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Effect of Portland Cement on Mechanical and Durability Properties of Geopolymer Concrete at Ambient Temperature

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Abstract

Environmental concerns have prompted researchers to focus on the development of alternative building materials like geopolymer concrete. However, their implementation requires curing beyond 60°C, which limits their application on building sites. This study aims to design a geopolymer concrete at room temperature (30 ± 5°C) in a laboratory in Burkina Faso using a metakaolin-based geopolymer binder activated by an alkaline solution of NaOH and natural aggregates. Portland cement type CEM I 42.5 was used by mass substitution (0 to 25%) of metakaolin to promote curing at ambient temperature. The samples were cured for 7 to 28 days and characterized for physical, mechanical, and durability properties. The results showed that the incorporation of 0 to 20% cement significantly improved the compressive strength from 9.9 to 30.5 MPa and the tensile strength from 1.2 to 2.2 MPa. However, Portland cement has various effects on the durability of geopolymer concrete. It reduces the porosity accessible by water from 15 to 13% and decreases the resistance to acid attack by increasing the mass loss from 2 to 7%. This confirms that common concrete types C20/25 or C25/30 can be casted using geopolymer concrete on the sites in Burkina Faso once their durability is confirmed.

Keywords: Portland Cement; Metakaolin; Geopolymer Concrete; Physico-Mechanical Property; Durability.

1. Introduction

Hydraulic concrete is one of the most common building materials in the world. It is obtained by a mixture of aggregates, water, and binder. The most widely used binder is ordinary Portland cement (OPC), and its global demand was estimated at 3000 million tons in 2020, with a growth rate of 4.7% per year [1]. This hydraulic concrete allows the realization of large civil engineering structures. It is relatively common nowadays to produce concrete with a compressive strength of 20 to 40 MPa using an average cement dosage of 350 kg/m^3, which is largely sufficient for the construction of common structures. Beyond its remarkable performances and facility to implement, hydraulic concrete has a high carbon footprint due to the use of OPC, among others. The cement industry has been a major player in global warming because of its manufacturing process, which generates a lot of CO_2 [1]. The share of global CO_2 emissions from cement production is estimated at 7% [2]. The increase in the world population combined with the increase in the standard of living, specifically in developing countries, increases the demand for new construction. This will necessarily

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induce an increase in the use of OPC despite its very high cost, particularly in countries like Burkina Faso, which does not produce it. It is therefore obvious that more pollution linked to the production of OPC can be expected in the coming years. Nowadays, the durability of hydraulic concrete is also problematic. Indeed, even if the design of concrete structures is carried out according to standards, the degradation of concrete over time in aggressive environments has been widely documented [3, 4]. It has been particularly observed that hydraulic concretes in corrosive environments (coastal or marine areas) begin to deteriorate after 20 to 30 years of service, whereas they were initially designed for a service life of at least 50 years [5].

To reduce the environmental impact of hydraulic concrete and consider its low durability in acidic environments, recent studies have aimed to find alternative materials. The geopolymer, considered an environmentally friendly binder obtained by alkaline activation of an aluminosilicate material, has attracted considerable attention. It has been used for the synthesis of concrete that is less polluting than hydraulic concrete [6, 7]. It has been shown that geopolymer concrete can reduce approximately 44-64% of greenhouse gas emissions compared to OPC [8]. However, many studies have shown the need for the thermal curing of geopolymers to increase their engineering performance. Nath & Sarker [9] reported that a moderate curing temperature is essential for the activation of geopolymers produced from aluminosilicates such as fly ash if the mixture does not contain enough calcium oxide. Other studies have achieved high initial mechanical properties as well as good durability in geopolymer concretes cured at moderately high temperatures, ranging from 60 to 90°C [10–12]. The requirement for thermal curing is not only energy-intensive and therefore imparts a high embodied energy and carbon footprint to the geopolymer, but it could also limit the large-scale use of geopolymer concrete on construction sites.

To limit the need for thermal curing of geopolymers, researchers [13, 14] have shown that the addition of CaO in the geopolymer matrix leads to the formation of C-S-H, which promotes the development of the resistance of geopolymers at room temperature. Khan et al. [15] investigated the workability and compressive strength of a geopolymer mortar at room temperature using ultrafine, low-calcium fly ash mixed with hydrated lime. The compressive strengths of these geopolymers were around 100 MPa at 28 days. It should also be noted that the heat of hydration of these cementitious materials also promotes geopolymerization kinetics. Cao et al. [16] reported that calcium aluminate cement (CAC) in geopolymer concrete plays an important role in the development of its strength and workability at room temperature. Fernández-Jiménez et al. [17] have shown that CAC was successfully absorbed into the geopolymer gel, resulting in a significant improvement in the mechanical properties of metakaolin-based geopolymer cured at 85 °C.

Unfortunately, all these studies, which were able to design the geopolymer at room or moderate temperature, made use of an expensive alkaline silicate. To date, few studies have been reported on the potential design of alkali silicate-free geopolymer concrete based on metakaolin and at room temperature. In addition, there is abundant availability of kaolinitic clay resources in Burkina Faso, which allows the use of clay-based materials for the design of geopolymer concrete.

The present study aims to add value to these local materials through the design of a geopolymer concrete at room temperature without the addition of an alkali silicate solution. This was achieved by using the calcined clay, metakaolin, as the source of aluminosilicate, which was substituted by 0 to 25% OPC, corresponding roughly to the content of cement of only 0 to 87.5 kg/m^3 in the concrete. The addition of cement to the matrix of the geopolymer could promote the geopolymerization reaction through the increase of CaO and the heat of cement hydration. This specifically involves setting up a mix design for the geopolymer concrete based on the literature [18–20] and evaluating the physico-mechanical properties and durability of the geopolymer concrete.

2. Materials and Experimental Methods

2.1. Materials

2.1.1. Aluminosilicate and Alkaline Activator

The aluminosilicate is from a kaolin-rich clayey material in Burkina Faso (Saaba: 12°22'46" N; 1°24'38" W and 317 m altitude) and calcined at 700 °C for 3 hours. It was called metakaolin (MK) in this article. This material has previously been characterized and used for the synthesis of a geopolymer binder for the stabilization of earthen materials by Sore et al. [21, 22]. The MK mainly contains silica (57.9%) and alumina (38.3%), with a molar ratio of SiO_2/Al_2O_3 of 2.57 (Table 1). Its physical characteristics are summarized in Table 2.

Table 1. Chemical composition of metakaolin, MK [21]

Oxide (%)	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O _	Na_2O	MgO	MnO_2	TiO_2	P_2O_5	LOI	SiO_2/Al_2O_3
MK	57.85	38.30	0.05	2.30	0.23	0.11	0.09	0.01	0.09	0.02	1.01	2.57

The alkaline solution used for the activation of the aluminosilicate is a 12 M NaOH solution obtained by the dissolution of NaOH crystals (99% purity) in distilled water.

