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Review

Efficiency of Waste as Cement Replacement in Foamed Concrete—A Review

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Abstract: Foamed concrete is a lightweight construction material that has gained popularity due to its excellent thermal and acoustic insulation properties. Foamed concrete production involves using cement as a binding agent, which results in a high carbon footprint. In response to sustainable development goals (SDG), there has been a growing interest in exploring alternative materials that can replace cement to improve energy efficiency, climate change, resource efficiency, and overall improvement of foamed concrete properties. Several tons of waste generated annually from industry, agriculture, and quarries are dumped into landfills and cause environmental impacts. Nevertheless, the efficiency of this waste presents an interesting question and there is limited knowledge of its use in foamed concrete. Hence, a review study is needed to evaluate the efficiency of different waste materials that could be used to replace cement in foamed concrete production. The objective of this research is to summarize the efficiency of industrial waste (IW) as a pozzolan alternative (PA) for cement replacement in foamed concrete (FC) production. This study aims to evaluate the chemical, physical, and pozzolanic reactions of selected IW and compare them to cement and selected pozzolans to determine the effect of efficient IW on the compressive strength and durability of FC. This research evaluated the efficiency of IW in PA by characterizing their chemical, physical, and pozzolanic reactions. The selected IW was studied and compared to cement and selected pozzolans using XRF and XRD analyses. This study also performed the Frattini test to determine the strength activity index (SAI) of efficient IW. The efficiency of IW in PA was evaluated by comparing the SAI of efficient IW to the minimum 75% required by BS3892. The compressive strength and durability of FC with efficient IW were determined by evaluating the microstructure of the hardened paste of FC using capillary void analysis. The study found that efficient IW, which was classified as siliceous pozzolan type F (ASTMC618-SAF > 70%), rich in amorphous silica and a high Blaine specific area, can replace cement in FC production. The XRF and XRD results showed that the most crystalline components obtained in the IW are SiO_2, Al_2O_3, $CaCO_3$, and Fe_2O_3. The efficient IW produced more calcium silicate hydrate (CSH) and denser FC, making it stronger, with fewer voids and higher resistance to water absorption. The Frattini test showed that the SAI of efficient IW is greater than the minimum 75% required by BS3892. Incorporating efficient IW as cement replacement in FC produced higher compressive strength and improved the durability of FC. The novelty of this research is in the evaluation of efficient IW as a replacement material for cement in FC production. This study shows that efficient IW can promote the use of waste materials, reduce CO_2 emissions, conserve energy and resources, and improve the properties of FC. This study's findings can be used by construction industry players to support sustainable development goals by reducing the use of cement and promoting the use of waste materials as a replacement material for cement.

Keywords: efficiency; industrials waste; cement replacement; foamed concrete

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1. Introduction

The growth of industrial activities has led to the generation of significant amounts of waste, known as industrial waste (IW). Most industries are unable to reuse these wastes due to their low value and higher cost [1]. In response to sustainable development goals (SDG), the construction sector has the potential to reuse large volumes of IW as they annually consume large volumes of materials such as cement, aggregates, sand, blocks, bricks, and tiles for the development of new buildings and projects. Additionally, the reuse of IW may lead to sustainable construction as the production of materials for buildings and projects consumes large volumes of natural raw materials and energy [2]. Globally, pozzolanic alternative (PA) materials are frequently used in construction as partial replacements for ordinary Portland cement (OPC) in mortar and concrete.

One of the most acceptable types of PA is pozzolanic waste material because of its environmental benefits during the production of OPC. The construction industry is one of the primary sectors facing the challenges of energy, climate change, and resource efficiency. Concrete is the most commonly used material in the construction industry due to its strength and durability, but its production has a negative impact on the environment. The world is facing the major challenge of producing more than 10 billion tons of concrete every year, which requires billions of tons of material to produce. OPC is a critical component of concrete, but its production has led to the generation of higher carbon dioxide emissions. Globally, the production of one ton of OPC releases one ton of CO_2 from the calcination of limestone [3,4].

