World Journal of Engineering and Technology, 2026, 14(2), 327-343
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Geopolymer Foamed Mortars Based on Pozzolan: Structure, Physical and Mechanical Behavior as Function of Metakaolin Addition

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How to cite this paper: Tchanang, G., Baldé, M.Y., Kepdieu, J.M., Keita, A., Tamo, B.S., Kouakep, F.-Z., Ekani, C.J., Djangang, C.N. and Blanchart, P. (2026) Geopolymer Foamed Mortars Based on Pozzolan: Structure, Physical and Mechanical Behavior as Function of Metakaolin Addition. *World Journal of Engineering and Technology*, **14**, 327-343.
https://doi.org/10.4236/wjet.2026.142019

Received: January 31, 2026
Accepted: March 17, 2026
Published: March 20, 2026

Abstract

To obtain porous mortars, sand and a foaming agent were added to geopolymer pastes. The latter were made by mixing an activating solution made of sodium silicate and sodium hydroxide with an aluminosilicate powder, primarily composed of pozzolan which was gradually replaced with metakaolin at 20%, 30%, and 40% by weight. Metakaolin was added as an accelerator to promote a higher compressive strength. The microstructures of the mortars were changed by the addition of a foaming agent, resulting in increased porosity as confirmed by the values of the open porosity and water absorption, attaining 27.6% - 73.3% and 14.9% - 40.2%, respectively. These materials are referred as porous and lightweight mortars due to their relatively low density between 1.51 - 1.7 g/cm^3. The mechanical strength is in the range of 12.4 - 16.1 MPa, which is consistent with that of some structural materials. The obtained materials may be of potential interest in civil engineering, trapping, storage, as well as in thermal and acoustic insulation.

Keywords

Pozzolan, Metakaolin, Foam, Geopolymer Mortar, Properties

1. Introduction

Construction is a key sector that promotes the development of countries all over

the world. It uses mostly cement and different types of binders for the fabrication of blocks and precast elements, and mortars are needed for the building of structures [1]. Particularly, cement helps us to shape the world since it is used in mortar and concrete for the construction of important engineering structures such as bridges, culverts, dams, tunnels, lighthouses, etc. [1] [2]. Beyond the very large use of Portland cement throughout the world, its production is considered as harmful to the environment since it requires a huge amount of $CaCO_3$ for the production of clinker, resulting to important atmospheric emissions of CO_2 during the calcination process [3]. Different statistical estimations indicate that the related industrial emissions of CO_2 is about 5% - 6% of the global emissions [4] [5]. Consequently, the need for sustainable materials replacing Portland cement is of great interest. It would be an alternative way of improving the sustainability of the construction sector. Geopolymers cements are a new class of inorganic polymers initiated by Davidovits later 80s [6]. Since then, they have been considered as good alternative materials for many applications including fire resistant and refractory panels, adhesives and coatings, waste encapsulation material, binders, etc. [7]. They are known as the most promising alternative and eco-friendly cement due to their lower energy consumption and environmental impact [5].

In general, geopolymer cements are made from alkali activation of aluminosilicate precursors such as metakaolin, volcanic scoria, fly ash, slag, etc. [7] [8]. Today, the use of both low-cost and less polluting materials, with improved methods, makes the process more economically and ecofriendly valuable [9]. Moreover, geopolymer cements and mortars, formulated with lightweight materials, help reduce the energy consumption of the building thank to the relatively high porosity, and the reduced thermal conductivity [10]. In general, lightweight materials are obtained by the partial substitution of solid materials by a pore-forming agent. The latter can be obtained from either renewable sources as products or by-products of agricultural crops such as the cob, several seeds, grass, rice husks, rice husk ash, etc. [11] [12] or from synthetic sources as foaming agents such as aluminum powder, hydrogen peroxide or a large range of commercial surfactant inducing the formation of foam with water [13]. The pore-forming agent contributes to high porosity value, up to 80 vol%. and low density (0.4 - 2 g/cm^3), in comparison to the Portland concrete density (2.2 - 2.4 g/cm^3).

In geopolymer cements and concretes, it would be interesting to obtain lightweight materials, and recent works evidenced the occurrence of improved properties, using a synthetic foaming agent [3]. Besides, the use of natural pozzolans from volcanic scoria is favorable to the lowering of density. The incomplete recrystallization of pozzolan during the rapid air cooling generates amorphous structure that is advantageous for the natural reactivity of the material. Furthermore, the presence of some active mineral like silica and alumina in pozzolan may favorise its reactivity in geopolymer formation but it remains less reactive than metakaolin. In this study, natural pozzolan has been associated with metakaolin, and with a synthetic foaming agent, to obtain lightweight geopolymer mortars. The

unique point of this work being the gradually replacement of Pozzolan with metakaolin at specific contents coupled to the influence of the foaming-agent dosage. The experimental work investigates the influence of the foaming-agent dosage on the main physical and mechanical properties of mortars such as the compressive strength, the water adsorption, the porosity, and the relative density.

