Article

Development of Geopolymers from Phosphate By-Products for Thermal Insulation Applications

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Abstract: Phosphate mining generates large quantities of waste rock and sludge annually, resulting in significant environmental issues. The large areas of mine sites used to store these wastes limit the availability of usable and agricultural land, alter the topography of the land, and degrade the landscape’s aesthetics. In this study, the acid activation of phosphate by-products to enhance their reactivity and suitability for the development of geopolymer-based thermal insulation materials was investigated. Four formulations of geopolymers were developed using varying ratios of calcined clay by-product and metakaolin as aluminosilicate sources. The activation of precursors was accomplished using a 5M concentration of phosphoric acid (H₃PO₄). Several analytical techniques, including mercury intrusion porosimetry (MIP), scanning electron microscopy (SEM), X-ray diffraction (XRD), thermogravimetric analysis (TGA), and X-ray fluorescence (XRF), were carried out to characterize both the raw clays and resulting geopolymers. Furthermore, the physical and mechanical properties of the synthesized geopolymers have been evaluated. The results demonstrated a notable increase in porosity from 25.63% to 45.56% with the escalation of calcined clay by-product and metakaolin as aluminosilicate sources. The activation of precursors was accomplished using a 5M concentration of phosphoric acid (H₃PO₄). Several analytical techniques, including mercury intrusion porosimetry (MIP), scanning electron microscopy (SEM), X-ray diffraction (XRD), thermogravimetric analysis (TGA), and X-ray fluorescence (XRF), were carried out to characterize both the raw clays and resulting geopolymers. Furthermore, the physical and mechanical properties of the synthesized geopolymers have been evaluated. The results demonstrated a notable increase in porosity from 25.63% to 45.56% with the escalation of calcined clay content in geopolymers. This enhanced porosity facilitated the preparation of building insulation materials where mechanical strength is not a main requirement, as the thermal conductivity reached a value of 0.08 W/mK.

Keywords: insulation; waste rock; phosphate; phosphoric acid

1. Introduction

Morocco is known to have the largest phosphate reserves in the world. These extensive reserves are concentrated within four Moroccan sedimentary basins, collectively holding approximately two thirds of the global phosphate reserves [1]. The extraction of this mineral results in significant quantities of mine waste, due to the deep location of the phosphate layers. Presently, there is a growing interest among researchers in repurposing and recycling these waste materials for various applications across diverse fields [2]. The goal is to reduce the amount of mining waste and concurrently develop eco-friendly and useful products. Studies have indicated that phosphate by-products could be used in construction applications, such as bricks, concrete, roads, and geopolymers [1, 2]. Geopolymers represent a class of inorganic materials prepared by activating an aluminosilicate source (metakaolin, fly ash, mine tailings, etc.) with an alkaline or an acidic solution (sodium hydroxide, potassium or sodium silicate, phosphoric acid) [3–5]. These materials consist of alternating AlO₄ and SiO₄ tetrahedra (with the addition of PO₄ in the case of geopolymers based on H₃PO₄) that share their oxygen atoms to form a 3D network [6]. The term ‘geo’ signifies their geological origin, while ‘polymer’ reflects the polycondensation reaction responsible for the three-dimensional structure formation [2]. Their main characteristics as geomaterials are that they have a low carbon footprint in addition to their ability to stabilize hazardous
waste [7]. Furthermore, it has been stated that replacing Portland cement with geopolymers could potentially reduce CO$_2$ emissions from the cement industry by 44%–64%, making it an eco-friendly material [8]. Recent research indicates that geopolymers synthesized by acid activation exhibit superior performances compared to those produced by alkali activation [9]. The use of H$_3$PO$_4$ as an activator has made it possible to produce materials with a wide range of properties, including excellent thermal stability, good corrosion resistance, and high mechanical properties. It also facilitates the development of porous materials that are well-suited for effective thermal insulation.

