International Journal of Academic Engineering Research (IJAER)
ISSN: 2643-9085
Vol. 7 Issue 4, April - 2023, Pages: 15-23

An Evaluation Of The Mechanical And Physical Properties Of Sisal Fiber-Reinforced Alkaline Activated Diatomaceous Earth-Based Geopolymer Concrete

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***Abstract**: To achieve sustainability in the manufacturing of concrete, numerous researchers have developed an interest in cutting-edge geopolymer technology and geopolymer composite production. The viability of employing diatomaceous earth from Nakuru, Kenya, reinforced with sisal fiber as a source for geopolymer concrete was evaluated in an effort to create a sustainable geopolymer concrete with acceptable performance attributes. Standard procedures were used to conduct the chemical and physical analysis of diatomaceous earth. The mechanical and physical characteristics of the sodium hydroxide/sodium silicate ($NaOH/Na_2SiO_3$) alkaline activated diatomite-based concrete specimens were evaluated using the standard test methods. According to the diatomaceous earth's chemical analysis, silica (SiO_2) made up 88.12 % of the material; Aluminium oxide (Al_2O_3) was 4.25 % while calcium oxide (CaO) was 4.26 %. Other oxides such as MgO, K_2O, TiO_2, MnO, Fe_2O_3, and P_20_5 were also present in trace amounts. The study of particle size revealed that the diatomaceous earth from Nakuru, Kenya, had a fine composition and an average particle size of less than 50.4 µm. The maximum property values for compressive strength, density and water absorption attained by the diatomite-based specimens were, 34.05 MPa, 1.38 g/cm^3 and 20.42 % respectively. The diatomaceous earth's chemical composition suggests that it is comparable to Class F pozzolan. The mechanical, physical and durability performance falls within the acceptable limits as provided in the reviewed literature. As a result of this research, it is possible to successfully use Kenyan diatomite reinforced with sisal fibers as a silica source in geopolymer formulations, opening up new possibilities for utilizing and recycling this resource of natural and industrial waste.*

Keywords— Diatomaceous earth, characterization, pozzolan, geopolymer, sustainability

1. INTRODUCTION

Several studies [1–3] have shown that the building and construction sector utilizes more than 40% of the world's energy and produces nearly the same amount of CO_2. As a result, the construction sector faces ongoing pressure to reduce its negative effects on the environment and high energy, raw material, and water use. The simplest way for architects to begin introducing sustainable concepts into construction projects is to carefully select eco-friendly building materials [4].

Numerous researchers have become interested in cutting-edge geopolymer technology and the creation of geopolymer composites as a means of achieving sustainability in the production of concrete. It has the potential to be a more environmentally friendly alternative to conventional Portland cement concrete because it uses a variety of wastes as supplementary cementitious materials (SCM) or precursors in the synthesis of geopolymers, at low temperatures and with little energy [5,6]. This could reduce the cement industry's CO_2 footprint by up to 80% [7]. The process of geopolymerization yields either sodium aluminosilicate hydrate (N-A-S-H) gel or calcium aluminosilicate hydrate (C-A-S-H) gel, which causes the geopolymers to harden, resulting in the production of materials with outstanding durability, strength, and sustainability [8].

In the realm of cement and materials research, the use of pozzolanic materials has been a major research emphasis in recent years in order to decrease consumption and dependence on cement [9]. Fly ash, ground granulated blast furnace slag, metakaolin, silica fume, and rice husk ash are some of the most widely used geopolymer precursors (aluminosilicate sources) that have been well investigated thus far [10]. Payá et al. [11] and other experts consider natural or spent diatomaceous earth, also known as diatomite, to be one of the geopolymer system components, however it hasn't received much attention as a source of aluminosilicate minerals. Its potential for usage as a geopolymer precursor material is made possible by its pozzolanic, porous, affordable, and ecologically sound nature [12].