In Malaysia, the annual production of 20 million tons of cement leads to the release of 20 million tons of CO_2 into the atmosphere [5]. It is estimated that approximately 7% of CO_2 is recognized as a greenhouse gas that contributes to global warming [3]. Therefore, utilizing pozzolanic material is one solution for reducing the amount of cement used in construction [6]. Foamed concrete (FC) is an eco-friendly and economical type of concrete that incorporates pozzolan alternatives as a partial cement replacement in an FC mixture. Several pozzolan materials, such as fly ash, silica fume, ground granulated blast furnace slag (GGBS), and rice husk ash (RHA), have been used effectively as partial cement replacements due to their ability to reduce greenhouse gas (GHG) emissions. FC is a mixture of cement paste and preformed foams that provides cost savings, ease of handling, is self-compacting, and lower density [7–9]. Any supplementary cementitious material or pozzolans can be used as sand or cement in FC, making it an attractive alternative to traditional concrete [10,11]. PA from industrial by-products or waste (IW) can also be used as a replacement for cement in FC, such as RHA [12], fly ash [13,14], silica fume [15], GGBS [16], sewage sludge ash [17], paper mill sludge [18], graphite tailing [19,20], palm oil fuel ash [21,22], and soil as a sand replacement [23].

Recent studies have explored the use of various waste materials in FC production, such as sugarcane bagasse ash (SCBA), rubber glove (RG), and waste glass powder (WGP). A study by Li et al. [24] investigated the effect of SCBA on the properties of FC and found that SCBA can be used as a partial replacement for sand in FC production to enhance its properties. Another study by Hameed et al. [25] explored the use of RV and WGP as a pozzolanic material in FC production and found that it significantly improved the compressive strength, workability, and durability of FC. Similarly, a study by Khan et al. [26] examined the use of WGP as a pozzolanic material in FC production and found that it can improve the mechanical properties of FC. Overall, the studies share similar findings, PA in FC enhances its long-term strength, durability, and microstructure. It is economical and eco-friendly as it reduces greenhouse gas emissions, including carbon dioxide, and reuses industrial waste while minimizing cement usage. In addition, the studies highlight the potential for using different types of waste as replacement materials for cement in FC production and the need for further research in this area to identify the most efficient types of waste to develop more sustainable and high-performance FC.

However, the properties of foamed concrete are highly dependent on the mix design parameters, which can make it challenging to predict the compressive strength and rheological properties of FC. Researchers have been investigating the effects of mixed design parameters on foamed concrete properties and using statistical analysis to identify correlations between these parameters and the strength and rheology of the material. Dao et al. [27] used a statistical approach to optimize the mix proportions of foamed concrete and identified correlations between the dry density, water-cement ratio, foam content, sand content, and the compressive strength of the foamed concrete. The compressive strength of FC decreased when the water-cement and sand-cement ratios increased. However, the study found that dry density positively affected compressive strength with a maximum R^2 value of 0.976. A study by Calis et al. [28] investigated the effects of ground calcium carbonate and glass fiber on the compressive and flexural strength and thermal conductivity of foamed concrete and found that the compressive strength and thermal conductivity were positively correlated with the amount of ground calcium carbonate. Additionally, the inclusion of glass fiber in the mix design contributes to the flexural strength of FC. Similarly, a study by Ullah et al. [29] investigated the influence of cement content, sand content, water-cement ratio, and foam volume on the dry density and compressive strength of FC. The study identified strong correlations of R^2 0.95 between the dry density and compressive strength of FC with the least statistical errors, 2% for the density model, and 91% of the predicted results have error values less than 5 MPa for the strength model. Overall, these recent studies demonstrate the importance of mixed design parameters in determining the compressive strength of the foamed concrete were positively correlated with the cement content and foam content and negatively correlated with the water-cement ratio and sand content. The foamed concrete's rheological properties highly depended on the water-cement ratio and foam content.

As per the ACI 232.1R-00 report by the American Concrete Institute (ACI), a pozzolan is a siliceous and aluminous material that reacts with calcium hydroxide (lime) from cement to create a secondary calcium silicate hydrate (CSH) gel [30]. Pozzolan, in itself, possesses little or no cementitious properties, but in finely divided form and in the presence of moisture, it significantly improves the workability, compressive strength, and durability of concrete [31–39]. The Greeks and Romans have used natural pozzolan to construct some of their most impressive buildings, and the pozzolanic reaction occurs when silica (S) reacts with calcium hydroxide (CH) and water (W) to produce additional calcium silicate hydrate (CSH) gel. The reactivity of pozzolan is dependent on its specific surface area, mineralogical composition, and reactive silica content. It's remarkable to see how something as seemingly simple as pozzolan can contribute to the creation of such impressive and long-lasting structures. The pozzolanic reaction happens during the hydration process as is shown in Equation (1) [40].

$$S + CH + H \rightarrow C - S - H \quad (1)$$

It is important to highlight that the characteristics of the waste generated depend on the technologies used by the industries, and as such, some IW is generated from the combustion process, such as fly ash and bottom ash, which have pozzolanic properties. Growing environmental concerns over the disposal of industrial by-products combined with carbon dioxide emissions during the OPC clinker's burning process have led to increased usage of pozzolan ash as a replacement material for cement. The efficient use of resources through using pozzolan alternatives as a replacement for industrial by-products or waste could reduce environmental issues and costs due to the high demand for OPC.