Table 2. Physical characteristics of metakaolin and cement

Characteristics of Materials	Laser granulometry		Absolute density	Specific surface area (m^2/g)	
	D_{50} (µm)	D_{90} (µm)		BET	Blaine
Metakaolin	09	25	2.63 ± 0.01	12.74 ± 0.03	-
Cement	10	35	3.10 ± 0.03	-	0.36

2.1.2. Portland Cement and Superplasticizer

The Portland cement type CEM I 42.5 R, which has an average compressive strength of 40 MPa and is produced in Burkina Faso by CIMFASO, was used for the substitution of MK. The CEM has a lower specific surface area (0.36 m^2/g) than the MK (12.74 m^2/g). The CEM also has a slightly higher grain size than MK, with median particle sizes D_{50} of 10 µm and 9 µm, respectively (Table 2**)**. Therefore, MK requires more water than Portland cement to achieve a similar consistency. This was taken into consideration by the use of the superplasticizer type DYNAMON NRG 1045, which has a density of 1.08. This superplasticizer was chosen given its pH of 6.5 ± 1 closer to neutrality, unlike others that have a more acidic pH and whose addition could significantly lower the basicity of the NaOH solution necessary for the activation of the aluminosilicate.

2.1.3. Aggregates

The quartzitic sand is sampled on the banks of a river in Manga (Burkina Faso). The granitic gravel is from a company that crushes granite rock in Koubri (Burkina Faso). The aggregates have particle sizes in the ranges of 0–2 mm and 4–8 mm, respectively, for sand and gravel. They were washed and dried at 105 °C in an oven for 24 hours and stored in a plastic container to avoid any contamination. Figure 1 presents the particle size distribution of the aggregates. The fineness modulus (MF) of the sand is 2.25, and its coefficient of uniformity (CU) is 2.22. This shows a wide particle size distribution and good quality for the design of concrete. Moreover, the CU of the gravel is 1.4, which is less than 2, meaning that its particle size is uniform.

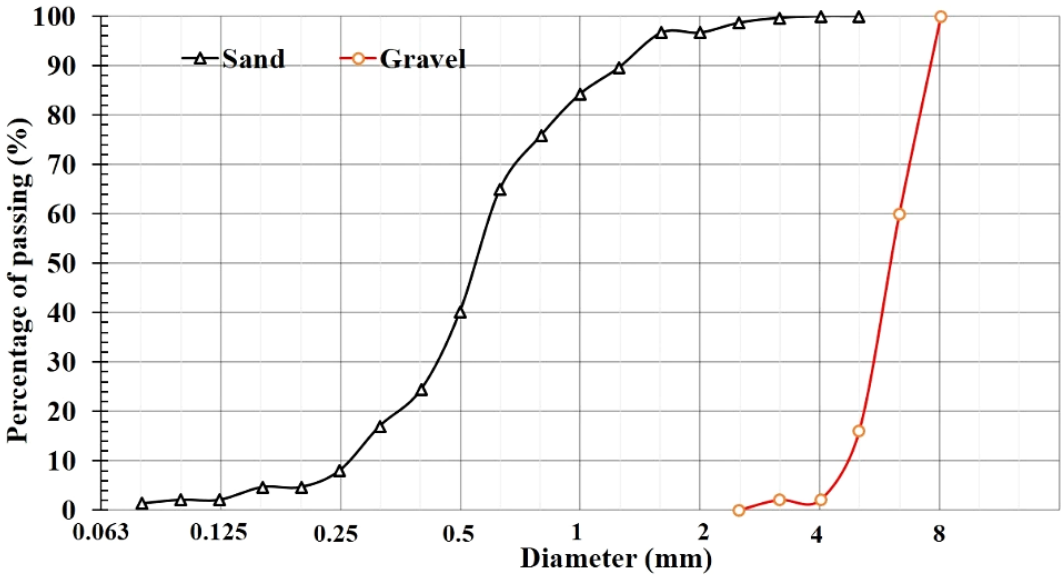


Figure 1. Particle size distribution of aggregates

2.2. Experimental Methods

2.2.1. Samples Preparation

The composition of the granular skeleton of geopolymer concrete was determined according to the literature, particularly referring to Pouhet & Cyr [19] and Cao et al. [16]. Six (06) mix designs were studied, corresponding to the different content of partial substitution of metakaolin (MK) by cement (PC) from 0 to 25% at steps of 5%. Geopolymer concrete is called G_XPC_Y, where X and Y respectively correspond to the percentage of MK and PC in the geopolymer binder. Table 3 presents the mix design to produce one cubic meter (1 m^3) of each type of geopolymer concrete.

Table 3. Mix design of geopolymer concrete

Materials (kg/m^3)	$G_{100}PC_0$	$G_{95}PC_5$	$G_{90}PC_{10}$	$G_{85}PC_{15}$	$G_{80}PC_{20}$	$G_{75}PC_{25}$
Metakaolin	350	332.5	315	297.5	280	262.5
Cement	0	17.5	35	52	70	87.5
Superplasticizer	23.82	23.82	23.82	23.82	23.82	23.82
NaOH crystals	126.4	126.4	126.4	126.4	126.4	126.4
Water	229.1	229.1	229.1	229.1	229.1	229.1
Sand	723.08	723.08	723.08	723.08	723.08	723.08
Gravels	958	958	958	958	958	958
water/binder*	0.48	0.48	0.48	0.48	0.48	0.48
Superplasticizer/binder*	0.05	0.05	0.05	0.05	0.05	0.05

Binder* = metakaolin + NaOH crystals + Cement

The aggregates, metakaolin, and cement are first homogenized in an electric mixer. The NaOH solution and the superplasticizer were gradually added as the mixing continued. The mixing took 5 minutes to obtain the concrete used to fill in the cylindrical molds Ø50 mm × H100 mm for testing the physico-mechanical properties and Ø40 mm × H 60 mm for testing the durability. The molds were filled in two layers and compacted by applying 60 strokes to each layer to reduce the air trapped in the mixture. The specimens were cured in the ambient conditions of the laboratory in Ouagadougou, Burkina Faso (average temperature of 30 ± 5 °C; relative humidity of 50 ± 10 %) for 28 days before testing their performances. In addition, some tests (apparent density, mechanical strength) were performed over the curing time (2, 7, 14, and 28 days). The methodological workflow of the study is presented in Figure 2.

