

# Geosynthesis of building and construction materials through alkaline activation of granulated blast furnace slag

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## HIGHLIGHTS

- NaOH and KOH can be used to alkali activate GBFS.
- NaOH possessed better activation potential and favours GBFS geopolymerization than KOH.
- The characterisation results showed the formation of zeolites leading to increase in UCS.
- NaOH alkaline activation resulted in a formation of calcium silicate hydrate (CSH) and calcium aluminate hydrate.

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## ABSTRACT

This article investigated the feasibility to synthesise geopolymer bricks from Granulated Blast Furnace Slag (GBFS) using alkaline activators without addition of sodium silicate or silica reactive source. Sodium hydroxide (NaOH) is a typical alkaline solution used in geopolymerisation compared to KOH with addition of silicate solution used as a catalyst to enhance the dissolution process. However, a comparative study between the two alkaline activators in the absence of silica solution are very scarce and limited. For this purpose, this article investigated the effect of type of alkali (NaOH and KOH) on unconfined compressive strength (UCS) with the aim to establish the best alkali activator that possess high activation potential and favours GBFS geopolymerisation. In addition, the effect of alkali concentration, liquid–solid ratio, curing temperature and time on the physical and mechanical properties of geopolymer bricks were investigated using UCS, SEM micrographs, XRD analysis, water absorption, and bulk density. Metal leachability and durability of the synthesised geopolymer brick was also investigated. The results show that geopolymer brick prepared with NaOH favours GBFS geopolymerisation. The optimum curing conditions that yielded the highest UCS of 72 MPa were 15 M NaOH, liquid to Solid ratio of 0,15, curing temperature and time of 80 °C and 5 days. The highest UCS was due to formation of a dense, less porous and more amorphous microstructure. The synthesised geopolymer brick met the minimum required UCS and the water absorption % to be used as facing and solid masonry brick in accordance with ASTM C126-99 and ASTM C216-07a respectively.

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## 1. Introduction

The rapid growth in steel industry has resulted in the generation of large quantities of Granulated Blast Furnace Slag (GBFS) which cause environmental issues during waste management. Dumping of industrial waste has become tough and costly because of the increasing strict environmental rules and regulations and, shortages of appropriate neighbouring dumping sites. Currently there is an upsurge of interest to develop novel, yet environmen-

tally safe, applications for the use of such material in building and construction. One of the novel technologies that has utilization potential of GBFS is through production of geopolymer material such as low cost facing and solid masonry brick that can be used in building and construction.

Ordinary Portland cement (OPC) and clay has been the main material (binder) used to produce conventional bricks for the past years [1]. The production of OPC and clay fired bricks presents so many problems. Globally, it is estimated that by 2020 the cement industries would release about 4.8 billion tons of harmful CO<sub>2</sub> gas [2]. Manufacturing of OPC and clay fired bricks emits enormous amounts CO<sub>2</sub> and NO<sub>x</sub> responsible for global warming and their production processes are also energy intensive [3]. For a country

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like South Africa facing severe energy crisis, causing power cuts; this puts more strain on the energy grid [4]. In addition South Africa is responsible for nearly half the CO<sub>2</sub> emissions for the entire continent of Africa [5]. It has also been reported that there is a shortage of clay globally and a call to preserve clay resources [6]. To address the aforementioned problems there is a need to find a viable, low cost, alternative binders to use in production of conventional bricks. One potential solution to this problem is geopolymerisation of industrial waste such as; Fly ash, mine tailings, foundry sand, basic oxygen furnace slag and granulated furnace slag as alternatives to OPC and clay resources [1–7]. Less than 6% of GBFS is used as supplementary cementitious material in South Africa [8]. However, it is reported that the waste from South African iron production companies is between 12 and 37 million tons [9]. It is therefore imperative to beneficiate GBFS in order to make it a natural resource for other valuable products, such as production of geopolymer bricks.

Geopolymerisation is dissolution of aluminosilicates in alkaline medium to form an amorphous to semi-crystalline 3D silicoaluminate polymeric structure [10]. The Al and Si source that are commonly used include slags, FA and metakaolin whilst the activating agents are NaOH and Na<sub>2</sub>SiO<sub>3</sub> [11]. The role of the activating agents is to release Si and Al ions to the solution by breaking the Si-O-Si, Al-O-Al, and Si-O-Al bonds producing a geopolymeric gel called a geopolymer [12]. Geopolymers are considered as radical materials that have excellent characteristics such as high unconfined compressive strength, low shrinkage, low liquid limit and energy efficient during production [13]. The excellent properties of geopolymers makes them highly preferred in building and construction, fireproof, waste treatment and manufacturing of radioactive waste container [14]. Furthermore, new applications are still being discovered [15].

Extensive research on geopolymers has been conducted and applied widely in building and construction. Valorisation of GBFS through geopolymerisation are not recent and is a very well documented topic [16–20]. Murri et al. demonstrated that it is possible to produce GBFS based geopolymeric binder using sodium hydroxide combined with sodium silicate as alkaline activators [17]. The developed GBFS based geopolymer material had UCS range of 19 to 44 MPa. Most of the researched work on GBFS geopolymerisation focused on increasing the silica by adding sodium silicate solution or a silica reactive source. A silica source is added so that the Si/Al ratio reaches 3–4 where it has shown good mechanical properties of GBFS geopolymers such as density, water absorption, mechanical strength (compressive, flexural, shear and bond), and microstructural properties [21–23]. In addition studies by [24,25] suggest that alkali silicates possess high activation potential and favours GBFS geopolymerization. However, of the raw materials used to produce geopolymer binders, alkali silicates are the most expensive and have the highest environmental impact [26]. A number of researchers [12,22,27–30] studied the feasibility of using NaOH as a alkali activator without addition of silica solution in geopolymerisation of Fly ash, mine tailings and copper slag. In these studies it was reported that silicate solution is not necessary to be added as there are improvement of mechanical properties observed by prolonging the curing time. Surprisingly, studies regarding the production of GBFS based geopolymer using alkali activators without addition of sodium silicate or silica reactive source are scarce and not well documented in literature. This study attempts to synthesise geopolymer bricks from Granulated Blast Furnace Slag (GBFS) using alkali activators without addition of sodium silicate or silica reactive source. Sodium hydroxide (NaOH) is a typical alkaline activator used in geopolymerisation compared to KOH with addition of silicate solution used as a catalyst to enhance dissolution process. However, a comparative study between the two alkali activators in the absence of silica solution