For industries like food processing and brewing, spent diatomaceous earth (SDE) is a substantial source of industrial waste [13,14]. The brewing industry, for instance, generates about 378.1 million kilograms of SDE each year [15]. This used diatomite is either dumped in landfills or utilized as organic fertilizer on crops, both of which waste resources and pollute the environment [13]. Use of diatomaceous earth in agriculture may also raise the danger of leaching nitrogenous chemicals found in waste diatomaceous earth. The regeneration of SDE might not be a possibility because of the high energy, labor, and cost demands. Therefore, it is crucial to use SDE in applications that are both economically and environmentally sound. Consequently, in order for diatomite to be used as a geopolymer resource, a fuller understanding of its physical, chemical, mechanical, and pozzolanic properties is required.

In spite of the fact that geopolymers have been found to have better mechanical characteristics and greater resistance to fire, sulfates, and acids than OPC-based materials [16], they exhibit brittle failure because of their low tensile strength, which may place several restrictions and limitations on the structural functions they may be used for [17]. According to the review by Zhang et al. [18] and other studies, adding fibers to concrete is an effective way to increase its ductility and toughness and prevent cracks from spreading. Jamshaid et al. [19] pointed out that the most promising methods for improving strength without harming the environment and enabling the efficient and sustainable use of renewable resources is to reinforce concrete with fibers. In line with Broeren et al. [20], sisal fiber has the potential to replace glass fiber in natural fiber composites. Therefore, the main goal of this study is to assess the effectiveness of an alkaline activated sisal fibre reinforced diatomaceous earth binder as a source of geopolymer concrete.

2. MATERIALS AND METHODS

2.1 Materials

The primary materials used in this investigation were raw diatomaceous earth, sisal fibers, and alkaline activators. In this case, sodium-based alkali activators were used, namely a solution of sodium hydroxide and sodium silicate gel ($NaOH/Na_2SiO_3$). The choice to employ $NaOH/Na_2SiO_3$ was made in light of earlier geopolymer concrete research, which was reviewed in the publication by Kipsanai et al. [21].

The research components were obtained from sources within Kenya; specifically, diatomaceous earth was obtained from Nakuru, Sisal fibres from Mogotio, while sodium hydroxide and sodium silicate were purchased from one of the outlet vendors in Eldoret. The incorporation of random short fibers was inspired by earlier researchers like Mahmood et al. [22] and Silva et al. [17] who discovered that random short fibers in a cementitious media enhance toughness, ductility, and strength by bridging and minimizing the cracks; and do not require complex processing procedures.

2.2 Diatomaceous earth characterization

Upon delivery, the diatomaceous earth was already finely ground. It was dried in an oven for 24 hours at 110°C to remove all the moisture. According to ASTM C114-10 [23], the chemical composition was determined using an X-Ray fluorescence (XRF) device (2010). The X-Ray diffraction (XRD) method was used to determine the crystalline structure of the diatomite for further mineralogical analysis. A particle size distribution examination was carried out using an LS 13 320 Laser Diffraction Particle Size Analyzer in accordance with ASTM B822–17 [24] criteria.

2.3 Geopolymer sample preparation

With reference to Geopolymers and other Geosynthetics [25] Figure 1 presents the flow diagram that was followed in the process of diatomite's chemical activation for geopolymer development.

The two-stage mixing sequence was adopted since the literature review revealed that it was the most typical for handling dry raw materials. The development of the specimens was carried out at room temperature, and the water utilized in the mixing process was simply laboratory distilled water.

The geopolymer specimens were prepared using a 12M NaOH solution, and the sodium silicate to sodium hydroxide ratio was maintained at 2.5 as in the works of Ganesan et al. [26] and Lavanya et al. [27]. 480 grams of NaOH were dissolved in 1000 millilitres of distilled water to create a 12M NaOH solution. A constant liquid-binder ratio of 0.7 was applied during the mixing process.

In accordance with Namango [28] work, long fiber bundles of decorticated fibers were extracted from the leaves of the sisal plant, cleaned, dried in the air, and then cut into average lengths of 3 to 10 mm; the percentage proportion range utilized for sisal fibres was 0.25%-1.25% wt.

Danso [29] recommendation for a continuous compaction pressure of 8MPa was followed for shaping the geopolymer bricks in a mold that measured 160mm by 40mm by 40mm. The brick specimens underwent heat treatment at 70°C for 24 hours after demolding, and then they were kept at room temperature for an additional 28 days before performance testing.

Table 1 depicts the experiment plan for producing the geopolymer specimens.

