Compressive strength of class F fly ash blended geopolymer-hybrid mortar

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Abstract. Day by day construction industry require large amounts of cement to satisfy development of buildings, facilities and infrastructures, that demand presented undesirable increase in CO2 emitted the environment as 1 ton of cement produce approximately 1 ton of CO2. Aiming to reduce usage of Portland cement new technology of binders was researched such as Geopolymer binders. General composition of geopolymer contain aluminosilicate source materials such as fly ash or fly ash combined with GGBFS, and alkaline activator such as a mixture of sodium hydroxide (NaOH) and sodium silicate solution. However, geopolymers suffer from some limitations such as the variation in chemical content, the calcium content, dosage of alkaline activator and Na2SiO3/NaOH ratio, additionally geopolymers has brittleness and low toughness which require additional materials to mitigate normally some sort of reinforcement fibres which can drive the cost very high. The objective of this research is to investigate the enhancement in compressive strength of geopolymer mortar by incorporating Ground Granulated Blast Furnace Slag (GGBFS) with class F fly ash in blended geopolymer, also the addition of commercial grout to form blended geopolymer–hybrid mortar. GGBFS replaced fly ash by 10%, 20% and 30% of total mass, and commercial grout then was added by 10%, 20% and 30% to each blended mixture. All samples were cured in ambient temperature. It was found that incorporating GGBFS and commercial grout increase the compressive strength in early age of curing and slightly at 28 days. Furthermore, 10M concentration of NaOH yielded the highest strength with the blended geopolymer-hybrid mortar.

1. Introduction
Manufacturing of cement is one of the most detrimental industrial activities there is, in terms of environment pollution. Although, recent advances in cement manufacturing has reduced the amount of CO2 emissions; the production of large amounts of cement still releases lots of gases into the atmosphere. Namely, one ton of cement emits 0.689t of carbon dioxide gas as well as other harmful gases such as nitrogen oxide and sulphur oxide. Carbon dioxide that is emitted is mostly due to the combustion of calcium carbonate (limestone). Such emissions are also caused by fuel combustion that takes place during production (Sultan et al, 2018).
Alternative materials such as geopolymers or inorganic polymers are in study in terms of cement production. For geopolymers, the main components are mainly geopolymer source materials (GSM) and alkaline activator. GSM’s are required to be rich in Silicon (Si) and Aluminium (Al); such as fly-ash, rice-husk ash, silica fume, slag, red mud etc. As mentioned by Sindhunata (2006), highly activated alkaline sources such as sodium hydroxide potassium hydroxide sodium silicates, potassium silicates, sodium aluminate, etc; must be used in order to activate raw materials containing reactive oxides such as Silicon and Aluminium. Such activation gives rise to inorganic polymeric binding materials (Sindhunata et al, 2006) (Rafizi et al, 2014). geopolymeric materials has far more superior advantages over Ordinary Portland cement(OPC) such as (Temuujin, van Riessen, & Williams, 2009), such as high compressive strength (Chindaprasirt et al, 2007), good fire resistance (Lyon et al, 1997). low thermal conductivity (Duxson et al, 2007), lower setting times and rapid hardening (Lee et al, 2002), low shrinkage (Lee et al 2012), durability and acid resistant (Susan et al 2014; Redmond et al, 2012).

Hydrated binders are dependent on the precursor chemicals such as ground granulated furnace blast slag (GGBFS); which is rich in calcium content. This hydration gives C–S–H and C–A–S–H, which are enhanced with the presence of an alkaline activator. binders with complex chemistry are the ones that contain medium levels of calcium (slag/fly ash, slag/metaakolin blends, and individual precursor materials) (Okoye, 2017). It was reported that these binders contain phases such as C–N–A–S–H, C–A–S–H and geopolymer gels (Bernal et al, 2013; Garc-ia-Lodeiro et al, 2011). Moreover, the reduced amount of energy that is used for the manufacture of these geopolymer based materials allow them to be of great interest. Factually, the reaction requires either metkaolin or raw silica-aluminates; which in turn reduces the emission of greenhouse gases up to 80% in comparison to the traditional cement-based materials (Redmond et al, 2012) (Ismail et al, 2014). Although natural aggregates are used to substitute artificial ones produced from industrial wastes (Yip & Van, 2003; Garc-ia-Lodeiro et al, 2011) the emission of CO2 is produced mainly due to the use of ordinary portland cement as a binder.