are very scarce and limited. For this purpose, this article investigated the effect of type of alkali (NaOH and KOH) on unconfined compressive strength (UCS) with the aim to establish the best alkali activator that possess high activation potential and favours GBFS geopolymerisation. In addition, the effect of alkali concentration, liquid–solid ratio, curing temperature and time on the physical and mechanical properties of geopolymer bricks was investigated using UCS, SEM micrographs, XRD analysis, water absorption, and bulk density. Metal leachability and durability of the synthesised geopolymer brick was also investigated. The alkali activated based geopolymer has been reported to be more attractive as it gives lower carbon footprint than alkali silicates based geopolymer [22]. This research therefore present full beneficiation and utilisation of GBFS as a low cost, environmentally friendly alternative materials to mitigate against pollution.

## 2. Materials and methods

### 2.1. Materials

GBFS was collected from a steel production company in South Africa. Sodium hydroxide (NaOH) and Potassium hydroxide (KOH) were used as alkaline activators. KOH was supplied by Sigma Aldrich South Africa and NaOH was supplied by Rochelle chemicals in South Africa. Table 1 shows the physical properties and the chemical compositions of GBFS. The major oxides were; MgO, Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, CaO. Fig. 1 shows the particle size distribution (PSD) of raw GBFS, GBFS had a D<sub>50</sub> value of 74 μm which suggest that GBFS contains relatively great fraction of large particles. This may reduce the surface area necessary for effective dissolution of SiO<sub>2</sub>, CaO and Al<sub>2</sub>O<sub>3</sub> [1]. Therefore; GBFS was then milled to a finer particles size to increase the surface area and enhance the dissolution of aluminosilicates which results in improved mechanical properties of geopolymer species [5]. The XRD diffractogram of raw GBFS in Fig. 2 shows a broad diffuse hump around 19°–39°, which revealed that GBFS predominantly possesses glassy amorphous phase with magnetite and quartz [31].

### 2.2. Experimental procedure

The geopolymer pastes were prepared using different mix proportions as shown in Table 2. NaOH and KOH were used as alkali activators. The concentration of the alkali activators were varied

**Table 1**  
Chemical composition of raw GBFS.

Chemical composition (%)	GBFS
Na <sub>2</sub> O	0.21
MgO	5.48
Al <sub>2</sub> O <sub>3</sub>	10.7
SiO <sub>2</sub>	27.2
P <sub>2</sub> O <sub>5</sub>	0.01
SO <sub>3</sub>	2.19
Cl	0.02
K <sub>2</sub> O	0.67
CaO	49.1
TiO <sub>2</sub>	0.97
Cr <sub>2</sub> O <sub>3</sub>	0.08
MnO	1.47
Fe <sub>2</sub> O <sub>3</sub>	1.22
NiO	0.01
SrO	0.29
Y <sub>2</sub> O <sub>3</sub>	0.02
ZrO <sub>2</sub>	0.10
BaO	0.30
LOI	0.23
Specific gravity	2.90
LOI	0.23

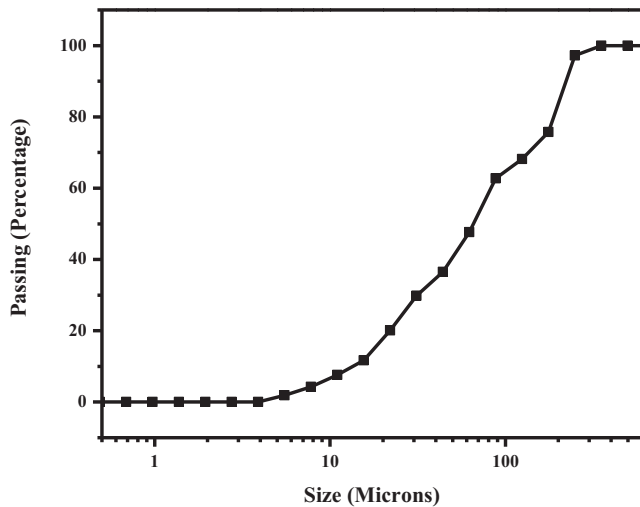


Fig. 1. Particle size distribution of raw GBFS.