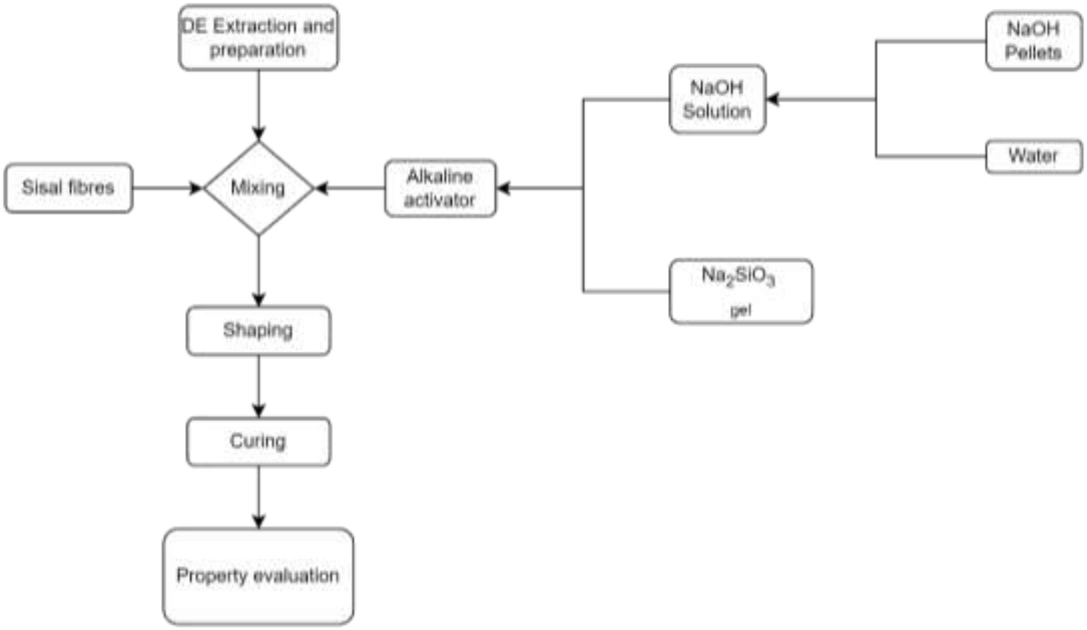

Figure 1. Flow chart for diatomite activation.

Table 1. Design of experiment for chemical activation of diatomite

Group	Run	A: DIATOMITE	B: SISAL	C: Alkaline activator		Specimen Name
		% wt	% wt	Na_2SiO_3 %wt	NaOH %wt	
1	1	100	0	50	20	D100
2	2	99.5	0.5	50	20	DS0.5
	3	99.125	0.875	50	20	DS0.875
	4	98.75	1.25	50	20	DS1.25

2.4 Geopolymer performance evaluation

The ASTM C109/C109M [30] standard was followed in determining the compressive strength of the bricks utilizing a 50kN-WP 310 universal Materials testing equipment. Although some studies argue that the wet compressive strength would be a better criterion to evaluate the durability of blocks, this work is based on the dry strength values. Because earth blocks will always be dry, determining the dry strength would be the most logical choice, according to [31]. The bulk density was determined in compliance with ASTM-C642, [32]. The water absorption experiment was conducted following ASTM C373-14, [33]. The dimensions of the brick samples were measured using a Mitutoyo ABSOLUTE Digimatic Vernier Caliper (500 series), which has a 0.01 mm precision. **Error! Reference source not found.** provides the pictorial descriptions of the experimental tests regarding compression strength, bulk density and water absorption.

3. RESULTS AND DISCUSSION

3.1 Diatomaceous earth characterization

i. Chemical and physical analysis

Table 2 displays the findings of the chemical analysis of diatomaceous earth.

Silica (SiO_2) was the predominant component, with 88.120%. This suggests that the diatomite under investigation is an acidic rock that falls under the opal A + CT group, as defined by Stefanou et al. [34]. The diatomaceous earth has a high siliceous content, and in accordance with ASTM C618 [35], since it contains more than 70% by weight of SiO_2, Fe_2O_3, and Al_2O_3 and less than 10% of CaO, it might be categorized as a Class F normal type of pozzolan or a silicate glass material. It was clear that the diatomite wasn't clayey because its alumina (Al_2O_3) content was lower than the literature's suggested range of 14–16%.[34,36]. Other oxides such as MgO, K_2O,

TiO_2, MnO, Fe_2O_3, and P_2O_5 were also present in trace amounts.