2. Materials and Experimental Procedures

2.1. Materials Sampling

The pozzolan (PZ) is quarried in Penja, and the kaolinite clay from Dibamba, all in the Littoral Region of Cameroon. PZ was dried, grounded and sieved below 75 μm. The kaolinite clay was enriched in clay fraction by wet sieving below 75 μm, removing large particles of quartz and other non-clayed minerals. The fine fraction was heated in an electric furnace (Nabertherm Model LH 60/14) with a temperature rate of 5˚/min up to 700˚C for 4 hours, to obtain a powder named MK. This temperature was selected based on previous research indicating its optimal use for the amorphization of kaolinite clays, enhancing their reactivity [14]. The quantification of the amorphous phase was done in previous works [15]. MK was used to substitute PZ respectively at 20, 30 and 40 wt.% to obtain solid precursors that will be denoted as 80/20, 70/30, 60/40. The liquid precursor was an equivolumic mixture of activating alkaline solutions of a 8 M aqueous sodium hydroxide (99%) and a sodium silicate (SiO_2/Na_2O = 44,209; H_2O 55.41%).

To obtain the foam, a commercial foaming agent called "aircrete" with a 0.32 g/L relative density was-mixed with distilled water in the volume ratio of aircrete/water = 4%, and then vigorously stirred with an electrical foam machine to obtain a foam having a density of 45 kg/m^3.

The sand used was standardized in accordance to EN 933-1 and EN 933-2 standard [16]. It was a mixture of Sanaga river sand and a fine equatorial sand from Yaoundé. The physical characteristics of sands are within the limits reported for standard sands with a specific particle size distribution. The fineness modulus (FM) is 2.97, the uniformity coefficient, UC = D60/D10 is 6.85, and the coefficient of curvature (CC) is equal to 2.204.

2.2. Preparation of the Geopolymer Mortars

To elaborate geopolymer mortars, each of the three solid precursors (PZ, MK and sand) was mixed to the activating solution, with a liquid (mL)/solid mass (g) ratio of 0.16 (**Table 1**). The mixture was homogenized for ten minutes using an M&O mixer (model N50-G) to create a paste. Foam was added to the mortar at 0, 1, and 2 wt.% under continuously stirring and the resulting pastes were labeled GM0, GM1, and GM2, respectively. The viscous mortars obtained were molded into cylindrical test discs with a diameter of 20 mm and a height of 40 mm. To remove larger air bubbles, a M&O electric vibrator (type 202 No. 106) was used for vibration. To prevent water evaporation during paste setting and hardening, the specimens were covered with a thin polyethylene film and left in the ambient atmos-

phere (24˚C ± 3˚C). Demolding was done 24 hours later.

Table 1. Composition of mortars.

	PZ/MK ratio in aluminosilicates	Mortar's components (wt.%)				
Formulation		Foam (wt.%)	PZ (wt.%)	MK (wt.%)	Sand (wt.%)	Activating solution (wt.%)
GM0	60/40	0	12.87	8.58	64.38	14.16
GM1		1			63.52	14,04
GM2		2			62.80	13.92
GM3		3			60.35	15.20
GM0	80/20	0	15.02	6.43	64.38	14.16
GM1		1			63.51	14,04
GM2		2			62.83	13.92
GM3		3			60.35	15.20
GM0	70/30	0	17.16	4.43	64.25	14.16
GM1		1			63.37	14.04
GM2		2			62.49	13.92
GM3		3			60.21	15.20

2.3. Technical Characterization

The starting materials (PZ and MK) were characterized by ICP for chemical composition, XRD, FTIR and amorphous phase content, spectroscopy method for the structural compositions and specific surface area. Amorphous phase quantification was measured using the method described in previous works (Balde *et al.*, 2021). The M_1 (g) sample was mixed with 30 mL of an 8 M sodium hydroxide solution in a 100 mL beaker in order to eliminate the acidic oxides present in the material. The mixture obtained was washed with distilled water and centrifuged using an Eppendorf type 5840 R centrifuge until a neutral pH is obtained. The residue obtained was neutralized with 30 mL of a 0.5 M hydrochloric acid and washed with distilled water. Filtration was carried out to recover the residue. The latter was dried at room temperature (25˚C ± 3˚C) and in a Heraeus brand dryer (VT 5042EK) at 110˚C for 24 hours. The residue was weighed (M_2) and the amorphous rate in the tested material was obtained by Equation (1):

$$\%\,\text{amorphous phase} = \left[\left(M1 - M2\right)/M1\right] \times 100 \quad (1)$$

The synthesized mortars were characterized by setting time according to the EN 196-3 [17] using a Vicat device, linear shrinkage using a digital caliper on cylindrical test discs, apparent density and open porosity with the Archimedes method. Optical microscopy was carried out using an optical microscope (Ceramics Instruments Model 101T-M7). The compressive strength was measured according to standard EN 1961 [18].

3. Results and Discussion

3.1. Characteristics of Starting Materials

Table 2 shows the chemical composition of the pozzolan and the metakaolin used in the formulation

Table 2. Chemical composition of PZ and MK.