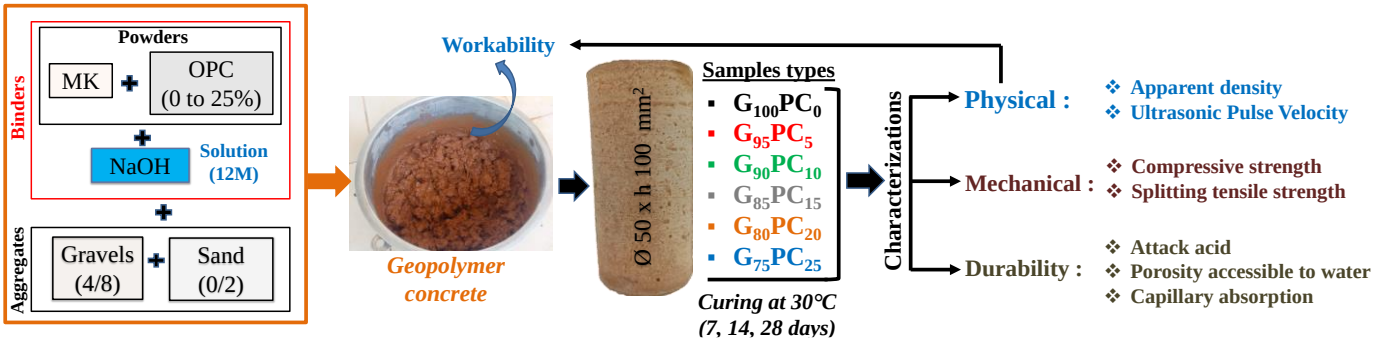


Figure 2. Methodology workflow of study

2.2.2. Characterization of Physical Properties

The workability of the concrete was determined by measuring the slump using Abram's mini-cone $Ø_1$5 cm × $Ø_2$10 cm × H15 cm (Figure 3-a), referring to standard NF EN 12350-2 [23]. The apparent density (ρ_d) was calculated using equation 1, where Md [g] is the mass of the dry sample and V [cm^3] is the volume of the sample. The compactness was assessed by the measurement of the ultrasonic pulse velocity through the sample using a portable non-destructive ultrasonic device (PUNDIT) of the lab, BeraTest (Figure 3-b).

$$\rho_d = \frac{M_d}{V} \quad (1)$$

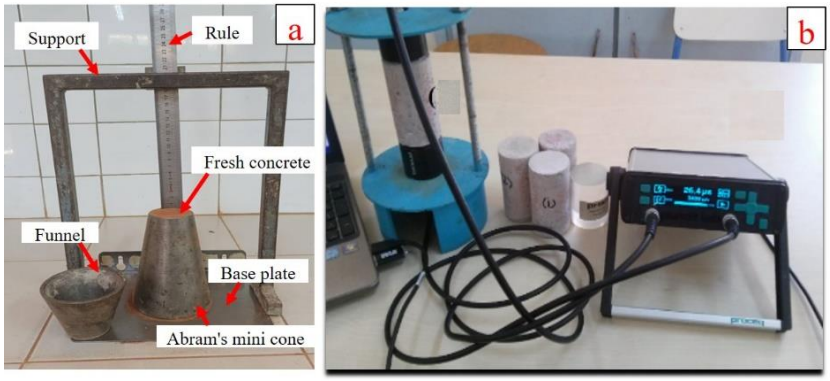


Figure 3. Experimental setups to measure a) workability of concrete, b) ultrasonic pulse velocity – Pundit

2.2.3. Characterization of Mechanical Properties

The test of compressive strength was performed on three cylindrical specimens of each mix design using a PROETTI hydro-electric press, which has a capacity of 300 kN. The specimens are subjected to an increasing load at a rate of 0.25 kN/s until failure. The compressive strength, R_C [MPa], is the ratio of the load at failure, P [N], and the cross-section area, S [mm^2] of the specimen (Equation 2). The tensile strength was determined using a splitting tensile test (Figure 4). It consists of measuring the load, P [N], necessary to break a cylindrical specimen subjected to linear diametral compression. The tensile strength, R_T [MPa], is calculated using Equation 3, where R [mm] is the radius and H [mm] is the height of the sample.

$$R_C = \frac{P}{S} \quad (2)$$

$$R_T = \frac{P}{\pi RH} \quad (3)$$

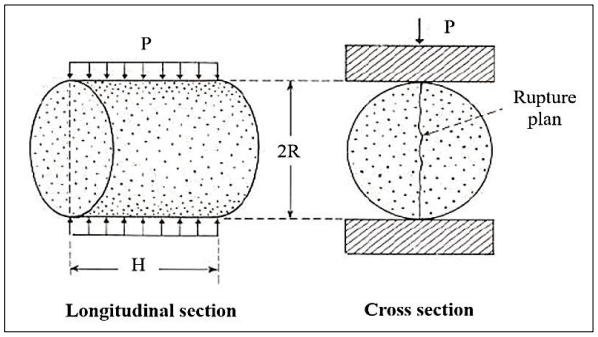


Figure 4. Experimental setup for splitting tensile test

2.2.4. Durability Tests

The resistance to acid attack consists of measuring the mass loss of concrete specimens immersed in a solution of sulfuric acid (H_2SO_4) whose volumetric concentration is 3% with a pH of 0.7 ± 0.05. This acid is chosen because it is one of the acids mainly found in acidic rain and chemical plants. After curing the samples for 28 days, the concrete specimens were immersed in the acid solution to measure the mass loss after 2, 7, 14, and 28 days of immersion. The pH of the solution increased over the immersion time and was therefore regularly adjusted by adding more sulfuric acid throughout the period of immersion of the samples, according to [24, 25].

The capillary water absorption capacity was measured on geopolymer concrete specimens after curing for 28 days. The samples were immersed in water at a depth of 5 ± 1 mm to allow water ingress in the bottom-up direction. The variation in mass was recorded over time for 24 hours. This is considered a durability indicator because it makes it possible to evaluate the water rise in the concrete, which is an environmental agent that can transport corroding agents in concrete structures.

The porosity accessible by water was evaluated through hydrostatic weighing of the sample after saturation by total immersion in water. It is expressed in Equation 4, where P_{water} [%] is the porosity accessible by water; $M_{air\,[g]}$ is the mass of the saturated specimen measured in air; M_{water} [g] is the mass of the saturated specimen measured in water; and M_{dry} [g] is the mass of the specimen dried to a constant mass at 105°C ± 5°C. This test is often used to characterize the durability of materials with regards to the diffusion of environmental agents in concrete structures [26].

$$P_{water} = \frac{M_{air} - M_{dry}}{M_{air} - M_{water}} \times 100 \quad (4)$$

The tests of capillary absorption and water-accessible porosity were carried out according to the directives of the AFPC-AFREM cited in Ntimugura et al. [27].

3. Results and Discussion

3.1. Physical Properties of Geopolymer Concrete

Workability and Apparent Density of Geopolymer Concrete

Figure 5 presents the evolution of the workability of geopolymer concretes with the substitution of metakaolin by cement. The slump increases from 10 to 37 mm for a cement content of 0 to 15%. This increase can be explained by the finer particle size of metakaolin and its higher water demand compared to cement. A low cement content (≤ 15%) improves the workability of geopolymer concrete, from a very plastic consistency ($slump < 10$ mm) to a very fluid consistency ($slump \geq 22$ mm), according to the standard NF EN 12350-2 [23]. This would potentially facilitate the implementation of this type of concrete on construction sites.