The XRD analysis (Figure 3) showed that cristobalite was the predominant mineral in the Kenyan sampled diatomaceous earth. With reference to the classification done by Ejigu et al. [37], the observed diffraction peaks are typical peaks for paracrystalline silica polymorph opal-CT derived from the volcanic environment.

The strongest reflection peak is at about 21.5°, with weaker peaks at around 29°, 32°, 36°, 45°, 57°, and 65°. The resulting diffraction peaks show the presence of α-cristobalite together with variable degrees of stacking disorder, which causes maxima that are linked to tridymite.

The X-ray diffractometry (XRD) mineralogical finding strongly supported Kogel & Society for Mining [38] and hypothesis that the Kenyan Rift Valley hosts diatomaceous earth deposits which appear to be of lacustrine origin (from lacustrine diatomite diagenesis) pre-dating one or more episodes of faulting and vulcanicity.

The XRF chemical analysis output (Table 2) and the XRD results (**Error! Reference source not found.**) agreed that silica (SiO_2) was the predominate chemical compound.

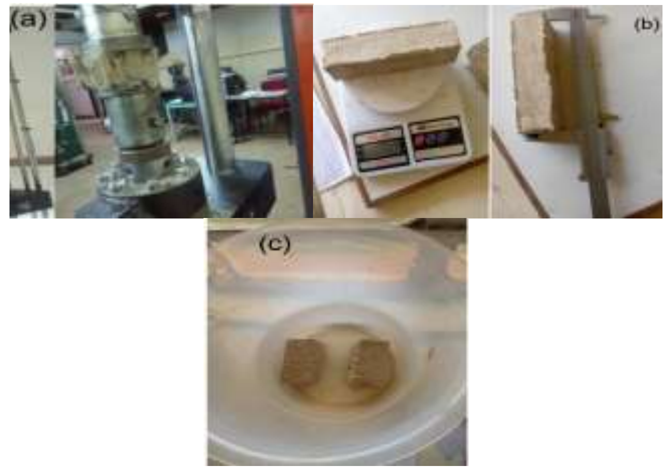

Figure 2. (a) Compressive strength testing (b) Bulk density testing (c) Water absorption test

Table 2. Diatomaceous earth chemical analyses results

Specimen type	**Chemical content (%)**								
	SiO_2	Al_2O_3	CaO	MgO	K_2O	TiO_2	MnO	Fe_2O_3	P_2O_5
Diatomite (Raw)	88.120	4.254	4.257	0.861	0.673	0.130	0.02	1.528	0.073

ii. *Particle size analysis of diatomaceous earth*

The raw diatomite particle size distribution analyzed by the laser particle analyzer was Dv (10): 7.58 µm, Dv (50): 23 µm, and Dv (90) 50.4 µm. Relating to Osborne's [39] analysis, the raw diatomite was found to be more similar to cement, in terms of particle size, since about 90% of its particles were smaller than 50.4 µm. Figure 4 shows the raw diatomite particle size distribution.

According to Makusa [40], fine-grained granular materials are the easiest to stabilize because of their large surface area to particle diameter ratio. The particle size analysis of the raw diatomite revealed that it is a fine-grained earth material, making it suitable for use as a geopolymer precursor.

3.2 Geopolymer performance evaluation

Table 3 summarizes the performance evaluation findings for the NaOH/Na2SiO3 activated diatomite geopolymer brick.

Table 3. NaOH/Na_2SiO_3 activated diatomite performance properties

S/No.	**Specimen Name (Mix ID)**	**28th day performance properties**		
		Compressive strength (MPa)	Density (g/cm^3)	Water Absorption (%)
1	D100	22.98	1.38	9.32
2	DS0.5	34.05	1.36	12.14
3	DS0.875	33.62	1.31	12.49
4	DS1.25	27.68	1.29	20.42

Figure 5 presents a visual distribution of the developed diatomaceous earth-based geopolymer activated with NaOH/Na_2SiO_3 in terms of compression strength, bulk density and water absorption.