Due to the brittle behaviour and the low flexural strength of geopolymer, it has been limited in the use as a structural material; henceforth, geoplymer composites have been in use. The blend of organic polymers such as such as polyvinyl acetate, polypropylene, polyvinyl alcohol, or water-soluble organic polymers (Zhang et al, 2010; Zhang et al,2004) allows the obtaining of geopolymer based composites (De Roma et al, 2011; Roviello, et al, 2007). An organic-inorganic hybrid composite has also been prepared by Ferone (2013), further development of Geopolymer composites has been achieved previously by adding additional non polymeric source material such as fibers (Xu, Deng, Peng, Zhu, & Chen, 2017), Portland cement (B. H. Shinde, 2016) etc. the advancement of geopolymeric composite led to new novelty synthetic approach done by slight incorporating organic and inorganic part that produced constant and diffused organic phase into the inorganic one called geopolymer- hybrid (Ferone et al., 2013).

The aim of this study is to use geopolymeric mortar that contains GGBFS/ Combination of GGBFS and commercial grout with varying NaOH levels; in order to reduce the environmental issues that is the direct outcome of cement manufacturing in addition to solve brittleness and toughness of geopolymeric materials. The strength of the mortar has been compared with neat geopolymer low calcium fly ash-based mortar. Moreover, the chemical and the physical properties of the raw materials have been analysed using a microstructural analysis.

2. Experimental work

2.1 Materials

Class f fly ash was the main source of aluminosilicate material for production of geopolymer mortar control group, provided by Tenaga National Berhad coal power generation plant located at port Dickson waste coast of Malaysia. commercially available Ground Granulated Blast Furnace Slag or GGBS from
YTL Cement Berhad as partial replacement for fly ash that created blended geopolymer mixture. Commercial grout contains which was ready mixture of cement and sand was used as an additive to the geopolymer which produced the geopolymer-hybrid mortar. Chemical composition of fly ash and GGBS in table 2 for grout composition as provided by the manufacturer (see figure 1). Alkaline activator solution was produced by mixture of sodium hydroxide with sodium silicate NaOH and Na2SiO3 respectively. Alkaline activator chemicals where provided by Evergreen chemicals Sdn. Bhd, Malaysia. sodium hydroxide solution prepared to the desired concentration by dissolving 95% pure pallets in distilled water to avoid contamination from the water source. Concentrations of sodium hydroxide was kept as 10M and 12M for all mixture combinations. Sodium silicate was dissolved according to the ratio 2.5 Na2SiO3/NaOH. Sand utilized in the mixture was commercial construction grade sand with nominal size of 1.18 mm. the only water was used in the laboratory work was that from the alkaline activator to reduce number of variables.

2.2 Preparation of Geopolymers Mortars
Geopolymer mortar mixtures proportioned to study effects of multiple mix parameters which including Fly ash geopolymer as control group, blended geopolymer, and Geopolymer Hybrid mixture. Additionally, alkaline activator containing two concentrations of sodium hydroxide. The mentioned parameters investigated to see the effect on workability of mortar, strength, and water absorption.

2.2.1 Mixture proportion.
Control group that provided the baseline for laboratory testing was produced by mixing class F fly ash with sand at ratio of 1:2 and fly ash to liquid ratio of 0.61; whereas, alkali activator Na2SiO3/NaOH ratio was 2.5 by mass for both NaOH 10M and 12M. These proportions were based on previous work done in Malaysia on class F fly ash (Leong, H. Y., Ong, D. E. L., Sanjayan, J. G., & Nazari, 2016).

