Effect of Burn Joss Paper Ash on Properties of Ground-Granulated Blast Furnace-Based Slag Geopolymer

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Abstract: The purpose of this study is to make geopolymers using burned joss paper ash (BJPA)—which is used in traditional Chinese festivals—and ground-granulated blast-furnace slag (GGBFS). GGBFS-based geopolymers were replaced by BJPA, by mass, at levels of 0%, 20%, 40%, 60%, 80% and 100% and the liquid-to-solid ratios (L/S) were 0.3, 0.4 and 0.5. The properties of fresh, hardening, durability and microscopic analysis were examined to determine the effect of BJPA-substitution ratios and L/S on the engineering properties of composite geopolymers. The results show that among the fresh properties, as the amount of BJPA replacement increases, the setting time tended to increase, but the fluidity slowed down. The maximum compressive strength reached 81.1 MPa. As the amount of BJPA replacement increased, the elastic modulus of the geopolymer increased and the brittleness decreased. However, in the dry shrinkage test, it was found that an increase in BJPA helped reduce the dry shrinkage of the geopolymer. X-ray diffraction analysis revealed that a rise in the BJPA-substitution ratio increased the peak value of calcium carbonate. Scanning electron microscope images showed that microcrack size decreased with an increase in the BJPA-substitution ratio, with maximum and minimum crack sizes of 5.80 µm and 176.8 nm, respectively. This was because BJPA was unable to undergo complete polymerization and therefore was able to fill the cracks produced during the polymerization. In conclusion, BJPA may be used for waste recycling in the production of geopolymers.

Keywords: burn joss paper ash; ground-granulated blast furnace slag; composite geopolymers; engineering properties

1. Introduction

Ordinary Portland cement (OPC) is made of blends of mineral admixtures and its usage as a binder of concrete material [1]. Although cement can provide the main strength source of OPC, its manufacturing process also greatly affects the environmental pollution. The carbon dioxide emissions produced each year also account for 6% of the global total [2]. For the maintenance of the global environmental climate, Scholars from all over the world are eager to find alternative cements, hoping to find environmentally friendly materials that can have the same benefits as cement under the premise of resource reuse. geopolymer is an engineering material term coined by Joseph Davidovits in 1978. It describes this kind of material as a geotechnical material with similar adhesive properties and can have the conditions to replace cement [3–6]. The main reaction of geopolymerization is to produce two chemical reactions with sodium hydroxide (NaOH) through silicon (Si) or aluminum (Al). The first reaction will destroy the structure of its chemical chain and cause Si or Al to be released from the material; The two reactions will become anhydrous calcium silicate and initiate...
the polymerization reaction [7]. Using industrial byproducts such as fly ash, slag and metakaolin, as materials for producing geopolymers [8–12] enables waste recycling and the production of new materials, as well as reduces the use of cement in concrete to decrease global carbon emissions [13,14]. Geopolymers possess excellent thermal stability as well as decent mechanical and physical functions, making them a type of green cement with properties similar to that of Portland cement [15] that can be used in precast concrete products during infrastructure development [16,17]. As an environmentally friendly material, geopolymers have been found to be ideal substitutes for ordinary Portland cement (OPC) [18–22]. Under the research and promotion of many scholars, it is generally believed that geopolymer concrete can provide better mechanical properties, durability and environmental protection than ordinary concrete.