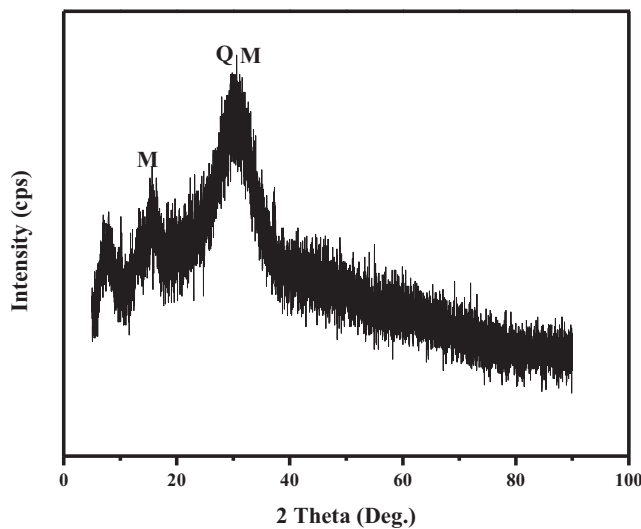


Fig. 2. XRD analysis of raw GBFS (Q = Quartz, M = Magnetite).

from 5 M to 30 M respectively, to establish which alkaline activator possesses high activation potential and favors the GBFS geopolymerisation. The alkaline activator that favoured the GBFS geopolymerisation was used to investigate the optimum alkaline activator concentration thereafter the optimum L/S ratio was investigated and was used to find the optimum curing temperature. The UCS was used as criterion for choosing the optimum curing conditions.

**Table 2**  
Mix proportion of the geopolymer paste.

GBFS (%)	Concentration (M)	NaOH (MPa)	KOH (MPa)	L/S (%)	Temperature °C
100	5 M	26.52	21.39	0.2	80
100	10 M	31.30	44.01	0.2	80
100	15 M	67.90	23.39	0.2	80
100	20 M	36.42	14.30	0.2	80
100	25 M	30.25	6.98	0.2	80
100	30 M	11.06	2.54	0.2	80
100	15 M	72.12	-	0.15	80
100	15 M	57.47	-	0.25	80
100	15 M	49.62	-	0.30	80
100	15 M	63.37	-	0.15	60
100	15 M	56.83	-	0.15	90

### 2.3. Preparation of the geopolymer paste

The geopolymer pastes were prepared by adding the alkaline activator solutions to the raw GBFS. The mixture was stirred until it was homogeneous. The paste was then transferred into a 50 mm × 50 mm × 50 mm mold, and vibrated for 1 min on a vibrating table. The prepared pastes were sealed with plastic and were allowed to set and harden for 24 h. The specimens were then unsealed, demolded and cured at varied temperatures (60 °C, 80 °C and 90 °C) for 5 days.

### 2.4. Unconfined compressive strength testing

The unconfined compressive strength of the geopolymer specimen were measured by placing the specimens within the cyber plus compression machine with a maximum load capacity of 100 kN, and the load of the compression machine was applied with a constant displacement rate of 2 mm/min until the geopolymer specimen failed.

### 2.5. Equipment

The XRF (Rigaku ZSX Primus II) was used to analyse chemical composition of the samples. X-Ray Diffraction (XRD) was used to quantify and identify mineralogy and SEM (Tescan Vega 3 XMU 1) was used capture the surface morphology of specimen. The cyber plus compression machine was used to test the unconfined compressive strength (UCS) of the produced geopolymers. Micro-trac particle size analyser was used determine the particle size distribution of GBFS and specimens.

### 2.6. Open porosity and absorption rate

The geopolymer sample was weighed and the mass ( $W_d$ ) was recorded, and then the geopolymer was dipped in deionised water for a period of 30 days. The geopolymer was then wiped off any water found on its surface and weighed again to find mass of the wet sample ( $W_s$ ). The wet specimens were weighed within 5 min after being removed from the water. Open porosity,  $f$ , was then calculated using Eq. (1) as follows (ASTM C373 – 14):

$$f = \frac{W_s - W_d}{V\alpha} \tag{1}$$

where  $W_s$  is the mass of the soaked specimen,  $W_d$  was the mass of the dry specimen,  $V$  was the volume of the specimen and  $\alpha$  was the density of water.

### 2.7. Toxicity characteristic leaching procedure (TCLP)

The environmental impact of the produced geopolymer brick was investigated using TCLP. TCLP was conducted following the

United States Environmental Protection Agency method (USEPA) [32]. The leachability of BOFS was determined using an extraction buffer of acetic acid and sodium hydroxide (pH  $4.93 \pm 0.05$ ) at a liquid/solid ratio of 20:1 (USEPA, 1992). A thermostatic shaker was used for the extraction and was subjected to 24 h shaking at  $25 \pm 2$  °C. After 24 h three samples were taken per test conducted and filtered. The leachate was analysed using ICP to determine the concentration of leached metals.

### 3. Results and discussion

#### 3.1. Effect of alkalis concentration on UCS

Fig. 3 shows that there was an increase in UCS with increase in both the alkaline activators (NaOH and KOH) due to the formation of denser microstructure that bonded the GBFS with less numbers of pores [33]. This was due to increase in hydroxyl anion which led to dissolution of silica and alumina species [34]. There was a 45% increase in UCS at 10 M KOH compared to NaOH. Whilst 15 M NaOH activation resulted in 52% increase in UCS as compared to 10 M NaOH. Meanwhile 15 M KOH geopolymer showed a 45% decline in UCS, this might be due to excess  $K^+$  in the frame work of the geopolymer [35]. This reveals that NaOH is a better alkaline activator, which resulted in a greater degree of aluminosilicate dissolution in GBFS at a relatively high concentration because 15 M NaOH geopolymer had a UCS 1.3 times greater than the 10 M KOH geopolymer. This is attributed by the fact that the use of NaOH alone could produce extra silicate in the system and allowed the geopolymerisation process to accelerate the dissolution of aluminosilicates, which led to the increased UCS [31]. These results and observations are also in agreement with studies by [36,37] that the smaller ionic size of  $Na^+$  makes it a better promoter of aluminosilicates than  $K^+$  which forms more oligomers that are responsible for high UCS development. There was 81% and 94% decline in UCS for geopolymers prepared with 20 M NaOH and 15 M KOH respectively. This observation is in agreement with literature reported by [38,40]. The decline in UCS is attributed by the following: (1) high alkalinity that reduced the connectivity of silicate anions and accelerated gel dissolution rather than accelerating gel formation [38], (2) at high alkali concentration, the dissolution of silica and alumina is accelerated but the poly-condensation was hindered. An excess hydroxide ion caused the alumina silicate gel precipitation at the early stage and resulted in lower UCS of the