However, beyond the cement content of 15%, the slump decreases to 14 mm and 15 mm, respectively, with 20 and 25% cement, which are still higher than the slump of the reference concrete. This decrease can be explained by the modification of the viscosity of the mixture by the relatively high quantity of Portland cement. It can also be attributed to the increase in calcium content through the substitution of metakaolin, which has a lower CaO content than Portland cement (Table 1). Thus, the calcium interacts quickly with the alkaline activator to initiate the geopolymerization reaction, which is accompanied by an exothermic reaction, resulting in a reduction in the workability of the paste. A similar observation has been reported by Khan et al. [15]. Aliabdo et al. [18] claim that the addition of chemical admixtures may be needed to improve the geopolymer's workability. However, Cao et al. [16] have obtained the opposite results, i.e., a decrease in workability with the addition of the cement, and attributed it to the increase in calcium content and its rapid reaction with the alkaline activator.

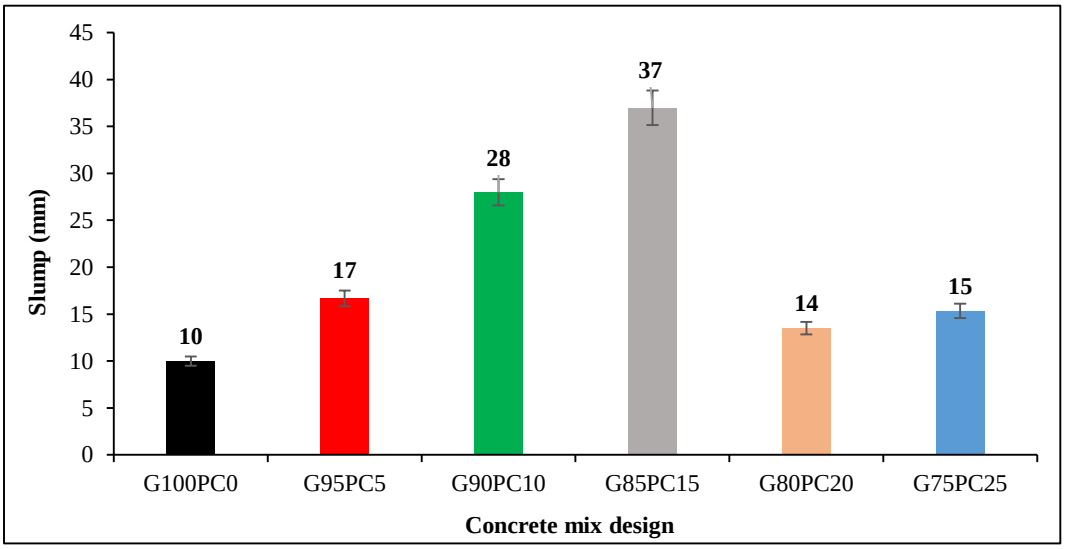


Figure 5. Evolution of the slump of geopolymer concretes with cement content

Figure 6 presents the evolution of the apparent density of geopolymer concretes with cement content and curing time. Firstly, there is a slight decrease in density with curing time, which is probably related to the loss of part of the water contained in the geopolymer matrix under the effect of geopolymerization between the metakaolin and the alkaline solution. This decrease corroborates the results of Pouhet et al. [19], who showed that the water contained in the geopolymer paste evaporated easily over the curing time. However, a slight increase in the density of the samples was observed with the cement content, more specifically for the curing times of 14 and 28 days (2.07 to 2.17 g/cm^3). This increase in density may be partly related to the fact that the specific density of metakaolin (2.63g/m^3) is lower than that of cement (3.10 g/cm^3). Therefore, the partial substitution of MK by cement would cause an increase in the density of the concrete matrix. It can also be related to the densification (reduction of internal porosity) of the concrete matrix by the geopolymer gel. The condensation of this gel may have been improved by the heat of hydration of the cement contained in the matrix, which increases the geopolymerization reaction. The results obtained in this study are comparable to those presented by Joshi & Kadu [10], who found a density between 2.20 and 2.35 g/cm^3.

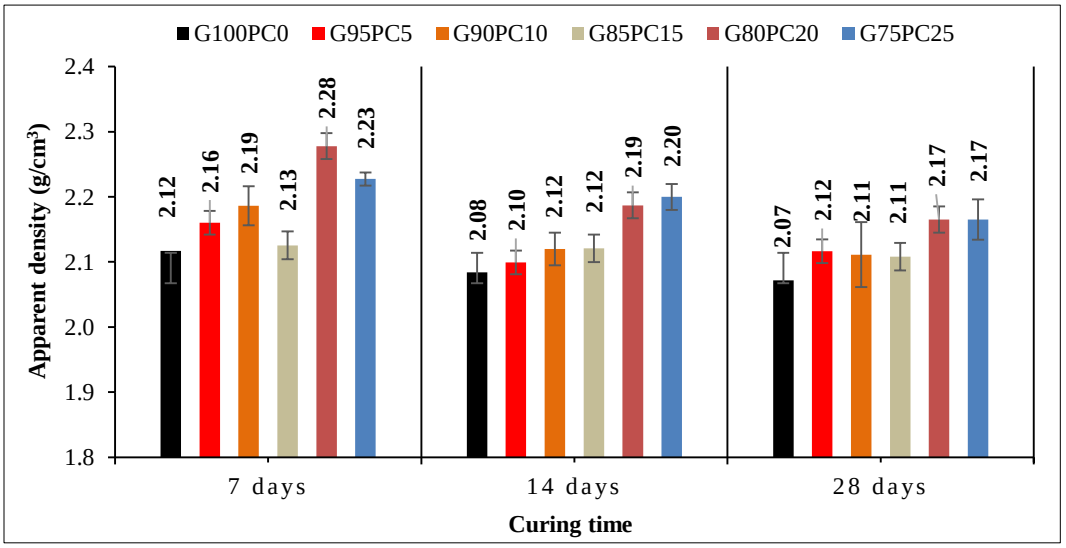


Figure 6. Evolution of the dry apparent density of geopolymer concretes with the curing time for different cement content

Ultrasonic Pulse Velocity

The evolution of the compactness of the different geopolymer concretes with the content of cement was assessed through the measurement of the ultrasonic pulse velocity after 28 days of curing (Figure 7). The ultrasonic velocity increases from 3553 to 4098 m/s, with the content of cement ranging from 0 to 20%. This reflects the densification of the geopolymer concrete with the content of cement up to an optimal of 20%, at which better mechanical resistance can be expected. However, the decrease in ultrasonic velocity to 3612 m/s with 25% cement would probably be due to a modification of the molar ratio SiO_2/Al_2O_3 in favor of calcium oxide (CaO), which may have led to adverse effects such as a decrease in the geopolymerization reaction and microcracks in the matrix following the high rate of hydration of CaO. This is in agreement with the results obtained on a geopolymer concrete (3420 m/s) produced by Kumar et al. [28].

