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Effect of Partial Portland Cement Replacement on Geopolymerization Process and Mechanical Properties of Fly Ash-Based Geopolymer Concrete

Lateef N. Assi[1], Rafal Anay[1], Vafa Soltangharaei[1], Paul Ziehl[1]
1 Department of Civil and Environmental Engineering, University of South Carolina, 300 Main Street, Columbia, SC 29208, USA; lassi@email.sc.edu (L.A.); ranay@email.sc.edu (R.A.); vafa@email.sc.edu (V. S.); ziehl@cec.sc.edu (P.Z.).

ABSTRACT

Portland cement is one of the main construction materials. Manufacturing of cement is a reason for increasing the carbon footprint worldwide. Therefore, developing a sustainable construction material is needed to fully or partially replace Portland cement applications in building constructions. Geopolymer concrete is a sustainable cementitious material that tends to reduce CO_2 emissions and utilizes waste materials such as fly ash, metakaolin, or blast furnace slag. In this study, fly ash-based geopolymer concrete with an activating solution of a mixture of silica fume, sodium hydroxide, and water will be investigated. Four Portland cement replacement weight ratios including 0%, 5%, 10%, and 15% by weight of fly ash have been studied. The effects of the Portland cement replacements on the geopolymerization process, compressive strength, modulus of elasticity and Poisson's ratio of geopolymer concrete were investigated. Acoustic emission monitoring results showed that the geopolymerization process was enhanced when the Portland cement replacement was increased. The compressive strength and modulus of elasticity were significantly increased when Portland cement ratio increased, while the Poisson's ratio reduced.
Keywords: alkali-activated fly ash concrete; initial and final setting time; silica fume activating solution; sucrose (sugar).

1. INTRODUCTION

In 2017, the production of Portland cement reached 4.8 billion metric tons approximately, making it second most consumed materials after water (statista; 2018). China produces almost half of the total Portland cement production worldwide followed by India and the United States with 86.3 million metric tons (statista; 2018). Production of a metric ton of Portland cement consumes numerous amount of fuel energy leading to high CO_2 emissions, estimated around one metric ton roughly (Hasanbeigi et al. 2010)(Hanein et al. 2018). Hence; a need for a sustainable concrete, which is fully or partially replace Portland cement, is urgent. Alkali-activated fly ash concrete is claimed as a sustainable concrete (Mclellan et al. 2011), which reduces CO_2 emissions and utilizes waste materials such as fly ash, metakaolin, or blast furnace slag.

Fly ash based-geopolymer concrete or alkali-activated fly ash concrete consists of a source of aluminate-silicate such as fly ash, fly ash, metakaolin, and blast furnace slag, an activating solution, and coarse and fine aggregates (Hardjito et al. 2004)(Rangan 2008)(Lloyd and Rangan 2010). The activating solution is either a mixture of sodium silicate, sodium hydroxide and water (Bondar et al. 2011; Yang and Song 2009); or mixture of sodium hydroxide, silica fume, and water (Tempest et al. 2009; Assi et al. 2018a; c). Al Bakri reviewed properties of fly ash-based geopolymer concrete and showed that the compressive strength increased when fineness fly ash used and geopolymer concrete showed higher resistance against elevated temperature and aggressive environment in comparison with Portland cement concrete (Mustafa et al. 2011). Geopolymer foam concrete showed excellent thermal insulation properties compared with Portland cement (Zhang et al. 2015). Adam's work showed that water sorptivity, high charge, and conductivity in chloride diffusion test, and chloride penetration properties of fly ash-based geopolymer concrete were much better than Portland cement (Adam 2009). Singh et al. stated that several studies had been conducted on geopolymer concrete/mortar and they showed the fresh and hardened states, bond with steel reinforcing bars, durability properties are comparable or even better than Portland cement concrete/mortar (Singh et al. 2015). Durability properties of alkali-activated geopolymer binders were reviewed by Pacheco-Torgal et al. (Pacheco-Torgal et al. 2012). It was reported that alkali-silica reaction (ASR), acid attacks, corrosion of steel reinforcement, and resistance against high temperature were good compared with ordinary Portland cement binder; however, efflorescences (white deposits) was a problem due to its aesthetic appearance (Pacheco-Torgal et al. 2012).