The polymerization process can be influenced by a variety of parameters, including the reactivity of the aluminosilicate materials, the concentration of the acid solution, the amount of water added, and the duration and temperature of the curing process [7]. By adjusting these factors, the properties of the geopolymer can be modified. H. Douiri et al. found that the structure of geopolymers could be influenced by the amount of phosphoric acid added to the metakaolin [10]. The results showed a clear correlation between phosphoric acid concentration and electrical conductivity, permittivity, and dielectric loss of geopolymers at room temperature. Some authors have studied the development of geopolymers using two different metakaolins (different reactivity), composition, and curing temperature [7]. The results showed that geopolymers synthesized from the more reactive metakaolin had a porous and uneven structure, while those synthesized from the less reactive precursor had a denser and smoother microstructure. H. Lin et al. used phosphoric acid concentration and curing temperature as variables in the preparation of geopolymers. Their results showed that both curing temperature and phosphoric acid concentration significantly affected the properties of the final product [11].

Moreover, various studies have investigated the development of geopolymer materials for thermal insulation by incorporating a pore-foaming agent to create porous materials. In this context, Natali Murri et al. have used metakaolin and biomass ash as precursors for the preparation of alkali-activated geopolymers that foam when exposed to H$_2$O$_2$ [12]. As a result, the thermal conductivity was 0.07 W/mK at 30 °C, demonstrating the feasibility of using the developed material in thermal insulation. Another study has used silica fume, which was added to metakaolin in different percentages for the generation of pores [13]. The precursors were activated by alkaline solution. The thermal conductivity of the final product was determined to be 0.22 W/mK, indicating its suitability as an insulating material. In addition, metakaolin was also used with limestone as a raw material and was activated by phosphoric acid [14]. The thermal conductivity reached 0.133 W/mK, which proves the ability of the materials to be used in thermal insulation. This study explores how to make phosphate by-products more suitable for creating thermal insulation materials using geopolymer technology through an acid-activation process. Generally, the Moroccan phosphate series consists of several layers. It contains marl, limestone, flint, and clay, all of which are considered phosphate by-products and must be removed to access the phosphate ore. Therefore, the material used in this study is a clay derived from phosphate by-product (referred to as “clay by-product”).

This by-product is not used as received but is subjected to a heat treatment process. This process has been shown to play a critical role in the case of unfired precursors, such as some mining wastes and clays [15]. It leads to structural changes in the material and a significant increase in the proportion of the amorphous phase, ultimately enhancing its reactivity in the geopolymerization process. Previous studies have investigated the ideal calcination temperature for phosphate mining rejects [16]. In general, the temperature used for calcination is between 700 °C and 900 °C.

The main objective is to assess how to generate pores in geopolymers made from metakaolin and calcined clay by-product using phosphoric acid. The aim is to create porous materials that are effective for thermal insulation purposes.

2. Materials and Methods
2.1. Raw Precursors

Geopolymers were synthesized using clay by-product and kaolin (purchased from LOBA Chemie (Mumbai, India)) as aluminosilicate sources. The clay by-product was
obtained from the Gantour phosphate deposit located in Ben Guerir, Morocco. In addition, kaolin was used in the composition of geopolymers to ensure a certain mechanical strength of the synthesized materials. In Table 1, the chemical compositions of the precursors are presented. X-ray fluorescence analysis results show that kaolin has high percentages of silicon oxide (SiO$_2$) and aluminum oxide (Al$_2$O$_3$): 48.56% and 34.99%, respectively. Furthermore, yellow clay has a low aluminum content of 6.26% and a SiO$_2$ percentage of 29%. However, the presence of dolomite in the clay by-product can be explained by the presence of CaO and MgO, which are found in amounts of 16.91% and 12.44%, respectively. The organic content of the clay by-product and kaolin was determined by Loss of Ignition (LOI) analysis, which involves evaluating the mass lost when the sample is heated to 1000 °C for 2 h. The LOI for the clay by-product was 30.8% and for the kaolin was 14.2%.