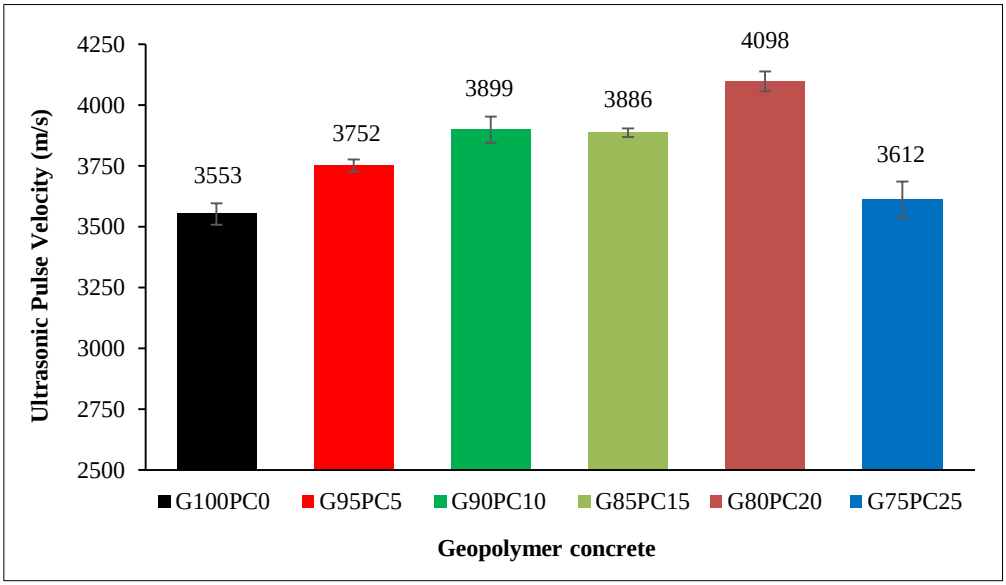
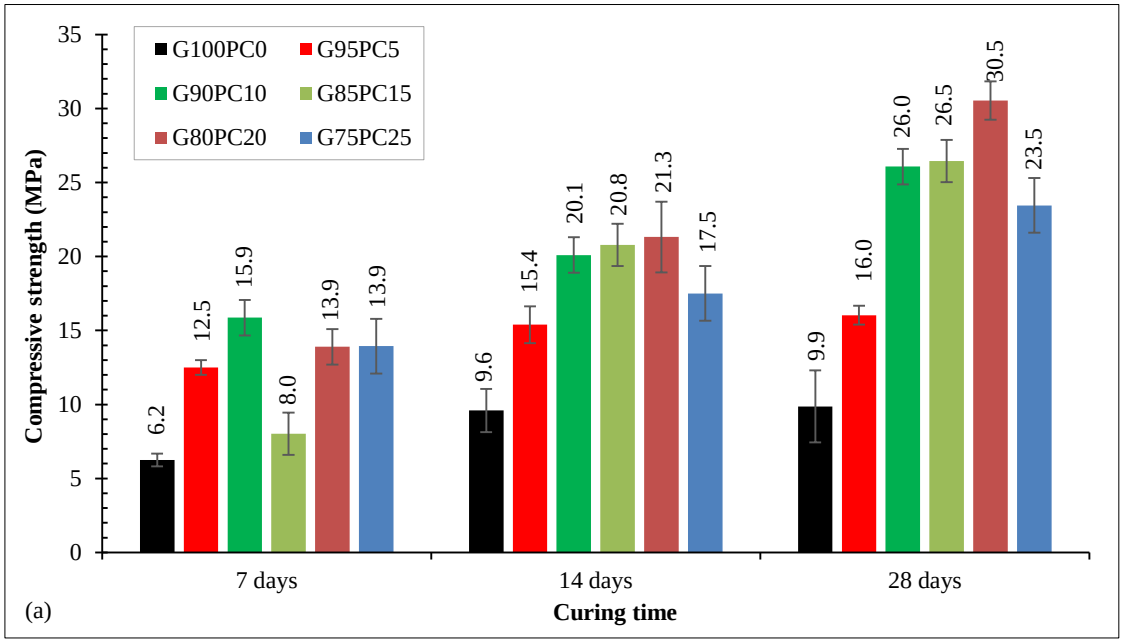


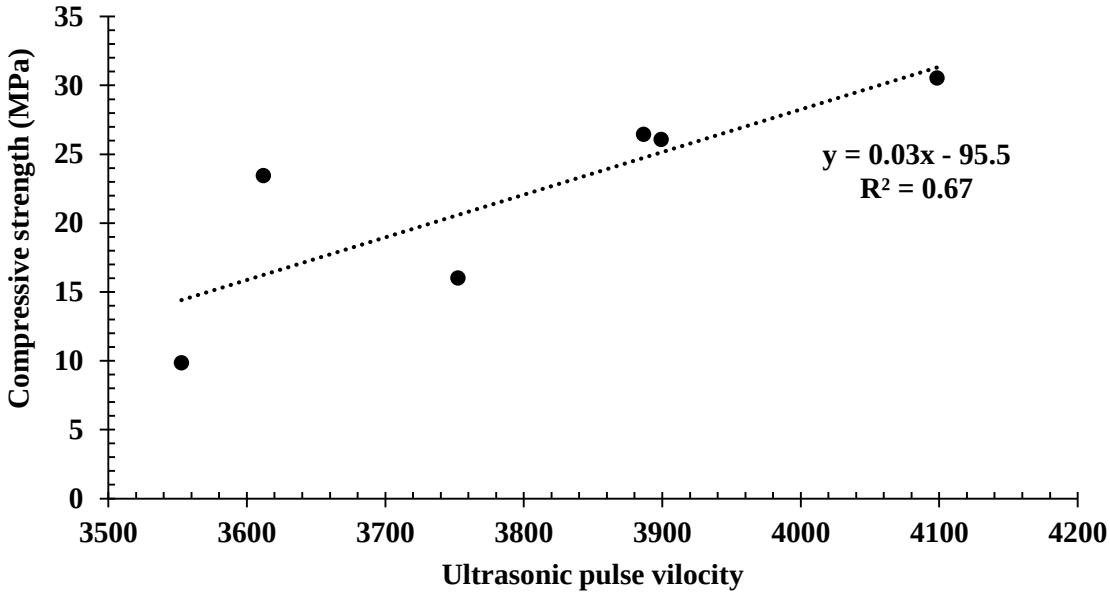
Figure 7. Evolution of ultrasonic pulse velocity of geopolymer concrete with the content of cement at 28 days

3.2. Mechanical Properties of Geopolymer Concrete

Compressive Strength

Figure 8-a presents the evolution of the compressive strength (R_C) of geopolymer concretes with the content of cement and the curing time. The compressive strength increases with the curing time up to 28 days for all the samples, except the samples that do not contain cement, whose strength does not increase beyond the 14th day of curing. The low compressive strength observed on $G_{85}PC_{15}$ on the 7th day compared to other samples containing cement could be explained by a phenomenon of segregation that may have taken place during the mixing. The low increase in strength over the curing time with the cement was also observed by Mehta and Siddique [14], who estimated a variation of less than 1% between 7 and 28 days of curing.





