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Research Article

Effect of Source Type on Pore Structure and Properties of Aerated Geopolymer Concrete

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A study has been carried out to produce environmentally friendly lightweight concrete by substituting cement with alternative geopolymer binders. Fly ash and silica fume (waste materials) were used as source materials and their effect on pore structure and properties of aerated geopolymer concrete was evaluated. Autoclaved aerated concrete, locally known as thermostone, was supplied from the market and tested as a reference mix. Three aerated geopolymer concrete mixes (around 550 kg/m^3 density) were produced by mixing source materials (fly ash and silica fume), activator solution (sodium silicate and sodium hydroxide), and aeration agent (aluminum powder). It was found that by not only enhancing the pore structure but also improving the binder medium, the aerated geopolymer mixes were stronger and less absorbed than the autoclaved aerated concrete mix. However, the thermal insulation of the aerated concrete mix was better than those of aerated geopolymer concrete mixes. In terms of the source material, it was found that usage of fly ash helped in enhancing the strength by about 100% of autoclaved aerated concrete. In addition, unless its lowest density, aerated geopolymer mix made with fly ash and silica fume in combination absorbed less water than the other investigated mixes. Adding superplasticizer to the geopolymer mix helped in enhancing its pore structure by making the pores smaller, their irregularity lesser, and their number higher. In general, an environmentally friendly lightweight material with strength and absorption better than those of autoclaved aerated concrete was produced by adopting a geopolymerization process.

1. Introduction

Concern over the current trends in energy use has increased as a result of people being more aware of the impacts of global climate change, the energy deficit, and rising greenhouse gas emissions [1]. Research on energy consumption in 27 EU members' homes and services sector reveals a consistent rise over the previous 15 years [2]. This rise is largely attributable to the heating and cooling of buildings. The EU has mandated thermal insulation use in the majority of European countries in order to counteract this rising trend in energy use, and the creation of novel and efficient insulators has emerged as a significant and developing field [3, 4]. The physical and chemical structures of insulating materials allow for the division of these materials into many subgroups. Organic and inorganic materials are the two main categories. Expanded polystyrene, extruded polystyrene, polyurethane foam, etc., are examples of organic materials which each have their own issues. For instance, polystyrene goods are highly combustible and, upon combustion, release polycyclic aromatic hydrocarbons that are hazardous to human health. In addition, this material takes a very long time to decompose, which is detrimental to the environment. Another issue is that polystyrene goods grow brittle when exposed to direct sunshine [3]. The most popular inorganic insulators used on the EU market are fibrous glass and stone wools. These fibers can irritate the skin and create respiratory issues despite being fire and high temperature resistant. These drawbacks of conventional insulating materials have spurred researchers to look for more practical and affordable alternatives. One such possibility for creating novel intumescent and porous materials is alkali-activated materials [5]. The earliest theory that alkali sources and alumina-silica rich solids react to generate a material with qualities resembling hardened concrete was discovered in the 1900s. Studies involving blast furnace slag, sodium hydroxide solutions, and numerous other additions were used to create these novel materials in the 1940s. Davidovits proposed using these techniques to create fire-resistant materials in the 1970s [6]. The fact that these new materials may be utilized to transform byproducts (waste), natural and low-value substances like fly ash, blast furnace slag, and silica fume into aluminosilicate powder offers both financial and environmental benefits, which is one reason for their popularity among researchers. Geopolymers were first described by Davidovits [7] as semicrystalline 3D aluminosilicate materials in the 1970s, which can be fabricated from natural/synthetic aluminosilicate minerals or industrial aluminosilicate byproducts/wastes (for instance, metakaolin, fly ash, slag, red mud, glass, perlite, sand, rice husk ash, clay, or a combination of them) mixed into an aqueous solution containing reactive components (such as potassium/sodium hydroxide, phosphoric acid, and potassium/sodium silicate) [8, 9]. By incorporating air bubbles into the mixture, foamed concrete generates a light, cellular substance with a density that ranges from 400 to 1850 kg/m^3 [10].

A promising area of research in the realm of porous materials is currently focused on porous geopolymers (PGs) or geopolymer foams (GFs, total porosity >70% vol%) because of their distinctive combination of advantageous physical features associated with great thermal [11], stability in chemicals [12], high mechanical qualities [13], minimal energy use, and CO_2 emissions [14]. They were utilized as membranes [15], membrane supports [16], filters and adsorbents [17, 18], catalysts [19], and thermal and acoustic insulators [20].