### Table 1. Chemical composition of clay by-product and kaolin.

<table>
<thead>
<tr>
<th>Chemical Composition, wt.%</th>
<th>Clay By-Product</th>
<th>Kaolin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>6.26</td>
<td>34.99</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>29.00</td>
<td>48.56</td>
</tr>
<tr>
<td>CaO</td>
<td>16.91</td>
<td>0.30</td>
</tr>
<tr>
<td>MgO</td>
<td>12.44</td>
<td>0.17</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>2.84</td>
<td>0.28</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.84</td>
<td>0.31</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.33</td>
<td>0.15</td>
</tr>
<tr>
<td>Loss of ignition (1000 °C)</td>
<td>30.8</td>
<td>14.2</td>
</tr>
</tbody>
</table>

The clay by-product was crushed, ground, sieved to 100 μm, and calcined at 850 °C for 2 h, while the kaolin was similarly calcined for the same duration and temperature. The calcined clay was mixed with metakaolin at different mass ratios (calcined clay/metakaolin: Geo 0%: 0/100, Geo 25%: 25/75, Geo 50%: 50/50, and Geo 75%: 75/25). Phosphoric acid 5M prepared from commercial solution (puriss. p.a., ACS reagent, reag. ISO, reag. Ph. Eur., ≥85%) was used as a geopolymerization activator. The solution was prepared 24 h in advance and stored at room temperature before the elaboration of the geopolymers. After stirring for 5 min, the resulting mixtures were poured into cylindrical molds measuring 3 cm in diameter and 6 cm in height. Initially, they were left to cure at room temperature for 24 h and then at 60 °C for 72 h. Finally, the samples were sealed in plastic films to avoid air contamination. The L/S ratio was maintained at 1.8 for all the formulations.

### 2.2. Analyses

The raw precursors and the synthesized materials were characterized using various methods. Thermal analysis (TGA) was employed to define the adequate temperature of calcination. Samples were heated to 1000 °C, and the heating rate was 10 °C/min. X-ray diffraction analysis (XRD) and X-ray fluorescence analysis (XRF) were used to determine the mineralogical and chemical compositions of both precursors using RIKAGU diffractometer with a copper anode and XRF Epsilon 4, respectively. To identify mineral phases, DiffracPlus EVA (Bruker AXS, Karlsruhe, Germany) was used. Mercury intrusion porosimetry (MIP) was performed to analyze the porosity of the geopolymers using Auto Pore IV 9500 V1.05 (Micromeritics Instrument Corporation, Norcross, GA, USA). Scanning electron microscopy (SEM) was used for microstructure examination using a TESCAN VEGA3 Emission scanning electron microscope (TESCAN, Brno, Czech Republic). A Hot Disk TPS 1500 (Hot Disk AB, Gothenburg, Sweden) was employed to determine the thermal conductivity. Moreover, an INSTRON 3369 electro-hydraulic machine (INSTRON Company, Norwood, MA, USA) was used for compression tests, and Bluehill software 3.0 (Instron, Norwood, MA, USA) was used for data processing and acquisition.
2.3. Characterization of Raw Precursors

Calcination is an effective method of removing hydroxyl groups that disrupt the structural organization. Upon heat treatment, two hydroxyl groups react to form a water molecule, leaving oxygen in the state of a superoxide anion. The resulting charge imbalance triggers the disintegration of the crystalline structure, resulting in the formation of metastable anhydrous aluminosilicates, a phenomenon commonly referred to as amorphization [17]. Based on the findings of the thermogravimetric analysis, as shown in Figure 1, the calcination temperature for both raw clays was chosen to be 850 °C. For the clay by-product, three losses can be seen in Figure 1a along with three distinct peaks observed in Figure 1b. The dehydration of the clay, which normally happens at temperatures around 105°, is represented by the first loss [1]. The dehydroxylation of montmorillonite ((Na,Ca)0.3(Al,Mg)2Si4O10(OH)2.n(H2O)), which takes place between 600 and 700 °C, is represented by the second peak [18]. The third peak denotes the complete dolomite (CaMg(CO3)2) decarbonation [2]. During the decarbonation process, calcite (CaCO3) and periclase (MgO) are formed first, followed by the decomposition of calcite to lime (CaO). For kaolin, a loss occurs between 450 °C and 800 °C, which marks the dehydroxylation of kaolinite. These results are in agreement with those obtained by the X-ray diffraction analysis (Figure 2). In the case of the clay by-product, the XRD analysis identifies three primary phases: dolomite, quartz, and montmorillonite. After calcination, montmorillonite and dolomite disappear while quartz persists. This is due to dehydroxylation of montmorillonite and decarbonation of dolomite, as confirmed by TG analysis. The presence of periclase (MgO), lime (CaO), and traces of calcite confirms incomplete decarbonation. Regarding kaolin, the disappearance of kaolinite (Al2Si2O5(OH)4) peaks in the XRD analysis (Figure 2) confirms the complete dehydroxylation of kaolinite. In addition, a hump was formed in the range of 15–36° in the spectrum of metakaolin, indicating the formation of an amorphous structure. This finding is in good agreement with previous studies. H. Peng et al. state that complete dehydroxylation of kaolinite to amorphous metakaolins occurs in the range of 600–700 °C [19]. Sperinck et al. also found that complete dehydroxylation of kaolinite takes place in the temperature range of 450 °C to 700 °C [20]. Additionally, A. Autef et al. highlighted that the dehydroxylation process of metakaolin, occurring at 750 °C, represents a crucial factor in promoting the formation of amorphous Si and Al phases [21]. Moreover, the quartz in both the clay by-product and the kaolin does not seem to be affected by the temperature. The scanning electron microscope images of clay and kaolin before calcination are consistent with XRD results. The carbonates in the clay by-product are presented in the form of rhombic crystals, as shown in Figure 3a. Furthermore, the appearance of the laminated structure in kaolin characterizes the presence of kaolinite (Figure 3b) [22].