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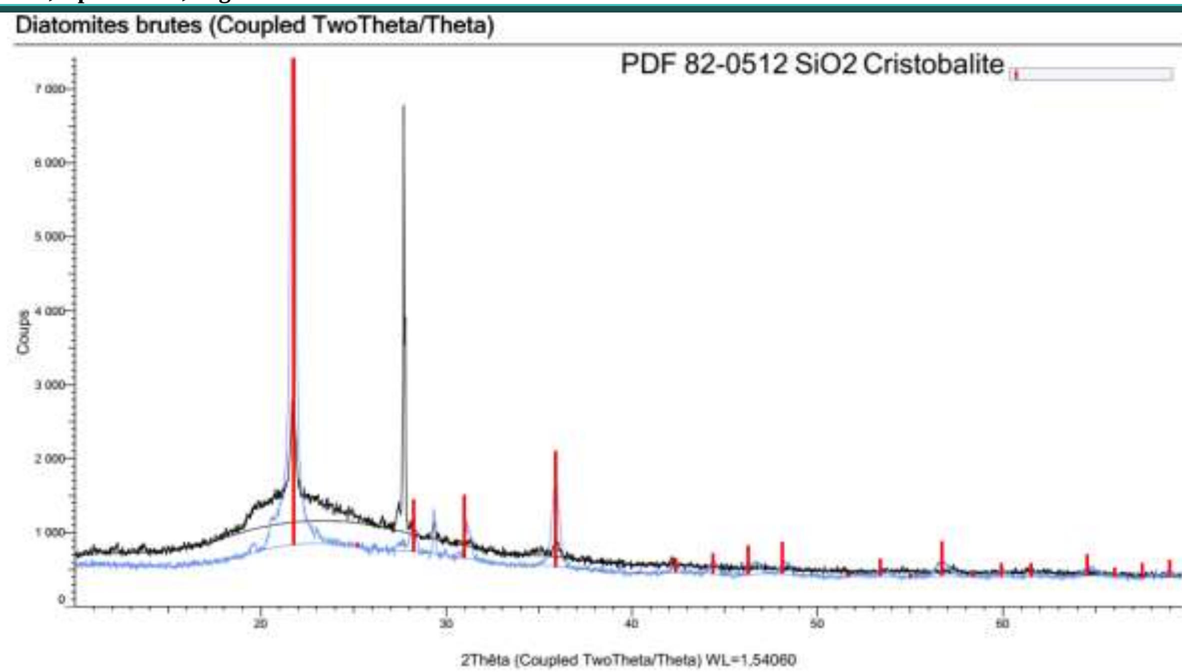

