440	0.93	G 8-2	10
7.64	11	1440	0.93	G 12-1	11
7.64	11	1440	0.93	G 12-2	
5*5*5 cm cube samples, AAC powder passing the sieve No.100, curing at 80°C					
1.56	2	1280	0.93	G 4-1	12
13.89	20	1440	0.93	G 4-2	13
4.87	7.4	1520	0.93	G 8-1	14
13.82	21	1520	0.93	G 8-2	15
6.88	11	1600	0.93	G 12-1	16
8.13	13	1600	0.93	G 12-2	17
5*5*5 cm cube samples, AAC powder passing the sieve No.50, curing at 80°C					
4.13	4.3	1040	1	G 4-1	18
7.32	8.2	1120	1	G 4-2	19
8.17	8.5	1040	1	G 6-1	20
7.14	8	1120	1	G 6-2	21
5.83	7	1200	1	G 8-1	22
7.5	9	1200	1	G 8-2	23
7.81	10	1280	1	G 12-1	24
4.41	6	1360	1	G 12-2	25
4.46	5	1120	1	G 14-1	26
5	6	1200	1	G 14-2	27
5*5*5 cm cube samples, AAC powder passing the sieve No.50, curing at 60°C					
3.12	3.5	1120	1	G 4-1	28
3.17	3.8	1200	1	G 4-2	29
3.2	4.1	1280	1	G 6-1	30
3.82	5.2	1360	1	G 6-2	31

3.16	4.3	1360	1	G 8-1	32
7.01	10.1	1440	1	G 8-2	33
7.64	11	1440	1	G 12-1	34
5.07	7.3	1440	1	G 12-2	35
2	3	1200	1	G 14-1	36
. 5					
2.73	3.5	1280	1	G 14-2	37

3.3 Application of GEP for Modelling Compressive Strength

Gene expression programming (GEP) is a new evolutionary computation algorithm that has been successfully used in a wide range of civil engineering issues especially in the field of geotechnical problems (Johari & Hooshmand Nejad 2015; Johari et al. 2021; Johari et al. 2022). In this study, GeneXpro Tools 5.0 (2013) was used to fine the best expression for predicting the compressive strength of the geopolymer material manufactured here using recycled AAC powder. Based on the recorded data sets in the experiments, the input parameters included *d0* (molarity or concentration of sodium hydroxide solution), *d1* (ratio of sodium silicate to sodium hydroxide), *d2* (sieve number), and *d3* (oven curing temperature). It should be noted that each data set is normalized in the range of [-1,1] using Eq. (2) for the sake of better prediction.

$$X_{norm} = 2\times\frac{X - X_{min}}{X_{max} - X_{min}} - 1 \quad (2)$$

where, X_{norm}, X_{min}, and X_{max} are normalized, minimum, and maximum values for the parameter. The settings of the key parameters defined in GeneXpro program are summarized in Table 6. According to the results, four equations were extracted as sub-expression (Sub-ET) trees as **Fig.8** with almost 85% of training accuracy (R^2). All parameters in **Fig.8**, except the input ones (*d0*, *d1*, *d*2 and *d*3), are constant values that the program calculated for each sub-ET. Since the addition linking function was used here, the final formula of the GEP models was defined by adding all the four sub-ETs together (Eq. (3)).

Table 6 - Main parameter settings in GeneXpro program

Parameter	Setting
Fitness Function	RMSE, ROC Threshold
Number of genes (ETs)	4
Number of chromosomes	30
Head size	9
Linking function	Addition
Function set	Addition, Subtraction, Multiplication, Division, Square root, Cube root, Inverse, x^2, x^3