There is a need to review the efficiency of different types of waste as a replacement material for cement in foamed concrete (FC) production. The efficiency of waste is questionable due to the different types of waste or origins, which can affect the pozzolanic reaction and other properties such as chemical and physical reactions. Therefore, a review of the waste's efficiency in enhancing the properties of FC is needed to identify the most efficient types of waste to use as a replacement material for cement. Thus, this research attempts to fill the gaps of knowledge by studying the effect of PSBE as a partial cement replacement in FC.

2. The Characterization Process of Waste

The ASTM C618-19 standard recognizes two classes of ash, which are Class C ash and Class F ash. Pozzolan materials are distinguished based on the sum of the oxides of silicon, aluminum, and iron (SAF). If the SAF is found to be less than 70%, the pozzolan material is classified as Class C ash and if SAF is more than 70%, the pozzolan material is classified as Class F ash. In Europe, there are also several standards that classify ash based on different classes, as well as the use of ashes in materials with a cement binder. One such standard is the EN 450 standard, which categorizes fly ash into three different classes: Class N, Class S, and Class P. This standard defines the classes based on the sum of the oxides of silicon, aluminum, and iron (SAI) rather than SAF, as in the ASTM C618-19 standard. Additionally, the EN 450 standard considers the chemical composition, mineralogy, and pozzolanic activity of the fly ash to determine its class. Another European standard that addresses the use of ashes in materials with a cement binder is the EN 197-1 standard. This standard defines five different types of cement, including Portland cement, and allows for the partial replacement of Portland cement with fly ash or other pozzolanic materials. The standard also includes requirements for the physical and chemical properties of these materials. This present study reviewed the properties of a pozzolan alternative (PA) as a partial replacement for cement based on the ASTM C618-19 standard. The study evaluated the efficiency of the PA to enhance the properties of FC, with the pozzolanic reaction forming additional calcium silicate hydrate (CSH) gel and improving the strength and durability of the FC. The study also established criteria for the chemical and physical properties of the PA, such as a specific surface area, silica content, and particle size. Finally, the study aimed to investigate the strength development of FC through the replacement of cement with PA, and aimed to provide more than 75% strength compared to the control at 28 days according to the EN 450 standard. By incorporating a pozzolan alternative as a cement replacement, the study suggests that waste materials can be utilized, and CO_2 emissions can be reduced while conserving energy and resources.

In the world of construction, finding the perfect materials for a project can mean the difference between success and failure. When it comes to evaluating and characterizing industrial waste (IW) for use as a pozzolan material in construction, the first stage of evaluation is crucial. Processed spent bleaching earth (PSBE) is the end product derived from the processing of de-oiled SBE after the oil is recovered. Bleaching earth is very fine powder clay, and its main component is silicon dioxide, which is used for the refining process of palm oil. Its by-product is known as spent bleaching earth (SBE) and is commonly disposed in landfills at a high cost. The availability of SBE due to its consistent disposal from palm oil mills could be explored to determine its potential for material production rather than dumping it as waste. This stage involves examining the chemical and physical properties of the IW. Chemical analysis obtained by XRF is one key factor that determines the success of the pozzolanic reaction indicating that the amount of SAF should be more than 70%. The mineral form, obtained by the XRD test, is another essential compound that must be evaluated. In addition to the chemical properties, the physical properties of the pozzolan material must also be characterized, including fineness, high specific surface area, and particle size (<45 um) with more than 60% of particles in this size range. After the chemical and physical properties have been evaluated, the next stage is to assess the pozzolanic reactivity of the IW when it reacts with lime. The final stage is to investigate the strength development of the FC by replacing cement with pozzolan material. This replacement should result in more than 75% strength compared to the control at 28 days, according to the EN 450 standard. It is important to note that the effectiveness of the pozzolan material in converting calcium hydroxide (CH) to calcium silicate hydrate (CSH) gel depends on its amorphous state, silica content, and specific surface area. Higher surface areas lead to higher adsorption of chemical substances and improved pozzolanic reaction. This reaction, in turn, creates additional CSH gel that improves the properties of the foamed concrete by creating a denser microstructure. The denser structure fills larger spaces and reduces the size of capillary voids, ultimately leading to better strength and durability.

