2024 Scienceline Publication

Journal of Civil Engineering and Urbanism

Volume 14, Issue 3S: 295-301; September 15, 2024 ISSN-2252-0430

DOI: https://dx.doi.org/10.54203/jceu.2024.32

Behaviour of Fly-Ash Geopolymer Mortar in Simulated Environments

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RESEARCH ARTICLE

PII: S2252043024000032-14

Received: June 25, 2024

Revised: September 02, 2024

Accepted: September 05, 2024

ABSTRACT

Concrete and mortar usually found themselves in normal and harsh environments. The environment has great influence on the mechanical and durability behaviours of the concrete. In this study, fly ash was processed using circular economy concept and subsequently used as precursor for geopolymer mortar. The fly ash from Morupule power plant station has previously been characterized for its physical, chemical, and microstructural properties. Based on its suitability, the fresh and mechanical properties of the geopolymer mortar were carried out, and afterward, the durability behaviour is investigated in this study. The geopolymer mortar was formulated from the mixture of fly ash, sand and alkaline activators and cured thermally at 70°C. The behaviour of the geopolymer mortar in sulphuric acid solution, sodium sulphate solution, water absorption and fire resistance properties were simulated, and their loss in compressive strength and weight were determined. The laboratory experiment indicated that geopolymer mortars are highly resistant to sulphate attack, water absorption with moderate resistance against sulfuric acid and fire resistance. The effects of varying other parameters on the performance of concrete can be looked into in the future studies.

Keywords: Geopolymer mortar, environment, durability, mechanical, fly ash, circular economy

INTRODUCTION

The drive to have sustainable, environmentally friendly, and economical construction materials has shifted research focus to investigation of alternative construction materials for cement and aggregates. The research has led to the understanding that pozzolans are good replacement of cement in concrete and mortar production. There are some common pozzolans that have been embraced in the industry and currently being used to produce blended cement in some part of the world which include fly ash, ground granulated blast furnace slag and silica fume. These pozzolans have cementitious ability in the presence of lime. Pozzolans are known to be rich in silicon oxide and aluminum oxide and have binding qualities in the presence of alkali activators to produce geopolymer products through geopolymerisation process.

The management of waste has some drawbacks due to the limited landfill for disposal and enhancing environmental pollution. On the other hand, construction materials produced using such wastes can lower the cost of construction materials. Hence, there is an awakening to investigate ways of turning these wastes into useful products that can enhance economy, innovation, and sustainable infrastructure. Some of the wastes that are generated massively in Botswana are fly ash, bottom ash and other mining wastes. The production of these wastes will be on the rise annually based on the energy demand and population increase, hence, more damage to the environment if different utilization strategies are not investigated. Therefore, the need to re-use and beneficiate the wastes (fly ash, copper slag, ore tailings, rice husk, blast furnace slag) that are pozzolanic in nature into useful resource is high.

According to Cossu and Williams (2015), there is no unified definition to the word circular economy. However, there is a cutting-edge understanding which revolves on extending the life-span of the material. MacArthur (2014) and Pratt and Lenaghan (2015) applauded the application of circular economy to reducing utilization of primary material, preserving natural resources and cutting down carbon footprint. The other socio-economic benefits of circular economy have been identified to be increase in gross domestic products, EEA (European Environment Agency) (2016), and significant savings in primary resource and energy, Schulze (2016). Shilar et al. (2022) utilized granite waste powder in the range of (10 – 30%) as a substitute to GGBS to produce geopolymer concrete with the variation of molarity from 12 to 18 M. It was reported that workability and mechanical performance of GGBS replaced with GPC performed very well up to 20%.

Huseien et al. (2018) worked on GGBFS geopolymer mortar modified with metakaolin for repair applications. With careful manipulation of the chemistry of binder oxides of Na_2O: dry binder of 8% and ratio of SiO_2 to Na_2O of 1.16, early strength of 48 MPa was achieved at the age of 24 hours at ambient temperature. Various fresh and mechanical tests including shear bond attested that the product as potential repair applications. Zhang et al. (2021) analyzed mechanical performance of metakaolin fly ash based geopolymer mortar modified with nano-silica and polyvinyl alcohol fibres. It was deduced that addition of nano silica to 1.5 % of the total binder improved compressive strength, elastic modulus and fracture energy.