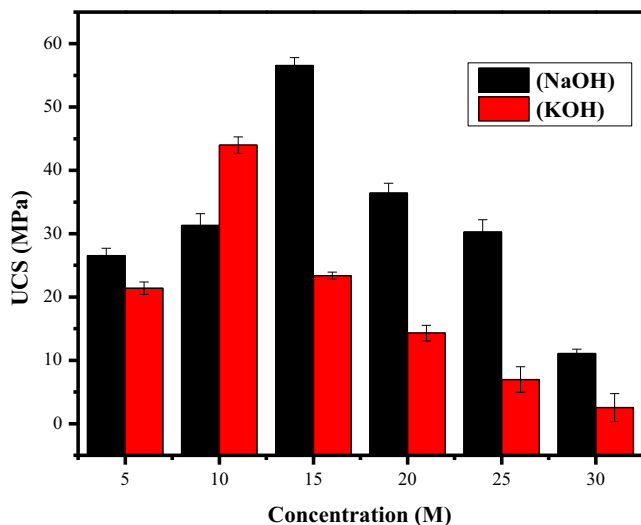


Fig. 3. Effect of alkalis concentration on UCS.

geopolymers [39]; (3) the dissolution of calcium was suppressed at high KOH and NaOH concentration resulting in less hydration products [12]. High alkali concentration may result in undesirable morphology and no uniformity of hydration products in the pastes, thus reducing strength [40]. The use of NaOH as an activator regulates hydration [40]. 15 M NaOH was chosen as the optimum curing conditions that yields the highest UCS.

#### 3.2. The effect of alkaline activator concentration in the mineralogy

Fig. 4 shows the XRD patterns of raw GBFS and GBFS based geopolymer specimens after alkaline activation. There is a broad diffuse hump around  $19^\circ$ – $39^\circ$  suggesting that the raw GBFS predominantly possesses glassy amorphous phase with magnetite and large quantity of silica as form of quartz. This observation is in agreement with previous studies by Huseien et al. [31]. The XRD patterns after alkaline activation showed a broad and amorphous hump at  $20^\circ$ – $40^\circ$  which confirms a formation of calcium silicate hydrate (CSH) and calcium aluminate hydrate. The calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) phases are responsible for the formation of a zeolite that mainly consist of alumina-silicates with  $SiO_4$  and  $AlO_4$  structures connected by shared oxygen atoms. The results are in agreement with observation reported by Falayi, [41] and Suwan et al. [43], revealed that formation of calcium silicate hydrate (CSH) phases contributes to higher strength developed in geopolymers matrix. which contributed to higher strength. There was also a development of new peaks on the amorphous hump at  $29^\circ$ – $30^\circ$  assigned to be the poorly crystalline phase of CSH, ettringite, calcite, hydrocalumite, CAH which indicates the formation of geopolymer products [44]. The development of a peaks at  $8^\circ$  after geopolymerisation (5 M, 10 M and 15 M) are ascribed to CSH for 5 M and 10 M samples while 15 M has CSH, ettringite and CAH. It is reported that CSH with low C/S ratio and CAH with low C/A ratio are the predominate hydration products in the system of geopolymerisation GBFS [45,46]. Crystalline phases in all three geopolymers samples (5 M, 10 M and 15 M) are very similar; The changes observed in the chemical structure of the gels over time are occurring in the amorphous phase of the samples and not many crystalline phases develop in the samples with increased alkaline concentration. This is attributed to the amorphous nature of the geopolymer gels, which makes their characterization difficult with XRD techniques

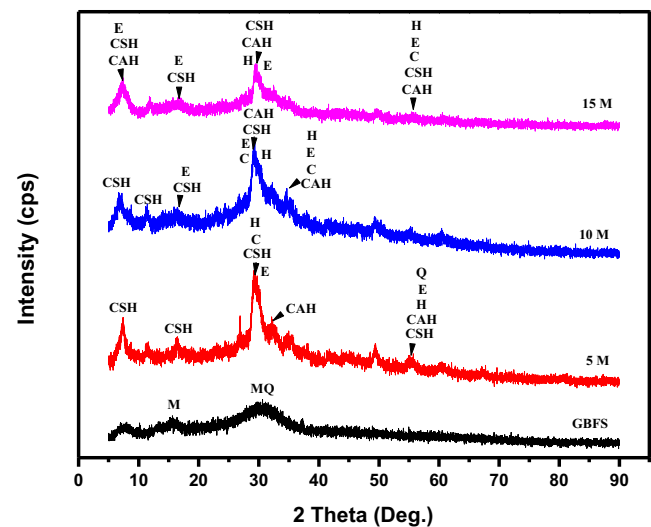


Fig. 4. XRD patterns of raw GBFS and GBFS based geopolymers at different alkali concentration (M = Magnetite, Q = Quartz, H = Hydrocalumite, CSH = Calcium silicate hydrate, CAH = Calcium aluminate hydrate, C = Calcite, E = Ettringite).