Blended geopolymer mortar was produced by the replacement of class F fly ash mass with GGBFS; which was 10%, 20% and 30% of mass of total dry source material ratio of blended material to sand ratio remain as 1:2. Similarly, blended material to liquid ratio of 0.16, each blended mixture will receive two variations; one with alkaline liquid contained 10M NaOH and the other with 12M NaOH concentration.

Geopolymer hybrid is mixture of blended geopolymer with addition of commercial grout. Every blended mixture received similar percentage of commercial grout as additional binder over the total mass, so that blended geopolymer with 10% GGBFS has received 10% of commercial grout. Similarly, for a blend with 20% and 30% GGBFS, 20% and 30% commercial grout was received respectively. Ratios of mixture remain same for this mixture. Furthermore, each blended geopolymer hybrid has two variants, 10M and 12M concentration of NaOH in the alkaline activator.

Since the alkaline activator has either 10M concentration or 12M concentration of NaOH for each mixture they were annotated Series A for 10M NaOH and series B for 12M NaOH, for further detailed quantities represented in table 1.

2.3 Mixing, sampling and curing
Every mixture went through the same mixing procedure. Each started with weighing the dry components such as geopolymer binder source material and sand thoroughly, for 2 minutes on the slowest setting of the mortar blender (model); in order to make sure that the mixture is homogeneous and no fine particles would escape from the blender. After the 2 minutes, the alkaline mixture is added and mixed for 5 minutes to form the desired mortar. It is important to note that alkaline solution must be prepared 24 hours before every mixture, if the hydroxide and the silicate components were in powder or pellets form. This is to ensure all of the components are well dissolved into the water. In addition, safety procedure should be followed strictly when dealing with chemicals.
## Table 1. Mixture proportions.

| Mixture No. | Binder % | Sand ratio | Alkaline activator | Total liquid | Series A | Series B |
|-------------|----------|------------|-------------------|--------------|----------|----------|
|             |          | FA GGBS    | Sika 215M         |              |          |          |
| Control     | 100      | 0          | 0                 | 2            | 610      | 69.72    |
| Blended     | 1        | 90         | 10                | 0            | 2        | 610      |
|             | 2        | 80         | 20                | 0            | 2        | 610      |
|             | 3        | 70         | 30                | 0            | 2        | 610      |
| Hybrid      | 1        | 90         | 10                | 10           | 2        | 671      |
|             | 2        | 80         | 20                | 20           | 2        | 732      |
|             | 3        | 70         | 30                | 30           | 2        | 793      |

Mortar was then casted in cubic moulds of size 50mmx50mmx50mm, it was then vibrated for 2 minutes to ensure compaction of sample and to let the air bubbles escape. Later, the samples were covered and placed in curing ovens at 60°C for 24 hours, it was then brought out to ambient temperature till testing date (Leong, H. Y., Ong, D. E. L., Sanjayan, J. G., & Nazari, 2016; Temuujin et al., 2009).

### 2.4 Methods of testing

X-Ray fluorescence (XRF) test was carried out at (CRIM laboratories, UKM, Malaysia) for the determination of chemical composition of the source materials, Fly ash and GGBFS. The results that were gathered from XRF test were qualitative. Particle Size Analyser (CILAS 1190), Scanning Electron Microscopy (SEM) (ZEISS SUPRA 40 VP SEM) and Loss on Ignition (LOI) were the tests that were used. they were used to test the PSD of GGBFS and fly ash; the morphology of fly ash, respectively. A muffle furnace was used to conduct the LOI test. A furnace at 1100 °C was used to heat the fly ash; the temperature was increased to 3.33 °C/min. After which the temperature was reduced to 110 °C. They were then allowed to cool in the furnace for two hours. The weight of the samples was monitored before placing into the furnace and after the test was completed. A flow table was used to measure the workability of the samples. This was done in accordance to the ASTM-C1437. Furthermore, the compressive strength was also tested in accordance to the standards of ASTM- C109/C109M. In order to obtain an average value of the compressive strength, three samples were obtained from each of the corresponding mixtures.