With proper evaluation and characterization, IW can become an invaluable resource for sustainable construction practices. Figure 1 summarized the flow of reviewing the research.

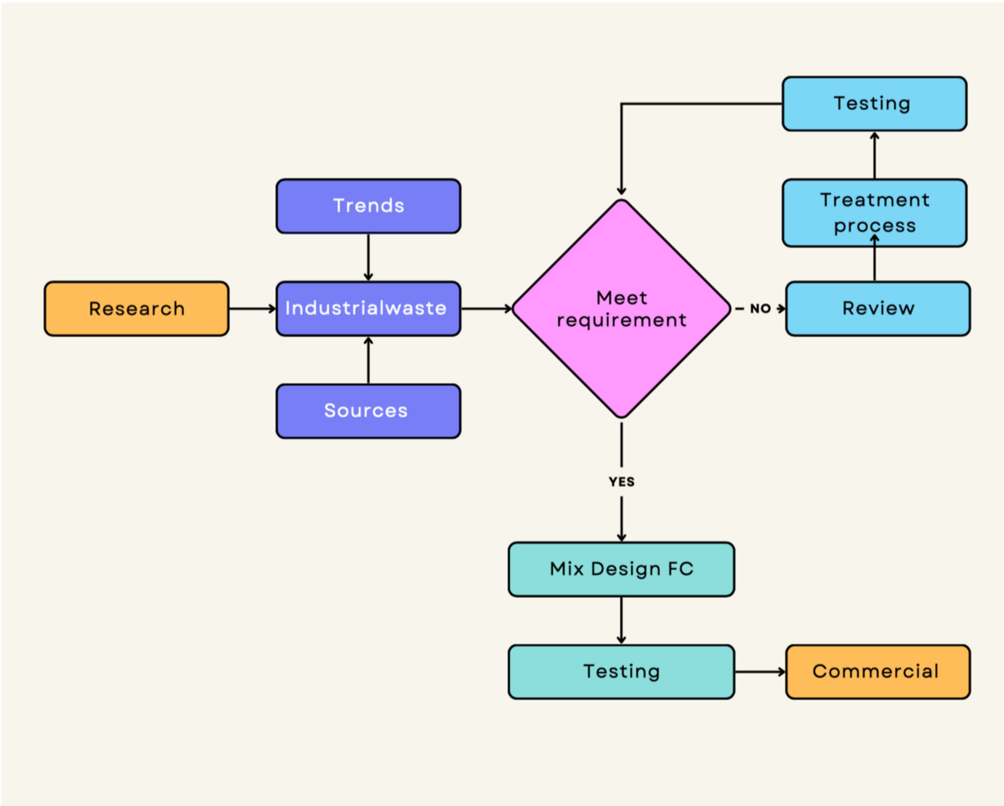


Figure 1. The flow of research.

2.1. Chemical Composition of Pozzolan Alternatives

In recent years, the utilization of industrial byproducts or waste (IW) with pozzolanic properties as partial cement replacement in foamed concrete (FC) has gained significant attention. Among the available options, fly ash (FA) [11], ground granulated blast furnace slag (GGBS) [41], silica fume (SF) [42], rice husk ash (RHA) [12], oil palm ash (POFA) [43], and processed spent bleaching earth (PSBE) have shown promising results in improving the mechanical and durability properties of FC. It is important to note that the chemical composition of the pozzolan material plays a critical role in determining its pozzolanic reactivity. The X-ray fluorescence test is commonly used to determine the chemical composition of both Portland cement and pozzolan materials. In particular, pozzolan materials with a high percentage of amorphous silica have been found to be most effective in improving the strength and durability of FC. Table 1 shows the chemical composition of Portland cement and selected pozzolan materials. Based on the analysis, it was determined that silica (SiO_2) was the main component of PSBE at 55.82%, followed by alumina (Al_2O_3) at 13.48%, and iron (Fe_2O_3) at 8.24%. From these results, it was confirmed that PSBE is an alumina silicate material and has a high potential to be good pozzolanic material. According to ASTM C618-19 for mineral admixtures in Portland cement, the total silica, alumina, and iron oxide (combined SiO_2 + AL_2O_3 + Fe_2O_3) content was calculated at 77.54%, which is well above the requirement of 70%, confirming that PSBE classified as Class N natural pozzolan. Additionally, sodium (Na_2O) and sulfur (SO_3) contents were way below the requirements at 0.18% and 0.06%, respectively.