Thokchom et al. (2009) reported that geopolymer mortar in sulfur acid suffered severe attack in the loss of strength compared to its counterparts in nitric acid under the same working conditions. An article by Bakharev (2005) presented an investigation into durability of geopolymer materials manufactured using a class F fly ash (FA) and alkaline activators when exposed to 5% solutions of acetic and sulfuric acids. The results showed that some geopolymer materials made with sodium silicate and a combination of sodium hydroxide and potassium hydroxide as activators showed a notable reduction in strength. A paper by Kong et al. (2007) investigated the effect of elevated temperatures on geopolymers manufactured using metakaolin and fly ash of various mixture proportions concluded that the fly ash-based geopolymers have large numbers of small pores which facilitate the escape of moisture when heated, thus causing minimal damage to the geopolymer matrix. The strength increase in fly ash geopolymers is also partly attributed to the sintering reactions of un-reacted fly ash particles.

This current work is focused on the coal fly ash from Botswana Power Plants located in Morupule, Botswana. Botswana is a country in the southern part of Africa with an estimated population of 2,352,000 million by United Nations as at 2020, United Nations (2019). The republic is endowed with enormous and diverse solid minerals including diamond and coal among many others, Figure 1 shows the spatial distribution of the minerals across the country.

The energy company, Botswana Power Corporation, BPC was enacted in the year 1970 as a corporation responsible for generation, transmission and distribution of electric power, the functions she has been dutifully performed since inception. BPC, is a coal- based thermal plant located in Palapye town on 22.5515° S, 27.1147° E with generation installed capacity of 132 MW from Morupule A power station and 600 MW from Morupule B power station respectively. The source of the coal for the two plants is Morupule Colliery Coal Mine (MCM) which is also located at the outskirt of Palapye. Botswana coal production, consumption, and coal ash generation are shown in Figures 2 and 3 respectively.

This study is aimed at examining the durability properties of the fly-ash based geopolymer activated with alkaline activators. The mix design is developed for the fly ash which is followed with determination of the compressive strength and resistance of the geopolymer mortar in acidic, basic, water and fire conditions.

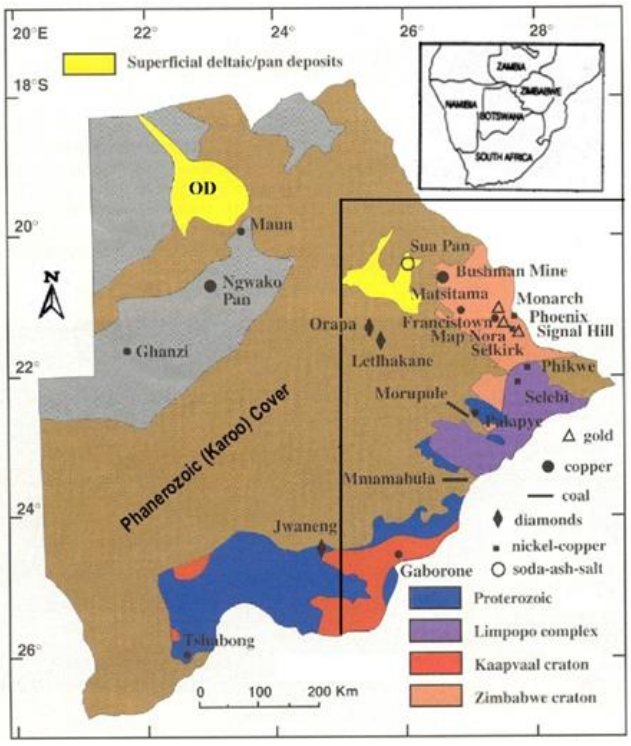

Figure 1. Geological map of Botswana showing main minerals (Ranganai et al., 2015).

