

# TUTDoR

## Enhanced reactivity of geopolymers produced from fluidized bed combustion bottom ash.

Item Type	Article
Authors	Osholana, Tobi Stephen;Dludlu, Mbuso Kingdom;Oboirien, Bilainu;Sadiku, Rotimi
DOI	<a href="https://doi.org/10.1016/j.sajce.2020.06.006">https://doi.org/10.1016/j.sajce.2020.06.006</a>
Publisher	Elsevier
Rights	Attribution-NonCommercial-ShareAlike 4.0 International
Download date	2026-06-11 01:40:28
Item License	<a href="http://creativecommons.org/licenses/by-nc-sa/4.0/">http://creativecommons.org/licenses/by-nc-sa/4.0/</a>
Link to Item	<a href="https://hdl.handle.net/20.500.14519/2234">https://hdl.handle.net/20.500.14519/2234</a>



## Enhanced reactivity of geopolymers produced from fluidized bed combustion bottom ash



Tobi Stephen Osholana<sup>a</sup>, Mbuso Kingdom Dlodlu<sup>b</sup>, Bilainu Oboirien<sup>c,\*</sup>, Rotimi Sadiku<sup>a</sup>

<sup>a</sup> Department of Chemical, Metallurgical and Materials Engineering, Division of Polymer Technology, Tshwane University of Technology, Pretoria 0183, South Africa

<sup>b</sup> Department of Chemistry and Polymer Science, Stellenbosch University, Stellenbosch 7600, South Africa

<sup>c</sup> Department of Chemical Engineering Technology, University of Johannesburg, 2006 South Africa

### ARTICLE INFO

#### Keywords:

Geopolymer  
Bottom ash  
Geopolymerisation  
Microwave  
Conventional oven

### ABSTRACT

In this study, waste bottom ash obtained from fluidized bed combustion of low-grade South African coal in a bubbling fluidized bed reactor was used to produce geopolymers. The geopolymers were cured using both a conventional oven and a household microwave. An alkaline solution of Na<sub>2</sub>SiO<sub>3</sub>/NaOH (1:0.5) was mixed on a 1:1 ratio with a mixture of bottom ash/kaolin (1:1) mixture. Thereafter the resulting mixture was mixed with sand on a 1:0.5 ratio. Characterization of the geopolymers carried out using the following techniques, scanning electron microscope (SEM-EDX) analysis, compressive strength test, Thermogravimetric analysis (TGA), X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis. A household microwave and a conventional oven were used to enhance the geopolymerisation process and strength of the geopolymers. The results showed that the microwave curing enhanced the reactivity and compressive strength of the geopolymers. The microwave and oven cured geopolymer had the highest Si/Al ratio of 4.42 and reached a reasonable high compressive strength test of 31 MPa in 7 days compared to geopolymers cured with a conventional oven only or with a microwave only. The microwave radiation followed by conventional oven curing reduced the heat curing time and energy but improved the reactivity and strength of the geopolymer.

### 1. Introduction

Fluidised bed combustion (FBC) is a clean coal technology used in the combustion of low-grade coals for power generation (Nkuna et al., 2017). The production of large solid wastes such as bottom ashes from this process is a huge challenge. The bottom ash contains some toxic elements that can leach out and contaminate surface and ground water. Hence, they can neither be disposed in landfills nor lagoons which was previously the practice. The toxic elements include copper (Cu), cadmium (Cd), zinc (Zn) and lead (Pb) are involved with the bottom ash (Kula et al., 2001). The production of geopolymers from bottom ash for structural and concrete applications is an option for their disposal (Boca et al., 2013; Wonga et al., 2016; Sathonsaowaphak et al., 2009). Geopolymers consist of polymeric silicon-oxygen-aluminum framework with silicon and aluminum tetrahedral alternately linked together by sharing all the oxygen atoms in three directions (Al Bakria et al., 2011). Geopolymers are inorganic polymeric materials with chemical compositions similar to zeolites but possessing amorphous structure (Marjanović et al., 2014; Hardijito and Fung, 2010). Geopolymers are newly innovative materials for new cement for concrete, fire resistant to

buildings, walls, bricks and blocks, new binders, toxic and radioactive waste encapsulation. Geopolymers are a class of inorganic polymer that can be made at room temperature by using industrial by-products as source materials to form a hard binder that looks like and performs a similar function to ordinary Portland cement (OPC) (Hardijito and Fung, 2010).

There are few reports on the production of geopolymers from the bottom ash generated from fluidised bed combustion process (Slavik et al., 2008; Topcu and Toprak, 2011; Chindaprasirt and Rattanasak, 2010). The strength of geopolymer produced was low; this was due to the low reactivity (rate of dissolution of the Si/Al species) of the bottom ash from the FBC process (Li et al., 2012). The reactivity can be improved by the blending of fluidized bed combustion (FBC) bottom ash and pulverized coal combustion (PCC) fly ash (Slavik et al., 2008), or by blending the blending of fluidized bed combustion (FBC) bottom ash and fluidised bed combustion (FBC) fly ash (Li et al., 2012). Other reports have shown that the reactivity of geopolymers produced generally from coal ash can be improved by microwaves curing (Chindaprasirt et al., 2013) or by blending with high metakaolin materials such as clays (Papa et al., 2014). To the best of our knowledge,

\* Corresponding author.