Because of the emergence of novel materials, it is of considerable help to the civil engineering community. Many scholars have also studied geopolymers. One of the main reasons is that the silicon and aluminum elements reacted in it can be obtained from industrial by-products [23,24]. Using nickel slag to replace 20% and sodium silicate modulus between 1.0 and 2.0 can obtain the best compressive strength and the lowest shrinkage [25]. Rice hull ash can increase the bonding strength of the Si–O–Si chain. When the substitution amount is 35% and the geopolymer produced by 10-M NaOH solution has a very dense crystal structure under the observation of scanning electron microscope (SEM) [26]. The addition of nano-silica helps to increase the high-calcium fly ash polymer’s martensitic strength and flexural strength. When adding one to two percent, the structure observed under the microscope will be denser [27]. Because of the distinct source of materials used, the base material will also indirectly influence the properties of the geopolymer. The most serious problem in terms of the durability of concrete structures is sulfate attack. The deterioration of cement paste is caused by expansion, peeling and embrittlement depending on the conditions of sulfate attack. By contrast, geopolymer concrete possesses a higher resistance against sulfate attack [28]. Geopolymers are high-strength alkali cementing materials that do not rely on calcium and are formed under high-alkali conditions through the blending of aluminosilicate materials with an alkali–metal–silicate solution [29]. A geopolymer is generally formed through the following four steps: (a) Aluminum silicate mineral powder is dissolved in alkaline solution; (b) the dissolved silicon and aluminum ions diffuse from the solid particle surface to the particle pores; (c) the alkali–metal–silicate solution undergoes polymerization with silicon and aluminum ions; (d) the gel gradually removes the remaining water and solidifies into an aluminosilicate geopolymer [30]. Its structural composition differs from that of OPC formed through the pozzolanic reaction in that OPC uses the calcium silicate produced after the pozzolanic reaction to form a calcium–silicate–hydrate (C–S–H) colloid through hydration bonding, whereas a geopolymer uses the hydroxyl ions in a strong alkaline solution to precipitate the Si and Al atoms within the aluminum silicate, using the chemical bonding of their ionic states to form Si–O–Al–O polymeric bonds.

Although geopolymers have considerable feasibility for replacing cement, the material is susceptible to temperature [31], curing environment [32] and different types and mixing concentrations of alkali activators [33,34], which will affect the strength of the geopolymer. A low-concentration alkali activator produces a geopolymer with lower structural strength and a slower hydration rate; although a high-concentration alkali activator can increase structural strength and accelerate coagulation, it will also produce fragile specimens that weather and break easily [35]. A more active material, coupled with a longer mixing time, will increase its compressive strength and ion dissolution, which contributes to more intense polymerization. An increase in L/S will dilute the concentration of the alkali equivalent and decrease its pH value and the amount of hydroxide, whereby the compressive strength decreases because of the inability to precipitate the silicon and aluminum elements. Chen et al. [36] found that the optimal geopolymer was prepared with metakaolin, sodium hydroxide, sodium silicate and water, with the molar ratio of SiO₂:Al₂O₃:Na₂O:NaOH:H₂O being 3.4:1.1:0.5:1.0:11.8. With further investigation using their advantageous characteristics (i.e., high strength, heat and chemical attack resistance and low thermal conductivity), geopolymers are likely to replace cement as a next-generation
construction material. Based on the related research done by scholars, this research team also tried to combine burned joss paper ash (BJPA) is similar to that of ground-granulated blast-furnace slag (GGBFS) as a new geopolymer material.

Religious beliefs and traditional customs in Taiwan have resulted in the production of a large amount of BJPA without a fixed processing site. Taiwan burns up to 34,920 tons of joss paper annually, which are generally discarded without further processing, producing waste that seriously pollutes the environment. Taiwanese scholars have been studying BJPA as a partial substitute for cement and fine aggregate, and discovered that a substitution ratio of 2.5–10% results in early and late strengths that are 11% higher than those of the control group, indicating that adding BJPA helps increase structural strengths [36]. Regarding the appropriate water-to-gel and substitution ratios, it is feasible to replace a portion of cement and fine aggregate with BJPA. Despite the effectiveness of the BJPA in replacing cement, the problem of the vast amount of ash produced annually remains unresolved. The effective recycling of BJPA not only reduces processing costs, but also turns it into a green recycled material that reduces environmental pollution.

No research has yet been conducted on the application of BJPA in geopolymers. Based on the concepts of energy saving, carbon reduction and resource sustainability, this study aims to use BJPA for reuse in GGBFS-based geopolymers. This study combines BJPA and GGBFS as the raw materials for geopolymers and investigates its fresh and engineering properties, as well as the effects of distinct ratio parameters on the fresh and hardened properties of a BJPA–GGBFS composite geopolymer.