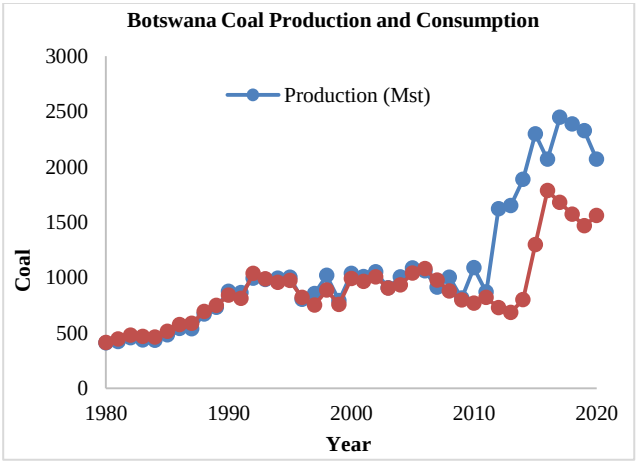

Figure 2. Botswana coal production and consumption (Mst) (EIA, 2020).

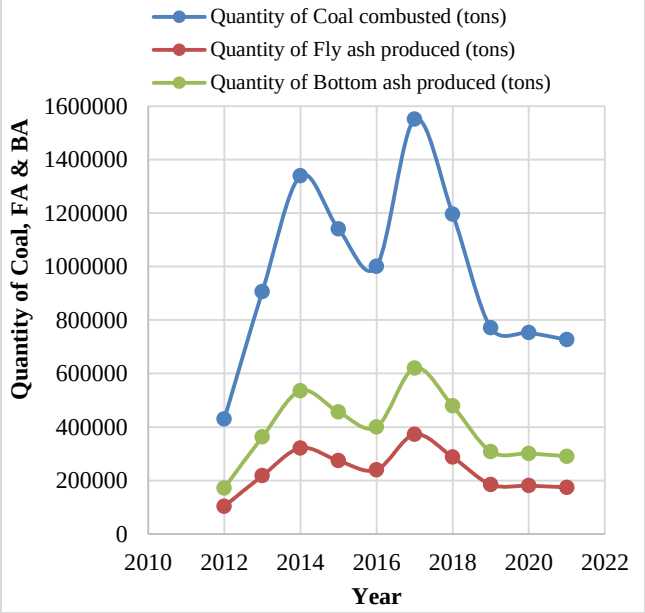

Figure 3. Quantity of Fly and bottom ashes generated between 2012 and 2021

MATERIALS AND METHODS

The fly ash used for this study was sourced from Botswana Power Plant in Morupule, Palapye located at 22.5515° S, 27.1147° E. The as-received fly ash was fine but later ground in a ball mill to obtain finer particles. The samples were further sieved with 75 µm sieve and tested for their inherent properties. The particle size distribution of the fly ash is shown in Figure 4 with d_{10} = 3.81µm, d_{50} = 21.24 µm, and d_{90} = 51.43µm. The specific gravity and specific surface area are calculated as 2.52 and 0.74 m^2/g respectively.

The results of the chemical and mineral compositions of the fly ash as determined by XRF and XRD are given in Table 1 and Figure 5. The scanning electron microscopy micrograph in Figure 6 shows that the fly ash is spherical in shape.

The fine aggregate used for the geopolymer mortar was sourced locally and was washed and oven dried for 24 hours. The alkaline activators for this project are Sodium hydroxide of (97 – 100 %) purity and sodium silicate with 14.7% Na_2O, 29.4% SiO_2 and 55.9% of water.

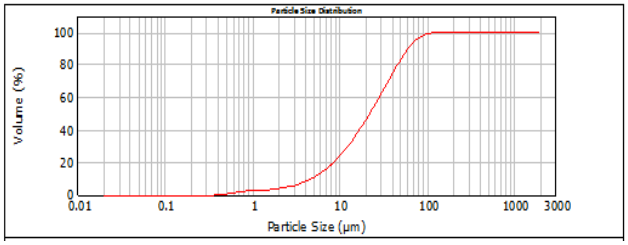

Figure 4. Particle size distribution of fly ash

Table 1. Chemical composition of the fly ash

Oxides	**(%)**	**(%)**	**0.09**
Fe_2O_3	8.75	P_2O_5	0.23
SiO_2	41.90	MnO	0.09
Al_2O_3	32.24	Cl	0.02
CaO	8.9	Cr_2O_3	0.05
SO_3	2.06	SrO	0.127
K2O	0.75	ZnO	0.02
MgO	0.94	ZrO_2	0.14
Na_2O	0.44	-	-