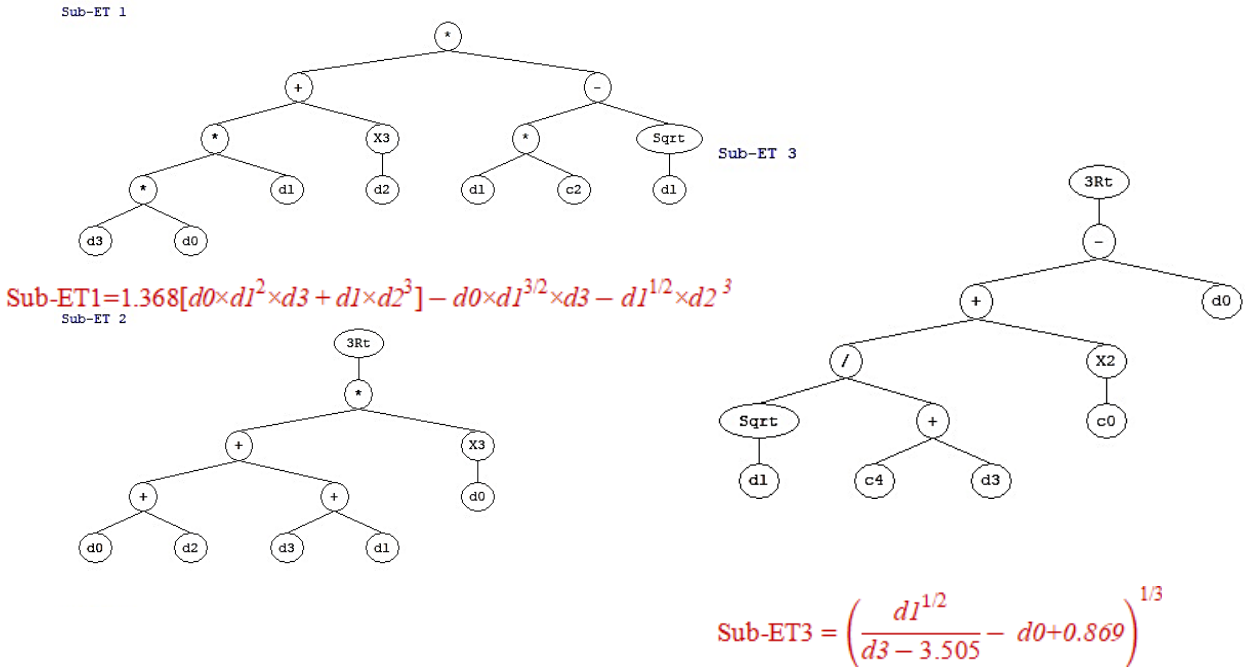

Fig. 8 - Expression trees (ETs) of the GEP model for compressive strength

$$\text{Comp. Str.} = 1.368[d0\times d1^{2}\times d3 + d1\times d2^{3}] - d0\times d1^{3/2}\times d3 - d1^{1/2}\times d2^{3} + d0\times\sqrt[3]{d0+d1+d2+d3} + \sqrt[3]{\frac{d1^{1/2}}{d3-3.505} - d0+0.869} \quad (3)$$

In this study, some new series of geopolymer mixtures were casted, cured under the defined conditions and then tested to determine the compressive strength with the same procedure described in part 2. The results were used to validate the proposed GEP model here. The specifications of mix designs of these samples as well as the amounts of the input parameters of the model are provided in Table 7.

Table 7 - Specifications of the validation samples and corresponding input parameters

Model input parameters number		number of samples		weight of the components (g)	WG/NaOH	Molarity	Name of mix design	No.
		Sodium silicate	NaOH	AAC powder				
AAC powder passing sieve No.100 → *d2*= +1								
d0 = 0.1, *d1* = +1, *d3* = 0.25	2*5	300	300	650	2	5	G5-2-50º	1
d0 = 0.1, *d1* = +1, *d3* = +0.75	2*5	400	200	650	2	5	G5-2-70º	2
d0 = 0.5,	2*5	300	300	650	2	9	G9-2-50º	3

d1 = +1, *d3 = 0.25*								
d0 = 0.5, *d1* = +1, *d3* = +0.75	2*5	400	200	650	2	9	G9-2-70º	4
d0 = 0.7, *d1* = +1, *d3* = 0.25	2*5	300	300	650	2	11	G11-2-50º	5
d0= 0.7, *d1* = +1, *d3* = +0.75	2*5	400	200	650	2	11	G11-2-70º	6

