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Stress-strain behavior of geopolymer under uniaxial compression

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Abstract. The various types of structural materials that are available in the construction industry nowadays make it necessary to predict their stress-strain behavior. Geopolymer are alternatives for ordinary Portland cement concrete that are made from pozzolans activation. Due to relatively new material, many mechanical specifications of geopolymer are still not yet discovered. In this study, stress-strain behavior has been provided from experiments for unconfined geopolymers. Modulus of Elasticity and stress-strain behavior are critical requirements at analysis process and knowing complete stress-strain curve facilitates structural behavior assessment at nonlinear analysis for structures that have built with geopolymers. This study intends to investigate stress–strain behavior and modulus of elasticity from experimental data that belongs for geopolymers varying in fineness and mix design and curing method. For the sake of behavior determination, 54 types of geopolymer are used. Similar mix proportions are used for samples productions that have different fineness and curing approach. The results indicated that the compressive strength ranges between 7.7 MPa and 43.9 MPa at the age of 28 days curing.

Keywords: geopolymer; stress-strain behavior; modulus of elasticity; uniaxial compression

1. Introduction

Buildings are energy consuming structures that have large impact on global climate change and other energy-related environmental issues. Buildings are responsible for almost 40 percent of the total primary energy consumption and 70 percent of electricity consumption. About 40 percent of CO_2, 50 percent of SO_2, and 20 percent of NOx emissions are produced in the US as a result of building-related energy consumption (Komnitsas 2011, Davidovits 1991). Concrete made from Ordinary Portland Cement is second only to water as the commodity most used by mankind today. Global cement production in 2008 was around 2.6 billion tones (Van Deventer *et al*. 2012) contributing conservatively 5-8% of global anthropogenic CO_2 emissions (Scrivener and Kirkpatrick, 2008).Under Copenhagen Accord, countries have agreed to keep global average temperature increase below 2°C. Increases in excess of 2°C can trigger dangerous anthropogenic interference with the climate system, including climate-tipping points, with unmanageable consequences to water supply, agricultural productivity, sea-level rise, human habitability, and global security (Van Deventer *et al*. 2012, Rockstrom *et al*. 2009). Reactions between solutions with high alkalinity and amorphous alumino-silicate materials produce an inorganic binder which is also known as inorganic polymer cement or geopolymers (Kamseu *et al*. 2014). Geopolymers are alternatives to ordinary Portland cement and concrete.

Davidotis invented and first used the term, geopolymer, on the basis of consisting of Al and Si which are both essential geological structural elements. How should we consider geopolymers? They are a new material, new binder, or new cement for concrete. Although different terminology (e.g., low-temperature alumino-silicate glass, alkali-activated cement, and hydroceramic) have been used by researchers, "geopolymer" is the generally accepted name for this technology (Davidovits 1991, Davidovits 1989, Davidovits 1989, Gimeno *et al*. 2003). The molecular structure of geopolymers consists of an alumino-silicate network that is a product of the chemical reaction between aluminosilicate and alkali-polysialate in a relatively highly alkaline medium (Allahverdi *et al*. 2008). Natural pozzolans are geological deposits with a wide range of chemical compositions which vary from batch to batch but they are usually high in available SiO_2 (Bondar *et al*. 2011). Pozzolans can be activated and condensed with sodium silicate in an alkaline environment to synthesize high performance cementitious construction materials with low environmental impact. Geopolymerization is an exothermic process carried out by oligomer (dimer, trimer), which is the basic unit structure for three-dimensional macromolecular structure, and also that geopolymerization can be perceived as analogue of zeolite synthesis. In other words, although the chemistry involved in geopolymerization is close to chemistry in the synthesis of zeolite, the geopolymer microstructure is amorphous and semi-crystalline rather than crystalline. Generally, geopolymerization involves a series of operations, such as dissolution, redirecting and solidification, as shown in Fig. 1.

The nature of the starting materials including mineral composition, chemical composition and crystal structure groups affects the formation of the geopolymer gel phase

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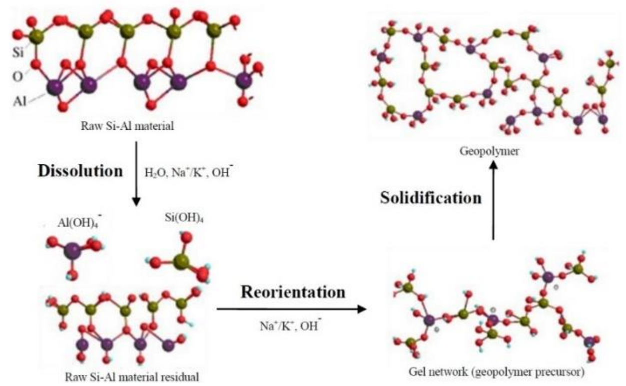

Fig. 1 Typical reaction mechanism of geopolymerization (He 2012)

(Bondar *et al*. 2011). The resulting products, i.e., geopolymer cements, usually exhibit good engineering properties such as relatively high compressive strengths, short to long setting times, and relatively high resistance against aggressive media compared to Portland cements (Allahverdi *et al*. 2008, Fletche *et al*. 2005). The silica to alumina ratio (in the amorphous precursors) and the alkali to alumina ratio (in the pore solution) directly affect the engineering properties as the stability of geopolymer cement (Kamseu *et al*. 2014) so the source material in the composition of the geopolymer mixtures affects the behavior of the geopolymers intensely. Precise understanding of behavior and performance of the geopolymers is becoming more important use of this type of construction material. It is important to estimate accurately the crucial mechanical properties of this structural material, including modulus of elasticity and compressive stress-strain (σ-ε) curve to arrive at a safe and economic analysis and design. We can summarize factors affecting the mechanical specifications. The mechanical properties of geopolymers are affected by a number of factors:

(1) The chemical composition of pozzolans and activators (e.g., Si/Al and Na/Si ratios);

(2) The particle size, shape of the pozzolans;

(3) The interfacial bonding strength between fillers and pure geopolymer binder;

(4) The relative concentrations of pure geopolymer and inactive fillers; and

(5) The extent and degree of complete geopolymerization.