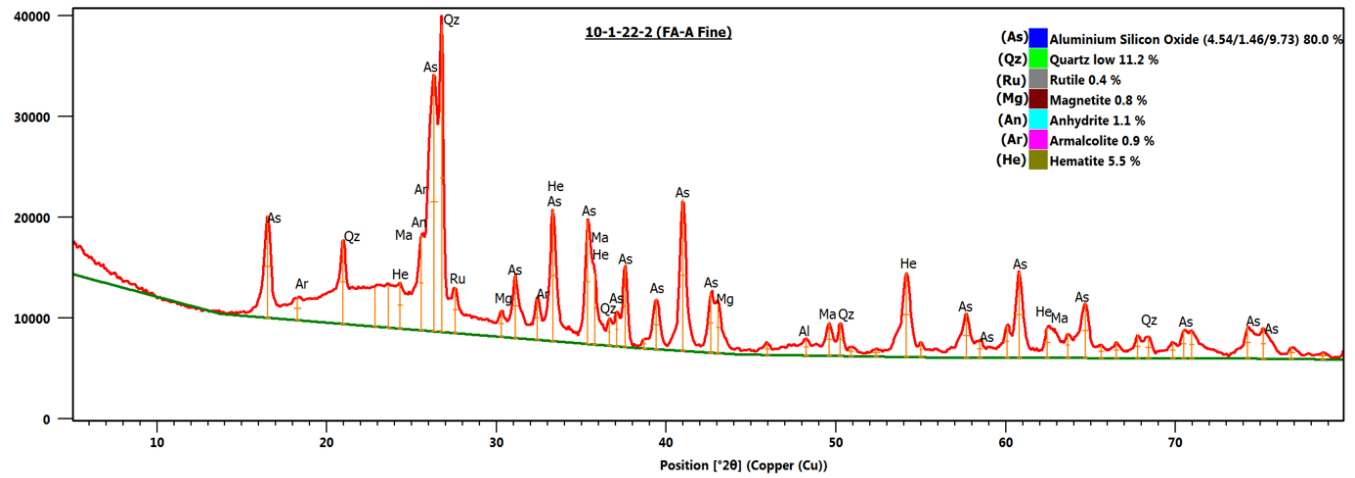

Figure 5. Mineral composition of the fly ash

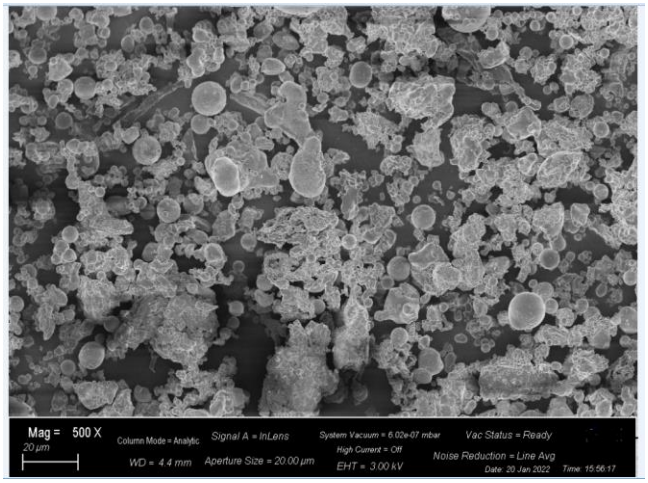

Figure 6. Scanning electron microscopy micrograph of fly ash

Compressive strength of geopolymer mortar

The geopolymer mortar mix design in Table 2 was earlier reported in Oyejobi et al. (2023), the production of geopolymer samples for the purpose of testing fresh and mechanical properties were also documented and illustrated in Figure 7. This procedure is followed by thermal curing at the temperature of 70°C for the period of 24 hours and left at ambient temperature until the testing date. The universal testing machine is 2000 kN and the settings followed the recommendation in ASTM C109-2020. At the end of 28 days, the samples were taken out for different durability tests which are outlined in the following sub-sections.