Oxides	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	Na_2O	K_2O	TiO_2	CaO	P_2O_5	BaO	LOI
PZ	47.37	19.44	14.19	0.26	3.88	3.28	1.01	2.69	6.80	0.98	0.10	0
MK	79.92	15.39	2.14	0	0.1	0	0.11	1.10	0	0	0	1.14

It can be noticed from Table 2 that silica (SiO_2) and alumina (Al_2O_3) are the major oxides in both PZ (Pozzolan) and MK (Metakaolin). The Si/Al molar ratio is 2.1 for the pozzolan and 4.4 for the metakaolin. It is in accordance with many works in the literature, proving that metakaolin has a higher capacity to strengthen the geopolymer tridimensional network [19] [20].

The Si/Al ratio of the solid precursor is known to be a key factor influencing both the properties of geopolymers and the geopolymerization mechanism [19]. Furthermore, geopolymers with a Si/Al ratio of 4 or higher exhibit significantly greater mechanical properties. This is due to the presence of a large concentration of Si-O-Si bonds acting in the strengthening in the structural arrangements [21].

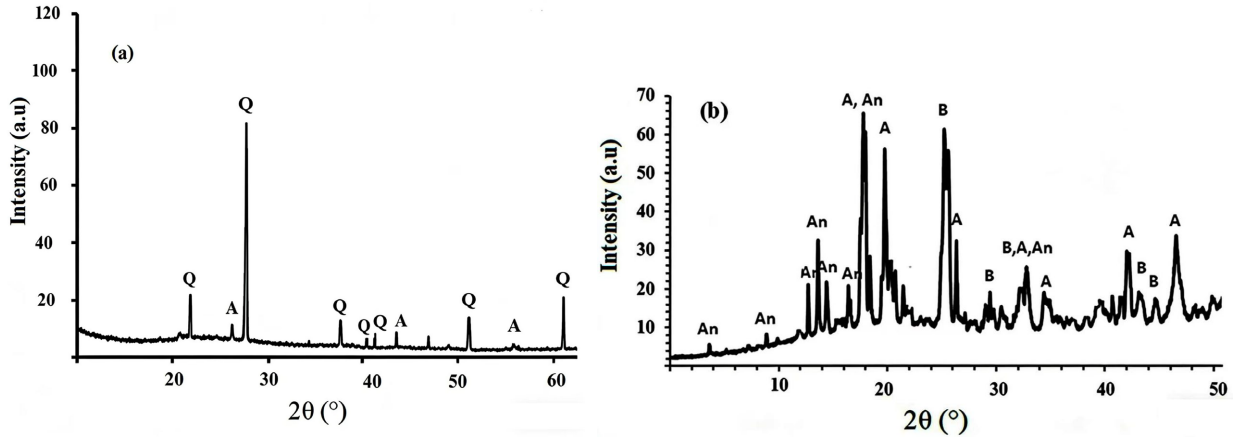

Figure 1. X-rays patterns of (a) MK and (b) PZ (A: Anatase/Augite, B: Biotite, An: Anorthite Q: Quartz).

Figure 1 shows the X-ray patterns of metakaolin and pozzolan. The identified phases in metakaolin are quartz (SiO_2, PDF 89-8934) and anatase (TiO_2, PDF 21-1272). In the pozzolan powder, augite (Ca, Na) (Mg, Fe, Al) (Si, Al)$_2O_6$, PDF 24-201), anorthite ($CaAl_2Si_2O_8$, PDF 41-1486) and biotite ($K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$, PDF 2-45) are detected. In the metakaolin pattern a dome in the range 18 - 28 2θ is evidenced, and for pozzolans, it is seen in the range 5 - 24 2θ. It is a clear indication of the presence of an amorphous phase (Figure 1).

Figure 2(a) presents the infrared spectrum of pozzolan. It shows an absorption bands at 1641 and 3349 cm^{-1}, which respectively express the deformation vibrations of the H-O-H valence bonds and of the O-H bonds of water molecules [22]. The absorption bands at 944 cm^{-1} corresponds to the symmetric and asymmetric elongation vibrations of Si-O-Si and Si-O-Al bonds, while the band at 730 cm^{-1} reflects the presence of the elongation vibrations of Al-O.

Figure 2(b) shows the IR spectrum of metakaolin (MK). The spectrum has a broad band at 1044 cm^{-1} reflecting the presence of the asymmetric and symmetric elongation vibrations of the Si-O-Al and Si-O-Si bonds. It demonstrates the presence of amorphous silica in metakaolin. The band at 546 cm^{-1} is attributed to the vibration of Al-O bond. The band between 789 and 776 cm^{-1} reveals the presence of the stretching vibration of Al-O. The band at 429 cm^{-1} is attributable to the deformation vibrations of the Si-O-Si and Si-O-Al bonds [23].