Therefore, evaluation of the mechanical properties of the final products is complicated by these factors, since quantitative analysis of the composition and concentration of pure geopolymer in the end products is challenging due to non-reacting Si and incomplete geopolymerization of even reactive Si and Al (He *et al*. 2011).

2. Experimental details

2.1 Raw materials used to make geopolymers

2.1.1 Perlite

The raw material employed in the paper was Perlite. In this study, Perlite obtained from Kaneh Azar Co. (Tabriz, Iran) was used as the basic aluminosilicate material to manufacture geopolymers. The prepared natural perlite was ground in mill. Knowing that particle size distribution of perlite powder can significantly influence the properties of geopolymer (Allahverdi *et al*. 2008), an analysis of particle size distribution was carried out using hydrometer Analysis. We have used three particle sizes in this study. The compressive strength of geopolymers also mainly depended on the content of pozzolan fine particles. The particle size distributions of ground perlite have been shown in Fig. 2. The specific surface areas of ground perlite are 3100, 3580 and 4300 m^2/kg respectively for Per1, Per2 and Per3 and the ground perlite density is 2.38 gr/cm^3. It was measured by BET N2 adsorption. The particle size approximately ranged between 3 and 90 μm and uniformity factor of each series are 3.8, 3.78, 3.16 respectively. X-ray powder diffraction (XRD) was used to characterize and identify the phase compositions and crystallinity of the samples. As a

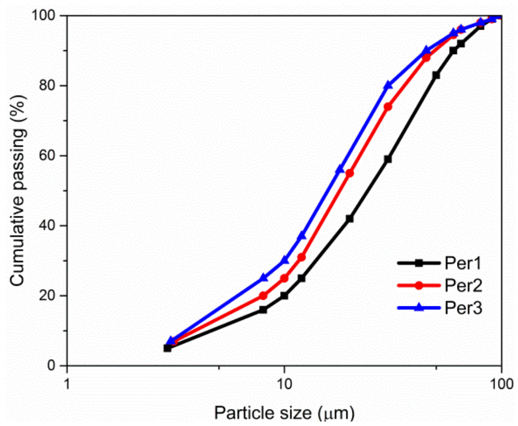

Fig. 2 Particle size distributions of ground perlite

Table 1 Chemical composition of tabriz ground perlite

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O+Na_2O	SO_3	Ti_2O	Mn_2O	Others	LOI
79.6	11.5	0.8	0.8	0.5	5.3	0.2	0.1	0.065	1. 135	1.135

Table 2 Some physical properties of tabriz perlite

Parameter	Data
Color	White
Softening Point	800-1000°C
Melting Point	1315-1390°C
pH	6.6-8.0

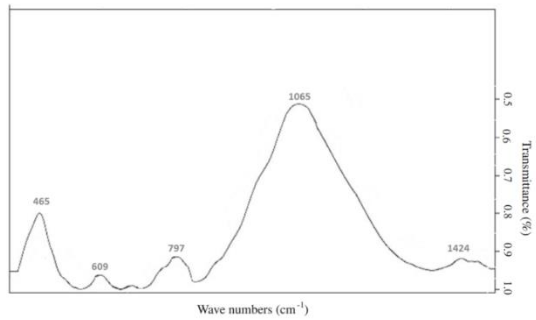

Fig. 3 The FTIR spectrum of un-expanded tabriz perlite

Table 3 Concentration of the sodium hydroxide solution

Chemical Formula	$NaOH*H_2O$
NaOH	32-33%
H_2O	67-68%
Appearance	Gel
Specific Gravity (20°C)	1.35

Table 4 Concentration of the sodium silicate solution

Chemical Formula	Na_2O*SiO_2 Colorless
SiO_2	22-24%
Na_2O	11-12%
H_2O	64-67%
Appearance	Gel
Specific Gravity (20°C)	1.38-1.397

result of the XRD analysis for Tabriz perlite, Tabriz perlite samples were found completely amorphous materials.

The chemical composition of the perlite determined by XRF is given in Table 1(Torab-Mostaedi *et al*. 2010) and The physical composition of the perlite has been presented in Table 2. The FTIR analysis has been done for determination of present chemical bonds that has been shown in Fig. 3.

The alumino-silicate bonds i.e., Si-O-Al are confirmed by FTIR analysis. Vibrating at approximately 1065 cm^{-1} is a poof of Si-O and Al-O bonding. Similarly the wavelength of 465, 609, 797cm^{-1} are concerned orderly with Al-O and Si-O, Si-O-Si and Si-O-Si bonds, additionally, the wavelength of 1424 cm^{-1} is related with O-C-O/CO_3 i.e., $CaCO_3$ bond (Cătănescu *et al*. 2012).

2.1.2 Sodium hydroxide

The common materials used as alkaline solution in producing geopolymer are sodium metasilicate (Na_2SiO_3) and sodium hydroxide (NaOH). Commonly the sodium hydroxides are available in solid state by means of pellets and flakes. In this study, the liquid sodium hydroxide was used and its physical and chemical properties are given by the manufacturer has been shown in Table 3.