2. Materials and Methods

2.1. Materials

The alkali activator consists of solid sodium hydroxide and sodium silicate solution. Its composition is displayed in Tables 1 and 2. Before the experiment, sodium hydroxide flakes and deionized water were mixed into a 5-M alkali sodium hydroxide activator solution. The raw materials for the geopolymer consist of water-quenched GGBFS (see Figure 1 for its SEM analysis) and BJPA. The latter was screened using a #100 sieve (see Figure 2 for its SEM analysis, Tables 2 and 3 [37] for its composition).

| Material     | NaOH | NaCO₃ | NaCl | Fe₂O₃ | SiO₂ | Na₂O | SiO₂/Na₂O |
|--------------|------|-------|------|-------|------|------|-----------|
| Sodium hydroxide | 98.20 | 0.165 | 0.0135 | 0.0004 | – | – | – |
| Sodium silicate | – | – | – | 0.2 | 28 | 9 | 3.11 |

Table 1. Chemical characteristics of sodium hydroxide and sodium silicate. (%).

| Material    | Specific Surface (cm²/g) | Specific Gravity | Baume Scale | Particle Size (µm) |
|-------------|--------------------------|------------------|-------------|-------------------|
| GGBFS       | 4000                     | 2.80             | –           | 45                |
| BJPA        | 6753                     | 2.75             | –           | 0.1               |
| Sodium hydroxide | –                    | 0.598           | –           | –                 |
| Sodium silicate     | –                       | 1.38             | 37          | –                 |

Table 2. Physical characteristics of material.

| Material | CaO   | SiO₂  | Al₂O₃ | MgO   | Na₂O  | K₂O   | SO₃   | Fe₂O₃  | LOI  |
|----------|-------|-------|-------|-------|-------|-------|-------|--------|------|
| GGBFS    | 42.11 | 33.65 | 13.67 | 6.53  | 0.57  | 0.57  | 1.87  | 1.18   | 0.58 |
| BJPA     | 62.83 | 15.98 | 9.39  | 3.24  | 2.82  | 0.39  | 2.46  | 1.13   | 10.7 |

Table 3. Chemical characteristics of ground-granulated blast-furnace slag (GGBFS) and burned joss paper ash (BJPA) by XRF analysis. (%).
2.2. Methods

This study used a fixed sodium silicate modulus (2.0) and alkali equivalent (4%), together with three L/Ss (0.3, 0.4 and 0.5) and six substitution ratios of BJPA (0%, 20%, 40%, 60%, 80% and 100%) as the material test variables.

The specimen mixing process was as follows: The BJPA and the GGBFS were placed in a blender and thoroughly mixed at 65 rpm for 60 s. An alkaline solution of sodium silicate and sodium hydroxide were then added in fixed quantities into the evenly blended powder within 15 s, and the resulting mixture was blended at a constant speed for 3 min to form a viscous liquid. It was then blended at 150 rpm for another 4 min 30 s, followed by tests on its fresh and hardened properties. The decreased BJPA substitution rate increased the ultrasonic pulse velocity of the geopolymer specimen by 39.6–55.7% (3 days), 36.2–54.2% (7 days), 35.5–49.6% (28 days) and 36.4–51.4% (56 days). Although the ultrasonic pulse velocity increased with the age of the specimen, a higher BJPA-substitution ratio reduced the density of the specimen and resulted in a sharp decrease in ultrasonic pulse velocity. Ultrasonic pulse velocity was proportional to compressive strength and decreased with an increasing BJPA-substitution ratio. The initial and final setting times of the geopolymer were measured according to ASTM C191 [38] standards as a reference for the execution time, the compressive strength was determined according to ASTM C109 [39] standards, the ultrasonic pulse velocity was determined according to ASTM C597 [40] standards, the shrinkage test was conducted in accordance with ASTM C157 [41] and thermal conductivity coefficient was conducted in accordance with ASTM C518 [42].
3. Result and Discussion