Many studied showed that the external heat, used for curing, has a dominant effect on the mechanical properties such as early and final compressive strength, the microstructure of geopolymer concrete. Ken et al. showed that the early compressive strength was improved when geopolymer concrete samples were cured between 24 hours -72 hours under 60 C^0 – 90 C^0 oven temperature (Ken et al. 2015). Heat cured geopolymer concrete structural cylindrical column members were investigated to verify its performance (Sujatha et al. n.d.). The results showed that the geopolymer concrete column samples, heat cured, exhibited an excellent performance such as load capacity, stiffness, and ductility under failure load (Sujatha et al. n.d.). The design provisions, stress-strain model by Popovics, predicted load-deflection curve, and deflection shape of ordinary Portland cement columns, cured under elevated temperature, can be used for geopolymer concrete columns w/o slight modifications (Sumajouw et al. 2007; Sarker 2009). In conclusion, the literature showed that geopolymer properties and structural performance were improved due to curing under elevated temperature; however, the need for external heat limits the geopolymer concrete utilization only for precast applications.

Several studies have been conducted to eliminate or reduce the need for the external heat in geopolymer concrete, mortar, or paste. Ground blast furnace slag was mixed with fly ash in various proportions to eliminate the external heat in geopolymer concrete by Nath and Sarker (Nath and Sarker 2012). It was found that including ground blast furnace slag was improved the early compressive strength and initial setting time of geopolymer concrete at ambient conditions (Nath and Sarker 2012). Portland cement was used as a replacement of fly ash weight to eliminate the need for external heat and accelerate the geopolymerization process. Therefore, the early compressive strength of geopolymer concrete cured in ambient conditions was improved significantly (Nath and Sarker 2015). Portland cement replacement was reported that it not only enhances the early and final strength but also it modifies microstructure of the sample matrix and mitigates microcracking formations (Assi et al. 2016a).

Using Portland cement as a partial replacement in fly ash-based geopolymer concrete has improved the early and final compressive strength by accelerating geopolymerization process. Some studies showed that the permeable void ratios and absorption ratios were reduced due to including partial Portland cement replacement (Assi et al. 2016a). However, the cons and pros, and effect of using Portland cement partially in geopolymer concrete have not been investigated on the compressive strength, early geopolymerization process, modulus of elasticity, and Poisson's ratio.

This paper aims to investigate the influence of using Portland cement as a partial replacement on the early geopolymerization process, compressive strength, modulus of elasticity, and Poisson's ratio.

2. MATERIALS AND METHODS

In this study, the activating solution is a mixture of sodium hydroxide, silica fume, and water. The sodium hydroxide, purity was 98% approximately, was purchased from the DudaDiesel Company. Fly ash (Type F) was supplied from a local power station, Wateree Station. The chemical composition for the fly ash is shown in Table 1 and Assi et al. work (Assi et al. 2018d). An X-ray fluorescence (XRF) test for the fly ash chemical analysis was conducted in Lafarge Holcim lab in Holly Hill, South Carolina. The silica fume (Sikacrete 950DP type) powder with a minimum silicon dioxide of 85% was bought from Sika Corporation, USA. Portland cement Type III was purchased from the local LafargeHolcim supplier. Course and fine aggregates were supplied by the Vulcan quarry at Columbia, South Carolina. More information about sieve analysis can be found in Assi et al. (Assi et al. 2016a).

The compressive strength, modulus of elasticity, Poisson's ratio, and geopolymerization process were conducted according to ASTM C39, ASTM C469 (ASTM C39 / C39M-18 2018; ASTM C469 / C469M-14 2014) respectively in the structural lab at the University of South Carolina. Partial Portland cement replacement was 0%, 5%, 10%, and 15% of fly ash weight. Table 2 tabulated mixture design proportions.

The compressive strength test was conducted at Seven days in the structural lab at the University of South Carolina. A 7-day sample age was used to observe the effect of various Portland cement weight replacement, including 0%, 5%, 10%, and 15% on the modulus of elasticity and compressive strength. The mix design proportions are shown in Table 2.