2.1.3 Sodium silicate

Sodium silicate is known as water glass and available in gel form. In this study, ratio between SiO_2 to Na_2O is 1.95-2.3 chemical specifications and the physical properties for used sodium silicate have been shown in Table 4.

2.1.4 Super plasticizer

In this study, Glenium C303 has been used as a superplasticizer (SP) and its properties have been shown in the Table 5.

2.2 Experimental techniques and sample preparation

In order to determine the Tabriz perlite activation properties on compressive strength, nine mix proportions for three fineness values have been designed as shown in Table 6. Fresh properties of perlite-bases Geopolymers are

Table 5 Technical properties of glenium C 303

Name	Glenium C 303
Density (gr/cm^3) (20°C)	1.023-1.063
Chlorine % (En 480-10)	<0.1
Color	Green
Homogeneousness	Homogenous
Chemical Content	Synthetic Polymer Based

shown in Table 7. In a small pilot study on whatever was reported by Palomo *et al*. this was found that the compressive strengths are higher in geopolymers made by adding alkaline hydroxide solution to natural pozzolan first followed by a sodium silicate solution, instead of adding alkaline and sodium silicate as a mixed solution to natural pozzolan. It seems that by adding alkaline hydroxide solution first, Al-Si bonds are broken up, thus causing a higher degree of the Al-Si disorder. Then gel formation in hydrated alkaline alumina-silicates is generated by sodium silicate. However, adding alkaline and sodium silicate as a mixed solution creates two opposite reactions. Therefore, the paste was prepared by adding the hydroxide solutions to the natural pozzolans and mixing for 15 min first. The mixing was continued with the addition of sodium silicate solutions for 3 additional minutes (Bondar *et al*. 2011). Resulting paste transferred to steel molds that have 50×50×50 mm. And then it has been vibrated for 2 minutes with vibrating table. Then specimens, at first curing phase, were left standing for 48 hours at 65°C in curing chamber and in the second method, the autoclave curing method has been used for curing. The surfaces of the molds with paste were covered with polyethylene film to simulate hydrothermal curing until demolding this process avoids excessive water evaporation in alkali-activated samples during thermal curing and is an important step because water is necessary for polymerization. Demolding was done at 48 hours for first curing method and then specimens unwrapped from films and left in laboratory without any curing approximately in 25°C and 28 days after casting the samples ready to compressive testing according to ASTM C39. Compressive strength was assessed by testing cube samples at a displacement rate of 1mm/min for compressive strength testing. The two ends of the specimens were polished by sand paper to obtain flat and parallel surfaces, followed by applying a thin layer of lubricant coating, in order to minimize the friction (and hence shear stress development) between the specimen end surfaces and polished stainless steel end platens. Compressive strength test for dried geopolymer have been done for all mixtures according to ASTM C39 and UPV test has been done for all samples. Average of 3 sample results have been used in this study for each test as authors previous work (Yadollahi *et al*. 2014, Yadollahi *et al*. 2015, Yadollahi *et al*. 2015). Knowledge of the elastic modulus of concrete is essential in the determination of the deflection of structures. The modulus of elasticity is usually divided in two: static and dynamic. In this study, only the static modulus of elasticity has been studied. 50×50×50 mm cube specimens have been subjected to uniaxial compression and deformation has been measured by means of ideal gauges fixed between certain gauge lengths. Dial gauge reading divided by gauge length

Fig. 4 A view of uniaxial compression testing machine

Table 6 Mix proportions for tabriz perlite-based geopolymers

Mix code	Perlite (g)	NaOH Solution (g)	Na_2SiO_3 Solution (g)	H_2O (g)	SP(g)	MS*	Na_2O (%)	w/b ratio
1	1214.08	142.678	109.59	258.38	48.56	0.52	4	0.36
2	1152.81	237.08	182.11	164.19	46.11	0.52	7	0.40
3	1096.27	322.08	247.40	80.02	43.85	0.52	10	0.44
4	1205.65	234.74	220.42	137.80	48.22	0.60	7	0.36
5	1144.11	317.93	298.52	24.25	45.76	0.60	10	0.40
6	1302.08	107.20	136.20	197.29	52.08	0.60	4	0.44
7*	1186.83	260.94	352.63	14.24	47.47	0.68	10	0.36
8	1173.49	122.93	138.91	270.46	46.94	0.68	4	0.40
9	1127.00	206.61	233.47	161.53	45.07	0.68	7	0.44

These mix proportions are for 1000 cm^3 geopolymer cement paste.
*NaOH amount in the seventh mix solution is different and 386.3 g NaOH has been used in 1 kg solution
*$MS=SiO_2/Na_2O$

Table 7 Fresh properties of perlite-based geopolymers

Mix no	Setting time (min)	Final Setting time (min)	Average density gr/cm^3	Flow table test (mm)		
				Per1	Per2	Per3
1	11.2	37.0	1.760	119	110	105
2	11.3	33.4	1.781	140	121	106
3	11.0	30.5	1.810	139	130	127
4	10.2	33.0	1.820	122	114	111
5	10.4	31.0	1.827	137	130	124
6	11.8	36.0	1.780	137	132	125
7	9.3	27.5	1.845	134	127	122
8	12.0	35.0	1.748	128	118	110
9	10.5	36.5	1.754	131	131	119

gives the strain while load applied divided by area of cross section gives the stress. A series of readings were taken and the stress-strain relationship was established. The modulus of elasticity found from actual loading is called static modulus of elasticity. The samples dimensions are cubic as defined but ASTM C469 i.e., standard test method for static modulus of elasticity of concrete in compression has been used for determination of static modulus of elasticity in produced geopolymer. The uniaxial compressive loading on the specimens was carried out using a 2000 kN capacity testing machine. Axial compression test was carried out on all the specimens after 28 days of curing. Two linear variable differential transducers (LVDT) installed symmetrically on both sides of the geopolymer specimens and between the platens of the testing machine were used to determine the axial deformation. The compressive loading on the geopolymer specimens was monotonically applied with a low rate of 0.7 kN/s as shown in Fig. 4.