Figure 3. XRD output for diatomaceous earth

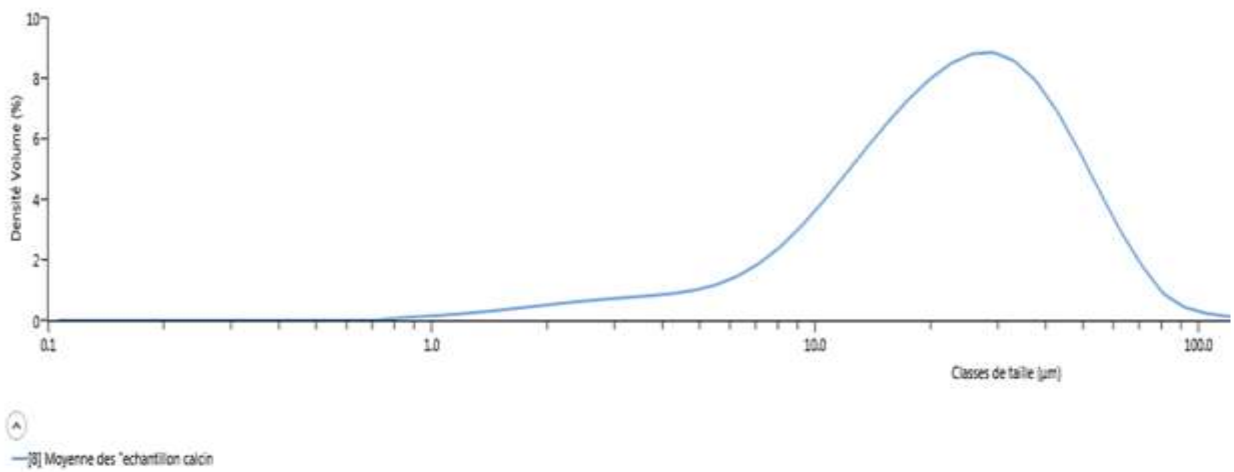

Figure 4. Raw diatomite particle size distribution

The $NaOH/Na_2SiO_3$ activated specimens yielded a maximum compressive strength (CS) of 34.05 MPa and a minimum CS of 22.98 MPa. The strength achieved with $NaOH/Na_2SiO_3$ alkaline activation is mainly due to the formation of hydration product Na-S-H (sodium silicate hydrate) gel which is formed due to hydration reactions [41]. The trendline of sisal incorporation versus compressive strength indicates that there is a linear relationship, so that the increase of sisal fibres leads to an increase in compression strength. The actual curve shows that the linear proportionality changes at some point (approximately 0.7% sisal fibre loading) beyond which the compressive strength is reduced. These observations, which are supported by the law of mixtures, have been made by a number of other studies, and they suggest that a further increase in fiber loading may lead to the formation of voids, which may then cause a material to fracture under compression stress. Increased sisal fiber content may have caused microfractures to form at the interfaces, lowering compressive strength. The fundamental reason for this flaw is that natural fibers are hydrophilic by nature due to the presence of hydroxyl groups and other polar groups, which makes them incompatible with the hydrophobic composite matrix.

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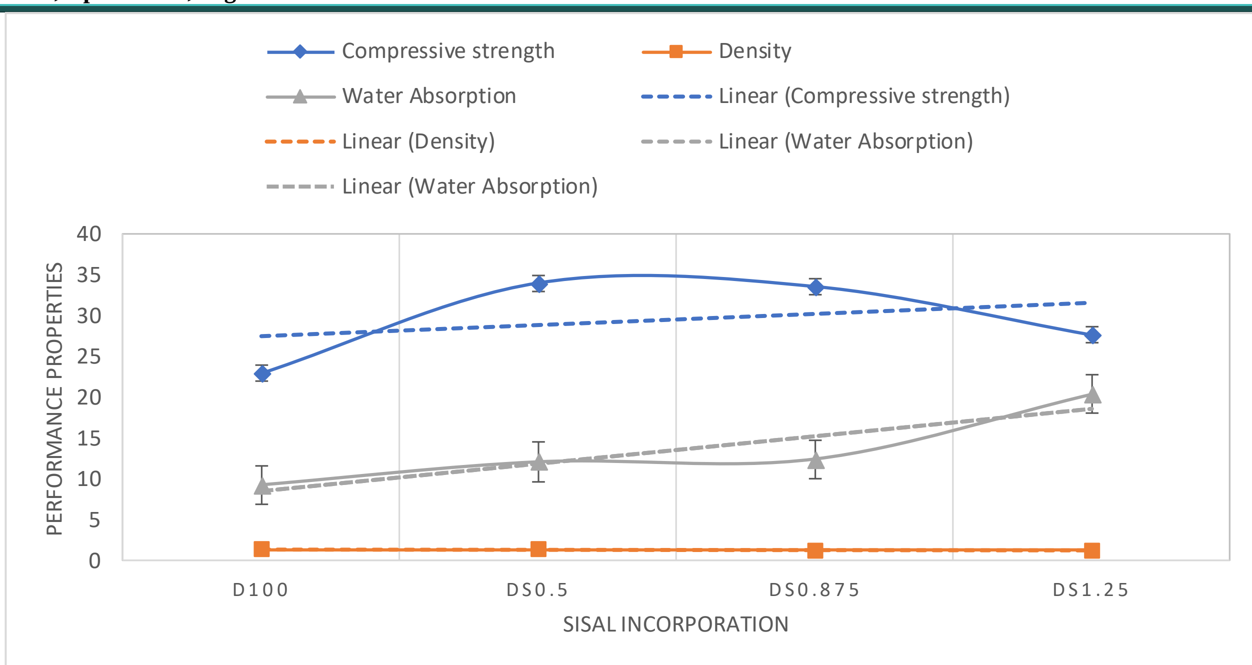