For the majority of civil engineering constructions, concrete serves as the primary material and its components are all naturally sourced. It is distinguished by the ability to form in any shape or cross section, and it exhibits good resistance to compressive loads [21].

Due to their performance and environmental advantages, lightweight geopolymers are replacing traditional low thermal conductivity materials [13]. In construction, geopolymer and geopolymer concrete are used as an alternative to traditional concrete because they exhibit great strength, increased durability, superior workability, reduced permeability, and reduced shrinkage, which limits cracking [22]. The vastly superior thermal resistance of geopolymers compared to traditional concrete is one of their key characteristics. Aerated concrete with a significant drop in density is essentially a mortar containing industrial waste like fly ash and pulverized sand as filler. Air is artificially trapped in these kinds of lightweight materials via chemical (metallic powder such as Al, Zn, and H_2O_2) or mechanical (foaming agents) facilities [23]. The following equations show the reaction mechanism between aluminum powder and alkaline activator to produce aerated geopolymer concrete [24].

$$\begin{gathered}2Al + 6H_2O + 2NaOH \longrightarrow 2Na\,Al\,(OH)_4 + 3H_2\\ 2Na\,Al\,(OH)_4 \longrightarrow NaOH + Al\,(OH)_3\\ 2Al + 6H_2O \longrightarrow 2Al\,(OH)_3 + 3H_2.\end{gathered} \tag{1}$$

This paper aims to produce aerated geopolymer concrete based on the chemical (gas) process by employing aluminum powder as the foaming agent. Also, the effect of the source type on the pore structure and properties of the aerated geopolymer concrete was evaluated. A comparison between the autoclaved aerated concrete (thermostone) and the aerated geopolymer concrete mixes will be carried out by evaluating their properties.

2. Experimental Details

2.1. Materials. In this paper, fly ash (FA) from the Eurobuild company and silica fume from CONMIX Ltd. company were utilized as a source of waste silicate and alumina. The chemical compositions of fly ash and silica fume are listed in Table 1. Crushed sand was employed, with a maximum size of 600 microns as filler. Sika Viscocrete 180GS is utilized as a superplasticizer in addition. A composition of sodium silicate was employed with 13.1–13.7 wt% Na_2O and 32-33 wt% SiO_2 and its viscosity is 775 CPS at 29.8°C, and sodium hydroxide with 99.9 wt% was used as an activator. In addition, aluminum nanopowder (Al) from the Karbala Thermostone Factory was used as an aeration agent.

2.2. Mix Proportions. The mixtures were created at a 550 kg/m^3 target density. At first, the alkaline activation solution was made by dissolving various amounts of sodium hydroxide flakes in pure water by first weighing a specific amount of sodium hydroxide flakes in a volumetric vial to prepare the required molarity, adding pure water to more than half of the volume of the vial and stirring it until the sodium hydroxide dissolves, then adding the water for completing the volume of the vial to the mark, which represents the volume of one liter of solution, and leaving the solution for 24 hours until the heat emitted from the solution preparation process dissipates [25]. After 24 hours, the sodium hydroxide solution was mixed with the solution of sodium silicate to obtain an alkaline activation solution and then the solution was cooled to a temperature of 15°C in order to slow down the reaction of formation of gas [26].

The autoclaved aerated concrete (ACC) mix consists of cement, lime, water, crashed sand, and Al powder supplied from the market as a reference mix in order to make a comparison with the aerated geopolymer mixes. Three aerated geopolymer mixes were designed and their components are listed in Table 2. In order to produce aerated geopolymer concrete (AGC), ground sand was mixed with the source of aluminum (Al) and silicon (Si) (fly ash and silica fume) first for homogeneity and then activated by cooled alkaline solutions (ASs) made of sodium silicate (SS) and sodium hydroxide (SH) solution. The geopolymer mixture (geopolymer, sand, and alkaline activation solution) was first mixed by hand for 1 minute followed by the

Table 1: Oxide compositions of fly ash and silica fume as determined by XRF.