3. Results and discussion

3.1 Stress strain behavior of tabriz-based geopolymers

In the present work, the effect of silica modulus, natural pozzolan fineness and curing condition on geopolymer compressive strength and static elastic modulus have been investigated. ASTM C109 standard test method for compressive strength of hydraulic cement has been used in this study to determine perlite based geopolymer compressive strength. The results are given in Table 8. Young's modulus or elastic modulus is the most commonly investigated property of geopolymers for its obvious importance towards engineering applications. Due to the porous nature of geopolymers, complicated fracture mechanics lead to wide ranges of uncertainties when strengths are experimentally evaluated due to the destructive tests (Lim and Ozbakkaloglu 2014). Xie *et al.* investigated (Xie and Ozbakkaloglu 2015) the behavior of geopolymer concrete (GPC) based on fly ash, bottom ash and blended fly and bottom exposed to curing at ambient temperature. The results of the study indicated that there is a strong correlation between the elastic modulus (E_c) and the compressive strength (f'_c) of GPCs, while the concrete modulus increases with increasing compressive strength. This observation was expected and consistent with the well-established relationship between elastic modulus (E_c) and compressive strength (f'_C) in the OPC. Another study of the authors (Ozbakkaloglu and Xie 2016) presented the results of an experimental study of the axial compressive behavior of concrete filled fiber reinforced polymer (FRP) tubes (CFFT) prepared using ordinary Portland cement (OPC) concrete (OPCC) or fly ash based geopolymer concrete (GPC). They concluded that the axial stress-strain behavior of CFFTs is affected by by the concrete type and that GPCFFTs improves a similar strength enhancement ratio but a lower axial strain enhancement ratio than the companion OPCCFFTs. The authors did another research (Xie and Ozbakkaloglu 2015) on the behavior of fly ash (FA) and bottom ash (BA) based geopolymer concretes (GPCs) cured at ambient temperature. The results of the study exhibited that the chemical composition of BA has a significant effect on the compressive behavior of GPCs with concrete produced with BA having a higher silicon dioxide/aluminum oxide ratio, which improves the strength. The results also showed that the grinding of the coal ash

Table 8 Stress strain behavior of tabriz-based geopolymers

*Sample No	Fineness of perlite	Curing type	28-day Compressive Strength (MPa)	Axial strain ε(%)	Young's modulus E (GPa)
Geo1-1	Per1	Air cured	7.70	0.42	7.145
Geo 1-2	Per2	Air cured	8.90	0.43	7.174
Geo 1-3	Per3	Air cured	8.01	0.44	7.157
Geo 1-4	Per1	Autoclave	8.18	0.44	7.142
Geo 1-5	Per2	Autoclave	9.20	0.44	7.200
Geo 1-6	Per3	Autoclave	9.13	0.43	7.142
Geo 2-1	Per1	Air cured	12.90	0.62	8.206
Geo 2-2	Per2	Air cured	12.01	0.58	8.192
Geo 2-3	Per3	Air cured	12.60	0.59	8.195
Geo 2-4	Per1	Autoclave	12.70	0.56	8.190
Geo 2-5	Per2	Autoclave	12.44	0.59	8.181
Geo 2-6	Per3	Autoclave	12.10	0.58	8.206
Geo 3-1	Per1	Air cured	26.01	1.00	10.129
Geo 3-2	Per2	Air cured	26.54	1.00	10.135
Geo 3-3	Per3	Air cured	28.21	1.01	10.153
Geo 3-4	Per1	Autoclave	28.14	1.00	10.161
Geo 3-5	Per2	Autoclave	30.87	1.08	10.420
Geo 3-6	Per3	Autoclave	31.79	1.16	10.450
Geo 4-1	Per1	Air cured	18.43	0.70	9.073
Geo 4-2	Per2	Air cured	18.90	0.69	9.066
Geo 4-3	Per3	Air cured	20.70	0.85	9.511
Geo 4-4	Per1	Autoclave	22.68	0.85	9.520
Geo 4-5	Per2	Autoclave	24.83	0.94	9.522
Geo 4-6	Per3	Autoclave	25.08	1.89	9.522
Geo 5-1	Per1	Air cured	28.73	1.04	10.700
Geo 5-2	Per2	Air cured	29.33	1.04	10.706
Geo 5-3	Per3	Air cured	27.80	1.05	10.690
Geo 5-4	Per1	Autoclave	30.18	1.04	10.763
Geo 5-5	Per2	Autoclave	35.10	1.07	10.769
Geo 5-6	Per3	Autoclave	33.17	1.15	10.766
Geo 6-1	Per1	Air cured	13.75	0.62	7.737
Geo 6-2	Per2	Air cured	13.69	0.61	7.739
Geo 6-3	Per3	Air cured	14.84	0.49	7.767
Geo 6-4	Per1	Autoclave	17.15	0.78	8.171
Geo 6-5	Per2	Autoclave	17.05	0.80	8.168
Geo 6-6	Per3	Autoclave	18.60	0.84	8.180
Geo 7-1	Per1	Air cured	37.03	1.54	11.059
Geo 7-2	Per2	Air cured	40.91	1.67	11.370
Geo 7-3	Per3	Air cured	36.90	1.83	11.360
Geo 7-4	Per1	Autoclave	42.77	1.50	11.630
Geo 7-5	Per2	Autoclave	43.91	1.59	12.066
Geo 7-6	Per3	Autoclave	43.01	1.83	11.692
Geo 8-1	Per1	Air cured	11.60	0.63	7.714
Geo 8-2	Per2	Air cured	13.83	0.62	7.742
Geo 8-3	Per3	Air cured	13.80	0.61	7.742
Geo 8-4	Per1	Autoclave	14.09	0.56	7.755
Geo 8-5	Per2	Autoclave	14.91	0.62	7.756
Geo 8-6	Per3	Autoclave	13.84	0.62	7.742
Geo 9-1	Per1	Air cured	20.03	0.93	9.629
Geo 9-2	Per2	Air cured	21.33	0.92	9.632
Geo 9-3	Per3	Air cured	23.00	0.86	9.65
Geo 9-4	Per1	Autoclave	25.94	0.91	9.658
Geo 9-5	Per2	Autoclave	27.88	1.05	10.077
Geo 9-6	Per3	Autoclave	25.09	1.00	9.661