### 3.0 Experimental results and discussion

The following section will present and discuss results abstained from XRF, SEM, and PDS for source materials characterization of chemical composition and particle size. Furthermore, results from compressive strength of hardened mortar samples and the effect of two different concentrations of sodium hydroxide NaOH will be presented in the following lines.
3.1 Source materials characterization

X-Ray fluorescence (XRF) device measure chemical composition of material sample through measuring X-ray emitted from sample. Table (2) provide chemical composition of Fly ash and GGBS. It showed that fly contained 71.29% in total of SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$. Moreover, with CaO of 3.32% with accordance to ASTM-C-618 classification, this study uses a class F low calcium Fly ash which has Pozzolan properties. On the other hand, GGBS exhibited lower values for SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$ around 47%. However, the calcium content is fairly high about 42%. Additionally, composition of the commercial grout provided from the data sheet provided by the manufacturer as in figure 1.

**Table 2.** Chemical composition of fly ash and GGBFS by XRD-F.

| Properties                          | Fly Ash | GGBS  |
|------------------------------------|---------|-------|
| **Chemical Composition (%)**       |         |       |
| Calcium oxide, CaO                  | 3.32    | 42.70 |
| Silicon dioxide, SiO$_2$            | 46.80   | 34.10 |
| Aluminum oxide, Al$_2$O$_3$         | 18.41   | 13.5  |
| Iron oxide, Fe$_2$O$_3$             | 6.08    | 0.36  |
| Magnesium oxide, MgO                | 1.15    | 4.5   |
| Titanium oxide, TiO$_2$             | 0.97    | 0 NA  |
| Potassium oxide, K$_2$O             | 1.34    | 0 NA  |
| Sodium oxide, Na$_2$O               | 1.20    | 0 NA  |
| Phosphorous, P$_2$O$_5$             | 0.41    | 0 NA  |
| Sulfate, SO$_3$                     | 0.53    | 0 NA  |
| SiO$_2$ + Al$_2$O$_3$ + Fe$_2$O$_3$ | 71.29   | 47.96 |
| **ASTMC618**                        |         | Class N |

| Physical Properties |
|----------------------|
| Specific surface area (m$^2$/g) | 1.13 | 0.85 |
| Median size (µm)     | 15.56 | 27.47 |

| Chemical Name              | CAS-No.  | Concentration (%) |
|----------------------------|----------|-------------------|
| Quartz (SiO$_2$)           | 14808-60-7 | >= 30 - < 60     |
| Cement, portland, chemicals | 85997-15-1 | >= 30 - < 60     |
| Fumes, silica              | 69012-64-2 | >= 1 - < 3       |

**Figure 1.** Commercial grout data sheet (Product Data Sheet, Edition 2011-11_1, SikaGrout®-215).

Subsequently scanning electron microscope (SEM) and Energy-dispersive X-ray (EDX) spectroscopy was tested in chemical engineering laboratory, faculty of engineering, UPM. SEM/EDX provides results for mixed structure is presented in spectrograph, mapping, and micrograph to check the shape of particles of the source materials. Port Dickson fly ash in figure 2a show high concentration of aluminium, silicon and oxygen. Furthermore, the spectrum fly ash showed similar results in the mapping; a large quantity of silicon, aluminium and oxygen. Since the fly ash contains more silicon and aluminium it will leach more alumina silicate gel. Particle shape is spherical and majority of particles are below 45µm; it can be estimated using the micrograph with 50 µm enlargement. It was found to be approximately 11 µm and below.
GGBS was also tested with SEM/EDX in figure 2b showed higher concentration of calcium compared to silicon and aluminium, unlike fly ash. GGBS is rich with calcium; also, there is low oxygen concentration. The spectrum of GGBS confirm the mapping results with high content of calcium followed by silicon and aluminium. The SEM micrograph shows the particle shape to be irregular with spike like structures on top of the particles and gaps between the particles. Estimated particle size from the micrograph is 45 µm.