Table 2. Geopolymer mix design

Mix ID	1
Fly ash (g)	423
Sand (g)	1163
Molarity	12
Na2SiO3	127
NaOH	85
Na2SiO3/NaOH	1.5
Alkaline liquid/Fly ash	0.5

Figure 7. Production of geopolymer mortar

Chemical resistance of geopolymer mortar

The procedure in ASTM C267-06 was modified and used for simulation of test conditions like acidic conditions in real life. Highly concentrated sulphuric acid (98 – 100%) at 5% weight was adopted. To keep the acidic level, the solution was monitored and changed every week for the duration of 12 weeks. At the test date, weight of the sample was taken, and the weight change was calculated as:

$$\text{Weight change} = \left[\frac{A-B}{B}\right] * 100 \quad \ldots\ldots 1$$

A = Weight of specimen after immersion (g) and
B = weight of specimen before immersion (g).

The appearance of the specimens was monitored, and the compressive strength determined.

Resistance of geopolymer mortar to sulphate solution

Sodium sulphate of molar weight of 142.04 g/mol was used to make 5% sodium sulphate solution. The specimens were immersed inside the solution for a period of three months. At the end of the immersion period, length change in the prism and resistance of the specimens to the sulphate were determined. This test modified the outline in ASTM C1012-09.

Water absorption test for geopolymer mortar

Percent absorption of geopolymer specimen was determined in accordance with ASTM C642-06. The geopolymer specimens after the end of 28 days were dried in an oven at a temperature of 105 ºC for a period of 25 hours. After cooling, the geopolymer specimens were fully immersed inside the cold water for a period of 48 hours. Their masses were determined after surface-dried with towel and increase in mass was less than 0.5%. The absorption after immersion in percent was determined as

$$\text{Percent absorption} = \left\{\frac{B-A}{A}\right\} * 100 \quad \ldots\ldots 2$$

A = mass of oven-dried sample in air (g), B = mass of surface-dried sample in air after immersion, g.

Fire Resistance of Geopolymer Mortar

A laboratory furnace with maximum temperature of 1500ºC was used to test the fire resistance of the geopolymer specimens. Specimens were subjected to temperature of 500, 700 and 1000 ºC respectively at the heating rate of 5 ºC per minute. This is in accordance with methodology given by RILEM 129-MHT (2020) recommendation. The temperature was maintained for a period of 2 hours, thereafter, the samples were allowed to cool down for 5 hours. The mass of the specimens before heating and after heating were noted before the compressive strength was determined.

RESULTS AND DISCUSSIONS

Compressive strength of geopolymer mortar

The compressive strength of geopolymer mortar is shown in Figure 8 with 52 MPa at 28 days. This value is equivalent to 52.5 MPa for Portland cement and the binder is suitable for construction. In addition, early gain strength is observed at day three with insignificant reduction of 4% at the 28 days. The strength gain can be attributed to good proportion of silica oxide and aluminum, high specific surface area of the fly ash which when combined with alkaline activators, they formed right geopolymer matrix.

Result of water absorption of geopolymer mortar

The response of the geopolymer mortar in terms of water absorption and reduction in compressive strength is shown in Figure 9. As the days of sample immersion in water progresses, there was a corresponding increase in water absorption which subsequently lead to reduction in the compressive strength at 28 and 56 immersion days, the percent of water absorption was almost the same with a slight drop in strength. This suggests that the pores have been fully saturated with maximum percent water absorption less than 6% and almost 2% reduction in compressive strength at 56 days.