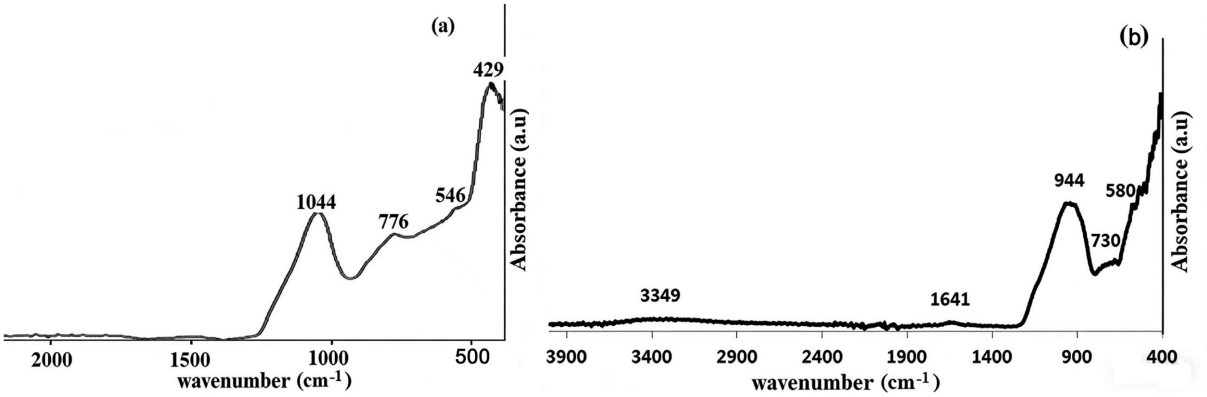

Figure 2. FTIR Spectra of (a) PZ and (b) MK.

The values of the specific surfaces areas (SSA) are 8.6 and 20.5 m^2/g for PZ and MK respectively. Since the specific surface area of metakaolin is greater than that of pozzolan, proving the higher reactivity of metakaolin compared to pozzolan [24].

The mass percentage of the amorphous phase is 45.1% and 65.2% for PZ and MK respectively and this is in accordance with the observation of the X-ray patterns exhibiting a dome around $2\theta = 22^{\circ}$ for MK. The relative quantity of the amorphous phase is equivalent to the reacting phase content with the activating alkaline solutions. The amorphous phase improve the geopolymerization process, resulting in a greater mechanical resistance after setting [25].

It was observed that the shaped discs of mortars containing 3 wt.% of foam are very porous and weak and will not be considered for further investigation. The results presented below are for mortars with 0; 1 and 2 wt.% of foam.

3.2. Characteristics of Geopolymers Mortars Containing the Foam

It was observed that the shaped discs of mortars containing 3 wt.% of foam are very porous and weak and will not be considered for further investigation. The

results presented below are for mortars with 0; 1 and 2 wt.% of foam.

3.3. Values of the Initial and Final Setting Times

Figure 3 shows the variation of the initial and final setting times of mortar pastes as a function of both substitution of pozzolan by metakaolin and percentage of foam.

It can be seen that the initial and final setting times of geopolymer mortars increase with the amount of the foam. For instance, the initial setting time increases from 180 min to 255 min when the foam quantity increases from 0 to 2 wt.% for PZ/MK = 60/40. Similarly, the final setting time increases from 420 min to 540 min with the addition of 0 to 2 wt.% of foam for PZ/MK = 80/20.

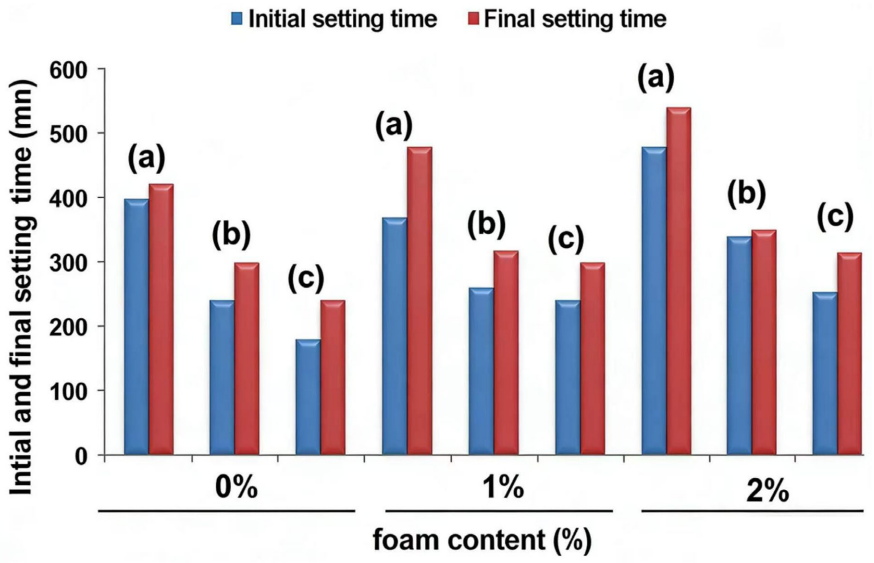

Figure 3. Initial and final setting times for the compounds 80/20 (a), 70/30 (b) and 60/40 (c) versus the foam content.