Among the various pozzolanic materials, SF has been found to be the most efficient in enhancing the strength and durability of FC due to its high surface area and content of amorphous silica. To ensure that the pozzolan material meets the necessary requirements for pozzolanic activity, ASTM C618-19 recommends a minimum content of approximately

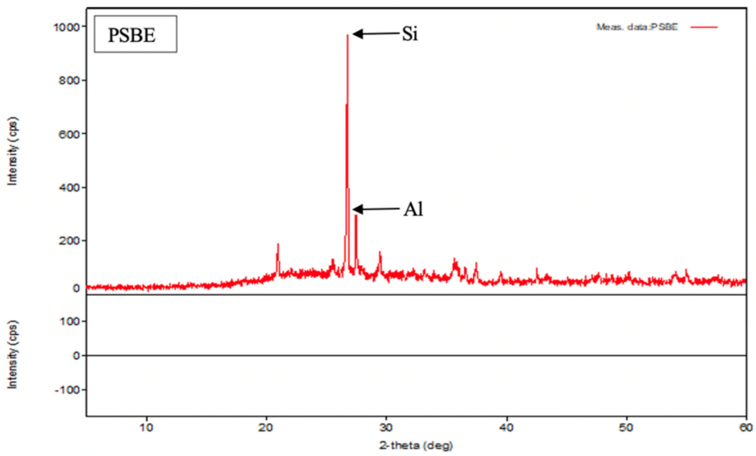
70% by weight in silicon dioxide, aluminum oxide, and iron oxide. Additionally, the loss of ignition (LOI) should not exceed 10% by weight. While natural pozzolan materials meet these requirements, pozzolan alternative (PA) materials often require processing before becoming pozzolanic. Examples of PA materials include fly ash, burnt clay, bauxite, rice husk ash, and slag [27]. The addition of pozzolan to FC has been found to greatly influence its durability by producing additional CSH through the pozzolanic reaction with CH. This reaction enhances the strength of FC and increases its resistance to sulfate attack and alkali–silica reaction by removing CH. Furthermore, the addition of pozzolan reduces pore size and porosity, ultimately increasing the strength of FC. However, it is important to note that the workability of the mixture may be reduced when pozzolan is used as a cement replacement [44]. In summary, the use of pozzolan materials as partial cement replacement in FC has proven to be an effective method for improving its mechanical and durability properties. Careful selection of the pozzolan material based on its chemical composition and processing requirements is crucial to ensure its pozzolanic reactivity. The benefits of utilizing pozzolan materials in FC include increased strength, improved durability, and reduced susceptibility to chemical attack.

Table 1. Chemical composition of pozzolan alternatives.

Component	Portland Cement Type 1 [11]	Fly Ash [11]	Silica Fume [36]	Rice Husk Ash [12]	Slag [35]	POFA [37]	PSBE
SiO_2	20.55	59.0	78.82	90.75	39.1	51.83	55.82
Al_2O_3	4.780	19.58	0.00	0.75	12.1	2.32	13.48
CaO	63.94	0.54	2.35	0.87	38.3	8.10	6.60
Fe_2O_3	3.64	7.23	0.98	0.08	1.03	7.60	8.24
MgO	1.50	4.64	6.41	0.63	8.50	3.13	5.94

2.2. X-ray Diffraction of Pozzolan Alternatives

The present study investigates industrial by-products called processed spent bleaching earth (PSBE) and ordinary Portland cement (OPC). X-ray diffraction (XRD) analysis was necessary to observe the crystallized and amorphous compounds through the peaks of the diffraction pattern. Figure 2 shows the XRD patterns of PSBE and OPC. It can be observed that the PSBE has a mainly amorphous phase due to the broad peak at 2θ and no crystalline peak was observed. From the XRD pattern, a peak at 27°, indicated by arrows, was identified as a silica peak, and a weak peak at 28.5°, was identified as alumina. Additionally, the gradual dense scatter of XRD pattern presents the amorphous state of the PSBE. Similarly, another study by [45,46] clearly shows that silica fume, RHA, and GGBS are mainly in the amorphous phase, as indicated by the broad peak at 2θ. RHA, on the other hand, has a smoother graph at the amorphous phase without any peak of crystalline [47]. To control the pozzolans' effectiveness, it is necessary to assess the amorphous silica and alumina content using XRD patterns. These research findings show that the pozzolan used is in the amorphous phase, and no crystalline peak was observed. Thermal analysis, such as differential and thermogravimetric analysis, can be performed to observe the amount of calcium hydroxide in the hydrated compound due to the pozzolanic reaction. In addition, the SEM morphology and compression strength test can also be used to evaluate the pozzolanic material. In conclusion, it is crucial to consider XRD analysis, along with other tests, to determine the effectiveness of the pozzolanic material before using it as a partial cement replacement in FC. This study recommends thoroughly evaluating the pozzolanic properties and considering the amorphous silica and alumina content in the material. This will help improve the strength and durability of the FC and reduce the pore size and porosity, which can increase the material's overall strength.