In **Fig. 9**, the experimental compressive strength results and the corresponding GEP predictions are plotted. **Fig. 9** shows the correlation quality of the model in which the correlation percentage R^2 is equal to 82%. Since, the idea of applying AAC waste as an aluminosilicate resource to produce geopolymer mixtures was introduced here for the first time, the authors could not able to find any other experiments to use in training and validation process of the GEP formulation. So, it seems there is a need to implement more experiments in this field to collect a comprehensive database for having the best prediction model.

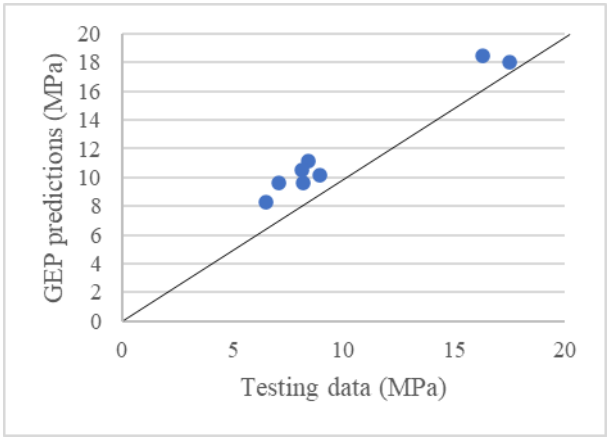

Fig. 9 - Compressive strength predictions by GEP model versus real test results (R^2=0.79)

3.4 Tensile and Flexural Strength of Geopolymer Material

For geopolymer specimens prepared using AAC powder passing through the sieve No.50, at 3, 7 and 28 days, with sodium hydroxide concentration of 8 M, and sodium silicate to sodium hydroxide ratio of 2, the mean values of the tensile and flexural strengths are shown in **Fig.**s **10** and **11**, respectively. It is clear that the significant growth in tensile and flexural strength was obtained in the first 3 days.

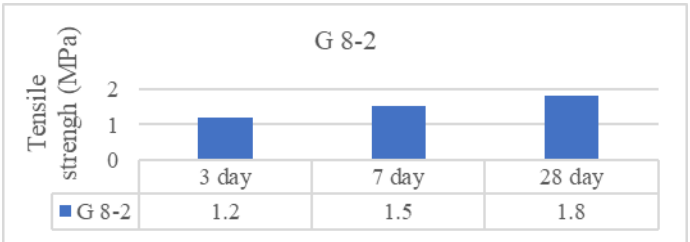

Fig. 10 - Tensile strength of geopolymer mortar prepared from AAC powder passing the sieve No.50 at 3, 7, and 28 days (curing at 80°C)

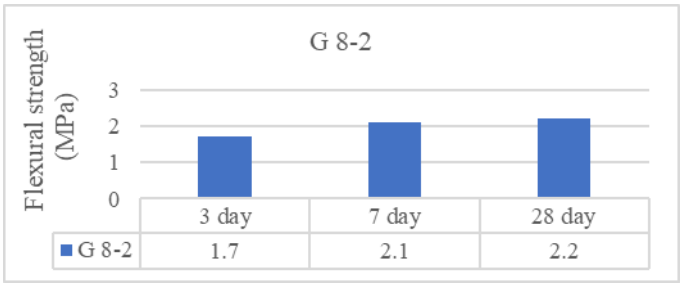

Fig. 11 - Flexural strength of geopolymer mortar prepared from AAC powder passing the sieve No.50 at 3, 7, and 28 days (curing at 80°C)

3.5 Water Absorption and Durability of Geopolymer Material

Here, samples made of AAC powder passing the sieve No.50, with a molar concentration of 8 M, and the sodium silicate to sodium hydroxide ratio of 2 were considered. To measure the durability of the samples, six different cases were examined, and for each case, 7-day compressive strength, and water absorption percentage of the samples were measured. In the following, these six cases are described.