In order to obtain the distribution of sizes in a sample of solid or liquid particulate material; Particle size distribution was conducted. The test was performed by chemical engineering laboratory, faculty of engineering, UPM. Fly ash particle size distribution curve shown in Figure 3, the graph peaks at 11.4 µm with highest volume of 4.06%. Then it goes down to 45 µm with little over 3%. Total percentage passing 45 µm is 78.06%. Smallest particle size is 0.4 µm and largest particle 831 µm; however, majority of the volume is below 45 µm.

GGBS is factory formulated, the curve peak at 26.3 µm that occupy 5.97% of the volume. Percentage passing 45 µm is 63.37%. Smallest particle measures 0.479 µm and the largest particle size measures 954.993 µm. as presented by figure 4.

3.2 Compressive strength
Compressive strength testing was done in accordance to ASTM C109 / C109M. The sample size was 50mmx50mm. The compressive strength measurement was taken in three intervals- 3, 7, and 28 days. Each mixture’s compressive strength was taken from averaging of 3 cubes for better accuracy of results.

Comparison between series A with 10M of NaOH and series B with 12M of NaOH in their alkaline activator was done in terms of compressive strength during 3, 7, & 28 days to check the effects NaOH has applied on different mixture proportions.

3 days’ strength in figure 5 showed that concentration of NaOH did not affect the early strength of the control group and the samples were too weak in both sets. It was observed in laboratory work that even to carry the sample can damage it badly.

Replacement of class F FA with GGBFS in the blended mixtures showed a noticeable increase of strength at 3 days; especially with series A samples. However, series B strength, although it increased
more than the control group but it was below series A, throughout. In blended mixture, the best results were yielded from blended mixture number 3 with 30% GGBFS and 10M NaOH concentration.

Blended geopolymer – hybrid mixture showed different results, where the highest strength at 3 days of curing was obtained from blended hybrid mixture number 3 with series B. Improvement was then compared to the blended number 3 series B was 88% and compared to blended 3 series A 11%.

As the age of curing increases, the strength will increase too. Looking at the results from 7 days curing figure 6 it was found that, control group strength increased by around 50% compared to 3 days curing; however, still too weak for both series A and B respective.
Figure 5. Compressive strength of Series A&B at 3 days age.

Blended geopolymer mortars showed similar trend of strength increase, especially with blended number 3 being the highest with strength increase by almost 30%. With the blended hybrid group series B again obtained the highest strength with almost 65% difference, compared to 3 days.

Figure 6. Compressive strength of Series A&B at 7 days age.
Finally, 28 days gave the final strength of any specimen. Figure 7 shows that control group did not improve much in strength reaching only 10MPa. Blended geopolymer number 3 showed small change, only by 3% which indicates slow development of strength between 7 and 28 days. Same can be noticed in the blended hybrid mixture. The highest final strength at 28 days was in blended hybrid number 2 from series B.

From the comparison, it is noticeable that the development of strength was not on a constant rate especially from 3 to 7 days. Where at 3 days most series A showed higher strength than series B but reversed at 7 days for blended mixture. This can be related to geopolymer being amorphous and unstable and its need to have sufficient time to change into crystalline as suggested by literature (Provis et al, 2009).

In terms of the control group; due to the lack of calcium compound to react with the alkaline activator, it had showed little to no strength; however, the geopolymers with higher CaO showed higher strengths (Diaz et. al, 2010). When fly ash was replaced by GGFBS, there was an increase in strength more and more rapidly over the control group in both series A and B. This was due to the GGBFS being a calcined source which will help increase strength (Van et al, 2002; Deb, Nath, & Sarker, 2014).

![28 DAYS COMpressive STRENGTH](image)

**Figure 7.** Compressive strength of Series A&B at 28 days age.

Strong compact binder microstructure was produced due to the increasing in the content of GGBFS in the geopolymer. It also formed a more cementitious C-S-H gel due to the GGBFS (Kumar & Kumar, 2010). Increasing the NaOH improved strength however it was below series A values in general; this was due to the effects of NaOH concentration and mixing time of the results of alumina and silicate leaching from the geopolymer source materials. Literature has recommended 10M NaOH and 5 to 10 min of mixing to yield better results (Rattanasak & Chindaprasirt, 2009). Also, its related to the early precipitation of aluminosilicate products and in some cases when NaOH concentration increase (Somna, Jaturapitakkul, Kajitvichyanukul, & Chindaprasirt, 2011).