Table 1: XRF chemical analysis of fly ash [28]

Chemical analysis	Wateree Station wt.%
Silicon Dioxide (SiO_2)	53.5
Aluminum Oxide (Al_2O_3)	28.8
Iron Oxide (FeO_3)	7.5
Sum of Silicon Dioxide, Aluminum Oxide	89.8
Calcium Oxide (CaO)	1.6
Magnesium Oxide (MgO)	0.8
Sulfur Trioxide (SO_3)	0.1
Loss on Ignition (LOI)	3.1
Moisture Content	0.1
Total Chlorides	-------
Available Alkalies as NaO_2	0.8

Table 2: Mixture proportions

Concrete type	Fly ash, kg/m^3 (lb/ft^3)	Water, kg/m^3 (lb/ft^3)	w/c%	Sodium hydroxide, kg/m^3 (lb/ft^3)	Silica fume, kg/m^3 (lb/ft^3)	Coarse agg., kg/m^3 (lb/ft^3)	Fine agg., kg/m^3 (lb/ft^3)	Portland cement %
FGC*-silica fume**	474 (29.6)	163 (10.2)	28	61.6 (3.81)	46.2 (2.92)	793 (49.5)	793 (49.5)	0.00
FGC*-silica fume**	450 (29.6)	163 (10.2)	28	61.6 (3.81)	46.2 (2.92)	793 (49.5)	793 (49.5)	5.00
FGC*-silica fume**	427 (29.6)	163 (10.2)	28	61.6 (3.81)	46.2 (2.92)	793 (49.5)	793 (49.5)	10.0
FGC*-silica fume**	403 (29.6)	163 (10.2)	28	61.6 (3.81)	46.2 (2.92)	793 (49.5)	793 (49.5)	15.0

*FGC: fly ash-based geopolymer concrete

**FGC-silica fume: the activating solution is a combination of silica fume and sodium hydroxide

***FGP-silica fume: fly ash-based geopolymer paste, the activating solution a combination of silica fume and sodium hydroxide

2.1. Activating Solution, Mixing, and Curing Procedure

The activating solution was prepared according to the Assi et al. procedure (Assi et al. 2016c). The sodium hydroxide pellets were mixed with tap water and then stirred for three minutes. Then, the silica fume powder was added to the solution and stirred for an additional five minutes. The resulting activating solution was kept in an oven under 70 C^o for 24 hours. The next day, it was mixed with dry materials of either fly ash for paste samples (geopolymerization process test) or fly ash with coarse and fine aggregates for concrete samples (modulus of elasticity and compressive strength tests). Samples were mixed in a cylindrical plastic concrete mold of 75 mm x 150 mm. The mold size and concrete mixing process were in conformance with ASTM C192 / C192M-16a (ASTM C192 / C192M-16a 2016).

For the 7-day modulus of elasticity and compressive strength test, the samples were held in an oven with a temperature of 75 C^0 for two days and then kept in ambient lab conditions until the test date. The test group consisted of four concrete samples in order to identify the standard deviations and consistency of the results.

The geopolymerization process was conducted according to Assi work (Assi et al. 2018a, 2016c). Two geopolymer paste samples were cast for each mix design including 0%, 5%, 10%, and 15% of Portland cement replacement. The samples were monitored for three days at ambient lab condition to investigate the effect of increasing Portland portion on the geopolymerization process. As shown in Figure 1, the test setup and mold size.