Case A: After 3 days of oven-curing at 80°C, the samples were stored at room temperature, and the compressive strength was measured on day 7.

Case B: After 3 days of oven-curing at 80°C, the samples were stored at room temperature, and on day 6, they were returned to the oven and cured at 110°C for another 24 hours. Then, the compressive strength was measured on day 7.

Case C: After 3 days of oven-curing at 80°C, the samples were stored at room temperature for 3 days, and then boiled in water for 5 hours. After measuring the water absorption percentage, they were placed in the oven at 110°C for 24 hours, and the compressive strength was measured on day 7.

Case D: After 3 days of oven-curing at 80°C, the samples were stored at room temperature. On day 6, the samples were immersed in water for 30 minutes and the percentage of water absorption was measured. Then, the samples were put inside the oven at 110°C for 24 hours, and the compressive strength was measured on day 7.

Case E: After 3 days of oven-curing at 80°C, the samples remained in water for 24 hours, and the water absorption of the samples was measured. The samples were again placed in the oven at 110°C for 24 hours, and then stored at room temperature until day 7. On day 7, the compressive strength was measured and compared with the other cases.

Case F: After 3 days of oven-curing at 80°C, the samples were stored at room temperature and on day 5, they were immersed in water for 24 hours. After measuring the water absorption, the samples were transferred to the oven at 110°C for 24 hours. The compressive strength was measured on day 7.

Fig.12 compares the compressive strength results for cases A to E. Since the compressive strength in Case F was similar to that in Case E, it has not been considered in **Fig.12**. As can be seen in **Fig.12**, in Case B, the strength of the specimens had increased compared to Case A. This can be due to the fact that returning of the samples to the temperature of 110°C, which accelerates the curing process and the geopolymerisation reactions, increased the mechanical strength. After boiling the samples, due to the losing some unreacted alkaline contents, the porosity of the sample increased. So, this caused the lower compressive strength comparing to the tests without boiling. In Case C, compared to Case B, returning the samples to the oven at 110°C did not increase the compressive strength, and the reason could be removing the unreacted alkaline contents.

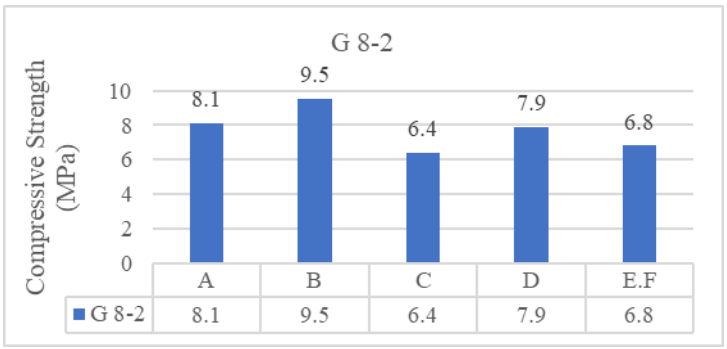

Fig. 12 - Compressive strength in cases A to E

The samples for Case D have a lower compressive strength compared to the boiled samples (case C) due to their half-hour immersion in water, and also the removal of the unreacted substances. However, in case D compared to case B, despite being stored at 110°C for 24 hours, the compressive strength did not increase at all. This could be due to the reduction of alkalis in the structure of the samples. In Case E, similar to Case C, since the unreacted alkaline materials

inside the structure of the samples had enough time to dissolve and leave the samples, it created a porous space and the compressive strength was reduced.

The results of the water absorption percentage of the samples are presented in **Fig.13**. The water absorption after 5-hour boiling, according to INBC-Part5 (2013), was 13%. In comparison with the recommended water absorption percentages for clay bricks, it can be concluded that geopolymer material made with AAC powder had an appropriate water absorption level. The half-hour water absorption percentage was also 11%, which was higher than the maximum water absorption percentage of Portland cement concrete (according to part 9 of Iranian National Building Regulations (2014)). So according to the results of this study, at different curing temperature ranges, the use of AAC materials is not recommended for making geopolymer concrete.