3.1. Setting Time

Figure 3 shows the setting times of the BJPA–GGBFS composite geopolymer. L/Ss of 0.3 and 0.4 yielded similar initial setting times, whereas an L/S of 0.5 resulted in an average rise of 104% in its initial setting time compared to that of an L/S of 0.3; similarly, L/Ss of 0.4 and 0.5 yielded similar final setting times, whereas an L/S of 0.5 resulted in an average rise of 156% in final setting time compared to that of an L/S of 0.3. In other words, an L/S of 0.3 produced shorter initial and final setting times compared to L/Ss of 0.4 and 0.50. An increase in the substitution ratio of BJPA also extended the setting time: For L/Ss of 0.3, 0.4 and 0.5, an increase in the BJPA-substitution ratio extended the initial setting time by 25 min, 22 min and 37 min, respectively; while the final setting time was extended by 30 min, 26 min and 33 min, respectively. In other words, the setting time of a geopolymer was extended following the increase of L/S and BJPA-substitution ratio.

![Figure 3](image_url)

**Figure 3.** The setting times of the BJPA–GGBFS composite geopolymer.

L/Ss of 0.3, 0.4 and 0.5 yielded initial setting times of 15–40 min, 30–52 min and 89–126 min, respectively and produced final setting times of 50–80 min, 124–150 min and 140–183 min, respectively. The setting time extended with a rise in L/S mainly because increasing the volume of the alkali activator (the liquid part of L/S) reduced the efficacy of activating GGBFS and BJPA, leading to a longer setting time with the increase of L/S. Both BJPA and GGBFS exhibit high degrees of fineness, with the former having a lower activity than the latter. Therefore, the BJPA was unable to fully react with the alkali activator, leaving the GGBFS on its own in the polymerization process and subsequently extending the setting time. Therefore, the setting time of the geopolymer decreased with an increase of the BJPA-substitution ratio.

3.2. Slump

Figure 4 shows the effects of L/S and BJPA-substitution ratios on the slump of the BJPA–GGBFS composite geopolymer. An L/S of 0.3 with a distinct BJPA-substitution ratio yielded a slump of 10.7 cm–6.9 cm, with the slump decreasing with an increase in the BJPA-substitution ratio; the corresponding slump for an L/S of 0.4 was 10.8 cm–7.1 cm, with a falling trend similar to that of an L/S of 0.3; the slump reached 11.7 cm–7.1 cm at an L/S of 0.5, a 6% increase compared to an L/S of 0.3; an L/S of 0.4 yielded an average rise in slump of 3.8%, meaning a rise in L/S increased the slump of the geopolymer. The main reason for this was because a rise in L/S meant an increase of the alkali activator within the same volume, which increased the lubrication effect between the BJPA and GGBFS. Thus, the slump of the geopolymer increased following a rise in L/S.
A rise in the BJPA-substitution ratio resulted in a decrease in the corresponding slump of the BJPA–GGBFS composite geopolymer. This was largely because the BJPA was irregularly and loosely diffused, as shown in Figure 2. Although given their highly irregular and edgy shape, the highly water-absorbent BJPA absorbed the alkali activator and reduced the friction between them. Thus, the slump of the geopolymer decreased with an increase in the BJPA-substitution ratio.

### 3.3. Compressive Strength

The results of the compressive strength conducted by this research are shown in Figure 5A–F, in this test project, each sample number is taken as the basis of the study of the number of 3 samples. The compressive strength of the geopolymer increased with a decrease in L/S. When the L/S decreased from 0.5 to 0.3, the compressive strength of a geopolymer increased by 24.1 MPa–27.8 MPa (3 days), 50 MPa–53.6 MPa (7 days), 55.3 MPa–57.4 MPa (28 days) and 56.2 MPa–57.9 MPa (56 days). Because a rise in L/S increased the volume of the alkali activator, the loss of excessive water within the specimen after the polymerization produced pores within its internal structure, which reduced its compressive strength or other engineering properties. An increase in the BJPA-substitution ratio decreased the compressive strength: changing the BJPA-substitution ratio under distinct L/Ss decreased the compressive strength by 14.9–23.2% (3 days), 5.3–46.4% (7 days), 7.7–19.0% (28 days), and 8.5–21.5% (56 days). However, BJPA could reduce the instability of the GGBFS geopolymer specimen, effectively decreasing the formation of internal drying shrinkage cracks.