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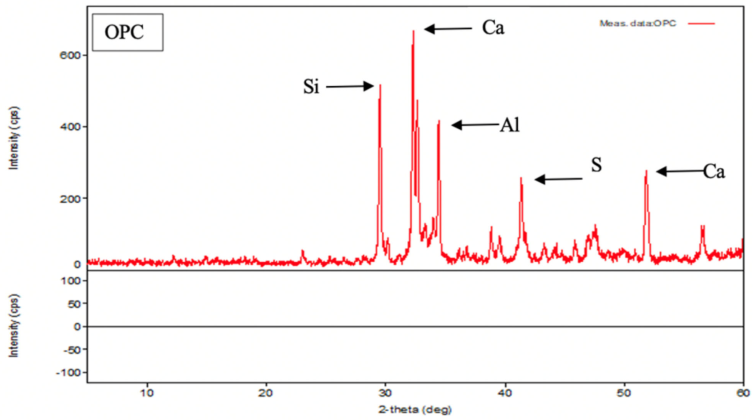


(**b**)

Figure 2. X-ray diffraction of PSBE and OPC. (**a**) PSBE; (**b**) OPC.

2.3. Physical Characteristics of Pozzolan Alternatives

Table 2 presents the physical characteristics of Portland cement and selected pozzolans. This investigation reveals that the average particle size of the chosen pozzolans is smaller than that of Portland cement. In addition, the particle fineness and specific gravity data indicate that pozzolan materials are less dense than Portland cement. It is noteworthy that the particle size of pozzolan is a crucial factor influencing its reactivity, which is closely related to its fineness. This review shows that pozzolan wastes with a higher degree of fineness demonstrate better acceleration in the dissolution process. Therefore, improving the fineness of any pozzolan waste can further enhance its activation. To determine the fineness of the pozzolan materials, the Brunauer–Emmett–Teller (BET) method provides clear information on the surface area characteristics of the specimen. As indicated in Table 2, silica fume has the largest surface area among the selected pozzolan materials, which in turn, will affect the dissolution and water absorption behavior in the future. Based on these findings, this study recommends that the pozzolan waste should be subjected to a process that improves its fineness to enhance its activation. In addition, this study suggests that future studies should explore other methods of enhancing the reactivity of pozzolan wastes, particularly those that improve the material's dissolution and water absorption behavior.

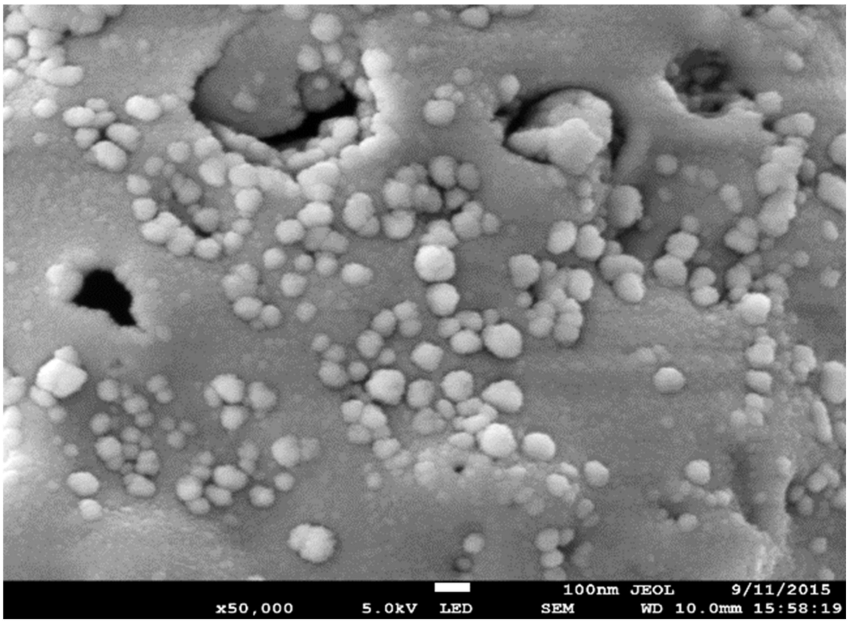
Table 2. Physical characteristics of OPC and selected pozzolan.