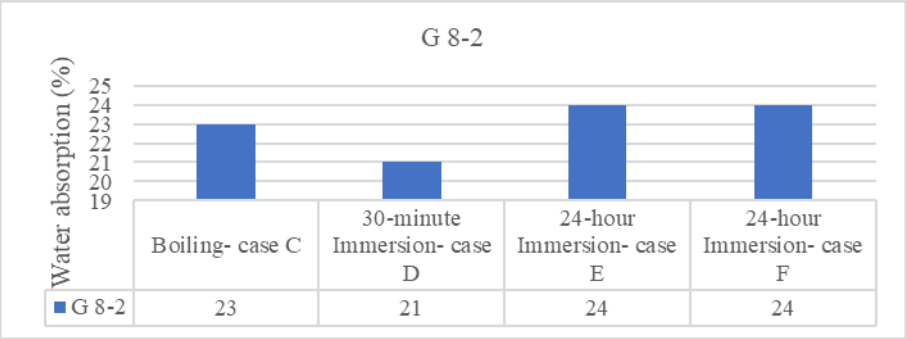

Fig. 13 - Water absorption percentage of geopolymer samples

3.6 XRD Results

Here, XRD analysis was performed on the AAC powder and AAC-based geopolymer samples. The tested geopolymer sample for this part was selected from the mix design with the highest compressive strength, i.e., G 8-2 prepared with AAC powder passing the sieve No.50. The XRD analysis of AAC powder is shown in **Fig.14**. As observed, AAC powder is composed of Quartz, Calcite, Tobermorite, Anhydrite and Gypsum minerals.