*Sample No instruction: For example in Geo1-1 the first number is related with mix design and second number is related with material fineness as shown in Fig. 2 and curing condition

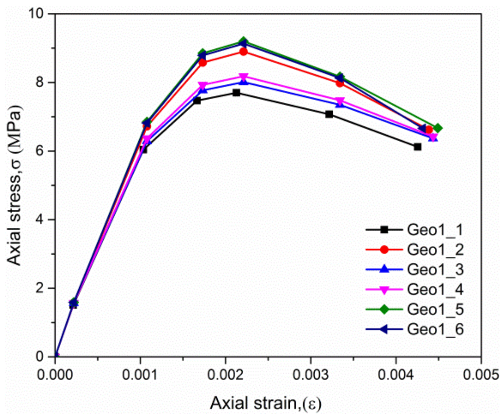

Fig. 5 Geopolymer strain-stress curves with different fineness and curing method for mixture1

and the increased content of calcium oxide in the BA both lead to significant improvements in the compressive strength of the GPCs. At the same time, it was found that strength gain of coal-ash based GPCs cured at ambient temperature continues beyond a concrete age of 28 d that the coal ash was significantly affected by the type, particle size, chemical composition and concentration of the sodium hydroxide solution. In our study, the compressive strength of geopolymer samples exposed to autoclave curing is higher than that of geopolymer samples exposed to air curing. The mixes containing high amount of Na_2SiO_3 solution exhibit higher compressive strength as seen for Geo3, Geo5 and Geo7. When the compressive strength results are examined, it can be seen that the fineness of ground perlites doesn't affect the strength of specimens significantly.

Figs. 4, 5, 6, 7, 8, 9, 10, 11, 12 show the unconfined axial stress-strain curves of the Perlite based geopolymers synthesized at varied mix designs and condition.

As seen from Fig. 5, the compressive strength increases with increasing specific surface increased in the second sample, but reduced in the third sample that can be justified by more solution requirement for mix. This reduction can be estimated because the amount of solution is fixed. It is similar for air and autoclave cured samples, resulting in more strength, more ultimate rupture strain and greater toughness.

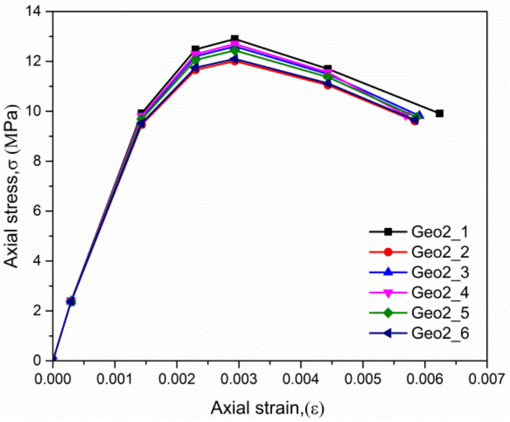

Fig. 6 Geopolymer strain-stress curves with different fineness and curing method for mixture2

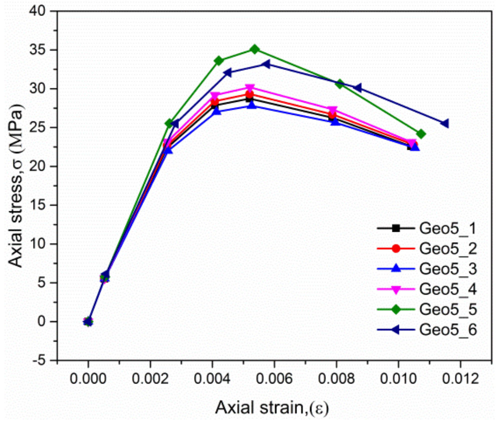

Fig. 9 Geopolymer strain-stress curves with different fineness and curing method for mixture5