But the setting time decreases with the percentage of metakaolin for a fixed quantity of foam in the mixture. For the addition of 1 wt.% of foam, and when pozzolan is replaced by increasing quantities of metakaolin, the initial setting time decreases from 370 to 240 min, and the final setting time decreases from 480 to 300 min. For the addition of 2 wt.% of foam, a similar replacement of pozzolans by metakaolin lead to the reduction of the initial setting time from 480 to 255 min, and of the final setting time from 540 to 316 min. The results align with the reactivity of metakaolin thank to its higher alumina and silica contents. An increase of Si and Al contents results in a higher quantity of the geopolymeric gel during the initial stage of the setting process [21]. Since the gel plays a critical role in the geopolymerization reactions, it strongly influences both the reaction rate and the initial and final setting times. Additionally, the addition of foam may reduce the viscosity of the mortar paste, leading to a decrease in paste consistency. This is also expected to increase the mobility of species and the dissolution rate of alumi-

nosilicates. However, foam induces the creation of voids from bubbles distributed in the volume [26] [27]. These physical discontinuities limit the diffusion process of species, and lower the setting rate. These statements are in on the same line with previous research that examined the effect of foam on the consolidation process by analyzing the kinetics of the reaction mechanisms [28] [29].

3.4. Fourier Transformed Infrared Spectra

Figure 4 presents the IR spectra of the different geopolymer mortars obtained by mixing PZ and MK with the PZ/MK ratio of 60/40 with different foam dosage of 0, 1 and 2 wt%.

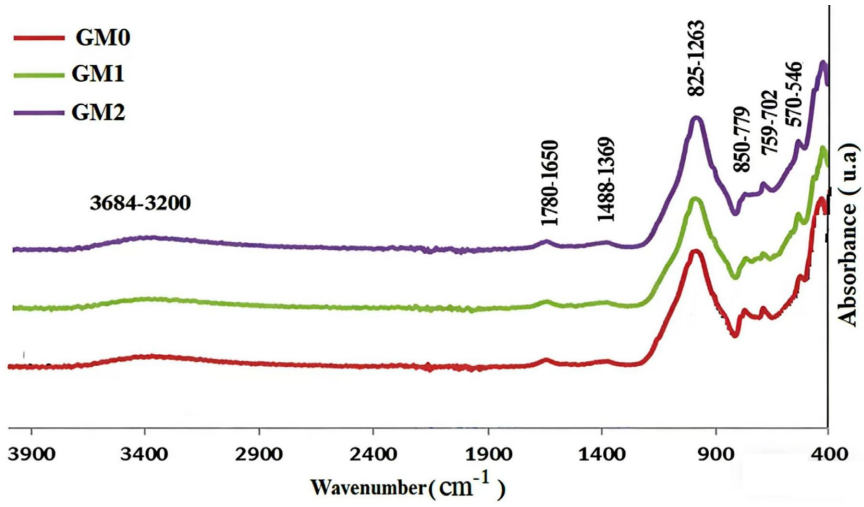

Figure 4. FTIR spectra of GM0, GM1 and GM2 (with PZ/MK = 60/40).

The FTIR spectra of the three geopolymers are similar proving that the effect of foam dosage is not noticeable as per structural composition. Anyway, the absorption bands at 3684 - 3200 cm^{-1} and at 1780 - 1650 cm^{-1} respectively reflect the presence of elongation and deformation vibrations of the O-H and H-O-H bonds of water molecules [30]. The absorption bands at 825 - 1263 cm^{-1} are attributed to the asymmetric stretching vibrations of the Si-O-Si and Si-O-Al bonds as well as those observed at 856 - 779 cm^{-1}, 759-702 and 570 - 546 cm^{-1} [31]. In fact, the ability of Al-Si oxides to inter-react with the other species characterizes the geopolymerization system and is also linked to the degree of polymerization alongside with the hardening properties.

3.5. Linear Shrinkage

Figure 5 displays the correlation between the linear shrinkage of the mortar specimens and the foam content. The shrinkage is also changed by the substitution of pozzolans by metakaolin, and a more pronounced effect occurs at a higher foam content (2 wt.%). Undoubtedly, during setting, water from the foam is firstly removed by a more or less effective combination with hydrolyzed aluminosilicates. A large amount of water is mostly removed by diffusion towards surfaces during

drying. It contributes to an internal readjustment of the system, resulting in an increased shrinkage when more foam is added. This physicochemical phenomenon contributes to obtain a more consolidated and hardened material [32]. It is also evidenced that the shrinkage rates are similar to those of common structural materials [33]. The specific role of metakaolin is related to its effective dissolution process at contact with the activating solution. This process leads to the formation of a structural tridimensional network [6]. It may limit the influence of metakaolin on the shrinkage during the hardening process, even though the solid/liquid ratio of precursors is predetermined.

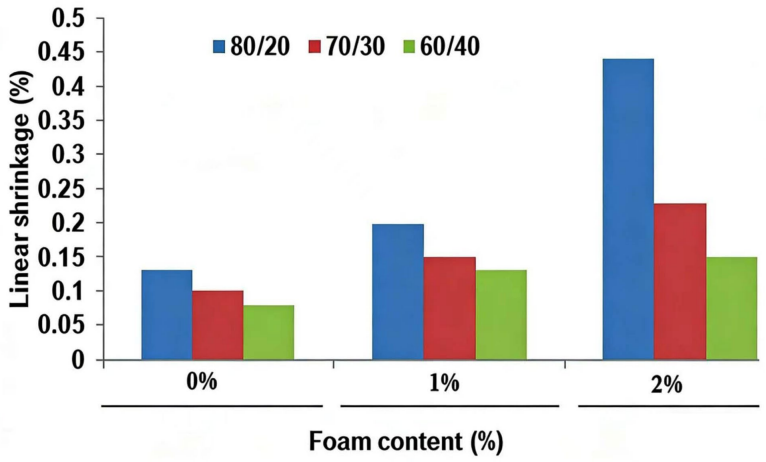

Figure 5. Linear Shrinkage of the mortar specimens at day 28 for 80/20, 70/30 and 60/40 PZ/MK ratios.