(b)

Figure 8. Evolution of the compressive strength a) with the curing time and the cement content, b) ultrasonic pulse velocity

Furthermore, the compressive strength increases with the content of cement for all curing times but is much greater at 14 and 28 days. The strength increases from 9.9 MPa to 30.5 MPa with 0% to 20% cement on the 28th day, resulting in a gain of the compressive strength 208% [(30.5-9.9)*100/9.9] with 20% cement compared to concrete without cement. This gain in strength can be attributed to the formation of cementitious hydrates, which are responsible for the development of the mechanical resistance of geopolymer concretes compared to the samples that do not contain cement. In addition, the improvement in resistance can be explained by the positive effect of the addition of CaO from the cement, whose heat of hydration leads to condensation of the geopolymer gel and acceleration of geopolymerization.

These results are in agreement with those of Askarian et al. [29], who also showed that the incorporation of Portland cement in geopolymer concrete under curing at a controlled temperature of 20 ± 3 °C and relative humidity of 65 ± 10% considerably improved its compressive strength. The substitution of MK by only 10% cement, i.e., 35 kg/m^3, allows the geopolymer concrete to be useful in common construction projects in Burkina Faso, where the concrete should have a compressive strength of 20 to 25 MPa, i.e., class C23/25. This is also interesting in terms of the limited environmental impacts and economic benefits that this would generate compared to the use of concrete containing up to 350 kg/m^3 of cement.

However, the compressive strength decreased to 23.5 MPa at 25% cement content; corroborating the decrease in the ultrasonic pulse velocity of concrete $G_{75}PC_{25}$ (Figure 7). In fact, a quasi-linear correlation was devised between the evolution of the compressive strength and ultrasonic pulse velocity (Figure 8-b). This would be explained by a reduction in the content of geopolymer gel, which provides the bond between the particles of the matrix, due to the increase in the content of CaO from the cement to the detriment of the content of amorphous silica and alumina from MK. In addition, the heat of hydration, whose intensity depends on the content of the cement, would cause microcracks in the matrix and result in a reduction in strength. Furthermore, Chen et al. [4] also showed that beyond the optimal content of CaO, the distances between the SiO_4/AlO_4 tetrahedra become large, causing a decrease in geopolymerization reactions due to the overabundance of Ca bonds at the expense of Si and Al geopolymer bonds. Thus, the additional Ca^{2+} precipitates into $Ca(OH)_2$ and OH^- in the alkaline reaction medium, preventing the dissolution of Ca^{2+} from the cement, which leads to a decrease in the strength of the geopolymer concrete.

Tensile Strength

The effect of the partial substitution of metakaolin by cement was also studied on the tensile strength (R_T) of geopolymer concrete at 7, 14, and 28 days of curing (Figure 9). Just like conventional concrete, the tensile strength of geopolymer concrete is very low compared to the compressive strength for the same mix design. However, a slight increase in this strength was observed over the curing time. For example, the tensile strength is 0.8 MPa at 7 days and slightly increases to 1.2 MPa at 28 days with 0% cement. Furthermore, there is also a variation in tensile strength with the content of cement. At 28 days, the tensile strength increases from 1.2 to 2.2 MPa with 20% cement; resulting in a ratio R_C/R_T of 14 for $G_{80}PC_{20}$. These results are similar to those reported by Ramujee & Potharaju [11], where the 28th day tensile strength of concrete of the same class of strength is 2.3 MPa.

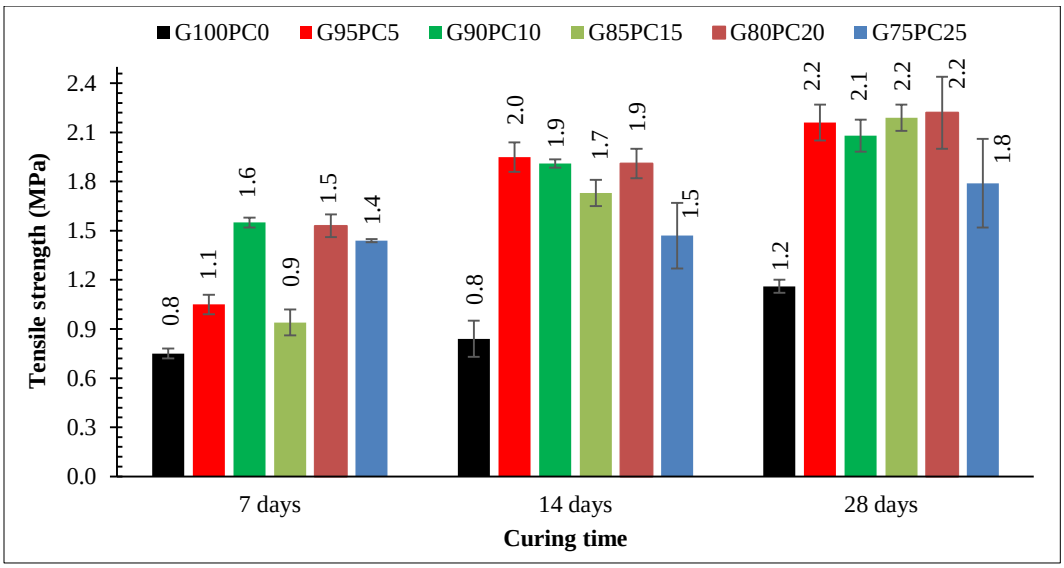


Figure 9. Evolution of the splitting tensile strength of geopolymer concrete with the curing time and the cement content

The improvement of the tensile strength with the addition of cement would be related to the formation of C-S-H type hydrates from the hydration of cement, which are responsible for the mechanical resistance of cementitious materials. It can also be attributed to the accelerated geopolymerization and condensation of the geopolymer gel due to the heat of hydration of the cement.

However, the tensile strength decreased to 1.8 MPa with 25% cement cured at 28 days, and the same phenomenon is also observed at 14 days of curing. This decrease would probably be due to an effect of inhibition of the geopolymerization reaction linked to a considerable decrease in the content of amorphous aluminosilicate in the metakaolin, comparable to the content of cement.

3.3. Durability of Geopolymers Concrete

Resistance to Acid Attacks

Figure 10 presents the evolution of the mass loss of geopolymer concrete soaked in a sulfuric acid solution (H_2SO_4), concentrated at 3% and pH 0.7 ± 0.05, for a continuous period of 28 days. It generally shows an increase in mass loss for all samples with the soaking time and the content of cement, except for 15% cement, which presents a particular variation. For all the soaking times (2 to 28 days), the maximum mass losses are recorded with the samples containing the highest content of cement at 25% (up 7.1% after 7 days), contrarily to the geopolymer concrete without cement, which presents the lowest mass loss (only 2.1% after 7 days). Moreover, the mass loss after 28 days of acid attack is only 8.3% for $G_{100}PC_0$ against 11.4% for $G_{75}PC_{25}$. This shows the detrimental effect of cement on the resistance to acid attacks of geopolymer concrete. This is related to the vulnerability of hydration products to sulfuric acid compared to geopolymerization products [30].