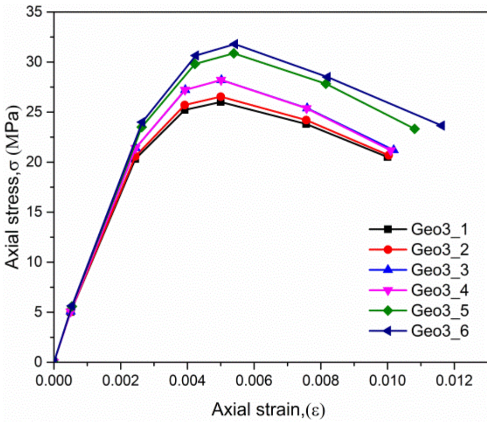

Fig. 7 Geopolymer strain-stress curves with different fineness and curing method for mixture3

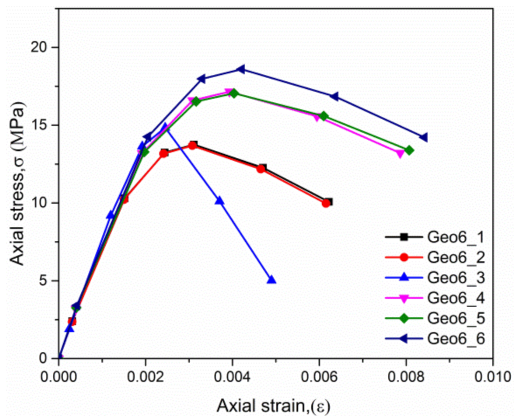

Fig. 10 Geopolymer strain-stress curves with different fineness and curing method for mixture6

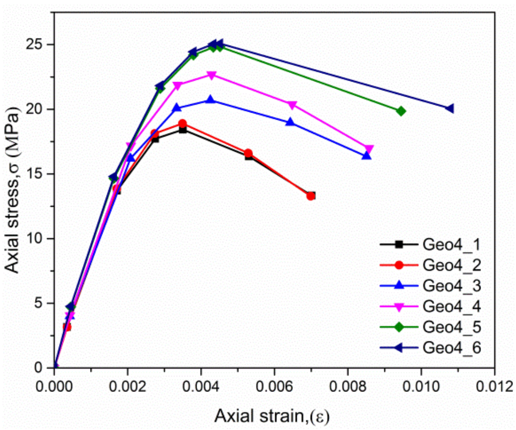

Fig. 8 Geopolymer strain-stress curves with different fineness and curing method for mixture4

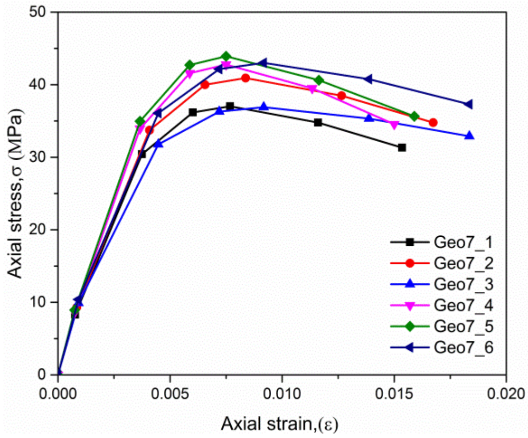

Fig. 11 Geopolymer strain-stress curves with different fineness and curing method for mixture7

In the Fig. 6, the results differ slightly from Fig. 5, that is, first sample has the most compressive strength, hence, the specific surface is small in first sample it is probable reason for gaining more compressive strength at this group.

As plotted in Fig. 7, the compressive strength increased by the increase of specific surfaces. It is similar for air and autoclave cured samples, in addition, autoclave cured samples have more compressive strength compared to air cured ones. As shown in Fig. 8, although the compressive strength increased for autoclave cured with increasing specific surfaces, the first sample in air cured method has the most compressive strength. Because the specific surface is small in the first sample and it can be explained as a reason to get more compressive strength at this group.

Similar to Fig. 5, as seen in Fig. 9, as the specific surface increased, the compressive strength increased in the second sample, but reduced in the third sample that can be justified with more solution requirement for mix. This

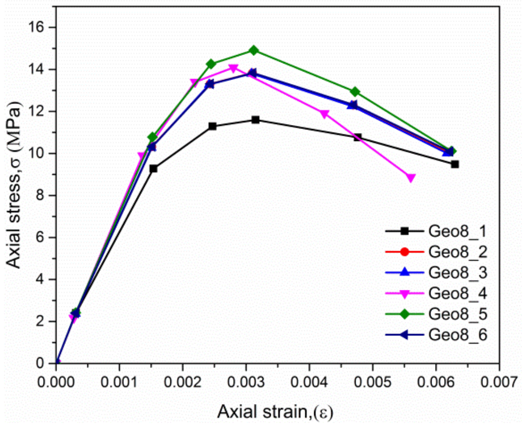

Fig. 12 Geopolymer strain-stress curves with different fineness and curing method for mixture8

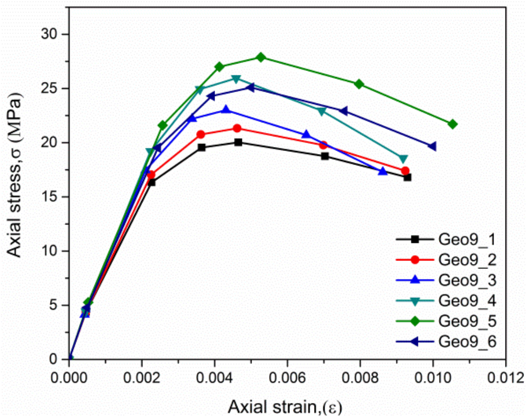

Fig. 13 Geopolymer strain-stress curves with different fineness and curing method for mixture9

decline is predictable because the amount of solution is fixed. It is similar for air and autoclave cured samples, resulting in greater strength, more final rupture strain and more toughness. As noticed from Fig. 10 that with increasing specific surfaces, the compressive strength increased except sample 6-5 in which reduction is negligible. It is similar for air and autoclave cured samples, in addition, the autoclave cured ones have more compressive strength compared to air cured.