[36]. It is well known that the hydrated pozzolanic materials contain major crystalline phases of CSH, CAH, ettringite and hydrocalumite that could be formed as the major hydration product of cement paste and concrete or as a secondary precipitate during the hydration of GBFS, fly ash and other waste materials [47,48]. In fact, results show that the content of hydrocalumite and ettringite phases are almost constant in all the samples [49]. Calcium oxide (CaO) also reacted with carbon dioxide (CO<sub>2</sub>) to form calcite [44].

### 3.3. Effect of variation of alkaline concentrations on the morphology structure

Fig. 5 shows the SEM micrographs of raw GBFS and GBFS based geopolymers prepared at different alkali concentration (5 M, 10 M and 15 M), GBFS has heterogeneous morphology and clearly porous [50,51]. The micrographs of GBFS based geopolymers prepared at different alkali concentrations namely 5 M, 10 M and 15 M reveal non-porous geopolymers due to the addition of NaOH, where the matrix became very compact and flat with better space-filling properties through the formation of CSH and CAH gel [52]. The formation of CSH are identified in the XRD and the flat/ compact matrix at 15 M explains the highest compressive strength obtained. Zeolites formation is seen on the all GBFS geopolymer samples as whitish, flaky, fluffy and dense material on the surface leading to increased UCS. Lower concentration

resulted in some unreacted particles on the samples to precipitate instead of condensing into CSH and CAH gel and that resulting into weaker geopolymer matrix [32]. As more Si and Al were dissolved in the highly alkaline solution, the GBFS particles tend to develop cracks increasing the surface area for geopolymerisation [3]. The cracking up of particles led to further formation of more zeolitic materials. Higher concentration (15 M) has the densest matrix, which shows the better geopolymerisation hence the highest UCS. However, the unreactive materials also served as inert aggregates and reduced the number of cracks as they limited the shrinkage of the sample during the hardening process [49]. These observations are in agreement with finding reported by Tekin et al. [53], which highlights that the concentration of the alkaline solution plays a vital role in the microstructure of the geopolymer matrix.

### 3.4. Effect of liquid-solid (L/S) ratio on UCS

Fig. 6 shows the effect of variation of L/S ratio from 0.15 to 0.3 on UCS with geopolymer samples prepared using 15 M NaOH. There was a decrease in UCS with increase in L/S ratio. The geopolymer sample prepared at 0.15 L/S ratio had the highest UCS of 72 MPa. These results indicate that a decrease in the S/L ratio promotes higher UCS. The 0.15 L/S ratio gave the most favourable workability with a highest UCS. The L/S ratio less than 0.15 reduces the workability of the mixture. The UCS confirms that

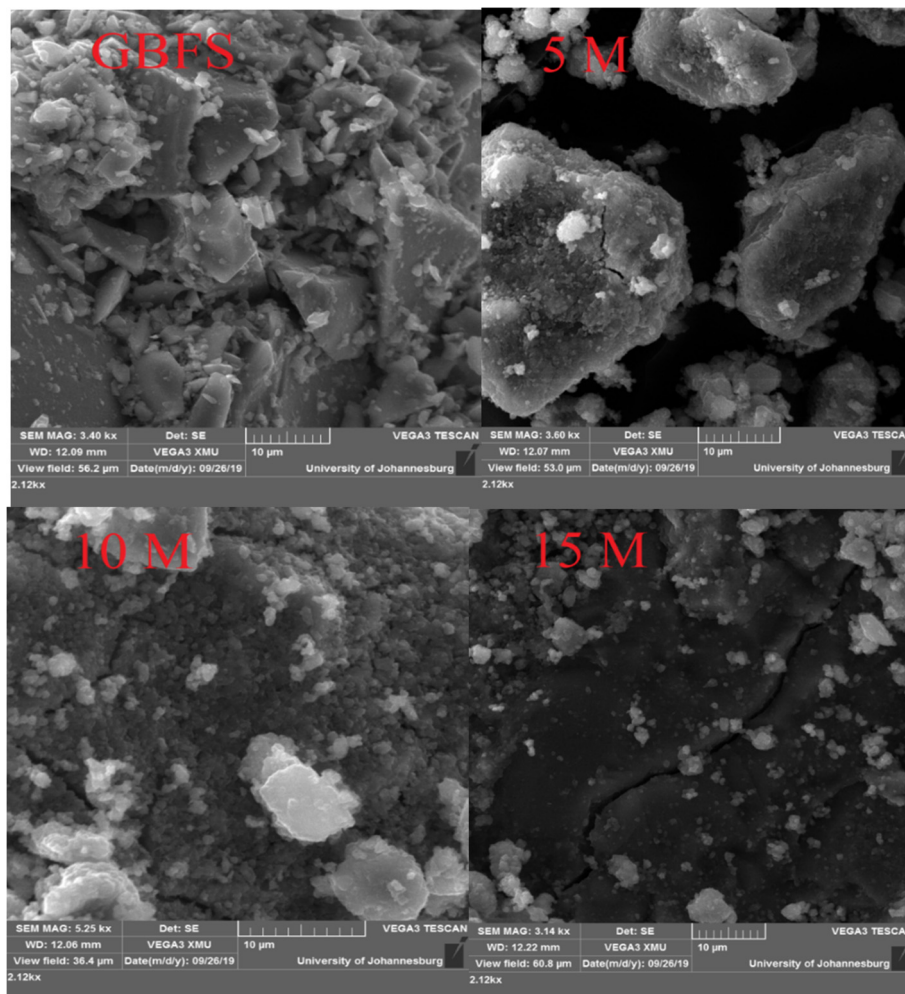


Fig. 5. SEM analysis of geopolymers with different alkali concentrations.