Figure 5. Visual presentation of $NaOH/Na_2SiO_3$ activated diatomite performance properties

The hydrophilicity of natural fibers denotes high fibre absorbability, which is the primary factor in the hydrophobic matrix's poor adhesion to them. This affects the surface's friction and abrasion as well as the swelling or delamination of the fibers [42]. This is also in agreement with the work of Ugwuishiwu et al. [43]. Sisal fibers had a tendency to clump together during mixing, which could have an impact on the composites' strength. Higher sisal fiber loadings may result in voids and uneven fiber orientation, which may explain the decreasing strength.

The relationship between the sisal fiber content and compressive strength of the geopolymer specimens is illustrated in Figure 6. Despite a positive gradient of the trendline, the regression coefficient, R^2=0.161, demonstrates a weak association between the two factors.

The lack of a strong association between the compressive strength and sisal fibres may indicate that many other elements besides sisal fibers may have had an impact on the compressive strength.

The $NaOH/Na_2SiO_3$ activated geopolymers yielded a maximum density of 1.38 g/cm^3 and a minimum density of 1.29 g/cm^3. The density values of the $NaOH/Na_2SiO_3$ activated geopolymer were found to be within the permitted range of less than 1.68 g/cm^3 for lightweight concrete, according to ASTM C1634 [44] . Since there is currently no standard for geopolymer concretes (or mortars), these criteria can be used to categorize geopolymer concretes (or mortars) based on unit weight. In this respect, it may be said that the combinations of geopolymer concrete that were developed can be categorically referred to as lightweight.

Despite a minute effect of the sisal incorporation on the density of the geopolymer specimens, it could be detected that the density decreased with the increase in the sisal fibre content. This is because addition of fibers would result in the introduction of more voids or air spaces, which would increase volume and cause a drop in mass, leading to low density. With an R^2 of 0.949, Figure 7 shows a significant association between the sisal fibre content and the bulk density of the developed geopolymer concretes.

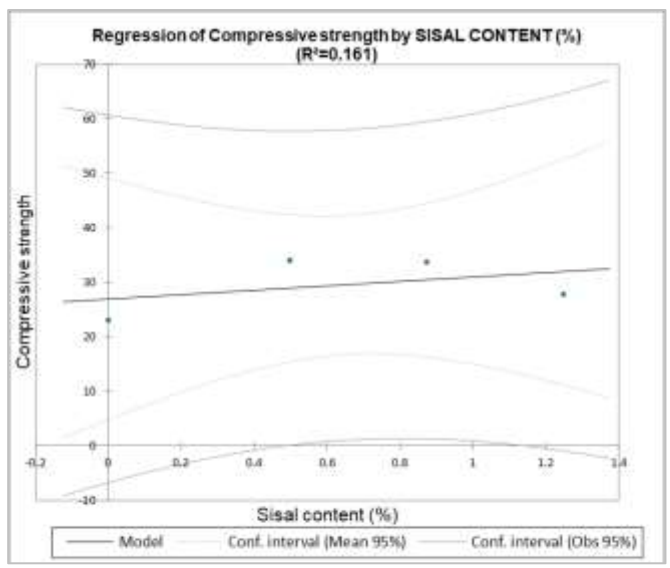

Figure 6. Correlation between the sisal fibre content and the compressive strength