![Figure 1. Thermogravimetric analysis of kaolin and clay by-product: (a) TG and (b) DTG.](image-url)
3. Results

Figure 4 displays the XRD analysis of the four geopolymers after 28 days. The presence of quartz after geopolymerization reaction has been distinguished in all geopolymers, indicating its resistance in an acidic environment. In addition, the presence of an amorphous content is distinguished in all patterns by the prominent hump within the 18°–38° range. For Geo 0%, containing 100% metakaolin, the formation of aluminum phosphate (AlPO₄) as well as AlPH (AlH₃P₃O₁₀·2H₂O) was observed. Mathivet et al. outlined a four-step process for geopolymerization when metakaolin is activated with phosphoric acid. This
process begins with the dealumination of metakaolin, followed by the polycondensation of $\text{PO}_4^{3-}$, $\text{Al}^{3+}$, Si-O, and the hydration of unreacted silica. The third phase involves the formation of a Si(OH)$_4$ and an alumino-phosphate network. Finally, all reactions result in the formation of a complex structure consisting of silica gel, a Si-O-Al network, and an Al-O-P network [23]. Geopolymers Geo 25%, Geo 50%, and Geo 75%, containing 25%, 50%, and 75% of calcined clay, respectively, also exhibited the presence of an AlPO$_4$ phase, along with the formation of other new phases. In Geo 25%, monetite (CaHPO$_4$) was distinguished as a result of the reaction between CaO and H$_3$PO$_4$. This reaction can be represented by Equation (1) [24]:

$$\text{CaO} + \text{H}_3\text{PO}_4 \rightarrow \text{CaHPO}_4 + \text{H}_2\text{O}$$  \hspace{1cm} (1)

In addition to the formation of monetite, Ca$_8$P$_6$O$_{28}$, and hydroxylwagnerite (Mg$_3$PO$_4$OH), newberyite (Mg(PO$_3$OH), 3H$_2$O) was formed in Geo 75% through the reaction between MgO and H$_3$PO$_4$, as presented in Equation (2) [25]:

$$\text{MgO} + \text{H}_3\text{PO}_4 + 2\text{H}_2\text{O} \rightarrow \text{Mg(PO}_3\text{OH)} + 3\text{H}_2\text{O}$$  \hspace{1cm} (2)

In Geo 75%, which contains 75% calcined clay, a reaction between lime and phosphoric acid resulted in the formation of brushite (CaHPO$_4$, 2(H$_2$O)) along with the formation of other phases such as newberyite and monetite. The formation of brushite could be represented as follows [26]:

$$\text{CaO} + \text{H}_3\text{PO}_4 + \text{H}_2\text{O} \rightarrow \text{CaHPO}_4 + 2(\text{H}_2\text{O})$$  \hspace{1cm} (3)
Figure 5 illustrates a cross-section of the developed geopolymers at 28 days after the day of activation. Increasing the amount of calcined clay from Geo 0% to Geo 75% resulted in a significant increase in foam production in the geopolymers, highlighting the positive impact of higher amounts of calcined clay on pore formation. It should be noted that the dissolution of lime and periclase in phosphoric acid, which is an exothermic reaction, may contribute to porosity formation. This is in agreement with the study of Walling and Provis, which states that highly basic oxides such as CaO and MgO react violently with phosphoric acid, resulting in pore formation [27]. Furthermore, pore formation may also be due to residual calcite. This can be attributed to the release of CO$_2$ during the reaction between calcite and phosphoric acid, resulting in the formation of bubbles and, consequently, the production of porous materials [28].