Oxide	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	K_2O	P_2O_5	SO_3	Na_2O	ZnO
Fly ash	42.72	3.96	15.7	13.04	0.19	0.69	19.59	1.59	0.635	0.59	1.72	—
Silica fume	89.353	—	—	2.691	0.305	—	1.701	5.942	—	0.024	—	0.425

Table 2: Components of the investigated aerated geopolymer concrete mixes.

Mixes	Consists								
	Target density (kg/m^3)	Sand (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	AS/binder	$NaOH/Na_2SiO_3$	SP %wt of binder	Al %wt of solid	Molarity (M)
AGCF	550	518	184	—	1.82	1	—	0.12	8
AGCFS	550	518	92	92	1.82	1	—	0.12	8
AGCFP	550	518	184	—	1.82	1	2	0.12	8

*The autoclaved aerated concrete (ACC) mix was supplied from the market in order to make a comparison with the aerated geopolymer mixes.

addition of the superplasticizer (SP) to mortar and then mixing for 3 minutes with an electric mixer. Aluminum powder was added to the geopolymer mortar as a foaming agent and mixed for 15 seconds. Aerated geopolymer mixture was then poured into cubical molds of 100 × 100 × 100 mm. The samples were left in the molds for 24 hours and at room temperature to allow the gel's air bubbles to condense. Then, after cutting (surface leveling process), it was processed in a 60°C oven for another 24 hours [27]. The specimens were then removed from the oven and kept at room temperature until a test day, see Figure 1.

In order to properly produce the aerated geopolymer concrete, numerous attempts were carried out. During the manufacturing process, a collapse problem was faced, as indicated in Figure 2(a). Numerous variables, including the molarity value, sand fineness, geopolymer type, ratio of Al powder, sodium silicate solution/sodium hydroxide solution ratio (SS/SH), and viscosity of sodium silicate solution (SS), were considered in order to solve this collapse problem, as shown in Figure 2(b). The ratio of aluminum powder and sodium silicate (SS) solution viscosity was observed to be the main cause of this collapse issue after many trials. It was noticed that the amount of superplasticizer should not be more than 2% of the fly ash weight. Above this point, there will be a reduction in compressive strength and a risk of pores separation from the solid structure [28].

From this research, it was determined that the alkaline liquid of sodium hydroxide of 8 molar and viscosity equivalent to 775 CPS for sodium silicate solution and aluminum powder ratio 0.12% were suitable for producing aerated geopolymer concrete with a target density of about 550 g/m^3, as shown in Figure 2(c).

3. Tests

Samples of aerated geopolymer concrete were tested in addition to the autoclaved aerated concrete, manufactured by the Thermostone Karbala Factory and bought from the market. Three samples of each mix were tested and the effect of the source type on the pore structure and properties of the final product was evaluated.

3.1. Dry Density. All samples were tested at the age of 28 days by dividing their dry mass (kg) by the corresponding measured volume (m^3) [29]. The dry density measurements were performed on cubical specimens with the size of 100 × 100 × 100 mm^3 as stated in ASTM C796 (2015) for foaming agents used in producing cellular concrete.

3.2. Pore Structure. The cellular concrete's mechanical and physical properties are directly influenced by the size and distribution of its pores. Consequently, the characteristics of the porous structure are crucial for aerated concrete. Gel pores, capillary pores, and air holes are the three different types of porosity seen in aerated concrete [30]. In contrast to capillary and air pores, gel pores have no impact on the strength of foam concrete [31]. For the purpose of pore structure analysis, three slices (40 × 40 × 10 mm) were cut from the centers of three prismatic specimens, vertically to the cast face. Then, images were captured for these slices.

3.3. Compressive Strength. According to ASTM C513 [32], the compressive strength test was carried out on 100 mm^3 cubes utilizing a digital compression testing machine with a 2000 kN capacity, see Figure 3. The test was performed at ages of 7 and 28 days [33], and for each age, the average of the three specimens' results was used.

3.4. Thermal Conductivity. Thermal conductivity (λ) is a ratio of the heat flow to the temperature gradient of concrete which is measured in "Watts per square meter of an area of the body when the temperature difference is 1°K per meter" ((W/m^2) × (m/K)) or (W/mK). In this study, the thermal conductivity was measured at age of 28 days using the transient approach, which involves taking a reading while the sample is being heated up, see Figure 4. The test was carried out using specimens of 100 × 100 × 100 mm^3 in accordance with ASTM C113 [34].