Figure 5A shows a pure GGBFS geopolymer. Its compressive strength was least affected by L/S when it was 3 days and 7 days old, and the value and changing trend of its compressive strength were roughly similar. When the geopolymer was 28 days and 56 days old, its compressive strength showed a slight increase at L/Ss of 0.3 and 0.4, compared to that of an L/S of 0.5. As shown in Figure 5B, when the BJPA-substitution ratio was 20%, its compressive strength showed a clear reduction compared to that of the pure GGBFS geopolymer; according to Figure 5C,D, when the BJPA-substitution ratio was increased from 40% to 60%, its compressive strength displayed a significant reduction. Figure 5F illustrates that, when the BJPA-substitution ratio reached 100%, its compressive strength was less than 1/4 that of the pure GGBFS geopolymer. Although the BJPA could undergo polymerization with the alkali activator, it was unable to be fully involved in the polymerization process. Which means that the gain in strength only came from the reaction of GGBFS with the activator, BJPA mostly plays the role of inert material. Table 3 shows that BJPA had a higher calcium oxide content, with the C–S–H colloid serving as the source of strength for the pure BJPA geopolymer, thus reducing its compressive strength when the BJPA-substitution ratio increased.
3.4. Stress–Strain Behavior

This study used BJPA and GGBFS as the base materials for geopolymer production to determine the effects of distinct L/S and BJPA-substitution ratios on stress–strain behavior through an examination of modulus of elasticity (Table 4). Figure 6A–C displays the stress–strain curve results, whereby the stress–strain behavior of OPC was between that of geopolymers with BJPA-substitution ratios of 40% and 60%. The trend of stress–strain behavior was consistent with that of compressive strength: its modulus of elasticity decreased by 5.7% when L/S decreased from 0.5 to 0.3; whereas the modulus of elasticity decreased by 50.6% when the BJPA-substitution ratio rose from 0% to 100%.
Table 4. Modulus of elasticity of BJPA–GGBFS composite geopolymer. (GPa).

| BJPA (%) | L/S 0 | 20 | 40 | 60 | 80 | 100 |
|----------|-------|----|----|----|----|-----|
| 0.3      | 53.1  | 46.5 | 42.1 | 34.8 | 29.6 | 22.5 |
| 0.4      | 51.5  | 47.2 | 42.2 | 35.8 | 31.4 | 27.4 |
| 0.5      | 43.2  | 40.2 | 33.6 | 24.6 | 29.0 | 29.0 |

Figure 6. Stress–strain behavior of the BJPA–GGBFS composite geopolymer.

Figure 6A indicates that the strain of the pure GGBFS geopolymer dropped from 0.44% to 0.15% (a 55% decrease) when its BJPA-substitution ratio reached 100%. In other words, an increase in the BJPA-substitution ratio reduced strain, and the same applied to stress: stress decreased by approximately 73% when the BJPA-substitution ratio increased from 0% to 100%. The strain of the pure GGBFS geopolymer, as well as those with 20% and 40% BJPA-substitution ratios, exceeded that of OPC by 33.3%, 25.7% and 8.7%, respectively. The stress–strain curve showed a larger drop when the BJPA-substitution ratio rose from 40% to 60%. Figure 6B shows that stress–strain behavior exhibited signs of decrease when the L/S increased. Strain decreased by approximately 61% when the BJPA-substitution ratio rose from 0% to 100%, and the stress–strain curve showed a larger drop when the substitution ratio rose from 40% to 60%. The stress and strain of the pure GGBFS geopolymer decreased by 1.2% and 5.8%, respectively, when the L/S increased from 0.3 to 0.4. Figure 6C indicates that when the L/S rose from 0.4 to 0.5, the overall stress and strain decreased by an average of 5.9% and
5.1%, respectively. Stress and strain increased by 10.7% and 4.4%, respectively, when L/S decreased from 0.5 to 0.3. Figure 6C also displays a larger drop in the stress–strain curve when the BJPA-substitution ratio increased from 40% to 60%.