E-mail addresses: [dludlumk@sun.ac.za](mailto:dludlumk@sun.ac.za) (M.K. Dlodlu), [boboirien@uj.ac.za](mailto:boboirien@uj.ac.za) (B. Oboirien), [sadikur@tut.ac.za](mailto:sadikur@tut.ac.za) (R. Sadiku).

<https://doi.org/10.1016/j.sajce.2020.06.006>

Received 4 February 2020; Received in revised form 10 June 2020; Accepted 18 June 2020

Available online 20 June 2020

1026-9185/© 2020 The Authors. Published by Elsevier B.V. on behalf of Institution of Chemical Engineers. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

there have been no report that combines the blending of FBC bottom ash and clays and then use microwaves in the curing of the geopolymer to increase its reactivity.

In this study, we improved the reactivity of geopolymers synthesized from bottom ash generated from fluidized bed combustion, by first blending it with higher reactive materials such as kaolin, adding a  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  alkaline activator and then curing the geopolymer samples using a microwave and conventional oven.

## 2. Experimental procedure

### 2.1. Materials

Bottom ashes were generated and sourced from the fluidized bed combustion of three low grade South African coals at CSIR, Material Science and Manufacturing Pretoria, South Africa. Full details of this reactor and the experimental conditions for bottom ash generation can be found in [Mathekga et al. \(2016\)](#). The bottom ash particle size was relatively large with a mean particle size of 850  $\mu\text{m}$  and a smaller milled size of 75  $\mu\text{m}$  to produce geopolymers. An industrial grade sodium silicate ( $\text{Na}_2\text{SiO}_3$ ), with a composition of 30.55%  $\text{SiO}_2$ , 15.67%  $\text{Na}_2\text{O}$ , and 53.78%  $\text{H}_2\text{O}$  and a specific gravity of 1.54 was obtained from Protea Chemicals in South Africa. An analytical grade of sodium hydroxide ( $\text{NaOH}$ ) with 99% purity was obtained from EDUCHEM South Africa and was used to prepare a concentration of 15 M. The sodium silicate solution ( $\text{Na}_2\text{SiO}_3$ ) and sodium hydroxide ( $\text{NaOH}$ ) were used as an alkaline liquid activator, which was prepared by mixing 24h prior to use. The graded river sand with fineness of 2.8  $\mu\text{m}$  and specific of 2.65  $\text{g}/\text{cm}^3$  was employed to prepare mortar samples for compressive strength test. An analytical grade of kaolin clay with 95% purity and 2.61  $\text{g}/\text{cm}^3$  density was obtained from EDUCHEM South Africa. It was used as a comparative raw material for the production of geopolymer. [Table 1](#) below show how the geopolymers were synthesized.

### 2.2. Geopolymer preparation

The geopolymer samples were prepared, firstly by preparing the activated solutions.  $\text{Na}_2\text{SiO}_3$  and 15 M  $\text{NaOH}$  were mixed in a mass ratio of 1: 0.5 ( $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ). The bottom ash was mixed with kaolin on a 1:1 mass ratio, thereafter the bottom ash/kaolin mixture was mixed with the alkaline solution on a 1:1 ratio. Finally, the bottom ash/kaolin and alkaline mixture was mixed with sand on 1:0.5 ratio. The solution was added to the mixture of bottom ash and kaolin in a pan mixer at 150 rpm and the paste was thoroughly mixed for 5 min and then cast in plastic cylindrical molds with a dimension of 25 mm diameter and 25 mm height. The process was done for each of the bottom ash/kaolin particle size samples. As shown in [Table 1](#) above for the microwave curing synthesis, the geopolymers were cured for 4 min using at 2.45 GHz in a household microwave (Input: 230V  $\approx$  50 Hz 1500 W and power output 1000 W) while for the oven curing synthesis, the geopolymers were cured at 40 °C for 72 hrs. Lastly, for the microwave and oven curing synthesis, the geopolymer were cured in the microwave for 2 min and in the oven at 40 °C for 36 h.

**Table 1**

The mixing ratios of the starting material and curing method for geopolymer synthesis.

Geopolymer ID and Particle size (Bottom Ash)	( $\text{Na}_2\text{SiO}_3/\text{NaOH}$ )	Kaolin/ Bottom Ash	( $\text{Na}_2\text{SiO}_3/\text{NaOH}$ )/ Kaolin and Bottom Ash	Geopolymer/ Sand	Curing method and Conditions
BAGP1 - 850 $\mu\text{m}$	1:0.5	1:1	1:1	1:0.5	72 h in Oven at 40 °C
BAGP2 - 850 $\mu\text{m}$	1:0.5	1:1	1:1	1:0.5	4 min in a Microwave
BAGP3 - 75 $\mu\text{m}$	1:0.5	1:1	1:1	1:0.5	4 min in a Microwave
BAGP4 - 75 $\mu\text{m}$	1:0.5	1:1	1:1	1:0.5	72 h in Oven at 40 °C
BAGP5 - 850 $\mu\text{m}$	1:0.5	1:1	1:1	1:0.5	2 min in Microwave & 36 h in oven at 40 °C

### 2.3. Characterization of the geopolymers

Characterization of the geopolymers was carried out using atomic ratios using from scanning electron microscope (SEM) analysis, compressive strength test, thermogravimetric analysis (TGA), X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis.