3.5. Water Absorption. By submerging an oven-dried specimen in water and determining the saturated mass, the water absorption can be quantified. For the water absorption test, 100 × 100 × 100 mm^3 cubical specimens at the

Figure 1: Geopolymer concrete cube production stages in order (mixing, molding, cutting, sample surface, curing, and final product).

(a) (b) (c)

Figure 2: Aerated geopolymer concrete: (a) with collapse issue, (b) after solving the production issue, and (c) fly ash- and silica fume-based geopolymer samples.

Figure 3: Compression test machine.

age of 28 days were used to examine how easily water can permeate them. The cubical specimens were dried in an oven at 60°C until they reached a constant dry mass, and they were then submerged in water for seven days to reach a constant wet mass [35]. Water absorption was calculated using the following equation [36]:

Figure 4: Thermal conductivity test.

$$\text{Abw} = \left(\frac{\text{Wsat} - \text{Wdry}}{\text{Wdry}}\right) \times 100, \quad (2)$$

where Abw represents an absorption in volume (%), Wsat represents a saturated weight in air (gr), and Wdry is the dry weight (gr).

4. Results and Discussion

4.1. Dry Density. As shown in Figure 5, the density range is 500–570 kg/m^3. Autoclaved aerated concrete mix made with ordinary Portland cement had the highest density value, followed by the mix of aerated geopolymer concrete-based fly ash. When the plasticizer was added to the fly ash mix, about 4% reduction in density was observed compared to the density of the fly ash samples alone. The cause of this decline is the increase in chemical reaction that resulted in an increase in the movement of the mixture outside the mold leading to a density reduction. More density reduction was noticed by about 9.35% when silica fume was added in combination with the fly ash (50% SF and %0% FA). This is because more mixture was spilling out from the mold during aeration and oven-curing processes, taking some of the solid materials with it and then reducing the sample density.

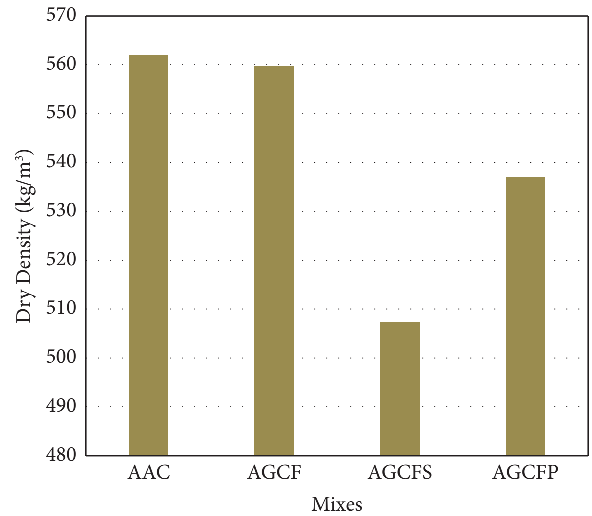

Figure 5: Densities of the investigated mixes.

4.2. Pore Structure. Porosity, permeability, pore size, and dispersion of the material all have an impact on the strength and durability of cement-based materials [31]. The cellular concrete's mechanical and physical properties are directly influenced by the size and distribution of its pores. Consequently, the characteristics of the porous structure are crucial for foamed concrete [37]. In general, the geometry of the used mold, the foaming agent, the preparation procedure, the type of materials, and the shape of the manufactured foams are the key determinants of the shape and structure. These variables have an impact on foam expansion and pore formation. The top surface of the mold and the primary volume of the paste all have an impact on the released gas path and the pressure that resulted in the slurry during the foaming process [38].

Figure 6 depicts the structure, size, and shape of the pores formed in the autoclaved aerated concrete (AAC) (Figure 6(a)) and aerated geopolymer concrete (AGC) mixes. Figure 6(b) shows that the fly ash samples (AGCF) generated the biggest void sizes. It was found that when silica fume (AGCFS) was used instead of half of the fly ash amount (Figure 6(c)), the number of voids increased with smaller diameters than when the fly ash was used alone. This suggests the significance of silicate presence in the creation of geopolymer materials and points to the silicate presence (high amount in silica fume) in the geopolymerization process.