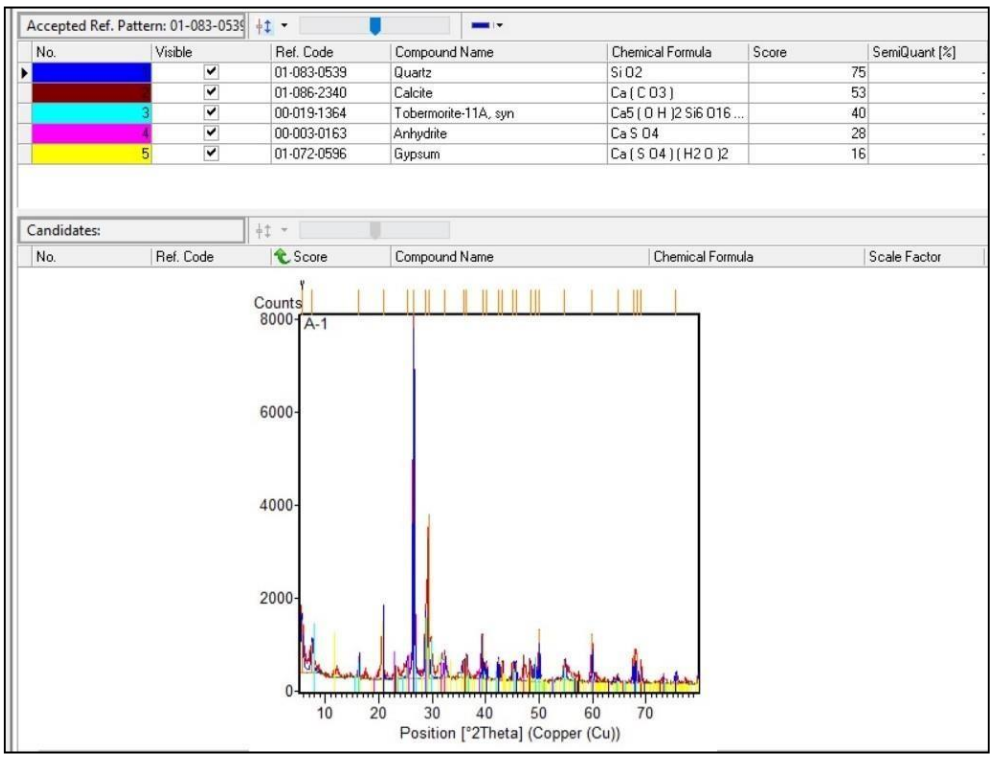

Fig. 14 - XRD analysis of AAC powder utilised here

For better comparison, the XRD patterns of the AAC powder and the powder of geopolymer mortar are plotted together in **Fig.15**. As can be observed from **Fig.15**, the peak values were different, and this was more evident for 2θ angle range of 27 to 30°. This phenomenon indicated the effect of alkaline activator solution on the structure of AAC powder materials and the production of geopolymer structures.

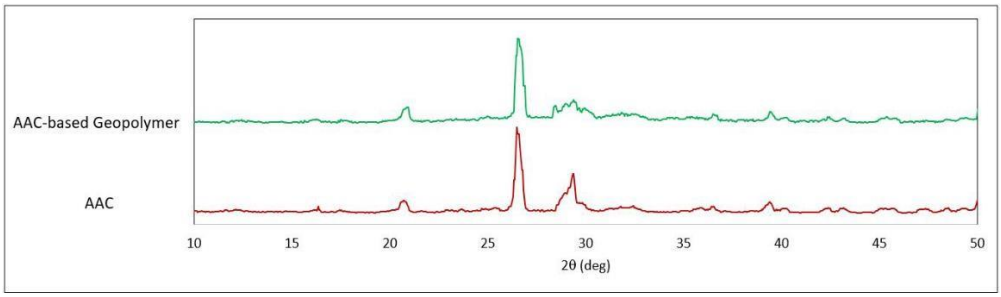

Fig. 15 - XRD patterns of AAC powder and geopolymer material based on AAC

3.7 SEM Analysis

SEM images of AAC block pieces used here, as well as geopolymer samples prepared in this study, are investigated in this section. Geopolymer samples were selected from the mix designs that showed the highest and lowest compressive strength. **Fig.**s **16**, **17**, and **18** are related to the AAC (solid) block, solid geopolymer sample with the highest compressive strength, and the sample with the lowest compressive strength, respectively. Image magnifications are equal to 500, 1000, 5000, 10000, 30,000 and 60,000X. From SEM investigation according to **Fig.**s **16** to **18**, it is clear that after adding the alkaline solution to the AAC waste powder, the material does not have a flake structure anymore. This is more noticeable in the sample with the highest compressive strength. As well, the porosity of the geopolymer sample is much less and smaller than the AAC sample.