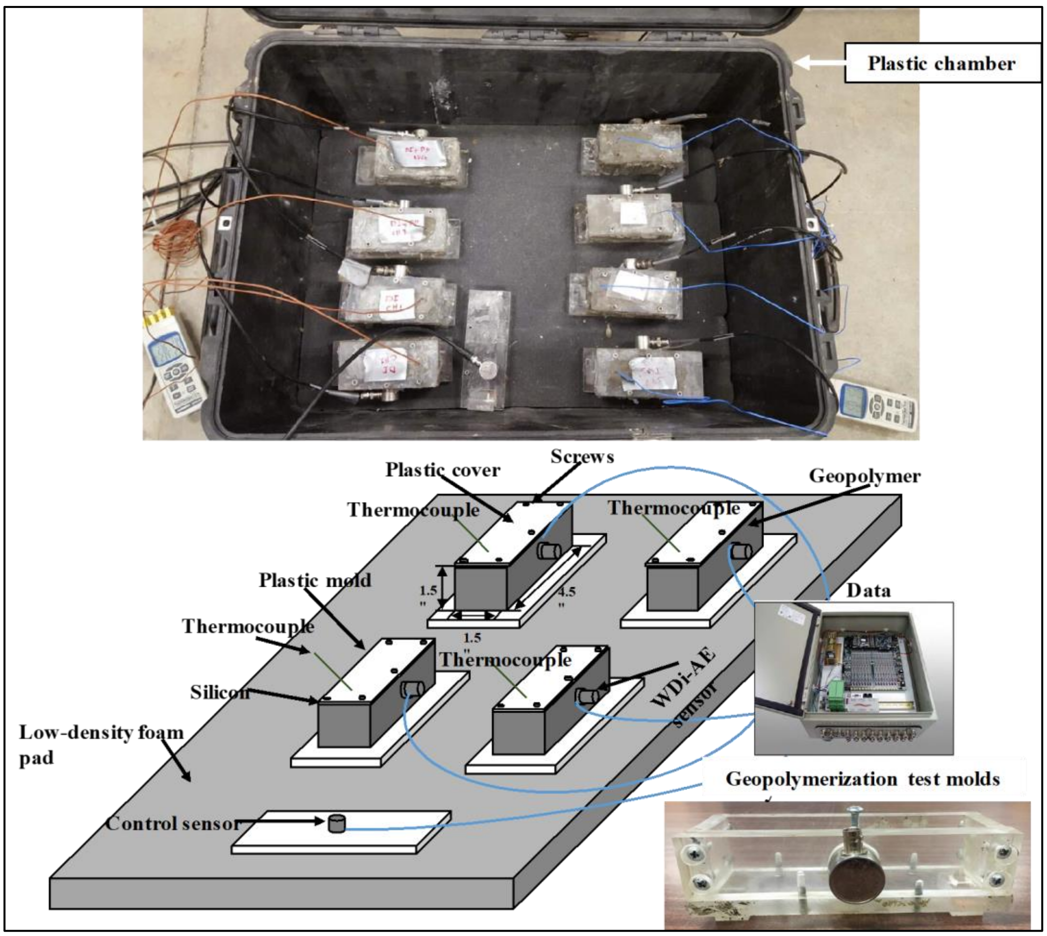

Fig.1. Experimental test setup

3. RESULTS AND DISCUSSION

In this section, the effect of Portland cement replacement on mechanical properties such as compressive strength and modulus of elasticity and Poisson's ratio. Furthermore, the geopolymerization process will be monitored using acoustic emission. The primary results showed that the geopolymerization was enhanced and the compressive strength was improved significantly. The Portland cement shows potential improvements the mechanical properties and geopolymerization process. However, the initial and final setting time was reduced, while Portland cement percentage was increased (Assi et al. 2018c).

3.1 Effect of Portland Cement on Amplitude and Cumulative Signal Strength

This test was conducted for three days to investigate the effects of Portland cement replacement on the early geopolymerization process. The geopolymer paste samples were monitored using acoustic emission technique. More information regarding test setup and techniques can be found in Assi et al. (Assi et al. 2018b, 2016b). The number of samples was four for each mix design proportion. A data temperature logger measured the internal temperature.

For geopolymerization samples with 0%, 5%, 10%, and 15% of Portland cement replacement, the maximum internal heat was 38 ^{o}C, 36 ^{o}C, 36.2. ^{o}C, and 35.8 ^{o}C respectively and it then reduces to ambient temperature, 26 ^{o}C for all the samples, within five hours of the test onset. The internal temperature pattern showed that the internal heat decreased when Portland cement portion was increased. Generally, the internal heat was less than of Portland cement, 38 ^{o}C or higher. Having a low internal temperature in concrete will lead to offset potential microcracks in the cement or geopolymer paste. The internal heat showed that using fly ash-based geopolymer concrete in concrete dams may have an advantage over Portland cement due to low internal heat, which leads to microcracks and fewer durability properties. Figure 1, and Figure 2 showed the results for amplitude and cumulative signal strength.

On the other hand, the average amplitude was not impacted significantly when the Portland cement percentage was increased approximately. While the average amplitude of all samples was almost constant, the signal strength was not constant. The signal strength was increased when Portland cement percentage was increased. For instance, the average signal strength was $5*10^4$ pVs, $10*10^4$ pVs, $13*10^4$ pVs, and $20*10^4$ pVs approximately when Portland cement replacement was increased by 0, 5%, 10%, and 15% respectively. The number of hits was increased predominately when the Portland cement replacement was increased. The acoustic emission activities were initiated at early stage almost at the test start and kept going until the test ended after 72 hours.