3.6. Density and Porosity

The decrease of the apparent density with increase of the amount of foam is evidenced in **Figure 6(a)**. Test discs with a ratio of 60/40 for PZ/MK, have a density of 1.7 g/cm^{-3} for 1wt.% of foam and a density of 1.51 g/cm^{-3} for 2 wt.% of foam. The values are similar to those of lightweight materials of other findings [13] [34]. Foam is used to aerate the microstructure by creating voids through the formation of bubbles during the setting process. These voids form a 3D network that increases porosity, resulting in an increased open porosity at a higher foam content. Correspondingly, Novais *et al.* (2020) found that voids can contribute to both closed and open pores [29]. **Figure 6(b)** also shows the variation of the apparent density versus the foam content. The occurrence of either open or closed porosity depends on various factors, such as the foam formation technique and concentration in the starting formulation. In this work, a direct foaming technique was used, meaning that foam was added into the geopolymer paste after the mixing of components. It results in a more pronounced open macro porosity with an accentuated interconnectivity [35].

3.7. Images from Optical Microscopy

Figure 7 displays micrographs of test discs made with different mortars. In all

cases, the morphology shows a homogeneous microstructure with sand grains distributed throughout the matrix, resulting in a compact microstructure. As foam is added gradually, the microstructure takes a honeycomb appearance with rounded cavities of varying sizes, becoming more pronounced with increasing foam content. This type of microstructure defines a material having a lower density and a high mechanical strength since the compressive stress is distributed along the rounded cavities [36].

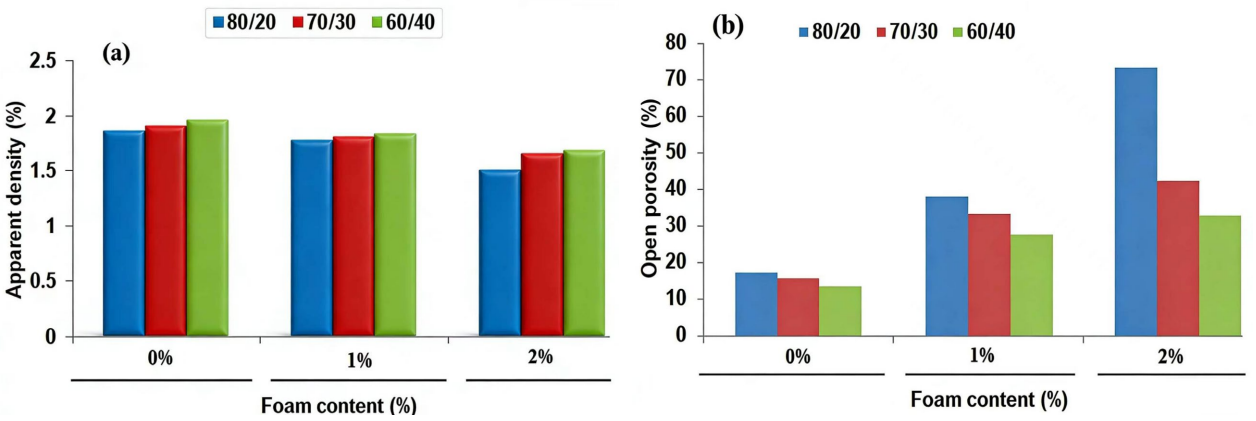

Figure 6. Apparent density (a) and Open porosity (b) of the mortar specimens after 28 days for 80/20, 70/30 and 60/40 PZ/MK ratios.

3.8. Compressive Strength

Figure 8 shows the variations of the compressive strength of the geopolymer mortars as a function of the foam content and the rate of substitution of pozzolans by metakaolin. It is evidenced that the compressive strength of the reference mortar without foam is greater than that of porous mortars. Increasing the foam quantity results in decreasing the density and the compressive strength of mortar [3]. Since the density of foamed concrete is generally correlated with strength, a balance between these two parameters could be found depending on the intended application. Generally, a denser foamed concrete has a higher compressive strength and a lower volume of voids, and a low density has a decreased strength. A good compromise is achieved by optimizing the composition and by selecting the appropriate quality and quantity of foaming agents having a significant foaming capacity. Generally, strength decreases with an increase of the number of bubbles, but it depends on the distribution of bubble size and in the foam stability with time. Besides, the increase of strength with the increase of the metakaolin relative content is explained by its specific contribution since it is the most active phase in comparison with that of pozzolan. More precisely, metakaolin promotes a local microstructural consolidation [37], particularly near pores where a decohesion process with the geopolymer matrix can occur.