#### 2.3.1. XRF analysis

The XRF analyses of the bottom ash was performed using the ARL PerformX Sequential XRF. The bottom ash sample was roasted at 1000 °C. A 1 g portion of the roasted sample was in turn placed together with 6 g of  $\text{Li}_2\text{B}_4\text{O}_7$  in a Pt/Au crucible and fused. The Quantas software, which analyses all the periodic table elements between Na and U, was used to analyze the results, the reported elements are only those found to be above the detection limits of 0 - 500 ppm.

#### 2.3.2. XRD analysis

The bottom ash mineralogical and phase composition as well as that of the geopolymer samples, were determined, using an X-ray diffraction (XRD). The Empyrean from PAN analytical with Cu  $\text{K}\alpha$  radiation was used for analysis and the operation conditions were 40 kV and 30 mA with a scan range of between 5 and 70°, at a step size of 0.02°

#### 2.3.3. TG analysis

The thermogravimetric analysis was used to determine the thermal stability of the geopolymer samples using a PerkinElmer Thermogravimetric Analyser TGA 7, with approximately 10 mg per sample analysed. This was carried out in a nitrogen gas atmosphere, at a heating rate of 20 °C/min between temperature range 30 - 1000 °C.

#### 2.3.4. SEM\_EDS analysis

The morphology of the samples was analysed using a JEOL JSM-7600F field-emission scanning electron microscope attached to an EDX. The SEM was operated at an accelerating voltage of 5 kV, under dry high vacuum conditions. SEM-EDX analysis was carried out using the small broken pieces of the compressive strength test samples. The atomic ratios of Na, Al, Si, C, Ca and Fe were obtained, while the atomic ratios of Si/Al, Si/Na and Na/Al were calculated.

#### 2.3.5. Compressive test analysis

After curing the samples for 7 days, a compressive test was performed using a Bosal HP-10 model machine. This was done to determine the compressive strength of each of the samples reported in MPa.

## 3. Results and discussion

### 3.1. XRF analysis

The X-Ray Fluorescence (XRF) analysis results are shown in [Table 2](#) below.

**Table 2**  
Chemical composition and physical properties of bottom ash.

Composition	%
SiO <sub>2</sub>	38,2
Al <sub>2</sub> O <sub>3</sub>	20,5
Fe <sub>2</sub> O <sub>3</sub>	5,5
TiO <sub>2</sub>	1,3
CaO	17,9
K <sub>2</sub> O	1,1
MgO	1,35
P <sub>2</sub> O <sub>5</sub>	0,95
Na <sub>2</sub> O	4,84
MnO	0,95
SO <sub>3</sub>	2,65
LOI	4,76

### 3.2. XRD analysis

Fig. 1 below shows the X-ray diffraction (XRD) patterns of geopolymer samples which underwent microwave radiation and conventional oven curing. The main peaks that are more prominent in the XRD pattern are that of crystalline quartz (SiO<sub>2</sub>) at  $2\theta = 21^\circ$ ,  $2\theta = 28^\circ$  and  $2\theta = 68^\circ$  and hematite (Fe<sub>2</sub>O<sub>3</sub>) between  $2\theta = 35^\circ$  and  $2\theta = 65^\circ$ . The mullite and quartz phases are very stable as and they do not dissolve easily in an alkali solution; as a result they lower the reactivity of the bottom ash and decreases the level of geopolymerisation (Chindaprasirt et al., 2009; Oboirien et al., 2013). In addition, the product was semi-crystalline with a high amount of amorphous gel as indicated by the broad hump and some sharp peaks of crystallinity. The sharp peak appearing at  $2\theta = 28^\circ$ , indicate higher amount of crystalline phases in the bottom ash geopolymer. The crystalline quartz phase improves the mechanical and physical properties because of the aluminosilicate compounds, hence the high compressive strength observed in the microwave cured geopolymer sample.

### 3.3. TG analysis

Thermal analysis was done to determine the strength of the geopolymer. The mass loss from room temperature to 800 °C for the five