As shown in Figure 2 and Figure 3, the acoustic emission signals near the maximum temperature have high amplitude and concentration. Acoustic emission hits and activities were observed at a very early time and continued throughout the test for all geopolymer paste samples. This event suggests a correlation between acoustic emission hits and the geopolymerization process.

Figure 2 and Figure 3 show the cumulative signal strength (CSS) for all geopolymer paste samples. The cumulative signal strength for the samples with 15%

Portland cement replacement is higher than the 0%, 5%, and 10% of cement Portland cement replacement samples because acoustic emission hit and signals energy 15% Portland cement replacement samples are more numerous than the other samples. The extra Portland cement replacement will enhance the early geopolymerization process leading to high signal energies. Furthermore, the results showed that the increase in CSS rate begins to take place after the deceleration region and extends a few hours for all samples except the 15% Portland cement sample, in which cumulative signal strength increased throughout the test.

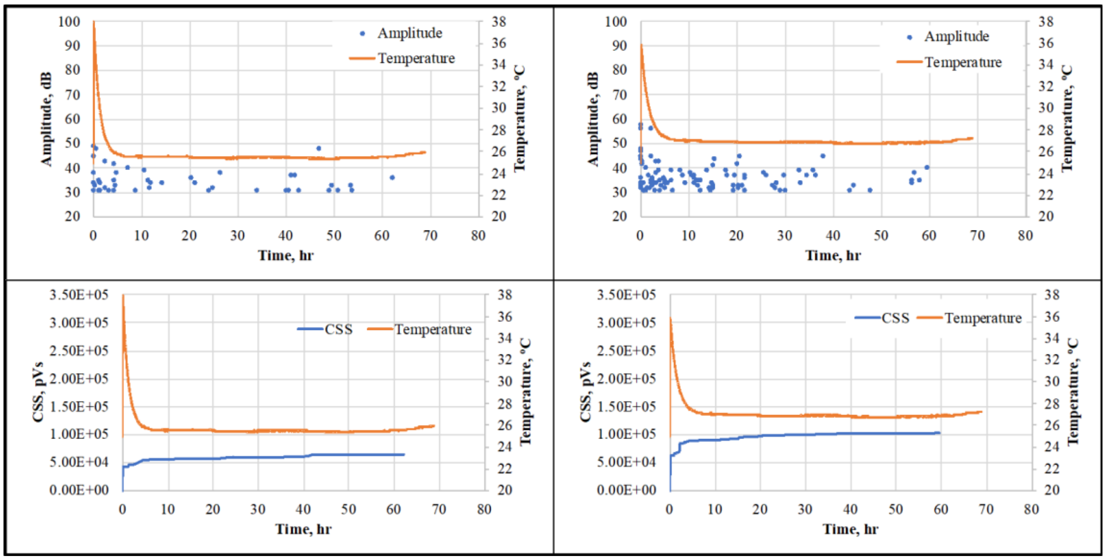

Fig. 2. The amplitude and cumulative signal strength of 0% and 5% of Portland cement replacement