Considering the chemical compositions, the Si/Al ratio of metakaolin is 4.4 whereas that of pozzolans is 2.1 which results in a greater quantity of MK leading to a greater mechanical strength. In addition, metakaolin has a high specific sur-

face in comparison to that of pozzolans, and metakaolin also has a high amorphous phase content. These parameters favor a larger quantity of geopolymeric gel during geopolymerization, and promote obtaining a more consolidated material having better mechanical resistance. This is in agreement with the work of Bondar and al. 2011 and others [38] who showed that mineral additives to pozzolan promote an increase in mechanical resistance.

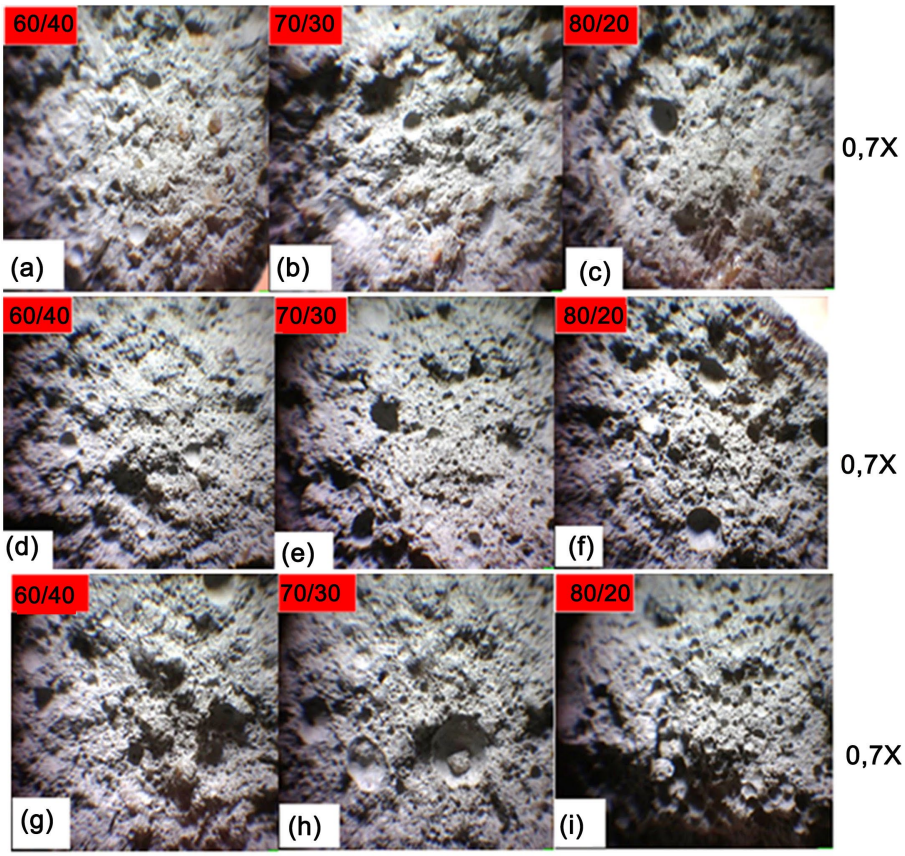

Figure 7. Optical micrographs of mortar after 28 days with 0 wt.% (a)-(c), 1 wt.% (d)-(f) and 2 wt.% (g)-(i) foam content.

Many researchers also reported that the structural stability of geopolymers increases with the content of silicate species. This is due to the formation of silicate oligomers having long structural arrangements, with the occurrence of Al-O-Si complexes. This could also explain the delay in the intake observed when the metakaolin content decreases [39].

Figure 9 reports the relationship between compressive strength and density for various foamed concrete compositions [40], including data from our present work. A very large distribution of data is obtained from the numerous parameters linked to the fabrication of foamed concrete. Despite the wide range of data, there is a clear trend of increasing strength with density. Our data fall just below the average strength value of the distribution that validates the process used in this work [3] [41].

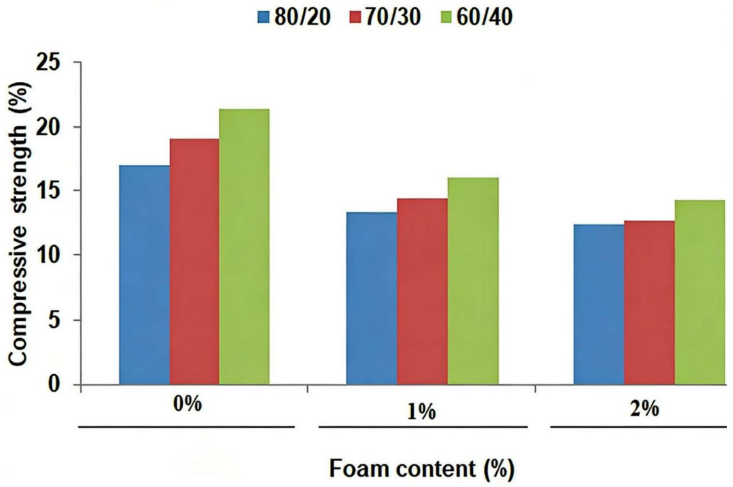

Figure 8. Compressive strength of the mortar specimens at day 28 for 80/20, 60/40 and different PZ/MK ratios.