geopolymers as shown in Fig. 2 below. Usually, geopolymer weight loss is characterised by at least three weight changes (degradation steps): firstly, it is the absorbed water that evaporates between 30 °C to 100 °C. Secondly, between 100 °C to 450 °C it is the chemically bonded hydroxyl groups that is converted to (Si-OH). And finally, there is a weight change that is observed between 450 °C to 700 °C due to oxidation and combustion of un-burnt coal entrapped inside the fly ash particles (Yao et al., 2013). Weight loss from 700 °C onwards continue to decrease although it then tends to stabilize and become constant. The weight loss is due to the decomposition of anhydrite (CaSO<sub>4</sub>), (ul Haq et al., 2014; van der Merwe et al., 2014). The mass loss of BAGP5, BAGP4, BAGP3, BAGP2 and BAGP1 is 3.0%, 4.4%, 5.2%, 8.8% and 9.1% respectively. BAGP5 the microwave/oven cured geopolymer resulted in a higher strength geopolymer with very little mass loss compared to the other curing methods used. This is an indication that a high degree of geopolymerisation took place in BAGP5 and there was very little water adsorption during the geopolymerisation process compared to the other geopolymers. This result is also confirmed by the compressive strength test, SEM-EDX results. The microwave/oven curing process was very effective even though the particle size of the bottom ash was 850 μm because of the use of the microwaves resulting in a high degree of geopolymerisation. This is also confirmed by the high crystallinity in the SEM micrographs. The second highest strength geopolymer is BAGP4 followed by BAGP3. This clearly indicates that other than the curing method used the particle size of the bottom ash plays a huge role in water adsorption during geopolymerisation. The smaller the particle size of the bottom ash the more reactive it is to form a geopolymer and less water adsorption (Fernández-Jiménez et al., 2006). Microwaves and oven curing was very effective in increasing the degree of geopolymerisation, this result is also confirmed by the compressive strength test, SEM-EDX results. BAGP2 and BAGP1 had the most water adsorption during the geopolymerisation process, this is due to the particle size of the geopolymer as well as the curing method used. There was 9.1% or less of water loss for the geopolymers, which clearly indicate that successfully geopolymerisation was achieved with all geopolymer samples. The main weight loss observed occurred between 120 °C to 450 °C in all the five geopolymers and this was due to the chemically bonded hydroxyl groups which was converted to (Si-OH).

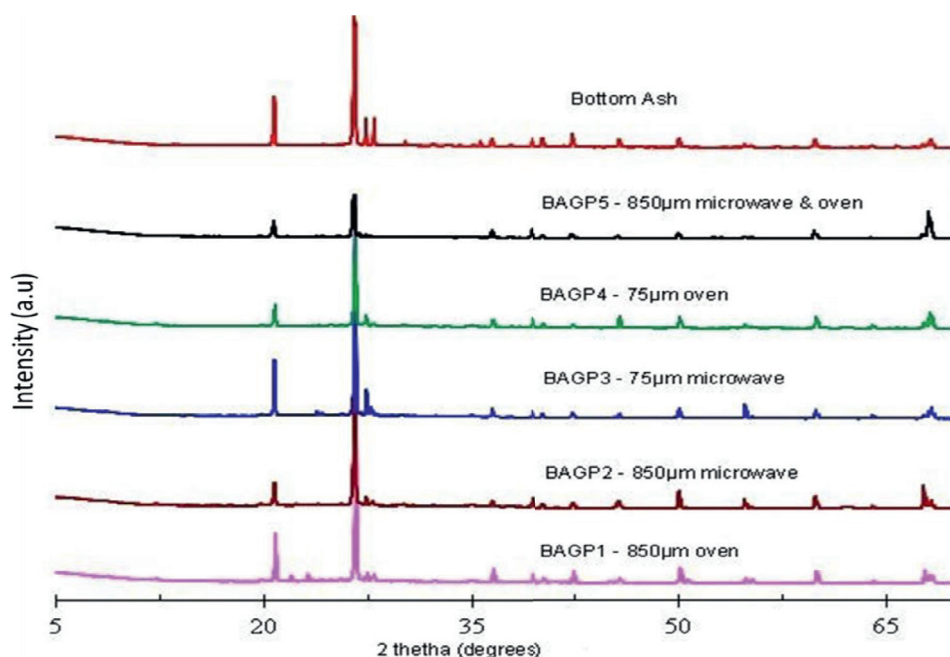


Fig. 1. XRD pattern of bottom ash and the synthesized geopolymers.

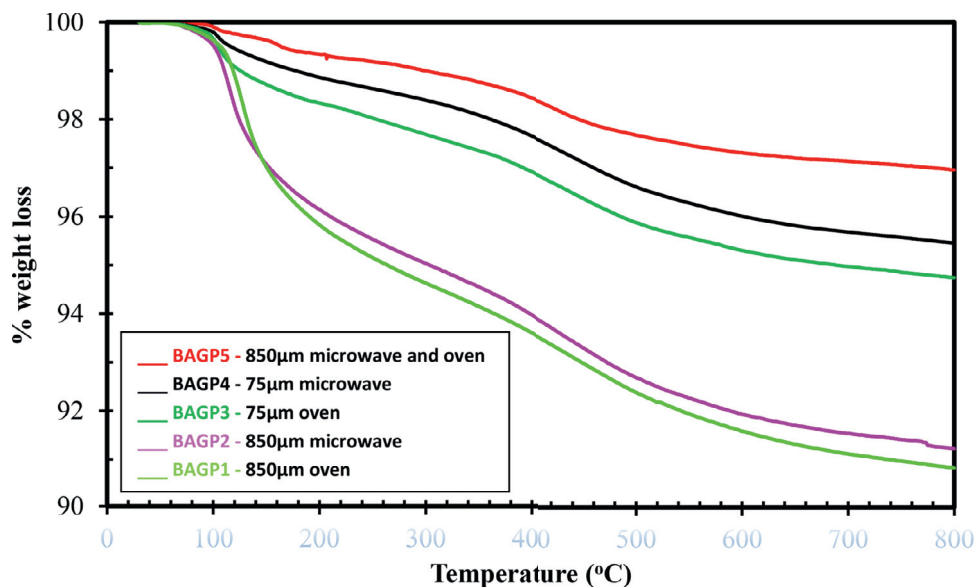


Fig. 2. TGA thermogram for the bottom ash geopolymers.