Figure 5. Cross-sectional view of the elaborated geopolymers.

Three samples of each formulation were tested for 28 days. Figure 6 illustrates the total porosity of the four different geopolymers and the distribution of pore sizes. As shown in Figure 6a, there is a clear correlation between the amount of calcined clay by-product and the porosity value. Notably, the porosity increases from 25.63% for Geo 0% to 45.56% for Geo 75% as the amount of calcined clay by-product in the mix increases. In Figure 6b, it is observed that as 25% of the metakaolin is replaced with calcined clay by-product, the pore size diameter decreases. This means that more pores are formed with a smaller diameter, averaging about 0.0731 µm compared to Geo 0%, which has a larger average pore size of 0.7667 µm. It is also worth noting that when the amount of calcined clay by-product exceeds 50%, there is a noticeable increase in both total porosity and pore size diameter. As mentioned above, the carbonates were not completely decomposed. The increase in porosity is due to residual carbonates (CaCO$_3$) reacting with phosphoric acid to produce bubbles from the generated CO$_2$ gas, resulting in porous materials. It was also mentioned before that the dissolution of CaO and MgO in phosphoric acid may also contribute to porosity formation. In Table 2, the mechanical strength, density, and thermal conductivity measurements are presented for Geo 0%, Geo 25%, Geo 50%, and Geo 75%. It is obvious that the addition of calcined clay had a notable effect on the geopolymers’ properties. The density decreased from 1.31 g/mL (for Geo 0%) to 0.46 g/mL (for Geo 75%). Moreover, there was a significant reduction in compressive strength (UCS) from 7.11 MPa for Geo 0% to 0.41 MPa for Geo 75% due to the generated porosity, and the thermal conductivity values also showed a slight decrease from 0.14 W/mK (Geo 0%) to 0.08 W/mK (Geo 75%). The findings of density, compressive strength, and thermal conductivity are consistent with the results of porosity. It has been shown that a sample with high porosity is less dense and less thermally conductive. From this, it can be said that the porosity of geopolymer pastes is inversely related to their thermal conductivity, density, and compressive strength. Furthermore, the thermal conductivity values of the developed geopolymers, whether they
contain only metakaolin (Geo 0%) or phosphate waste (Geo 25%, Geo 50%, and Geo 75%), indicate their good thermal insulation performance. The reason for this could be linked to the elevated L/S ratio employed in the formulation. Papa et al. have noted that both the characteristics of geopolymers and the foam’s structure are affected by the choice of blowing agent and the amount of water present [29].

![Figure 6. Total porosity of Geo 0%, Geo 25%, Geo 50%, and Geo 75% after 28 days of curing as well as the pore size distribution: (a) total porosity; (b) Log DI (mL/g) vs. pore size diameter.](image)

![Table 2. Physical and mechanical characteristics of geopolymers.](table)

<table>
<thead>
<tr>
<th>Geopolymers</th>
<th>Geo 0%</th>
<th>Geo 25%</th>
<th>Geo 50%</th>
<th>Geo 75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compositions (calcined clay/metakaolin)</td>
<td>0/100 25/75 50/50 75/25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (g/mL)</td>
<td>1.31 1.05 0.85 0.46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UCS (MPa) at 28 days</td>
<td>7.11 ± 0.69 4.95 ± 0.98 2.24 ± 0.35 0.41 ± 0.21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>0.14 ± 0.07 0.12 ± 0.02 0.08 ± 0.05 0.08 ± 0.04</td>
<td></td>
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4. Discussion