BJPA-substitution ratio had a greater influence on stress–strain behavior than L/S did, whereby the decrease in stress was more obvious. Both stress and strain substantially decreased at a BJPA-substitution ratio of 60%, thus forming a considerable drop in the stress–strain curve.

3.5. Ultrasonic Pulse Velocity

Ultrasonic pulse uses solid or liquid as its travel medium. According to its transfer characteristics, when an ultrasonic pulse was transferred from the transmitter to the receiver, specimens with more pores or cracks exhibited longer transmission paths and times. Therefore, the principle of ultrasonic pulse velocity can be used to assess the internal uniformity and density of the BJPA–GGBFS composite geopolymer. The results are shown in Figure 7A–F.
Figure 7. The ultrasonic pulse velocity of the BJPA–GGBFS composite geopolymer.

At an L/S of 0.3, 0.4 and 0.5, the ultrasonic pulse velocity increased by 37.3–50.7% (3 days), 36.1–54.2% (7 days), 35.5–49.6% (28 days) and 36.4–51.4% (56 days). This was mainly because the ratio of the alkali activator in the overall volume was lower at an L/S of 0.3.

The latter phenomenon resulted from the BJPA not being fully involved in the polymerization process, resulting in larger pores within the specimen and a decrease in the density of the specimen, which reduced the ultrasonic pulse velocity and compressive strength.

3.6. Thermal Conductivity Coefficient

The transfer modes of heat include conduction, convection and radiation. This study investigates the thermal conduction properties of a BJPA–GGBFS composite geopolymer. A thermal conductivity probe was used to conduct heat release and reception to simultaneously measure the temperature per unit area of the specimen in relation to time progression. The thermal conductivity coefficient was
calculated, whereby a lower coefficient meant lower thermal conductivity and thus a greater thermal insulation effect.

Figure 8 shows that, under different BJPA-substitution ratios as well as L/Ss of 0.3, 0.4 and 0.5, the thermal conductivity coefficient decreased with an increase in curing age: the thermal conductivity coefficient decreased by 21.4–9.2%, 26.1–10.5% and 29.3–13.5%, respectively, when the specimen progressed from 3 to 56 days old. The results indicated a drop in the thermal conductivity coefficient following a rise in the L/S because the latter increased the volume of the alkali activator within the specimen, which resulted in moisture reduction and more pores. The thermal conductivity coefficient was influenced by L/S, BJPA-substitution ratio and specimen age: a rise in the BJPA-substitution ratio reduced the thermal conductivity coefficient because BJPA had lower activity and was unable to completely react with the alkaline solution, leading to a less dense and more porous internal structure. Consequently, the thermal conductivity coefficient was reduced, which in turn enhanced the thermal insulation and heat resistance of the specimen.

![Graphs showing thermal conductivity over time and L/S ratio for different BJPA substitution ratios](image-url)
3.7. Shrinkage

This study measured the change in length and shrinkage of the BJPA–GGBFS composite geopolymer to determine its volume stability. Figure 9 indicates that an increase in the BJPA-substitution ratio led to a significant decrease in the shrinkage of the composite geopolymer. The less formation of reaction product due to less reactive BJPA replacement leading to less shrinkage. Thus, the shrinkage of the composite geopolymer decreased following a rise in the BJPA-substitution ratio.