3.4. SEM\_EDX analysis

The SEM images of the geopolymer samples are shown in Fig. 3 below. The elemental analyses of the micrograph (EDX) in atomic percentage of all the geopolymer samples are shown in Table 3 below. SEM analysis is used to study the microstructure and morphology of the bottom ash and that of the geopolymers. This is done in order to identify the aluminosilicate and particle size, while the EDX is

combined with the SEM to study the elemental composition of the samples (Ul Haq et al., 2014; Boke et al., 2015). The morphology of the bottom ash affects the characteristics of the resultant geopolymer, while the particle size of the ash is the parameter that determines the surface available for alkaline solution attack in order to leach-out the aluminosilicate. Small ash particles are good for geopolymerisation because they contain high glass phase composition and react faster than large particles. However, it must be noted that particle size is not the overall

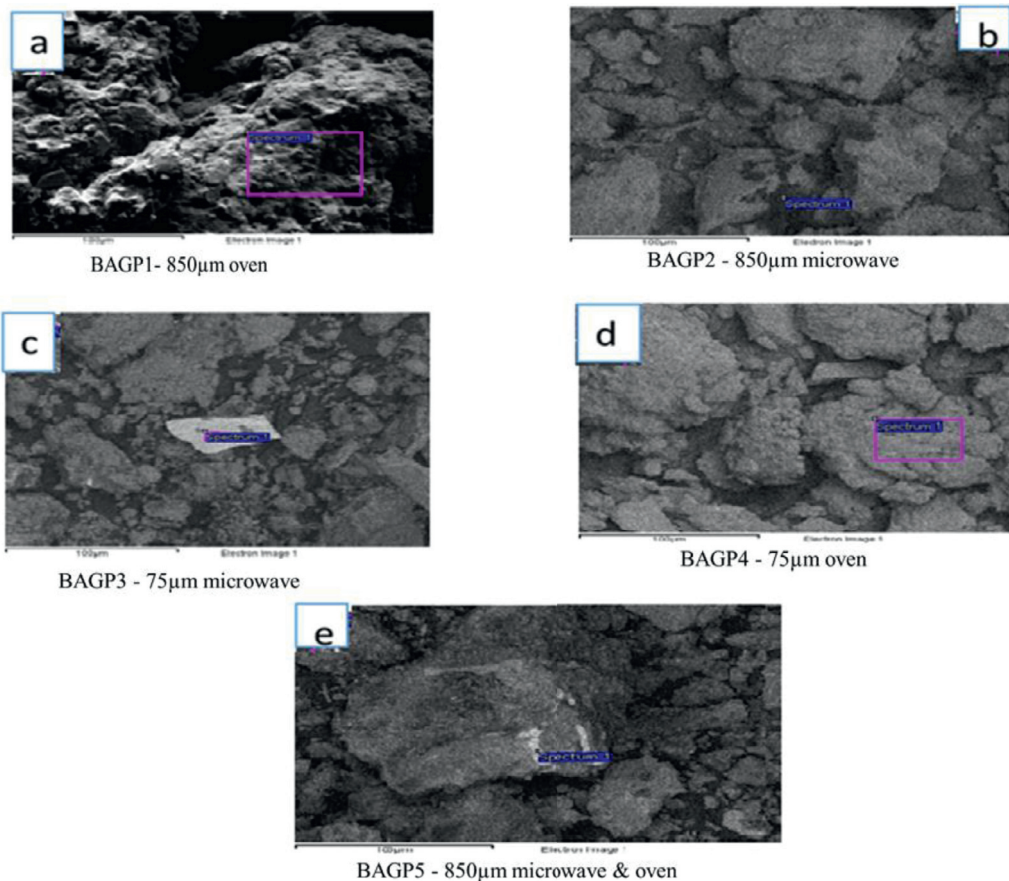


Fig. 3. SEM micrographs of the geopolymers.