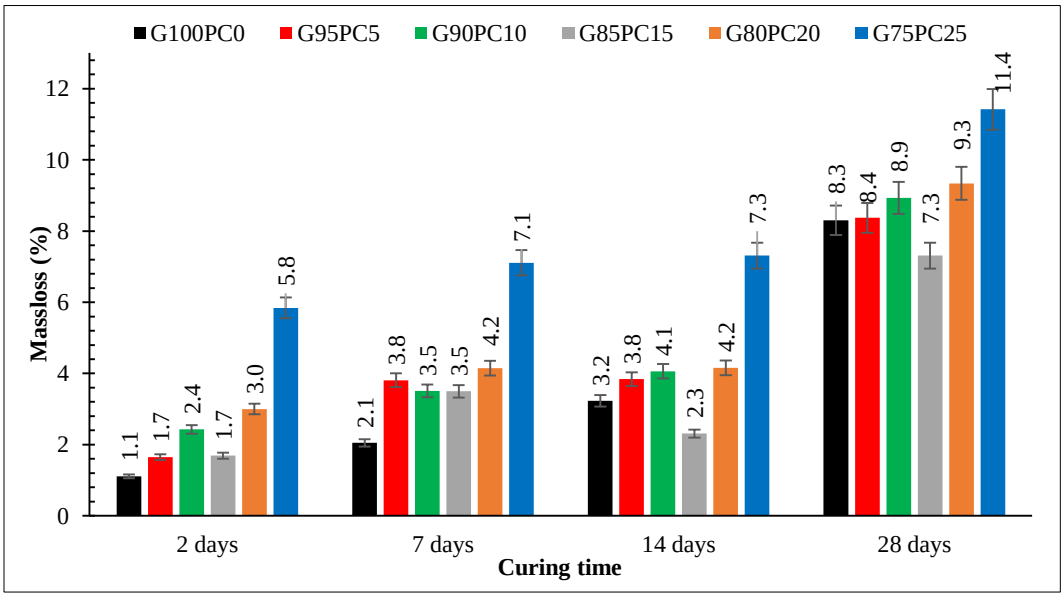


Figure 10. Evolution of the weight loss of geopolymer concrete exposed to acid sulfuric attack (pH of 0.7 ± 0.05)

The increase in mass loss is attributed to the leaching of hydration products from the cementitious binder during exposure to acid attacks [31]. It can also be attributed to the consumption of reactive silica and alumina from metakaolin by the soluble CH to form supplementary cementitious products, which are more vulnerable to sulfuric acid. Sulfuric acid, in addition to leaching the cementitious products, may generate ettringite, which leads to expansion and creates microcracks that further accelerate the leaching and mass loss of the material [30].

Porosity Accessible by Water and Capillary Absorption

The effect of cement on the water-accessible porosity and capillary water absorption of geopolymer concretes is presented in Figures 11 and 12. They show a low porosity for the concrete containing cement compared to the reference concrete without cement. The porosity decreases from 15 to 13.2% between 0 to 20% cement (Figure 11). Moreover, the same phenomenon is observed in capillary absorption (Figure 12), whose rate of absorption (sorptivity) also decreases with increasing the content of cement. These confirm a possible relationship between these two parameters; as the most porous samples would absorb the highest amount of water rapidly. The high porosity of the sample without cement (15%) led to a very high sorptivity (4.82 kg/m^2.h$^{1/2}$) and saturation in only about 4 hours of capillary immersion. However, the sample that contains 20% cement has the lowest porosity (13.2%), sorptivity (2.12 kg/m^2.h$^{1/2}$), and absence of saturation up to 24 hours of capillary immersion. The water absorption depends on the characteristics of the porous network in the material, essentially the size of the pores, their connectivity, and their shape.