Admixtures are chemicals or natural materials which are used to improve special properties of fresh or hardened concrete such as durability, workability, or strength characteristics of a given concrete [22]. Commonly used admixture in geopolymer concrete is superplasticizer. It was discovered that including 2% of superplasticizer (AGCFP mix) resulted in a noticeable improvement in the pore structure in terms of the distribution, size, and circularity of the pores, as shown in Figure 6(d). It was noticed that the finer the pores, the more the pore number and the lesser the irregularity. A pronounced difference in the samples pore structures (AGCF and AGCFS) compared to the pore structure of the autoclaved aerated concrete (AAC) was observed by comparing the form, size, and distribution of voids in the aerated geopolymer samples with the aerated concrete ones. This is caused by the high amount of limestone (CaO) in the autoclaved aerated concrete (AAC), which serves to lessen the reaction force and stabilize the foam, resulting in smaller pores. Previous research showed that the addition of superplasticizer improved the workability of the fresh concrete. It has less effect on the compressive strength for about two percent addition to the mass of fly ash. The dosage varies from 0.6 to 2% of the weight of fly ash. Beyond this value, there is some degradation of the compressive strength and risk of segregation [23]. According to Nematollahi [24], the effect of different superplasticizers on the workability and strength of fly ash-based geopolymer directly depends on the type of activator and superplasticizer. Therefore, AGCFP mix was similar in terms of the void size and distribution to the AAC mix. By comparing

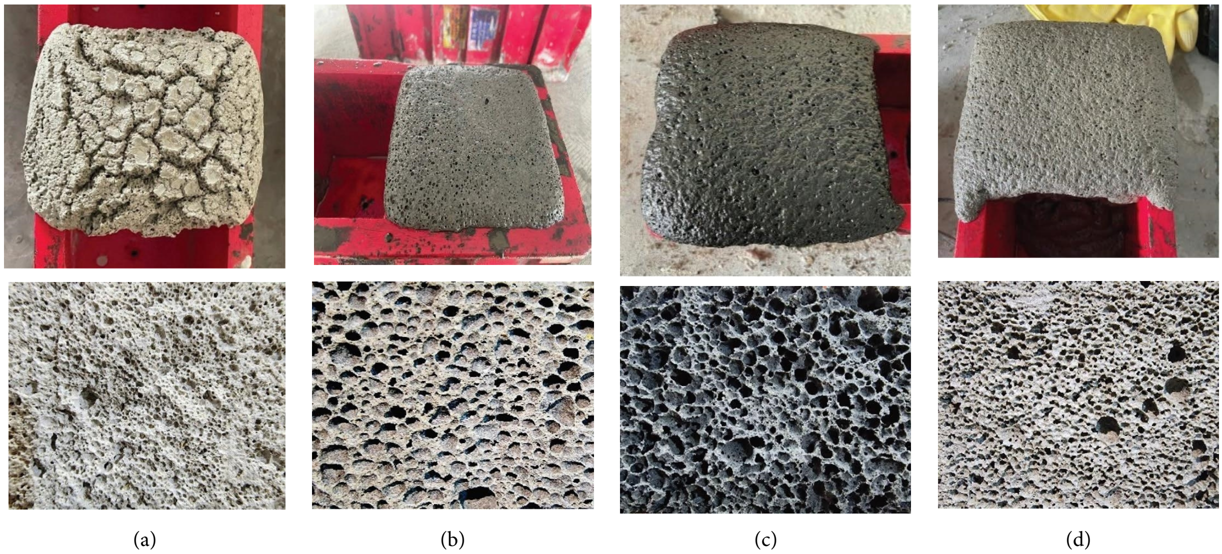

FIGURE 6: Pore structures of (a) AAC mix, (b) AGCF mix, (c) AGCFS mix, and (d) AGCFP mix (dimensions of pore images are 4 cm width and 3.5 cm height).

the form of the AGCFP mix void structure to the AGCF mix, it can be shown that adding the right quantity of superplasticizer significantly alters the product pore structure, enhancing pore size distribution and lowering density.