**Table 3**  
Elemental analyses of the micrograph (EDX).

Sample	Na	Al	Si	C	Fe	Si/Al	Si/Na	Na/Al
BAGP1 - 850 $\mu\text{m}$ oven	7.60	3.44	9.49	28.06	0.22	2.76	1.25	2.21
BAGP2 - 850 $\mu\text{m}$ microwave	8.95	4.53	12.58	17.67	0.44	2.78	1.41	1.98
BAGP3 - 75 $\mu\text{m}$ microwave	6.01	4.32	14.94	15.78	0.59	3.46	2.49	1.39
BAGP4 - 75 $\mu\text{m}$ oven	10.77	3.75	10.12	16.90	0.18	2.70	0.94	2.87
BAGP5 - 850 $\mu\text{m}$ microwave & oven	13.96	2.44	10.78	28.07	0.42	4.42	0.77	5.72

parameter to be considered for the reactivity of the amorphous phase of the ash in geopolymerisation or its workability during casting and curing (Rickard et al., 2012). A low water content in bottom ash is desirable in the production of geopolymers because it reduces shrinkage that results in cracks during curing (Rickard et al., 2011). SEM-EDX micrographs will indicate the atomic ratio (%) on specific points in the geopolymer samples and the Si/Na or K ratio and Si/Al determines the degree of geopolymerisation. A high ratio of Si/Al indicates a geopolymer with a high compressive strength, while a low Si/Na is an indication of a high rate of reaction. A high Si/Al atomic ratio and a low Si/Na atomic ratio indicate a crystalline structure of an aluminosilicate gel (Topcu et al., 2014). Bottom ash with a low Ca content, tends to form a geopolymer that comprises of a sodium alumina silicate hydrate (N-A-S-H) gel due to the reaction between the alkaline activator solution NaOH/Na<sub>2</sub>SiO<sub>3</sub> and the silica and the alumina phases in the bottom ash (Hoy et al., 2016).

Fig. 3 shows that the non-microwave assisted geopolymer samples has a less compact geopolymer structure compared to the microwave-assisted geopolymer samples which presents well-formed homogeneous geopolymer matrices. It is also reasonable to suggest that BAGP5 geopolymer developed a higher compressive strength than other geopolymers, which is supported by the compressive strength test results shown in Fig. 5 below, and the Si/Al ratio of 4.42 indicate a high strength geopolymer. Therefore, the higher Si/Al atomic ratio and lower Si/Na atomic ratio in sample BAGP5 corresponds to a crystalline stage of the aluminosilicate gel. Increases in crystalline products increases the compressive strength of the geopolymer. Moreover, the Si/Na ratio can be used to verify the degree of reaction of dissolved group. A lower ratio implies a high degree of reaction and thus a high strength of the geopolymer (Sathonsaowaphak et al., 2009). The Si/Al ratio for non-microwave geopolymers BAGP1 and BAGP4 are 2.76 and 2.70 respectively while for the microwave-assisted geopolymers BAGP2, BAGP3 and BAGP5, the Si/Al ratio was 2.78, 3.46 and 4.42 respectively. This implies that microwaves played a role to boost the strength of the geopolymer. Additionally, a higher Si/Na ratio symbolizes an early stage of the geopolymer formation and a higher unreacted material. The Si/Na ratio for non-microwave geopolymers BAGP1 and BAGP4 are 1.25 and 0.94 respectively, while for microwave geopolymers BAGP2, BAGP3 and BAGP5 the Si/Na ratio are 1.41, 2.49 and 0.77 respectively.

### 3.5. Compressive strength test analysis

Compressive strength tests were performed on all five geopolymer

samples immediately after the 7 days of curing. Fig. 4 below show the geopolymer samples used for the compressive test and Fig. 5 shows a summary of the compressive strength results of the geopolymers BAGP1 - 15.0 MPa, BAGP2 - 22.0 MPa, BAGP3 - 24.0 MPa, BAGP 4 - 17.5 MPa and BAGP5 - 31.0 MPa. BAGP5 has the highest compressive strength that means it experienced the highest degree of geopolymerisation followed by BAGP3 followed by BAGP2 then BAGP4 and lastly, BAGP1. The effects of the microwave radiation played a huge role to enhance the geopolymerisation process because all the microwave-cured geopolymers gave higher compressive strength results. The geopolymers that were cured in an oven BAGP4, had a higher compressive strength compared to BAGP1 that was synthesized with larger particle size bottom ash as compared to BAGP4 that was synthesised with smaller particle size of bottom ash. The smaller the particle size of bottom ash the better the geopolymerisation process because a small particle size bottom ash has a high reactivity (Sathonsaowaphak et al., 2009). The results in Fig. 5 shows that all the microwave-assisted geopolymers have a high compressive strength, which implies that microwaves, enhance the strength of geopolymers more than the conventional heat curing method. The compressive strength results are consistent with the results obtained from TGA, SEM-EDX results. Based on the result so these geopolymers they are a perfect replacement for Ordinary Portland Cement in different applications, such as, tooling and moldings, fire-resistant materials, ceramics and cements, high-tech materials and matrices for hazardous waste stabilization.

### 3.6. Conclusions

Bottom ash must be reduced to smaller particles size because it is normally available in larger particle sizes. The smaller the particle size the higher the reactivity and higher the degree of geopolymerisation and the greater the range in the gel phase. This presents an opportunity for the alkaline activator solution to dissolve the highest number of particles possible in order to favor the structural formation and accelerated geopolymerisation. The size of the particles and the curing conditions (microwave or oven or a combination of both) seem to have a direct influence in the degree of geopolymerisation process to form the desired geopolymers. Based on the results obtained, the bottom ash generated from fluidized bed combustion of low grade coals can be used as a source material for making good geopolymers. A household microwave and conventional oven were used to enhance the strength of the geopolymer. The Si/Al ratio for microwave assisted geopolymer BAGP5, BAGP3 and BAGP2 was 4.42, 3.46 and 2.78 respectively. The



Fig. 4. Geopolymer samples used for compressive strength test.