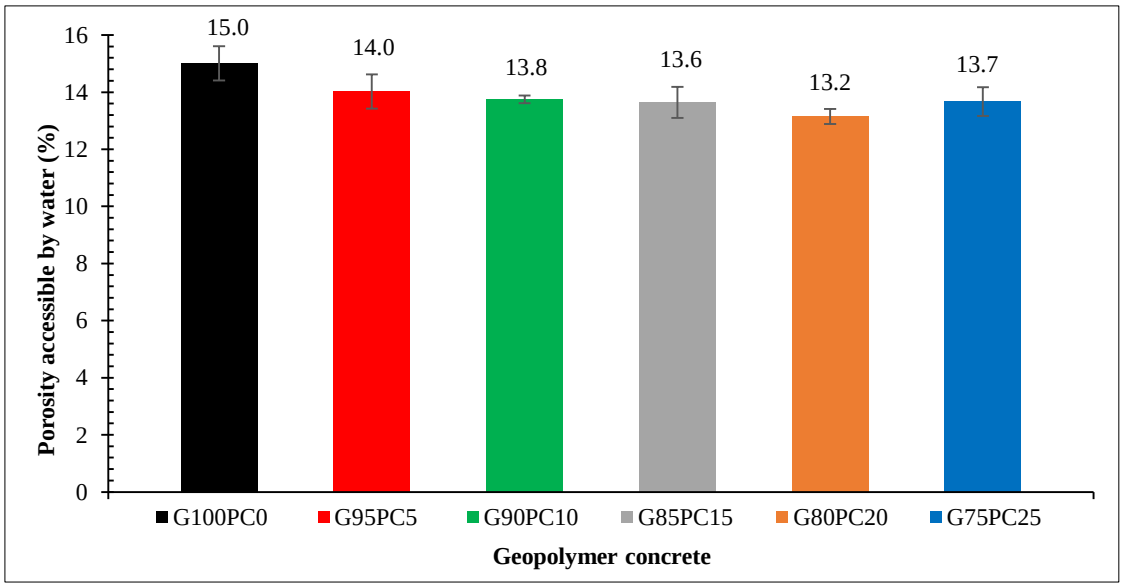


Figure 11. Evolution of the porosity accessible by the water with cement content

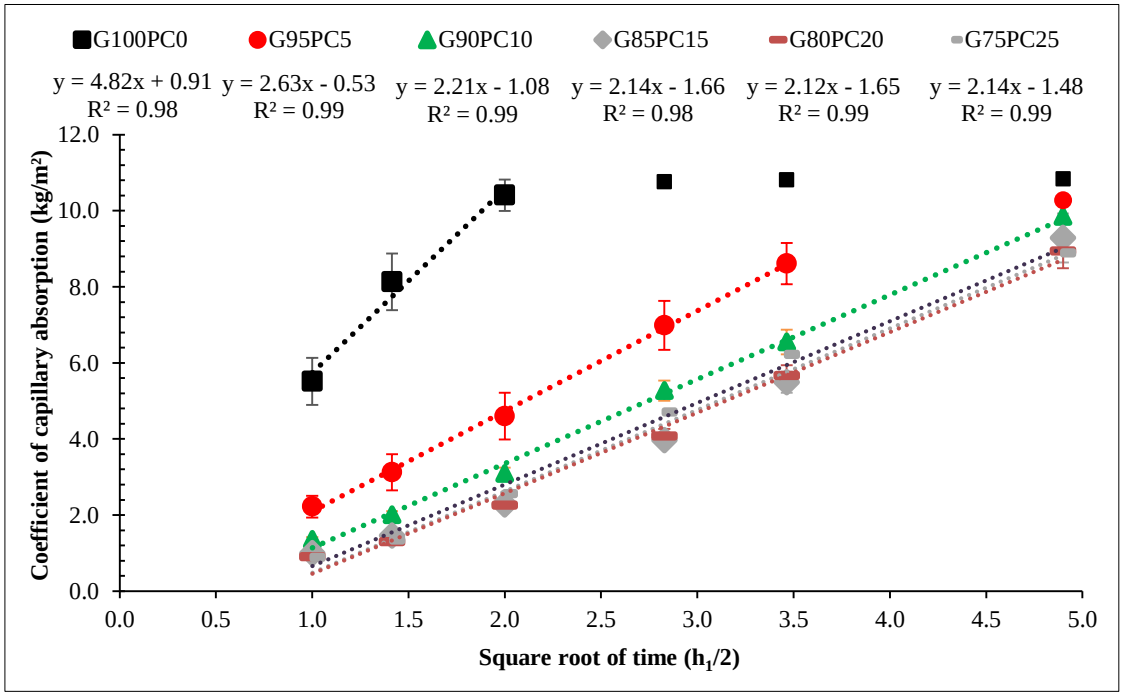


Figure 12. Evolution of water capillary absorption between 1 and 24 hours

The decrease in porosity and sorptivity with the increase in cement content is due to a densification of the geopolymer matrix network following the heat of hydration of the cement, which favors an acceleration of the geopolymerization. This made it possible to reduce the porous texture of the concrete matrix by closing the capillary porosity with geopolymer gel and hydrates and increasing the discontinuity of the percolation paths. Therefore, the more cement in the matrix, the less capillary porosity and water absorption occur in the geopolymer. These results corroborate those of the pulse velocity (Figure 7) and the mechanical resistance (Figures 8 and 9), where the highest ultrasonic velocity is observed on the least porous samples, also presenting the highest mechanical resistance.

4. Conclusions

This study aimed to design and characterize the engineering and durability properties of geopolymer concrete produced using calcined clay and Portland cement type CEM I 42.5 at room temperature in the context of Burkina Faso. The analysis of the results can lead to the following conclusions:

- The physical properties of the geopolymer concrete improved with cement, reaching a good workability characterized by values of slump between 15 and 37 mm and thus guaranteeing its implementation on site. The apparent density also slightly increases with the content of cement for all the curing times, and more specifically for the curing times of 14 and 28 days. The compactness of the concrete also increased with the content of cement in the geopolymer concrete.
- The mechanical properties generally improved when the metakaolin was partly substituted by Portland cement. At 28 days, the gain in compressive strength reached 208% for the content of cement of 20%, compared to concrete without cement. The tensile strength of different samples changes very little with age and the content of cement.
- The durability of geopolymer concretes improved through the decrease of capillary sorptivity (4.83 $kg/m^2.h^{1/2}$ with 0% cement against 2.12 $kg/m^2.h^{1/2}$ with 20% cement) and porosity (15% with 0% cement against 13.2% with 20% cement). However, it has been observed that cement leads to more degradation of geopolymer concrete exposed to sulfuric acid. The mass loss is only 8.3% for geopolymer concrete without cement against 11.4% with 25% cement after 28 days of immersion in acidic solution. Although the cement made it possible to decrease the porosity of geopolymer concretes, it also had a very damaging effect on their resistance to acid attack.

The present study has shown the feasibility of producing geopolymer concretes without heat treatment by substituting metakaolin with cement, which improves their engineering properties. The cement content of 10%, i.e., only 35 kg/m^3, can allow the applications of geopolymer concretes class C25/30 on construction sites in Burkina Faso, with a low environmental impact compared to its counterpart hydraulic concrete containing up to 350 kg/m^3. However, further studies should be carried out to study the microstructure of geopolymer concretes containing cement to better understand its microbehaviors, as well as the correlation that may exist between the strength and other parameters such as the ultrasonic pulse velocity. The possibility of using alternative mineral additions that are less polluting than Portland cement should also be considered.

5. List of Abbreviations

Symbols	Definitions	Symbols	Definitions
°C	Degree centigrade	NaOH	Sodium hydroxide
M	Mole	CEM I 42.5 R	Ordinary Portland cement of characteristic resistance 42.5 MPa
OPC	Ordinary Portland Cement	MPa	Mega Pascal
CO_2	Carbon dioxide	C-S-H	Calcium Silicate Hydrate
CAC	Calcium Aluminate Cement	CaO	Calcium Oxide
MK	Metakaolin	D_{50}	Size of the particles for which 50% of the sample is smaller
D_{90}	Size of the particles for which 90% of the sample is smaller	BET	Brunauer, Emmett and Teller (specific surface area)
CU	Coefficient of uniformity	MF	Fineness Modulus
GxPCy	Geopolymer concrete sample containing x% metakaolin and y% cement	Ø	Diameter of a sample
H	Height of a sample	ρd	Apparent density
Md	Mass of a dry sample	V	Volume of a sample
R_C	Compressive strength	P	Force applied to the sample
S	Cross-sectional area of a sample	R_T	Tensile strength
R	Radius of a sample	H_2SO_4	Sulfuric acid

P_{water}	Porosity accessible by water	M_{air}	Mass of a saturated sample measured in air
M_{dry}	Mass of a sample dried to constant mass at 105°C ± 5°C	M_{water}	Mass of a saturated sample measured in water
SiO_2	Silicon oxide	Al_2O_3	Aluminum oxide
Fe_2O_3	Iron oxide	K_2O	Potassium oxide
MgO	Magnesium oxide	Na_2O	Sodium oxide
MnO_2	Manganese oxide	TiO_2	Titanium oxide
P_2O_5	Phosphorus oxide	LOI	Loss on ignition

6. Declarations

6.1. Author Contributions

Conceptualization, S.O.S., A.M., and G.E.; methodology, S.O.S., Y.D.A., P.N., A.M., and G.E.; formal analysis, S.O.S, Y.D.A., P.N., A.M., and G.E.; investigation, S.O.S, Y.D.A., and A.M.; resources, S.O.S. and A.M.; writing—original draft preparation, S.O.S. and P.N.; writing—review and editing, S.O.S., Y.D.A., P.N., A.M., and G.E.; supervision, A.M.; project administration, A.M. and G.E.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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