4.3. Compressive Strength. It is widely known that a decrease in compressive strength results from an increase in voids or pores in any material when the other parameters stay unchanged [39]. Therefore, the most porous aerated geopolymer foams were found to have the poorest mechanical characteristics. In addition, it is thought that the binding material characteristics play a bigger role in determining how strong samples' compression is. This primarily depends on how fine the material is and the SiO_2/Al_2O_3 ratio. Despite the size of the voids in the AGCF mix, Figure 7 shows that the fly ash mix (AGCF) produced the maximum strength, which was 2.9 MPa at the age of 28 days. The finer fly ash combination, which enhances bonding, is thought to be responsible for the increase in resistance compared to other samples, as well as the suitable SiO_2/Al_2O_3 ratio. The value of compressive strength decreased to 2.29 MPa at the age of 28 days, when 50% of the fly ash was replaced with silica fume. This is because the pore volume increased (density decreased) when fly ash was replaced with silica fume. A high concentration of silicates in silica fume also has a detrimental impact on strength, indicating the presence of an optimum SiO_2/Al_2O_3 ratio. Noting that, the range of 3.4–3.8 was the best SiO_2/Al_2O_3 ratio for the development of strength in geopolymer systems [40]. It is obvious that the effect of the SiO_2/Al_2O_3 ratio is stronger despite the fact that the porous structure of AGCFS became better when the fly ash was replaced with silica fume. This attributes to the aluminate role (the amount of aluminate is greater when using fly ash alone) in the geopolymerization process and implies the significance of aluminate presence in the production of geopolymer materials.

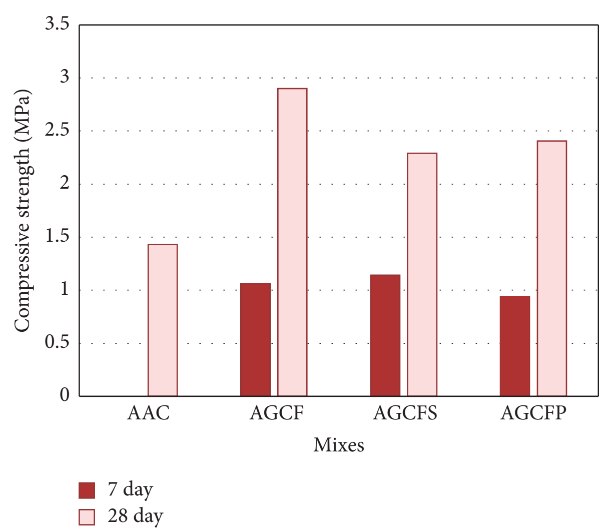

FIGURE 7: Development of the compressive strength of the investigated mixes.

Positive correlation exists between the density and compressive strength of porous materials. Compressive strength increases with increasing density and vice versa. Porous materials, on the other hand, are frequently thought of as lightweight, low-strength materials while some applications required high strength at low density materials [41]. Although the addition of the superplasticizer to the fly ash was intended to increase compressive strength by strengthening the pore structure of the samples, the really result was a 17% reduction in strength. This drop coincides with a 4% decrease in density (increase in air void) when compared to the fly ash sample alone. The reason for the strength loss in the AGCFP mix is also because adding SP increases the mortar workability, which increased the aeration reaction, leading to increase in the amount of mortar

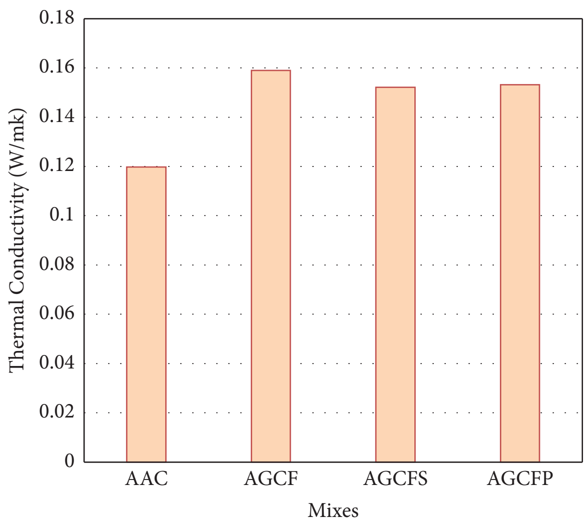

Figure 8: Thermal conductivity of the investigated mixes at the age of 28 day.