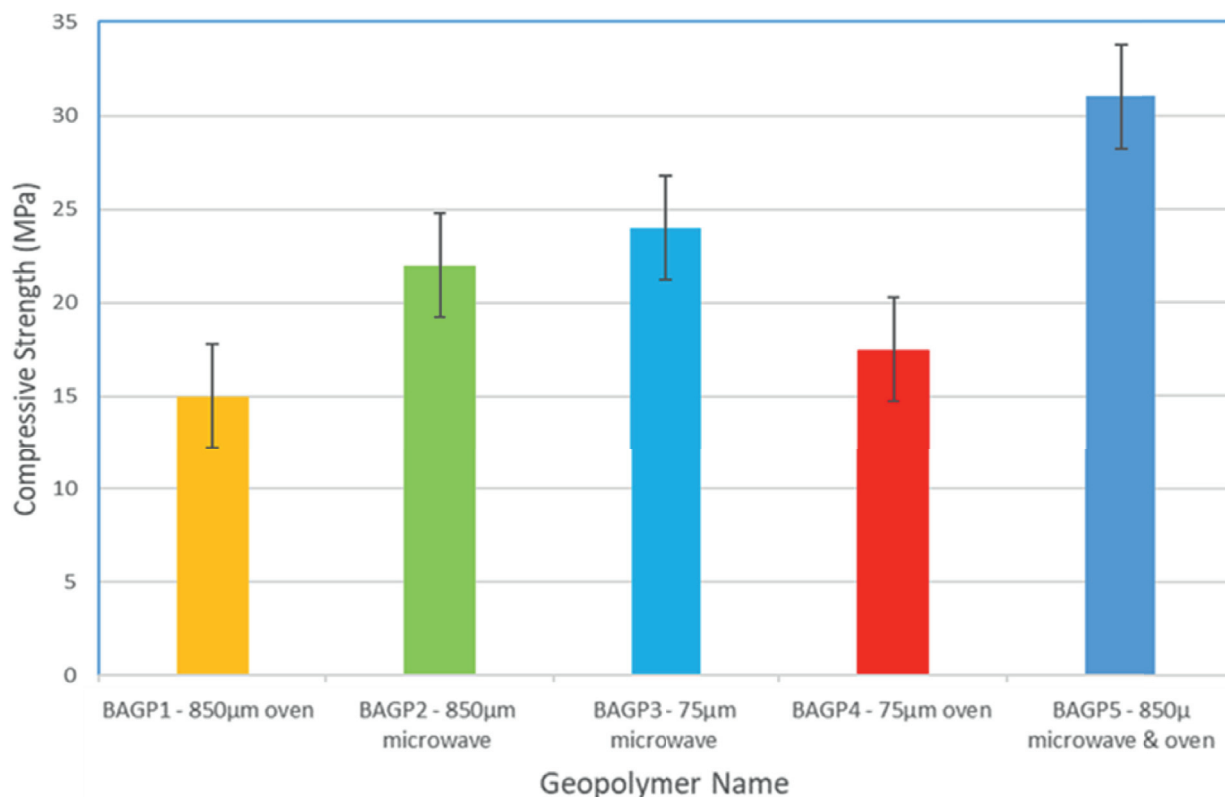


Fig. 5. Compressive strength test results of bottom ash geopolymers.

compressive strength results also shows that microwave and oven-assisted geopolymer BAGP5 reached a reasonable high 7-day compressive strength of 31.0 MPa compared to other four geopolymers with low compressive strength.

#### Authors contribution

**Tobi Stephen Osholana:** Investigation; **Mbuso Kingdom Dlodlu** Formal Analysis, Writing- Original draft presentation; **Bilainu Oboirien.:** Conceptualization, Methodology, Supervision, Reviewing and Editing Data; **Rotimi Sadiku:** Supervision

#### Declaration of Competing Interest

This is to declare that no of the authors have any conflict of interest.