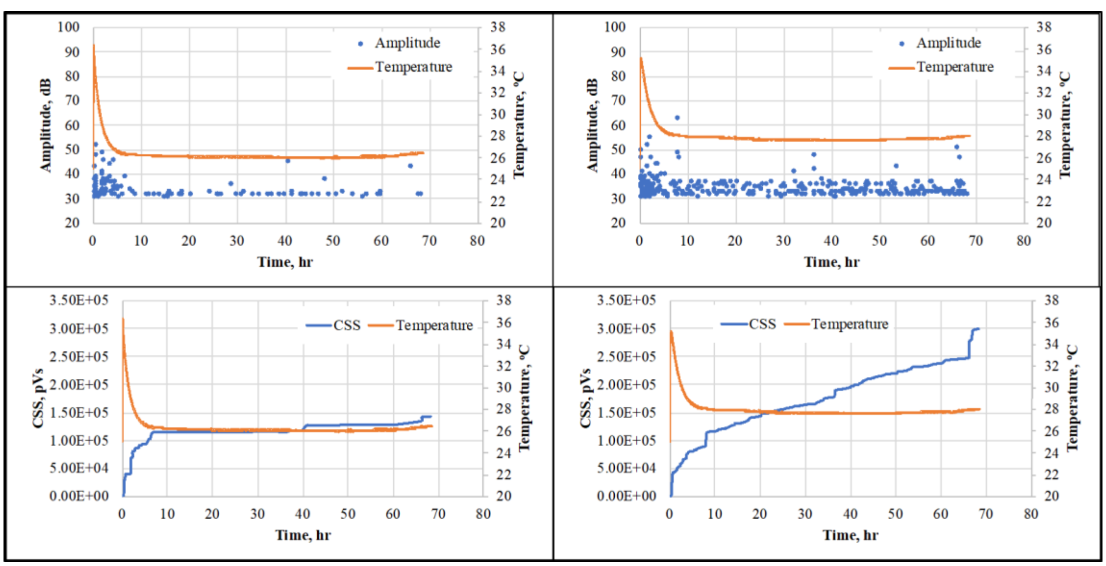

Fig. 3. The amplitude and cumulative signal strength of 0% and 5% of Portland cement replacement

3.2. Effect of Portland Cement Replacement on The Seven-Day Compressive Strength

For the compressive strength test, 0%, 5%, 10%, and 15% of fly ash weight ratio were replaced by an equivalent amount of Portland cement. The test was conducted at seven days. The samples were cured for 28 hours under 75 C^0 to accelerate the geopolymerization process. Four geopolymer concrete samples were tested and averaged for each mix design. Figure 3 shows the seven days-compressive strength. The average compressive of was 16.8 MPa, 45.2 MPa, 62.1 MPa, and 65.0 MPa for 0%, 5%, 10%, and 15% Portland cement replacement respectively.

By considering the average compressive strength of 0% Portland cement replacement samples as a reference, the compressive strength was increased by 63%, 73%, and 74% when the Portland cement replacement percentage by weight was increased from 0% to 5%, 10, and 15% respectively. The compressive strength increase shows that using only 5% or 10% has improved the compressive strength significantly while there is not a major effect on final cost or fuel energy. In addition, the high compressive strength was achieved within a short period, seven days.

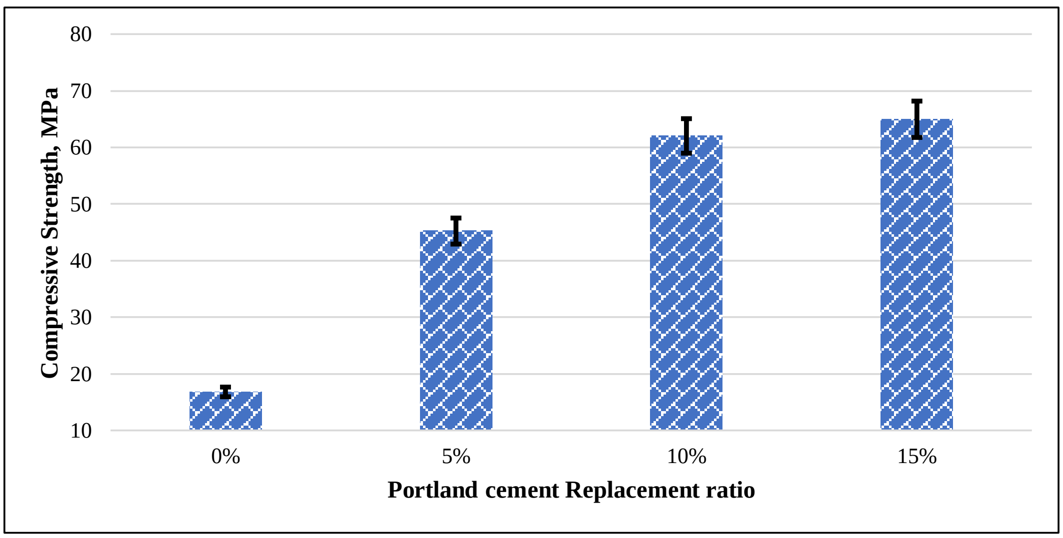

Fig. 5. Compressive strength results

3.3. Effect of Portland Cement Replacement on Modulus of Elasticity and Poisson's Ratio

For investigating the effect of including Portland cement on the modulus of elasticity of fly ash-based geopolymer concrete, modulus of elasticity and Poisson's ratio tests were conducted according to ASTM C469 / C469M [ref.]. The test samples were cured in the oven for 48 hours with a temperature of 75 $C^{0,}$ and the test sample age was seven days when the tests were conducted. Based on ASTM C469 recommendations, three samples were tested for each mixture. The average results are presented in Figure 6.