Blended geopolymer hybrid mortars had the highest compressive strength of all mixture in both early and final strength. This is because the mixture contains commercial grout which is believed to provide cohesive microstructure with reduction of micro cracks. Also, hybrid composite specimens produce a
progressive fracture behaviour over the brittle nature; consequently, requiring higher fracture energy than
the neat geopolymer mortar (Colangelo, Roviello, Ricciotti, & Ferone, 2013; Du, Bu, Shen, Hou, &
Huang, 2016)

4. Conclusion
In this study, effects of replacing fly ash with GGBFS and addition of commercial grout on mechanical
performance of geopolymer were tested at ambient temperatures. Respective experiments and tests have
allowed the conclusion of the following outcomes:

1) Strength increased by increasing the GGBFS in the blended geopolymer reaching more than 200%
over control group for both series A and B
2) Blended geopolymer- hybrid mortar showed improved strength by more than 38% in comparison
to blended geopolymer.
3) Blended geopolymer-hybrid has developed higher early strength
4) NaOH concentration of 10M was found to give higher strength than 12M concentration
Further investigation is recommended on use of commercial grout with blended geopolymer as repair
material and incorporate new types of alkaline activator that is not chemical. Also, the effects of using
water in the mixture additional to the water in the alkaline activator can be studied.

References
[1] Bernal, S. A., Provis, J. L., Walkley, B., San Nicolas, R., Gehman, J. D., Brice, D. G., ... & van
Deventer, J. S. (2013). Gel nanostructure in alkali-activated binders based on slag and fly ash,
and effects of accelerated carbonation. Cement and Concrete Research, 53, 127-144.
[2] Bernal, S. A., & Provis, J. L. (2014). Durability of alkali-activated materials: progress and
perspectives. Journal of the American Ceramic Society, 97(4), 997-1008.
[3] B. H. Shinde, D. K. N. K. (2016). Effect of Addition of Ordinary Portland Cement on Geopolymer
Concrete with Ambient Curing. International Journal of Modern Trends in Engineering and
Research, (2349), 28–30.
[4] Chindaprasirt, P., Chareerat, T., & Sirivivatnanon, V. (2007). Workability and strength of coarse
high calcium fly ash geopolymer. Cement and concrete composites, 29(3), 224-229.
[5] Colangelo, F., Roviello, G., Ricciotti, L., & Ferone, C. (2013). Preparation and Characterization of
New Geopolymer-Epoxy Resin Hybrid Mortars, 2989–3006. https://doi.org/10.3390/ma6072989
[6] De Roma, A., Yang, H. J., Milione, S., Capacchione, C., Roviello, G., & Grassi, A. (2011). Atom
transfer radical polymerization of methylmethacrylate mediated by a naphtyl–nickel (II)
phosphane complex. Inorganic Chemistry Communications, 14(4), 542-544.
[7] Deb, P. S., Nath, P., & Sarker, P. K. (2014). The effects of ground granulated blast-furnace slag
blending with fly ash and activator content on the workability and strength properties of
geopolymer concrete cured at ambient temperature. Materials & Design (1980-2015), 62, 32-39.
[8] Diaz, E. I., Allouche, E. N., & Eklund, S. (2010). Factors affecting the suitability of fly ash as
source material for geopolymers. Fuel, 89(5), 992-996.
[9] Duxson, P., Lukey, G. C., & van Deventer, J. S. (2006). Thermal conductivity of metakaolin
geo polymers used as a first approximation for determining gel interconnectivity. Industrial &
engineering chemistry research, 45(23), 7781-7788.
[10] Deb, P. S., Nath, P., & Sarker, P. K. (2014). The effects of ground granulated blast-furnace slag
blending with fly ash and activator content on the workability and strength properties of
geopolymer concrete cured at ambient temperature. Materials and Design, 62, 32–39.
[11] Du, J., Bu, Y., Shen, Z., Hou, X., & Huang, C. (2016). Effects of epoxy resin on the mechanical
performance and thickening properties of geopolymer cured at low temperature. JMADE, 109,
[12] Ferone, C., Roviello, G., Colangelo, F., Cioffi, R., & Tarallo, O. (2013). Novel hybrid organic-geopolymer materials. *Applied Clay Science, 73*, 42-50.