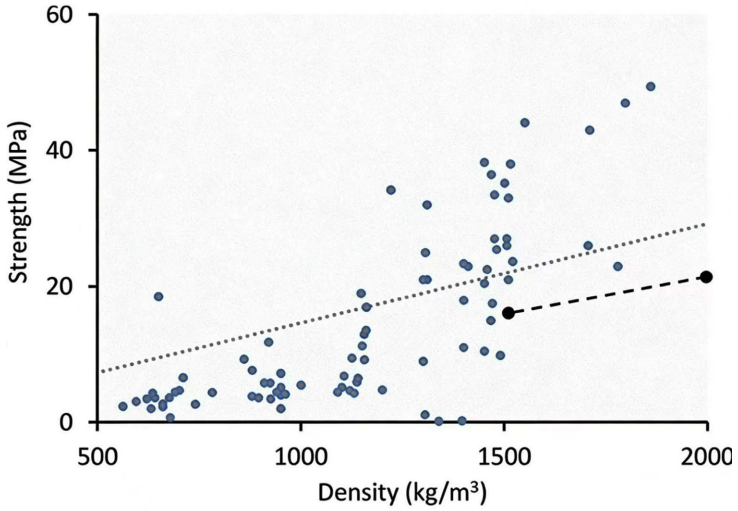

Figure 9. Compressive strength values from this work (black line) in comparison to data (gray line) from the literature [40].

Table 3 reports the comparison of some properties of the geopolymers from this study with that from different published works. The data are focused on values of compressive strength, apparent density, linear shrinkage and porosity.

Similar strength values are observed when the density is close to 2 g/cm^3. However, the strength is increased or decreased significantly when the compositional domain is altered by adding volcanic ash or rice husk ash. This demonstrates the significant role of each component in the behavior of mortar. Additionally, it proves that metakaolin is an efficient component due to its high reactivity and availability at a moderate environmental cost.

After comparing the characteristics of various geopolymer mortars found in the literature, it can be concluded that the mortars used in this study are of the lightweight range.

Table 3. Comparison of mortar properties after 28 days of setting.

Geopolymer Mortar composition	Compressive strength (Mpa)	Apparent density (g/cm^3)	Linear shrinkage (%)	Porosity (%)	Initial and final setting times (h)	Related references
Pozzolan + metakaolin + Sand	21.4	2.07	0.44	13.7	3 - 4	Present work
Pozzolan + metakaolin + Sand + foam	12.4 - 16.1	1.51 - 1.80	0.13	32.6	4 - 5	
Volcanic ash + Sand	20.5	2.120	/	14.5	/	[8]
Metakaolin-rice husk-based mortars	0.75 - 28.92	1.88 - 1.70	/	34.26 - 82.76	/	[42]
Fly ash-based geopolymers	16.3 - 47.3	1.36 - 1.86	/	16.16 - 21.33	/	[43]
Fly ash and slag	8.5 - 47.50	1.50 - 2.45.	/	/	/	[44]
Geopolymer foamed concrete	3.8 - 36.6	1.19 - 1.34	/	/	/	[45]

4. Conclusion

Foamed geopolymer mortars were obtained by alkali activation of pozzolan substituted with thermally activated kaolinite clay (MK). Three different PZ/MK ratios were tested: 80/20, 70/30, and 60/40. The study found that the addition of foam in geopolymers mortars containing PZ substituted with MK resulted in lightweight materials with interesting properties. The study measured the initial and final setting times of the mortars in the fresh state. Additionally, the physical, mechanical, and microstructural properties of the mortar specimens after setting were compared to the reference mortar without foam. The results indicate that geopolymer mortars based on pozzolan require a minimum of 20 wt.% of metakaolin as an aluminosilicate mineral additive to set within a reasonable time. Metakaolin also acts as an accelerator of the geopolymeric consolidation, increasing the mechanical resistance of the products. The foam does not create an additional phase but reduces drastically the density and increases the porosity. The obtained lightweight products have a density ranging from 1.8 to 1.5 and a minimum mechanical resistance of 12.4 MPa, which is within the limit of the mechanical resistance of the structural construction materials that are used in construction. Products can be used when a high porosity and a low density are required.

Informed Consent Statement

All the authors are voluntarily participating for the submission of this research work.

Consent to publication

The authors confirm that this manuscript has not been submitted or published previously to any other journal and give full consent for publication of the re-

search work.

Data Availability

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

Authors Contributions

Gustave Tchanang & Jean Marie Kepdieu: Investigation, Roles/Writing-original draft, Data curation. Njiomou Djangang Chantale: Conceptualization, Methodology; Writing-review & editing, Visualization. Berthelot Sop Tamo, Cyprien Joel Ekani & Phillipe Blanchard: Investigation, Writing-review & editing. Mamadou Yaya Baldé, Ansoumane Keita: Writing-review & editing.

Conflicts of Interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter discussed in this manuscript.

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