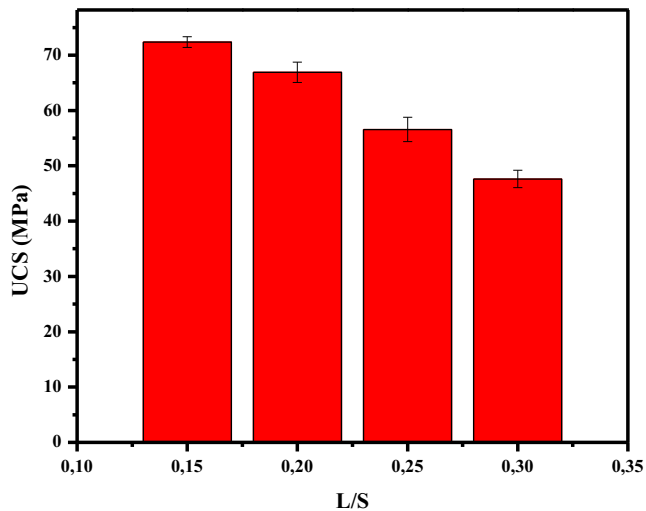


Fig. 6. Effect of liquid–solid ratios on UCS.

the activator content was optimum at 0.15 ratio that accelerated the dissolution of Si and Al without hindering the polycondensation rate during the geopolymer synthesis [54]. The increase of L/S ratio from 0.25 to 0.3 resulted in the mixture having very low gelation to permit molding and was of much reduced workability for good compaction, respectively [55]. This could be expected because an increase in the L/S ratio generally leads to a decrease in the concentration and alkalinity of the activator, which also weakens its impact on the geopolymers. Moreover, increasing the L/S ratio renders a larger number of pores in the hardened paste, which also leads to a decrease in the mechanical properties of synthesized products [56]. However, based on the microstructural analyses it is evident that the 0.15 L/S ratio is optimum its morphology appeared non-porous, flat and compacted contributing to the highest UCS was obtained. The results are in agreement with observation reported by Jenni et al. [25] which indicates that the molarity of the alkaline solution and L/S ratio can greatly affect the workability and the formation of geopolymer gel of the produced paste and ultimately degrade the mechanical performance of the produced geopolymer [56].

### 3.5. Effect of curing temperature on UCS

Fig. 7 shows there was an increase in UCS with increase in temperature. The geopolymers cured at 60 °C had UCS of 63 MPa. When the curing temperature was increased to 80 °C there was a 12.5% increase in UCS as compared to geopolymers cured 60 °C.

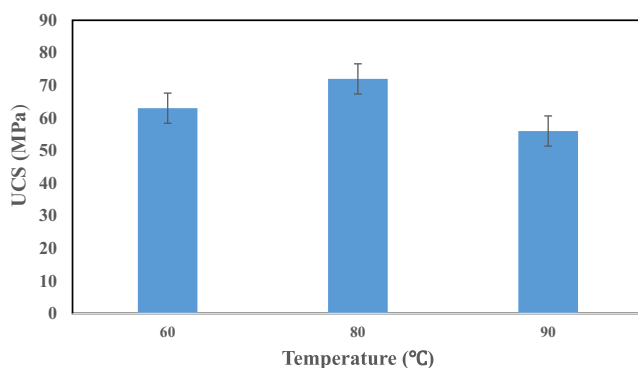


Fig. 7. Effect of curing temperature on UCS.

This is due to increase in the rate of reaction [57]. The increase in temperature led to a faster dissolution of Ca, Si and Al monomers from the source materials [58], which accelerates the formation of a calcium silicate hydrate (CSH) and aluminosilicate hydrate (CAH) gel as identified in the XRD patterns [31]. When the curing temperature was increased to 90 °C, there was a 11% decline in UCS. The decrease in UCS was due to most of the condensation polymerization had been completed at 80 °C [46]. Furthermore, the stability of NaOH might have been affected at elevated temperatures (>80 °C), as the temperature was close to the melting point of NaOH and the evaporation of the liquid phase could have hindered the geopolymerization process to complete, which resulted in reduced UCS [59]. Elevated temperature curing has been reported to improve the properties of geopolymers [60]. Furthermore, the aimed application for the produced geopolymer brick is to be used as a solid masonry brick. The thermal treatment for production of clay brick ranges between 1000 and 1200 °C with a minimum curing age of 50 h depending on the type of clay. Thus, the curing temperature in this study significantly reduces the energy consumption related to production of clay bricks. It is reported in literature that the production cost of geopolymer bricks is 6.4 times lower than the traditional fired clay brick [6].

### 3.6. XRD analysis of geopolymer samples cured at different temperatures

The XRD patterns of geopolymers cured at different temperatures are shown in Fig. 8. Raw GBFS predominantly possesses glassy amorphous phase with quartz and a smaller amount of magnetite [31]. Geopolymer samples cured at elevated temperatures (60 °C, 80 °C and 90 °C) show a broad and amorphous hump around 20°–40°, which confirms the formation of CSH and CAH phases [41,42]. The changes observed in the chemical structure of the gels with increasing temperature are occurring in the amorphous phase of the samples and not many crystalline phases develop in the geopolymers [36]. CSH appeared stronger at 7, 30 and 38° for samples cured at 80 °C [32]. The observations indicate that UCS was the highest at 80 °C due to the more CSH peaks responsible for the gain in UCS [41].