The results indicated that the yielded length of the geopolymer specimen decreased with a rise in the BJPA-substitution ratio, and its shrinkage increased with a rising L/S. A 56-day specimen with an L/S of 0.5 and a substitution ratio of 0% achieved a shrinkage range of $-0.2718$–$1.574\%$. An increase in the BJPA-substitution ratio caused a drop in compressive strength and ultrasonic pulse velocity. However, the inability of the ash to fully react with the alkali activator could lead it to fill the thermal cracking during the GGBFS reaction, effectively suppressing the shrinkage of the pure GGBFS composite geopolymer.
Figure 9. Cont.
3.8. Scanning Electron Microscope (SEM).

Microstructural changes of the BJPA–GGBFS composite geopolymer at different L/Ss, BJPA-substitution ratios, and ages were observed using SEM. Researchers have discovered that the GGBFS is a base material that is capable of active cementation. Using SEM images to understand the microstructural changes, researches have shown that a geopolymer has a different reaction mechanism compared to that of the hydration reaction of cement: while a geopolymer undergoes polymerization, the GGBFS produces microcracks that influence the durability properties of the geopolymer [43–45]. This study observed the microcracks and the polymerization products of a BJPA–GGBFS composite geopolymer.

The results are shown in Figures 10–12 as scanned SEM of geopolymer specimens under distinct BJPA-substitution ratios and L/Ss with a magnifying power of 6000 times to observe the microstructure. The microcracks showed an increase in number and size when the L/S increased, with the largest crack size being 5.80 μm. However, the number and size of the cracks decreased with a rise in the BJPA-substitution ratio, with the smallest crack size being 176.8 nm. Because BJPA is a less active material that is unable to completely undergo polymerization, the unreacted and incompletely reacted ash will indirectly become an effective filler for the cracks produced by GGBFS.
Figure 10. SEM image of the BJPA–GGBFS composite geopolymer. (L/S = 0.3).

Figure 11. SEM image of the BJPA–GGBFS composite geopolymer. (L/S = 0.4).

Figure 12. SEM image of the BJPA–GGBFS composite geopolymer. (L/S = 0.5).

4. Conclusion
4. Conclusions

1. The setting time of the BJPA–GGBFS composite geopolymer increased with a rise in the L/S and BJPA-substitution ratios. An L/S of 0.5 and BJPA-substitution ratio of 100% resulted in the longest initial (126 min) and final (183 min) setting times;

2. The slump flow value dramatically decreased at BJPA-substitution ratios of 60%, 80% and 100%, whereas the slump value dropped with a rise in the L/S. The optimal slump value was 11.7 cm and the slump flow value was 21.6 cm;

3. At an L/S of 0.3 and a BJPA-substitution ratio of 0%, the maximum compressive strength of a 3-day geopolymer was 33.4 MPa; the maximum compressive strength of a 56-day geopolymer was 81.1 MPa and the strength decreased by 8.5–21.5% with the increasing BJPA-substitution ratio;

4. In terms of stress–strain behavior, an L/S of 0.3 and BJPA-substitution ratio of 0% obtained a maximum strain of 0.41% and a maximum modulus of elasticity of 53.1 GPa. BJPA-substitution ratios of 0%, 20% and 40% all resulted in higher moduli of elasticity than that of OPC;

5. The growth trend of ultrasonic pulse velocity was consistent with that of compressive strength. The pores within the specimen reduced compressive strength and ultrasonic pulse velocity, with the highest and lowest velocity being 4274 m/s and 1695 m/s, respectively. In terms of the thermal conductivity coefficient, although the pores within the specimen reduced the compressive strength, they were effective in thermal insulation: a BJPA-substitution ratio of 100% achieved a minimum thermal conductivity coefficient of 0.8614 W/mK;

6. The best ratio result of this study is that when L/S = 0.3, the BJPA substitution amount is 10%;

7. The SEM revealed that crack size decreased with an increase in the BJPA-substitution ratio, with the maximum and minimum sizes being 5.80 µm and 176.8 nm, respectively. Because the BJPA was unable to undergo full polymerization, the unreacted and incompletely reacted BJPA indirectly filled the cracks formed by the GGBFS during polymerization.

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