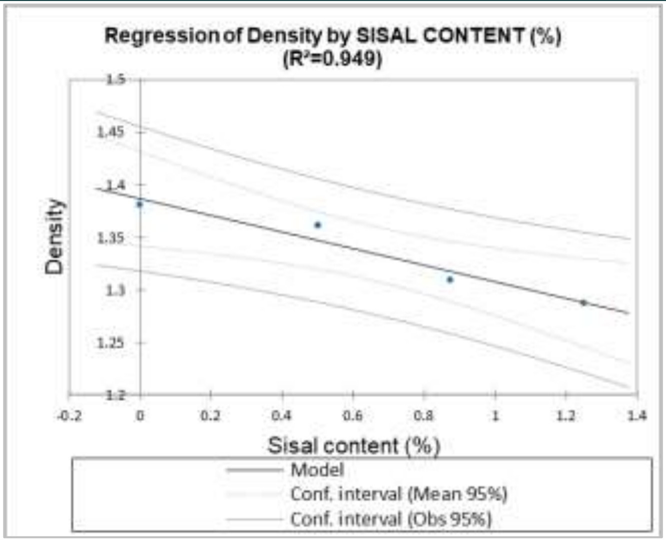

Figure 7. Correlation between the sisal fibre content and the density

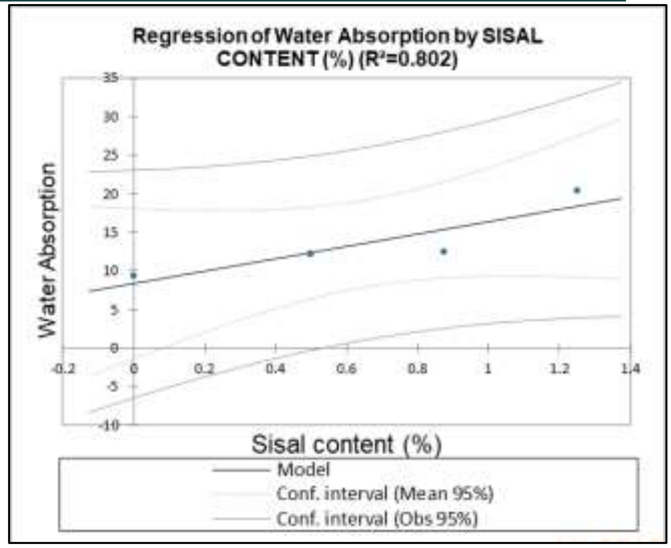

Figure 8. Correlation between the sisal fibre content and the water absorption

In terms of water absorption, most of the specimens could remain intact in water for 24 hours, with a bit of weathering being noted in some bricks. The results showed that the diffusion coefficient and maximum water content values increase as the fibre content increases, although all the values fall within the acceptable range of ≤20%. Higher fiber loading percentages resulted in greater water absorption ability. This phenomenon can be explained by the hydrophilic nature of vegetable fibres. The specimens with a higher fibre content have a greater diffusion coefficient, due to the fact that absorption of water is higher, as a result of a higher content of cellulose. The formation of microcracks at the interface region, induced by fibre swelling, can increase the diffusion transport of water via them. The high cellulose content in the sisal fibres, could further contribute to more water penetrating in to the interface through the voids induced by swelling of fibres [45]. The strong correlation between the sisal fibre content and the water absorption of the geopolymer specimens is illustrated in Figure 8.

4. CONCLUSION

This research sought to evaluate the viability of using diatomaceous earth from Nakuru, Kenya, as a resource for geopolymer concrete. The chemical composition showed that silica (SiO_2) was the predominant component, indicating that the diatomite under study is an acidic rock belonging to the opal A + CT category. Given that the diatomite's total amount of SiO_2, Fe_2O_3, and Al_2O_3 was greater than 70% by weight and contained less than 10% CaO, it may be inferred from its chemical composition that it is of a relatively high grade, similar to the Class F typical kind of pozzolan or a silicate glass substance. The particle size analysis showed that the raw diatomaceous earth from Nakuru, Kenya, is a fine material.

All of the tested specimens met the prerequisite requirements for the concrete masonry units as per ASTM C1634 [44]. The improvement in strength with $NaOH/Na_2SiO_3$ alkaline activation occurs mainly due to the formation of hydration product Na-S-H (sodium silicate hydrate) gel which is formed due to hydration reactions. The incorporation of diatomite and sisal fibres in the concrete mix translated into a gain of the porosity, accompanied by losses on the density.

Diatomaceous earth can be used successfully as a silica source in geopolymer formulations, offering promising solutions to exploit and recycle the mineral resource. However, from the observed effects of sisal fiber inclusion on the characteristics of geopolymer concretes, it can be inferred that fiber inclusion needs to be critically assessed in order to strike a healthy balance.

5. Acknowledgment

The authors thank Moi University and Université Clermont Auvergne in France for facilitating access to their research resources.

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