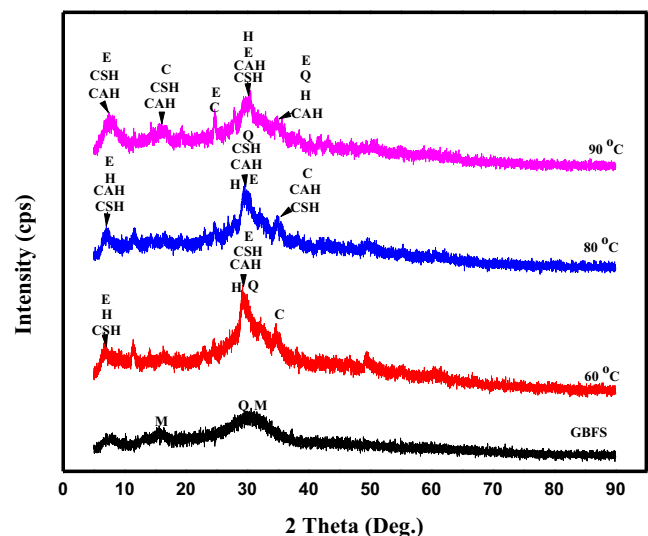


Fig. 8. XRD patterns of samples (M = Magnetite, Q = Quartz, H = Hydrocalumite, CSH = Calcium silicate hydrate, CAH = Calcium aluminosilicate hydrate, C = Calcite, E = Ettringite).

3.7. SEM analysis of samples cured at different temperatures

Fig. 9 shows the microstructural changes between the raw GBFS and geopolymers cured at different temperature. Raw GBFS had a heterogeneous morphology and clearly porous [50,51]. The geopolymer cured at 60 °C the particles are compact with whitish particle suggesting incomplete geopolymerisation. In addition the particles had some cracks revealing an increase in surface area of the particles which enhance the rate of geopolymerisation. The increase in temperature up to 80 °C led to a higher rate of the geopolymerization process, which accelerated the hardening of geopolymer pastes. In addition the geopolymer cured at 80 °C had a more compact/ dense microstructure with maximum packing of particle which led to highest UCS [31]. The geopolymer cured at 90 °C revealed a non homogeneous distribution of Interfacial transition zone along the aggregate surface [56]. This is caused

by high curing temperature that results in a quick hardening process thus leading to impairing the strength of the geopolymer [41].

3.8. Variation in UCS with wet and dry cycles

Fig. 10 shows the variation of UCS with wet-dry cycles. The wet-dry cycle test was used to measure the durability of the developed GBFS based geopolymer. There was a gradual decrease in UCS with increase in number of cycles until the 8th cycle. Thereafter, there was resistance in the gradual decrease of UCS with wet and dry cycles. After the 10th cycle, the GBFS based geopolymer had a UCS loss of 12% which suggest that the geopolymer is stable under wet and dry cycles and can be used in building and construction in areas experiencing floods and droughts [41]. Table 3 shows the absorption rate and open porosity of the GBFS based geopolymer.