Result of resistance of geopolymer mortar to Sulfuric acid

At 5% acidic solution, the resistance of the geopolymer mortar over 90 days immersion period is reported in Fig. 10. The weight loss under the attack of acid solution was marginally small and increased with time. This could be attributed to densified mixture which was characterized with low water absorption. In Sata et al. (2012), a weight loss between 1.4 to 3.6% depending on the precursor but this was much lower compared to range of 77.2 to 95.7% as recorded for blended cement and Ordinary Portland Cement (OPC) mortar. A lower mass loss was credited to the stability of aluminosilicate framework in (Yang et al., 1996). There was a drop in the compressive strength over the immersion period with (%). These percentage reductions were much lower when compared with ordinary Portland cement-based mortar. In Djobo et al. (2016), 60% loss in strength was reported for volcanic based geopolymer mortar. Hence the resistance could be said to be a function of precursor characteristic.

Result of resistance of geopolymer mortar to Sodium Sulphate solution

In sodium sulphate solution, there was no change in colour, and the structural integrity was maintained. The result in Figure 11 follows the same trend with geopolymer response to sulphuric acid; however, the reduction in strength and loss of weight were much lower in sodium sulphate solution compared to Fig. 10. This shows that geopolymer mortar has higher resistance to basic attack.

Result of resistance of geopolymer mortar in elevated temperature

The geopolymer samples show visible cracks when exposed to fire resistance. In Fig. 12, the weight loss at 500 and 1000ºC were higher compared to 700ºC. The geopolymer product formed at 700℃ could be regarded to be more stable and behaved like ceramic and at a temperature beyond 700ºC, there was thermal expansion which resulted in the significant loss of compressive strength.