We can notice from Fig. 11, for mixture 7 with increasing specific surface, the compressive strength has been increased in the second sample but decrease in the third sample that can be justify with more solution requirement for mix. This decrease is likely because the solution amount is fixed. It is similar for air cured and autoclave cured samples, consequently, the more strength the more final rupture strain and the more toughness is. The highest compressive strength occurs for this group of geopolymer specimens. Autoclave cured per2 sample has gained the highest compressive strength value of 43.9 MPa. As compared to other geopolymer specimen groups, geo7 specimen group has higher compressive strength both in air and autoclave curing. Geo7-2 has gained the highest compressive strength value of 40.91 MPa in air curing. We can notice from Fig. 12 with increasing specific surfaces, the compressive strength have been increased except

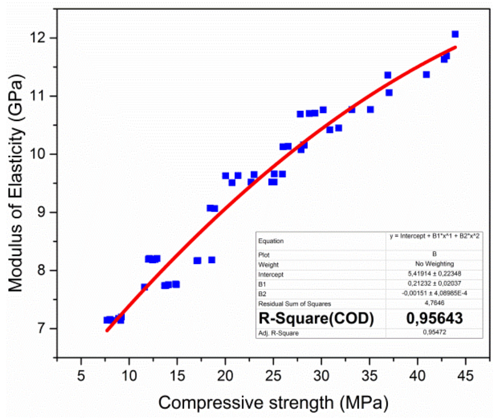

Fig. 14 Relationship between compressive strength and modulus of elasticity

sample 8-6. It is similar for air cured and autoclave cured samples, additionally, the autoclave cured have been resulted the more compressive strength compared with air cured.

As demonstrated in Fig. 13, the compressive strength increased with increasing specific surfaces except sample 9-6, the autoclave cured samples exhibited more compressive strength compared to air cured ones. Influence factor in our study is compressive strength and Modulus of elasticity. Obviously with increasing compressive strength stiffness, axial strain will increase and ductility will also increase for all specimens. All curves exhibit a well-defined linear elastic regime and approximately brittle failure mode. A feature common to all curing condition is readily observed: the higher the MS content, the higher the compressive strength and stiffness (or Young's modulus *E*), and the higher the axial strain. Geopolymers with a higher compressive strength tend to behave more ductile. These results are similar for fineness increase and curing method. i.e. with fineness increasing the compressive strength and Young's modulus will increase. Also the autoclave curing causes more strength, more ductility and more Young's modulus. Range of Elastic Modulus values for perlite based geopolymers are 7.142 to 12.066 GPa in this study for Tabriz perlite based geopolymer. Typical values for Young's modulus reported throughout the literature for metakaolin based geopolymers without aggregates range from 1 GPa to 6 GPa (Duxson *et al*. 2005). Similarly to the compressive strength, the Young's modulus tended to increase in value as the Si/Al ratio increased until the maximum value. Two possible reasons may account for this:

(1) The higher contents of reactive silica and alumina in perlite result in higher degree of geopolymerization and more geopolymeric binder;

(2) The fine particle size and very high specific surface area of perlite make geopolymers behave more ductile.

3.2 Relationship between compressive strength and modulus of elasticity

Modulus of elasticity of structural materials is a key factor for estimating the deformation of structural elements so relationship of modulus of elasticity of geopolymer with compressive strength has been shown in Fig. 14. Conspicuously with increasing compressive strength, stiffness increase for all samples. As shown in Fig. 14, a very high coefficient of determination was obtained (R^2=95) between the modulus of elasticity and compressive strength and a good representation of the relationship between the compressive strength and modulus of elasticity can be observed.

4. Conclusions

Based on the research results presented, the following conclusions were drawn:

1. It is possible to activate Tabriz Perlite and produce geopolymer using NaOH & Na_2SiO_3 so Tabriz based Geopolymer can be used as alternative solution to the CO_2 producing problem in Portland cement production.

2. Increasing fineness cause increasing in compressive strength, stiffness, axial strain in samples produced with Tabriz based perlite.

3. Autoclave curing is a good approach and is recommended for prefabricate geopolymer production. Autoclave curing cause increasing in compressive strength, stiffness, axial strain in comparison with normal cured samples.

4. With increasing compressive strength stiffness, axial strain will increase and ductility increase for all mix and samples.

5. The geopolymer samples may be considered isotropic with regards to their elastic properties. This implies that the porosities are aligned randomly and are evenly distributed throughout the geopolymer binder. This results is similar to Joseph results (Lawson 2008).

6. The mixes containing high amount of Na_2SiO_3 solution exhibit higher compressive strength as seen for Geo3, Geo5 and Geo7.

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References

Allahverdi, A., Mehrpour, K. and Kani, E.N. (2008), "Investigating the possibility of utilizing pumice-type natural pozzonal in production of geopolymer cement", *Ceram-Silikat*., **52**(1), 16-23.

Bondar, D., Lynsdale, C.J., Milestone, N.B., Hassani, N. and Ramezanianpour, A.A. (2011), "Effect of adding mineral additives to alkali-activated natural pozzolan paste", *Constr. Build. Mater*., **25**(6), 2906-2910.