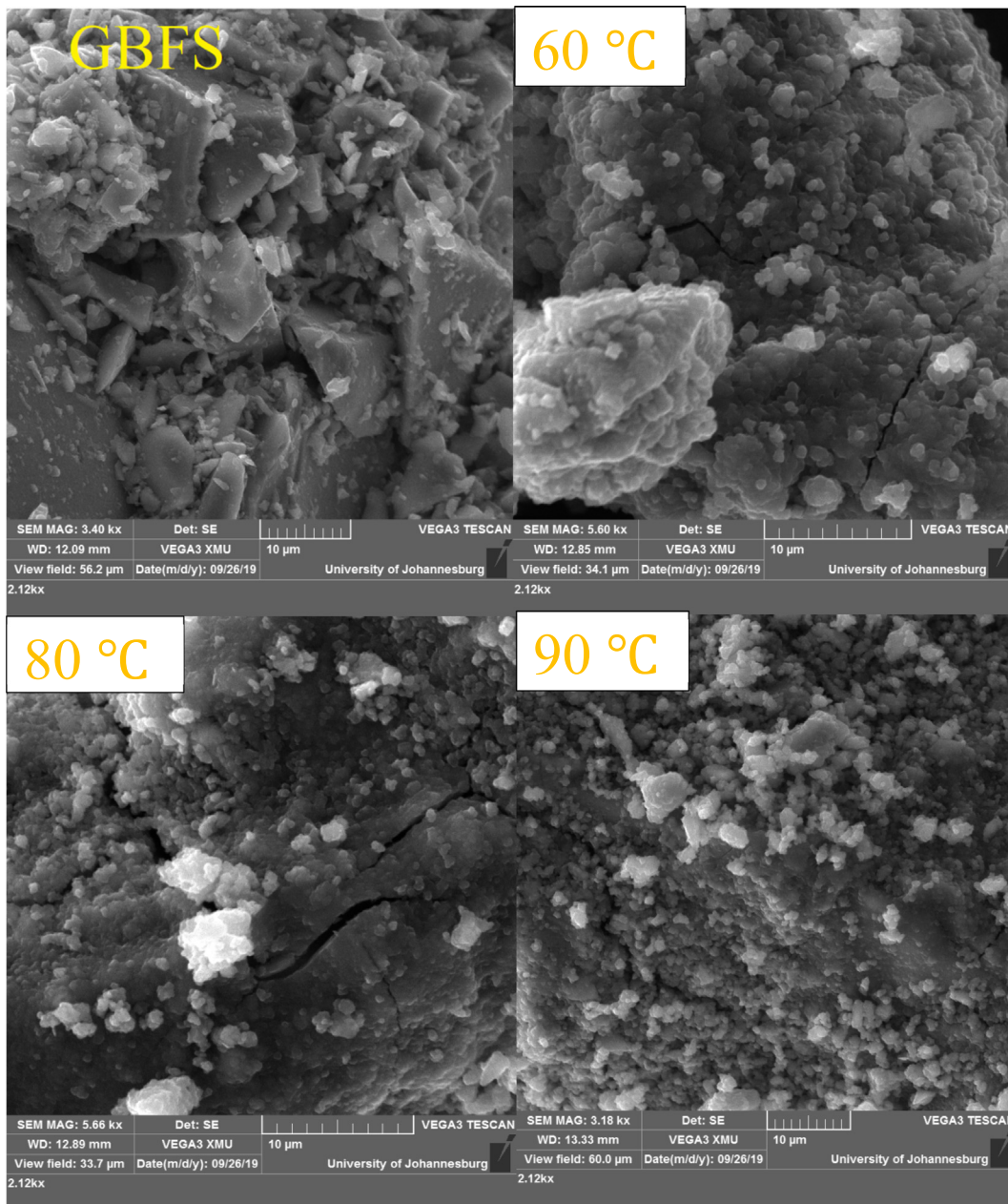


Fig. 9. SEM micrographs of raw GBFS and geopolymers cured at different temperatures.

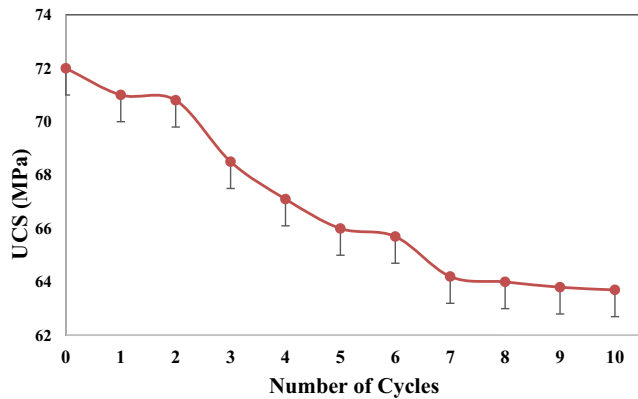


Fig. 10. Variation of UCS with wet-dry cycles.

### 3.9. The effect of a 30 days soak on the UCS, absorption rate and open porosity

Table 3 shows the physical properties of the GBFS based geopolymer after a 30 days soak.

It can be seen that there was a strength reduction of 25% after 30 days soaking as shown in Table 4. The GBFS geopolymer composite had the lowest water absorption rate of 3%. The lowest water absorption rate is due to a flat, dense and compacted microstructure presented in the SEM results and low porosity related to such composites [61]. Furthermore the low water absorption was attributed to the formation of additional hydration products that created strong bonds that filled the pores of the geopolymer matrix and connected particles in an enhanced structure [33].

### 3.10. Tcpl

The leachability of metals from raw GBFS and GBFS based geopolymer is shown in Table 4.

The TCLP analysis of raw GBFS and GBFS based geopolymer brick are shown in Table 4. The TCLP results show that raw GBFS metals concentration did not exceed the USEPA metal concentration threshold. The results show that there was effective immobilisation of heavy metals with over 98% reduction in leachability of the heavy metals in Table 4. The results indicate that the produced geopolymer brick is environmentally friendly and can be classified as a green building brick. The TCLP results agrees with the established literature by Kubba et al. [62].

## 4. Conclusion

Feasibility to synthesise geopolymer bricks from Granulated Blast Furnace Slag (GBFS) using alkali activators without addition of sodium silicate or silica reactive source was studied. The study also investigated the best type of alkali between NaOH and KOH,

Table 3  
A 30 days soak of geopolymer composite properties.

Geopolymer	
Mass of cured sample (g)	274.9
Mass of cured sample after 30 days soak (g)	283.4
UCS before soak (MPa)	72
UCS after soak (MPa)	55.9
% water absorption	3.0
% reduction in UCS	25
Open porosity	0.07

Table 4  
TCLP of raw GBFS.

Constituents	Raw GBFS Concentration (mg/L)	GBFS based geopolymer brick Concentration (mg/L)	USEPA maximum allowed concentration in leachate (mg/L)
Mn	1.45	0.39	5
Fe	1.20	0.02	10
Cd	0.019	N.D	1
Cr	0.008	N.D	5
Cu	0.005	0.001	5
Ni	0.005	N.D	0.2
Zn	0.002	N.D	0.1

suitable for GBFS geopolymerisation. In addition, the effect of alkali concentration, liquid–solid ratio, curing temperature and time on the physical and mechanical properties of geopolymer bricks was investigated using UCS, SEM micrographs, XRD analysis, water absorption, and bulk density. Metal leachability and durability of the synthesised geopolymer brick was also investigated. The study showed a stable geopolymer brick with high UCS (72 MPa) can be produce without addition of silica solution. Based on the result the following conclusion can be drawn:

- NaOH based geopolymer had higher UCS compared to KOH based geopolymer due to a greater degree of aluminosilicate dissolution in NaOH solution, more oligomers formed and developed high UCS. A geopolymer brick prepared with 15 M of NaOH, L/S ratio of 20%, the curing temperature 80 °C and curing age 5 days had the highest UCS compared to other curing conditions
- According to the ASTM C126-99 and ASTM C216-07a; the synthesised geopolymer brick met the minimum required UCS of 20.7 MPa and water absorption of less than 17% to be used as facing and solid masonry brick respectively.
- The synthesised geopolymer brick is environmentally friendly and can be classified as a green building brick as the metals concentration did not exceed the USEPA metal concentration threshold. This research paper therefore present full beneficiation and utilisation of GBFS as a low cost, environmentally friendly alternative building and construction material to mitigate against environmental pollution.

### CRedit authorship contribution statement

**N.T. Sithole:** Conceptualization, Methodology, Investigation, Writing - original draft. **T. Mashifana:** Conceptualization, Writing - review & editing.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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