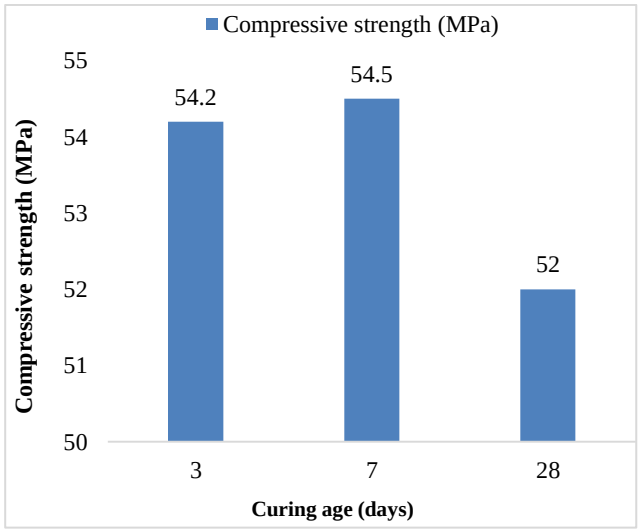

Figure 8. Compressive strength of geopolymer mortar

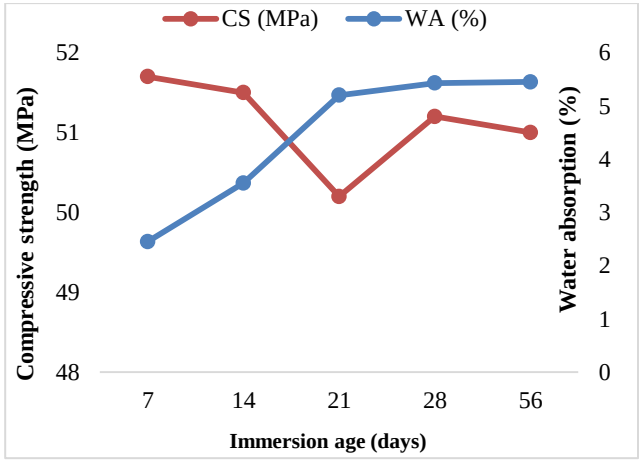

Figure 9. Effect of water absorption on the compressive strength

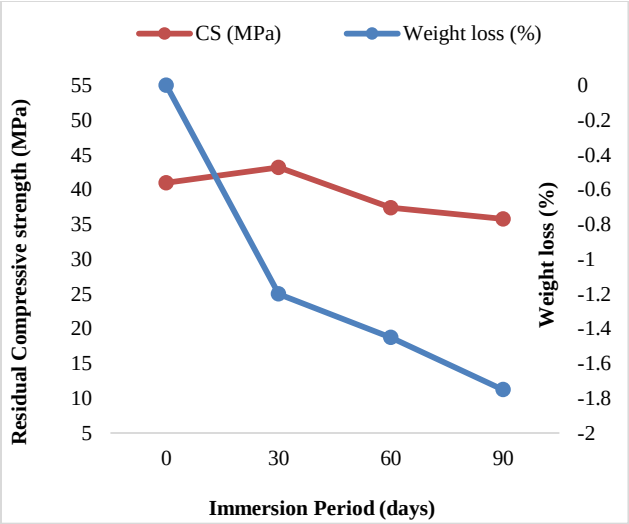

Figure 10. Resistance of geopolymer mortar to sulfuric acid

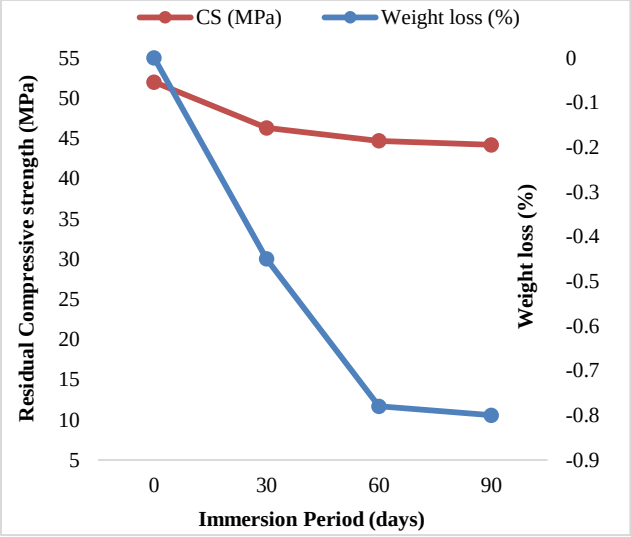

Figure 11. Resistance of geopolymer mortar to sodium sulphate solution

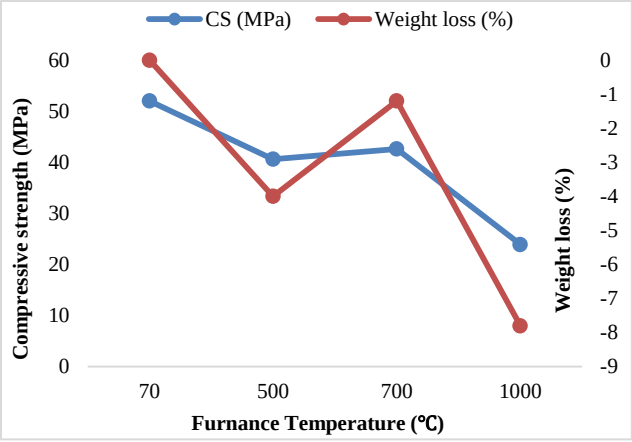

Figure 12. Resistance of geopolymer mortar in elevated temperature

CONCLUSIONS

The raw fly ash was re-engineered using circular economy concept and the performance of the fly-ash based geopolymer is reported as follows:

The fly ash from Morupule power plant is characterized and classified as Class F based on its properties.

The geopolymer binder performed excellently in terms of compressive strength with maximum compressive strength of 52 MPa.

In hierarchy of resistance in simulated service conditions, it is of order of water absorption, sulphate attack, acid attack, and elevated temperature with maximum residual strengths of 98%, 85%, 69% and 46%, respectively.

The recycling of industrial waste from Botswana Power Corporation requires lesser energy for binder production, saves environment from pollution and degradation and found suitable, sustainable and durable for the use as construction material.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Acknowledgements

The author would like to thank University of Botswana for sponsoring the presentation of these findings at the International Conference on Civil Engineering for Sustainability and Resilience in the 21st Century and Beyond (ICCESR 2024) at the University of Botswana, Gaborone, Botswana.

Authors' contribution

The author developed the concept, carried out the experiment and wrote the manuscript.

Competing interests

The author declare no competing interests in this research and publication

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