Bondar, D., Lynsdale, C.J., Milestone, N.B., Hassani, N. and Ramezanianpour, A.A. (2011), "Effect of heat treatment on reactivity-strength of alkali-activated natural pozzolans", *Constr. Build. Mater*., **25**(10), 4065-4071.

Bondar, D., Lynsdale, C.J., Milestone, N.B., Hassani, N. and Ramezanianpour, A.A. (2011), "Effect of type, form, and dosage of activators on strength of alkali-activated natural pozzolans", *Cement Concrete Compos*., **33**(2), 251-260.

Cătănescu, I., Georgescu, M. and Melınescu, A. (2012), "Synthesıs and characterızatıon of geopolymer binders from Fly ash", *Sci. Bullet. Ser. B: Chem. Mater. Sci*., **74**(1).

Davidovits, J. (1989), "Fast-curing cement", *Chem. Eng. News*, **67**(27), 4-5.

Davidovits, J. (1991), "Geopolymers-inorganic polymeric new materials", *J. Therm. Anal*., **37**(8), 1633-1656.

Davidovits, J. (1989), "Geopolymers and geopolymeric materials", *J. Therm. Anal*., **35**(2), 429-441.

Duxson, P., Provis, J.L., Lukey, G.C., Mallicoat, S.W., Kriven, W.M. and Van Deventer, J.S.J. (2005), "Understanding the relationship between geopolymer composition, microstructure and mechanical properties", *Coll. Surf. A*, **269**(1-3), 47-58.

Fletcher, R.A., MacKenzie, K.J.D., Nicholson, C.L. and Shimada, S. (2005), "The composition range of aluminosilicate geopolymers", *J. Eur. Ceram. Soc*., **25**(9), 1471-1477.

Gimeno, D., Davidovits, J., Marini, C., Rocher, P., Tocco, S., Cara, S., Diaz, N., Segura, C. and Sistu, G. (2003), "Development of silicate-based cement from glassy alkaline volcanic rocks: Interpretation of preliminary data related to chemical-mineralogical composition of geologic raw materials", *Bol. Soc. Esp. Ceram. V*, **42**(2), 69-78.

He, J. (2012), *Synthesis and Characterization of Geopolymers for Infrastructural Applications*, Nottingham University, U.K.

He, J.A., Zhang, G.P., Hou, S.A. and Cai, C.S. (2011), "Geopolymer-based smart adhesives for infrastructure health monitoring: Concept and feasibility", *J. Mater. Civil Eng*., **23**(2), 100-109.

Kamseu, E., Cannio, M., Obonyo, E.A., Tobias, F., Bignozzi, M.C., Sglavo, V.M. and Leonelli, C. (2014), "Metakaolin-based inorganic polymer composite: Effects of fine aggregate composition and structure on porosity evolution, microstructure and mechanical properties", *Cement Concrete Compos*., **53**, 258-269.

Komnitsas, K.A. (2011), "Potential of geopolymer technology towards green buildings and sustainable cities", *Proc. Eng*., **21**, 1023-1032.

Lawson, J.L. (2008), *On the Determination of the Elastic Properties of Geopolymeric Materials Using Non-Destructive Ultrasonic Techniques*, Master of Science Rochester, Rochester Instıtute of Technology, New York, U.S.A.

Lim, J.C. and Ozbakkaloglu, T. (2014), "Stress-strain model for normal- and light-weight concretes under uniaxial and triaxial compression", *Constr. Build. Mater*., **71**, 492-509.

Ozbakkaloglu, T. and Xie, T.Y. (2016), "Geopolymer concrete-filled FRP tubes: Behavior of circular and square columns under axial compression", *Compos. Part B-Eng*., **96**, 215-230.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., De Wit, C.A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. and Foley, J.A. (2009), "A safe operating space for humanity", *Nat*., **461**(7263), 472-475.

Scrivener, K.L. and Kirkpatrick, R.J. (2008), "Innovation in use and research on cementitious material", *Cement Concrete Res*., **38**(2), 128-136.

Torab-Mostaedi, M., Ghassabzadeh, H., Ghannadi-Maragheh, M., Ahmadi, S. and Taheri, H. (2010), "Removal of cadmium and nickel from aqueous solution using expanded perlite", *Brazil. J. Chem. Eng*., **27**(2), 299-308.

Van Deventer, J.S.J., Provis, J.L. and Duxson, P. (2012), "Technical and commercial progress in the adoption of

geopolymer cement", *Miner*. *Eng*., **29**, 89-104.
Xie, T.Y. and Ozbakkaloglu, T. (2015), "Behavior of low-calcium fly and bottom ash-based geopolymer concrete cured at ambient temperature", *Ceram*. *Int*., **41**(4), 5945-5958.
Xie, T.Y. and Ozbakkaloglu, T. (2015), "Influence of coal ash properties on compressive behaviour of FA- and BA-based GPC", *Mag*. *Concrete Res*., **67**(24), 1301-1314.
Yadollahi, M.M., Demirboga, R. and Polat, R. (2014), "Effect of heat treatment temperature on ground pumice activation in geopolymer composites", *Sci*. *Eng*. *Compos*. *Mater*., **21**(3), 377-382.
Yadollahi, M.M., Benli, A. and Demirboga, R. (2015), "Effects of elevated temperature on pumice based geopolymer composites", *Plast Rub*. *Compos*., **44**(6), 226-237.
Yadollahi, M.M., Benli, A. and Demirboga, R. (2015), "The effects of silica modulus and aging on compressive strength of pumice-based geopolymer composites", *Constr*. *Build*. *Mater*., **94**, 767-774.

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