#### References

- Al Bakria, A.M., Kamarudin, H., Binhussain, M., Nizar, I.K., Zarina, Y., Rafiza, A., 2011. The effect of curing temperature on physical and chemical properties of geopolymers. *Phys. Procedia* 22, 286–291.
- Boca Santa, R.A.A., Bernardin, A.M., Riella, H.G., Kuhnen, N.C., 2013. Geopolymer synthesized from bottom coal ash and calcined paper sludge. *J. Clean. Prod.* 57, 302–307.
- Hardijito, D., Fung, S.S., 2010. Parametric study on the properties of geopolymer mortar incorporating bottom ash. *Concrete Res. Lett.* (3), 115–123.
- Boke, N., Birch, G.D., Nyale, S.M., Petrik, L.F., 2015. New synthesis method for the production of coal fly ash-based foamed geopolymers. *Construction and Building Materials* 75, 189–199.
- Chindaprasirt, P., Chai, J., Rattanasak, U., 2009. Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Miner. Eng.* 29.
- Chindaprasirt, P., Rattanasak, U., 2010. Utilisation of blended fluidized bed combustion (FBC) ash and pulverized coal combustion (PCC) fly ash in geopolymer. *Waste Management* 30, 667–672.
- Chindaprasirt, P., Rattanasak, U., Taebuanhuad, S., 2013. Role of microwave radiation in curing the fly ash geopolymer. *Advanced Powder Technol.* 24, 703–707.
- Fernández-Jiménez, A., Palomo, A., Sobrados, I., Sanz, J., 2006. The role played by the reactive alumina content in the alkaline activation of fly ashes. *Micropor. Mesopor. Mat.* 91 (1), 111–119.
- Hoy, M., Horpibulsuk, S., Aarurajah, A., 2016. Strength development of Recycled Asphalt Pavement – Fly ash geopolymer as a road construction material. *Construction and Building Materials* 117, 209–219.
- Kula, I., Olgun, A., Erdogan, Y., Sevinc, V., 2001. Effect of colemanite waste, cool bottom ash and fly ash on properties of cement. *Cement and Concrete Research* 31, 491–494.
- Li, Q., Xu, H., Li, F., Li, P., Shen, L., Zhai, J., 2012. Synthesis of geopolymer composites from blends of CFBC fly ash and bottom ashes. *Fuel* 97, 366–372.
- Marjanović, N., Komljenović, M., Bašcarević, Z., Nikolić, V., 2014. Improving reactivity of fly ash and properties of ensuing geopolymers through mechanical activation. *Construction and Building Materials* 57, 151–162.
- Mathekga, H.I., Oboirien, B.O., Engelbrecht, A., North, B.C., Premllall, K., 2016. Performance evaluation of South African coals under Oxy-fuel combustion in a Fluidised Bed Reactor. *Energy and Fuels* (30), 6756–6763.
- Nkuna, C., Oboirien, B., Sadiku, E.R., Lekitima, J., 2017. A comparative study of geopolymers synthesized from OXY-combustion and chemical looping combustion bottom ashes. *Construction and Building* 136 246–25.
- Oboirien, B., North, B., Sadiku, E., 2013. Microwave-assisted synthesis of geopolymers from fluidised bed gasifier bottom ash. In: *International Conference of Coal Science and Technology*, State College. Pennsylvania, USA. 29 September– 3 October 2013.
- Papa, E., Medri, V., Land, I.E., Ballarin, Miccio, F.B., 2014. Production and characterization of geopolymers based on mixed compositions of metakaolin and coal ashes. *Mater. Des.* 56, 409–415.
- Rickard, W.D., Temuujin, J., Van Riessen, A., 2012. Thermal analysis of geopolymer pastes synthesised from five fly ashes of variable composition. *J Non Cryst Solids* 358, 1830–1839.
- Rickard, W.D., Williams, R., Temuujin, J., Van Riessen, A., 2011. Assessing the suitability of three Australian fly ashes as an aluminosilicate source for geopolymers in high temperature applications. *Mater. Sci. Eng.* 528, 3390–3397.
- Sathonsaowaphak, A., Chindaprasit, P., Pimraska, K., 2009. Workability and strength of lignite bottom ash geopolymer mortar. *J. Hazardous Mat.* 168, 44–50.
- Slavik, R., Bednarik, V., Vondruska, M., Nemeč, A., 2008. Preparation of geopolymer from fluidized bed combustion bottom ash. *J. Mater. Process. Technol.* 200, 265–270.
- Topcu, I.B., Toprak, M.U., 2011. Properties of geopolymers from circulating fluidized bed combustion coal bottom ash. *Mater. Sci. Eng.* 528, 1472–1477.
- Topcu, I.B., Toprak, M.U., Uygunoglu, T., 2014. Durability and microstructure characteristics of alkali activated coal bottom ash geopolymer cement. *J. Clean Prod.* 81, 211–217.
- Ul Haq, E., Padmanabhan, S.K., Licciulli, A., 2014. Synthesis and characteristics of fly ash and bottom ash based geopolymers a comparative study. *Ceram. Int.* 40, 2965–2971.
- Van Der Merwe, E.M., Prinsloo, L.C., Mathebula, C.L., Swart, H.C., Coetsee, E., Doucet, F.J., 2014. Surface and bulk characterization of an ultrafine South African coal fly ash with reference to polymer applications. *Appl. Surf. Sci.* 317, 73–83.
- Wonga, A., Zaeteng, Y., Sata, V., Chindaprasit, P., 2016. Properties of lightweight fly ash geopolymer concrete containing bottom ash as aggregates. *Construction and Building* 11, 637–643.
- Yao, Z., Ye, Y., Xia, M., 2013. Synthesis and characterization of lithium zeolites with ABW type from coal fly ash. *Environ. Prog. Sustain. Energy* 32 (3), 790–796. <https://doi.org/10.1002/ep.11689>.