Material		Mean Size of the Particle (μm)	Surface Area (m^2/kg)	Particle Shape	Specific Gravity
[11]	Portland cement	20–30	300–400	Angular, irregular	3.1–3.2
[11]	Fly ash	10–15	<1000	Spherical	2.06
[36]	Silica Fume	0.1–0.3	20,000	Spherical	2.37
[12]	Rice husk ash	10–20	<10,000	Cellular, irregular	2.0–2.3
[35]	GGBS	10–15	<1000	Angular, irregular	2.63
[37]	POFA	0.1–75	<1000	Angular, irregular	2.05–2.5
	PSBE	0.1	<1000	Spherical	2.44

2.4. Morphology of Pozzolan Alternatives

In confirming the previously mentioned physical characteristics, observations of the selected pozzolanic materials at the microstructure level have provided further insights. In Figure 3, this study presents the SEM morphology of PSBE and Portland cement (OPC). The SEM results for PSBE and OPC specimens at 50,000× magnification observed that the particle shape of PSBE was spherical, had a smooth surface, and a porous structure. Meanwhile, the shape of the OPC particles consists was angular and irregular. Consequently, SEM micrographs for both of them clearly show the wide range of particle sizes. As compared to OPC, the average particle size of PSBE is finer than OPC. Portland cement appears to have stone-shaped or diamond-like particles with angular and irregular shapes [48]. Similarly, the SEM image of slag (GGBS) also revealed a similar shape [49]. Fly ash (FA) and silica fume (SF), on the other hand, exhibited a similar spherical shape [46,50]. Rice husk ash (RHA), with its spongy, porous, and cellular structures, have angular and irregular shapes [47]. In contrast, POFA displays a combination of spherical and irregular-shaped porous structures. However, this review recommends that further treatment of POFA and RHA through grinding can result in finer particles, as the porous structures are crushed and broken down into smaller fractions, leading to an increased surface area [51]. Therefore, this study recommends that further studies be conducted to explore the impact of grinding on the surface area and the reactivity of pozzolan materials, particularly those with porous structures. Furthermore, additional research can investigate the optimal grinding conditions to yield the desired results.

Microstructural analysis is a crucial factor in evaluating pozzolanic materials' effectiveness in improving cement performance. This analysis confirms that the selected pozzolans can enhance the performance of cement through the pozzolanic reaction. The use of scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis enables the examination of the mineral phase changes and microstructure of hydration products, while X-ray diffraction (XRD) and differential thermal analysis (DTA) and thermogravimetric (TG) analysis provides data on the phase composition of hydration products. Figure 4 illustrates the SEM morphology of the hydration products of cement, which mainly comprises calcium silicate hydrate (CSH), calcium hydroxide (CH) or portlandite, and the hydration products of calcium aluminate (ettringite). Three distinct images characterize the morphology of the hydration products. Fibers or needles show an increase in the CSH gel, called honeycomb, which transforms into a closed-packed isometric grain. The CH appears in hexagonal crystals, while the ettringite are elongated crystals resembling needles [52]. Furthermore, Figure 5 shows the various forms of the hydration products of cement using SEM-EDS analysis. These findings demonstrate that using pozzolanic materials can lead to significant changes in the mineral phase and microstructure of the hydration products of cement. Based on the results, this study recommends that future studies explore the optimal dosage and type of pozzolanic materials for cement production. In addition, further research can investigate the influence of different pozzolanic materials on the mineral phase changes and microstructure of the hydration products of cement, particularly the impact on CSH gel formation. Furthermore, it is essential to investigate the durability of cement with pozzolanic materials, particularly in harsh environments, to ensure that it can withstand the test of time.