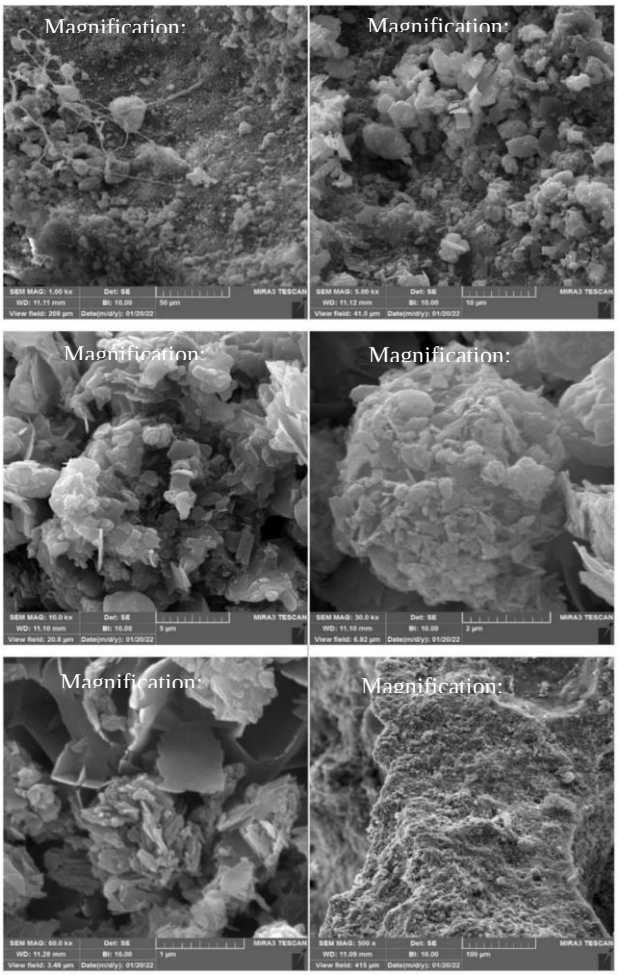

Fig. 16 - SEM analysis of AAC solid piece

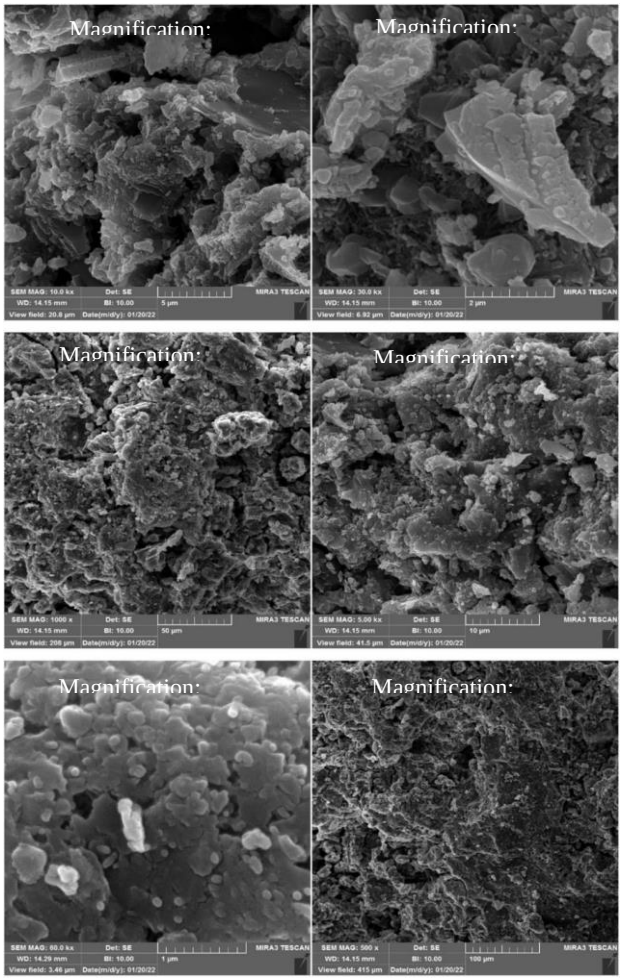

Fig. 17 - SEM analysis of the geopolymer sample with the highest compressive strength