The modulus of elasticity was 13,417.8 MPa, 20,426.5 MPa, 25,550.0 MPa, and 26,276.7 MPa for a fly ash-based geopolymer concrete with 0%, 5%, 10%, and 15% of Portland cement replacement. By considering the average results of the modulus of elasticity for fly ash-based geopolymer concrete with 0% of Portland cement as a base reference, the modulus of elasticity was increased by 34%, 47%, and 49% for 5%, 10%, and 15% of Portland cement replacement respectively. However, the Poisson's ratio was decreased by 7%, 11%, 15% when the Portland cement replacement was increased by 5%, 10%, and 15% respectively. The results showed that Portland cement replacement increased the modulus of elasticity significantly, while the Poisson's ratio decreased. Regarding found results, when the modulus of elasticity should be increased, using Portland cement as a partial replacement might be considered. Controversially, Portland cement might be used if Poisson's ration is needed to decrease.

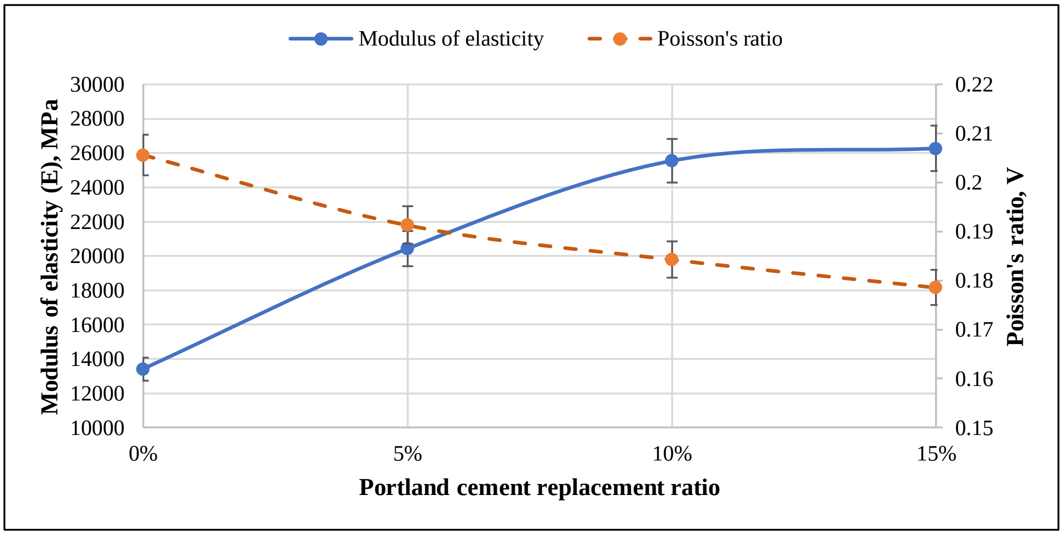

Fig. 6. Modulus of elasticity and Poisson's ratio results

4. CONCLUSIONS

1. The Portland cement replacement enhanced the early geopolymerization process. A number of hits was raised once Portland cement was introduced and the percentage was increased.
2. Cumulative signal strength was increased significantly when Portland cement replacement was increased from 0% to 15% of fly ash weight.
3. The acoustic emission techniques proved that it is sensitive to detect the occurred differences in the geopolymerization process due to including Portland cement in the mixture proportions.
4. The seven-day compressive strength results showed that the compressive strength increased significantly when Portland cement was included up to 15% of fly ash weight. For instance, the compressive strength was increased by 73% when 15% of Portland cement was replaced fly ash by weight.
5. The modulus of elasticity and Poisson's ration were impacted significantly when Portland cement replacement ratio was increased. In comparison with

0% Portland cement replacement, the modulus of elasticity was increased by 49%, while the Poisson's ratio was dropped by 15% when 15% of Portland cement was included.

5. ACKNOWLEDGMENT

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