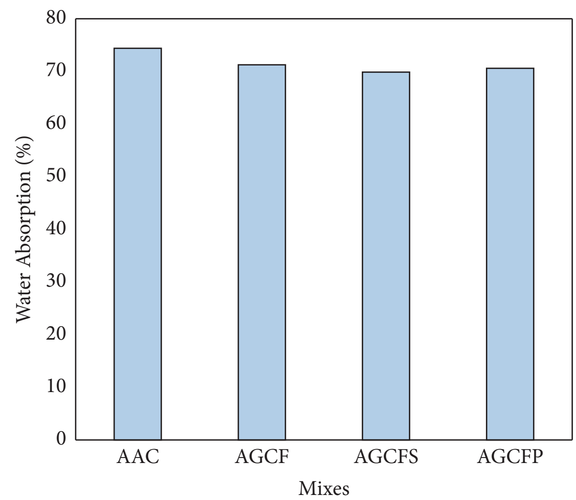

Figure 9: Water absorption of the investigated mixes.

spilling out from the mold, as shown in Figure 6(d). This, in turn, resulted in a decrease in the amount of solid in relation to the amount of air void in the sample, and a decrease in the slurry components (binder, filler, activation solution, and gas generation agent) happened, leading to weakening the material.

In general, the compressive strengths of the three investigated aerated geopolymer mixes were higher than that of autoclaved aerated concrete mix, as shown in Figure 7.

4.4. Thermal Conductivity. The thermal conductivity data for all evaluated mixes at 28 days are shown in Figure 8. The (AAC) mix was the best as a thermal-insulating material since it was recorded as lower thermal conductivity value than the geopolymer mixes.

Comparing the results of compressive strength and thermal conductivity, it can be seen that the mix with the highest thermal conductivity value was AGCF, which is also the mix with the highest compressive strength. This mix was followed by the AGCFP mix, which had the second-highest compressive strength value and the second-highest thermal conductivity value, and lastly, the AGCFS mix which, when compared to other geopolymer concrete mixes, had the lowest compressive strength and thermal conductivity values.

4.5. Water Absorption. Figure 9 depicts the difference in water absorption between autoclaved aerated concrete (AAC) and geopolymer aerated concrete mixes (AGCF, AGCFS, and AGCFP) that were submerged in water for seven days. It has been noted that aerated geopolymer concrete (AGC) mixes absorbed less water than autoclaved aerated concrete (AAC) mixes. Figure 6 shows that the fly ash combination alone has the highest void volume of all the mixtures but because the interior pores are not connected, the fly ash mixture did not absorb the highest water amount. In addition, a noteworthy finding is that mixes created with silica fume and fly ash in combination had a lower water absorption rate than the other tested mixes. The greater number of trapped air pores and their near-circular forms, which make them discontinuous (closed), suggest that the fusion of trapped pores is less common in geopolymer mixtures. This can be supported by the decreased water absorption. Due to the target low density of the samples (high pore volume), the absorption values of all the mixes are ultimately close.

5. Conclusions

From the experimental work, the following conclusions can be drawn:

(1) In comparison to the fly ash mix (AGCF), it was discovered that the addition of silica fume (AGCFS mix) and the superplasticizer (AGCFP mix) significantly reduced the density, i.e., increased the air pore volume.

(2) By examining the pore structure, it was discovered that the using of fly ash as a source material (AGCF mix) helped in generating larger pores than the others. In addition, adding silica fume (AGCFS mix) resulted in a slight improvement in the pore structure, whereas adding the superplasticizer (AGCFP mix) resulted in a significant improvement in pore structure; pores are smaller, the irregularity is lesser, and the pores number is higher.

(3) All compressive strength values of aerated geopolymer concrete (AGC) mixes were higher than that of autoclaved aerated concrete (AAC) mix. It was found that the compressive strength of aerated geopolymer concrete is greatly affected by its density and the SiO_2/Al_2O_3 ratio. The maximum compressive strength value was recorded for the aerated geopolymer-based fly ash mix (AGCF).

(4) Autoclaved aerated concrete (AAC) mix recorded the lower value of thermal conductivity (0.119 W/mK).

However, a slight increase in the thermal conductivity of the investigated aerated geopolymer mixes made with the different source materials was recorded.

(5) Autoclaved aerated and aerated geopolymer concrete mixes absorbed about the same amount of water (70–74%).

(6) In general, an environmentally friendly lightweight material with strength and absorption better than those of aerated concrete was produced by adopting a geopolymerization process.

Data Availability

All data used in this study are provided in the results section of this paper.

Disclosure

This research was performed as part of MSc project at the College of Engineering/University of Anbar/Iraq.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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