[13] Garcia-Lodeiro, I., Palomo, A., Fernández-Jiménez, A., & Macphee, D. E. (2011). Compatibility studies between NASH and CASH gels. Study in the ternary diagram Na2O–CaO–Al2O3–SiO2–H2O. *Cement and Concrete Research, 41*(9), 923-931.

[14] Ismail, I., Bernal, S. A., Provis, J. L., San Nicolas, R., Hamdan, S., & van Deventer, J. S. (2014). Modification of phase evolution in alkali-activated blast furnace slag by the incorporation of fly ash. *Cement and Concrete Composites, 45*, 125-135.

[15] Kumar, S., & Kumar, R. (2010). Influence of granulated blast furnace slag on the reaction, structure and properties of fly ash based geopolymer, 607–615Lloyd, R. R., Provis, J. L., & van Deventer, J. S. (2012). Acid resistance of inorganic polymer binders. 1. Corrosion rate. *Materials and structures, 45*(1-2), 1-14.

[16] Lee, W. K. W., & Van Deventer, J. S. J. (2002). The effect of ionic contaminants on the early-age properties of alkali-activated fly ash-based cements. *Cement and Concrete Research, 32*(4), 577-584.

[17] Lee, N. K., Jang, J. G., & Lee, H. K. (2012, October). Effect of blast furnace slag on drying shrinkage of fly ash-based paste and mortar activated with sodium silicate. In *The 5th international conference of Asian concrete federation, Pattaya, Thailand*.

[18] Lyon, R. E., Balaguru, P. N., Foden, A., Sorathia, U., Davidovits, J., & Davidovics, M. (1997). Fire-resistant aluminosilicate composites. *Fire and materials, 21*(2), 67-73.

[19] Provis, J. L., & Van Deventer, J. S. J. (Eds.). (2009). *Geopolymers: structures, processing, properties and industrial applications*. Elsevier.

[20] Somna, K., Jaturapitakkul, C., Najitvichyanukul, P., & Chindapasrirt, P. (2011). NaOH-activated ground fly ash geopolymer cured at ambient temperature. *Fuel, 90*(6), 2118–2124.

[21] Sultan, M. E., Abo-El-Enein, S. A., Sayed, A. Z., EL-Sokkary, T. M., & Hammad, H. A. (2018). Incorporation of cement bypass flue dust in fly ash and blast furnace slag-based geopolymer. *Case Studies in Construction Materials, 8*(February), 315–322.

[22] Temuujin, J., van Riessen, A., & Williams, R. (2009). Influence of calcium compounds on the mechanical properties of fly ash geopolymer pastes. *Journal of Hazardous Materials, 167*(1–3), 82–88.

[23] Van Jaarsveld, J. G. S., Van Deventer, J. S. J., & Lukey, G. C. (2002). The effect of composition and temperature on the properties of fly ash and kaolinite-based geopolymers. *Chemical Engineering Journal, 89*(1-3), 63-73.
[29] Xu, F., Deng, X., Peng, C., Zhu, J., & Chen, J. (2017). Mix design and flexural toughness of PVA fiber reinforced fly ash-geopolymer composites. *Construction and Building Materials, 150*, 179–189.

[30] Zhang, S., Gong, K., & Lu, J. (2004). Novel modification method for inorganic geopolymer by using water soluble organic polymers. *Materials letters, 58*(7-8), 1292-1296.

[31] Zhang, Z., Yao, X., & Zhu, H. (2010). Potential application of geopolymers as protection coatings for marine concrete: II. Microstructure and anticorrosion mechanism. *Applied clay science, 49*(1-2), 7-12.