A building material’s thermal conductivity plays an important role in assessing its insulation and heat transfer characteristics [30]. While the use of phosphoric acid to activate metakaolin may not be as widespread as alkaline activators, it provides distinct benefits, such as providing a material with reduced thermal conductivity [31]. Alkali-activated geopolymers are often used in thermal insulation applications that require the addition of foaming agents (metallic silicon, hydrogen peroxide (H₂O₂), and aluminum powder) to achieve the desired porosity [14]. According to the results obtained in this study, acid-based geopolymers do not require the foaming agent often employed in the preparation of alkaline-based geopolymers. The activation of geopolymers by phosphoric acid results in high porosity as the calcined clay content increases. As shown in Figure 6a, the porosity increases significantly from 25.63% in the geopolymer with 100% metakaolin to 45.56% when 75% of the metakaolin is replaced with calcined clay. The increase in porosity is visible to the naked eye when the formulation is changed from GP 0% to GP 75% (Figure 5) and is likely attributed to the reaction between phosphoric acid (H₃PO₄) and calcium carbonates (CaCO₃), resulting in the release of CO₂. In terms of mechanical properties, the values obtained decrease from 7.11 Mpa for GP 0% to 0.41 Mpa for GP 75%.
According to Natali Murri et al., materials with similar properties could be used in a variety of applications where mechanical strength is not a main requirement, such as lightweight thermal barriers [12]. In addition, Sakkas, K.M. et al. state that although the compressive strength might initially appear low, it is important to consider that these porous materials are explicitly designed for insulation and not to support structural loads [32]. In the literature, geopolymers density, porosity, and thermal conductivity are often correlated with mechanical properties. The same trend was observed by Morsy et al., who prepared geopolymers based on metakaolin as a precursor, employing $\text{H}_3\text{PO}_4$ as an acid-activator, and incorporating limestone as a less expensive alternative to commonly used, expensive foaming agents. As a result, the developed geopolymers showed excellent effectiveness in creating air bubbles, reducing density, and increasing porosity, which resulted in a decrease of thermal conductivity to 0.133 W/mK [14].

A.M. Rashad et al. performed a study to explore the potential of reusing residual carbonation lime (a sugar beet by-product) as a blowing agent in phosphoric acid-activated metakaolin geopolymers. As with traditional blowing agents, the introduction of recycled residual lime as a blowing agent resulted in a reduction in compressive strength, thermal conductivity, and bulk density, while increasing total porosity. The findings showed that the incorporation of 6% of this sugar beet by-product resulted in the development of geopolymers with a thermal conductivity of 0.08 W/mK [31]. In addition, Tchakouté et al. conducted a comparative investigation in which they evaluated the use of both commercial calcium carbonates and calcium-rich waste materials, including eggshells, oyster shells, and snail shells, as porous agents in geopolymers composed of metakaolin and phosphoric acid. The results revealed thermal conductivity values spanning from 0.2 to 0.14 W/mK. This shows the effectiveness of using these calcium-rich wastes as porous agents to produce materials that can be used for thermal insulation [28]. Therefore, acid-based geopolymers, based on phosphate by-products, could potentially replace the use of pore-foaming agents generally used during the synthesis of alkaline-based geopolymers. This is due to the fact that when aluminosilicate material is dissolved in a phosphoric acid solution, pores are immediately created, making them promising materials for thermal insulation applications [12,33,34].

5. Conclusions

This research work has successfully implemented a plan to use clay by-product, a waste material from phosphate extraction, in the development of geopolymers through acid activation, with the objective of assessing their use as porous materials for thermal insulation. Geopolymers were synthesized through acid activation of metakaolin and calcined clay in varying proportions: Geo 0% (0% calcined clay/100% metakaolin), Geo 25% (25% calcined clay/75% metakaolin), Geo 50% (50% calcined clay/50% metakaolin), and Geo 75% (25% metakaolin/75% calcined clay). The introduction of calcined clay resulted in an increase in porosity from 25.63% to 45.56%. Consequently, the thermal conductivity showed a slight decrease from 0.14 W/mK to 0.08 W/mK. It is noteworthy that even if the difference in thermal conductivity values between geopolymers containing calcined clay or only metakaolin is not as high, it is evident that the incorporation of phosphate waste in geopolymers proves to be effective, especially for insulation purposes. In summary, these materials have the potential to reduce mining waste and contribute to the production of environmentally friendly building materials.

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References


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