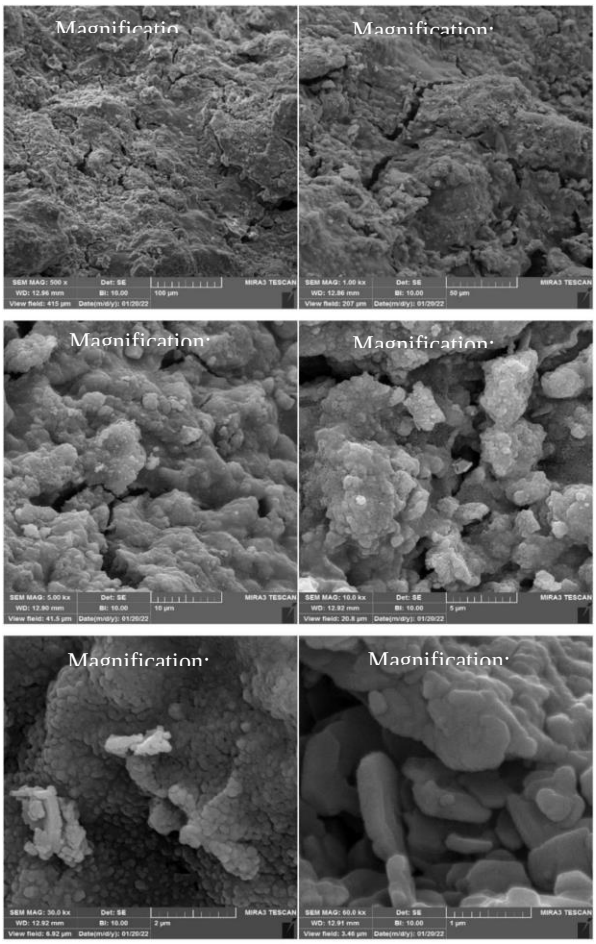

Fig. 18 - SEM analysis of the geopolymer sample with the lowest compressive strength

4. Conclusion

In this study, as an innovative idea, the feasibility of using autoclaved aerated concrete (AAC) block wastes as a source of silica-rich aluminosilicate to produce geopolymer binders was evaluated. For this purpose, the cube, briquette and prism samples were prepared based on AAC powder passing through sieves No.50, and 100 in combination with an activator solution containing sodium hydroxide and sodium silicate (with different concentrations), and under curing temperatures of 40, 60, and 80°C. Compressive, tensile and flexural strengths as well as the water absorption of the samples were determined for different mix designs. The main challenge here, is to investigate the effect of the curing temperature, the concentration of the activator solution, and the size of AAC powder on the mechanical strength of AAC-based geopolymer mortar samples. Also, an expression was extracted by Gene Expression Programming based on the experimental results for the compressive strength of the geopolymer material produced using recycled AAC powder. The most important results are as follows:

- By increasing the sodium silicate to sodium hydroxide ratio from 1 to 2, an increase was observed in the mechanical strength of the samples.
- Increased temperature of oven-curing led to an increase in the strength.
- The grain size of AAC powder was influential on the compressive strength of the samples. Geopolymer samples made of AAC powder passing the sieve No.100 had higher strength than those made of AAC powder passing the sieve No.50.
- In general, by placing the samples in water, the compressive strength decreased slightly due to the increase in porosity because of the dissolution of the unreacted alkali materials.
- A slight decrease in compressive strength was observed by immersing the samples in water for 30 minutes due to increased porosity. For the same reason as above, by keeping the samples in water for 24 hours, the compressive strength decreased more than 30-minute immersing, and this was more pronounced in the case of boiling the samples.
- Measuring water absorption using half-hour immersion and boiling for 5 hours, showed that producing geopolymer bricks based on AAC waste powder is possible, according to the requirements of INBC-Part 5 for clay bricks. However, the idea of making geopolymer concrete using AAC waste powder, needs to be more investigated according to the requirements of INBC-Part9.

- The formulation extracted by GEP model with about 85% of training accuracy (R2) included molarity of sodium hydroxide solution, mass ratio of sodium silicate to sodium hydroxide, sieve number, and oven curing temperature as input variables.
- Validation process of the GEP formulation were performed using an extra series of test results implemented by the authors. However, it seems there is a need to implement more experiments to collect a comprehensive database for having the best prediction model.

To continue studies in this field, the authors evaluate the mechanical properties and durability of the geopolymer concrete samples made of AAC block waste with curing in ambient conditions. Also, the use of AAC waste powder with the grains passing the sieve No.200 is the other investigation area.

Acknowledgement

The authors had officially registered the idea of "Production of Geopolymer Building Materials using AAC Blocks Waste" at National Patent Office of Documents Registration Organization System of I.R.Iran on 03-01-2022, with national patent NO.106073 and international classification of G06Q 50/08;B07B 1/28;B28B 13/02;G06F 19/00. *Available on*: https://ipm.ssaa.ir/Search-Result?page=1&DecNo=14005014000300202 7&RN=106073

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