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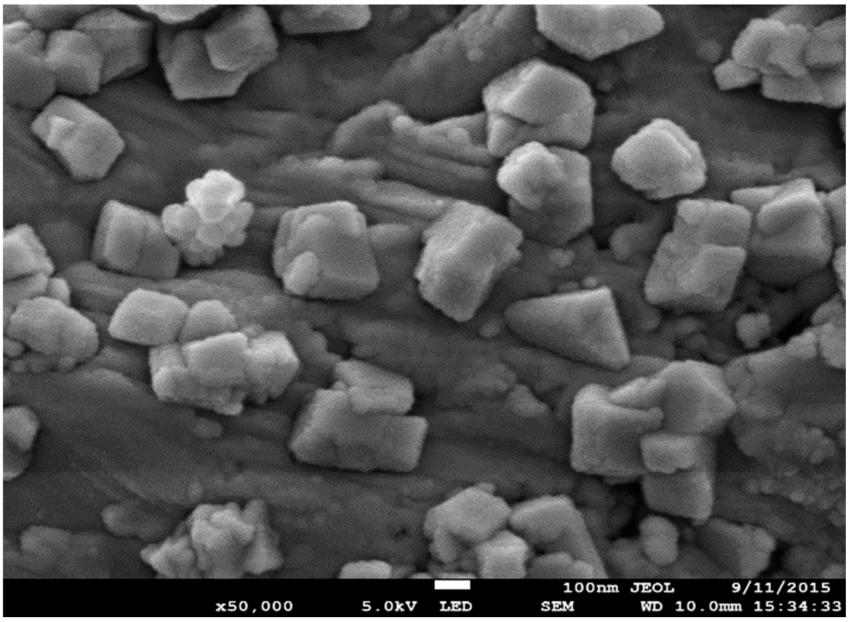

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Figure 3. SEM morphology of PSBE and OPC. (**a**) PSBE at 50,000× magnification, (**b**) OPC at 50,000× magnification.

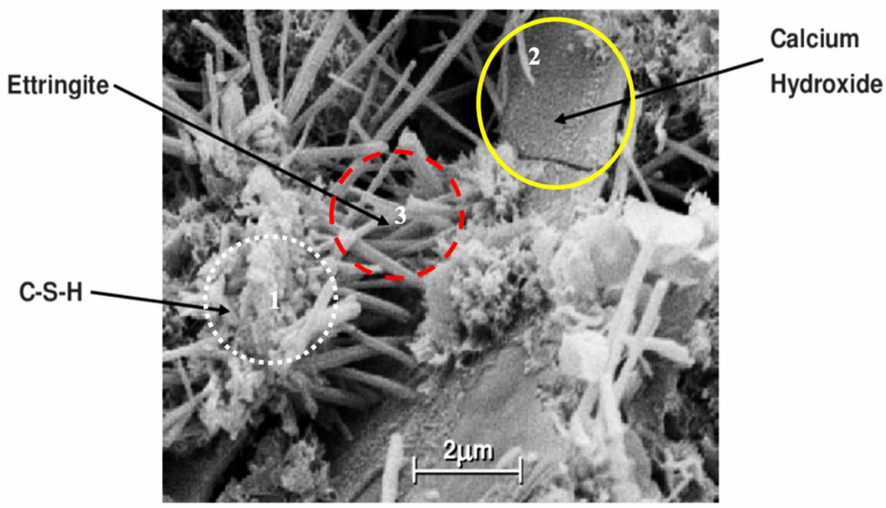


Figure 4. SEM morphology of hydration products of cement. Adapted from [48].

Based on SEM-EDS analysis, it was observed that paste I exhibits a dense and fibrous form of CSH, with no visible ettringite crystals present. The dominant peaks in the EDS analysis are attributed to calcium (Ca) and silicon (Si), with weaker peaks detected for aluminum (Al), magnesium (Mg), and potassium (K). On the other hand, paste II exhibited the presence of ettringite crystals in the form of thin needles that were growing in the pores. The calcium aluminate products are shown to have strong peaks due to calcium (Ca) and aluminum (Al), with weaker peaks present for silicon (Si) and iron (Fe). In paste III, the fibrous form of CSH and calcium aluminate were growing in pores and connected in a network with visible cracks present. The dominant peaks in the EDS analysis are attributed to calcium (Ca) and aluminum (Al) components. Based on these observations, it is recommended that further investigations should be conducted to understand the role of pozzolan in the formation of different phases and microstructures. In addition, the impact of different pozzolanic materials on the growth of CSH and ettringite crystals, as well as their morphology, should be explored. This will provide valuable insights into the optimal use of pozzolanic materials in enhancing the microstructure and strength of concrete.

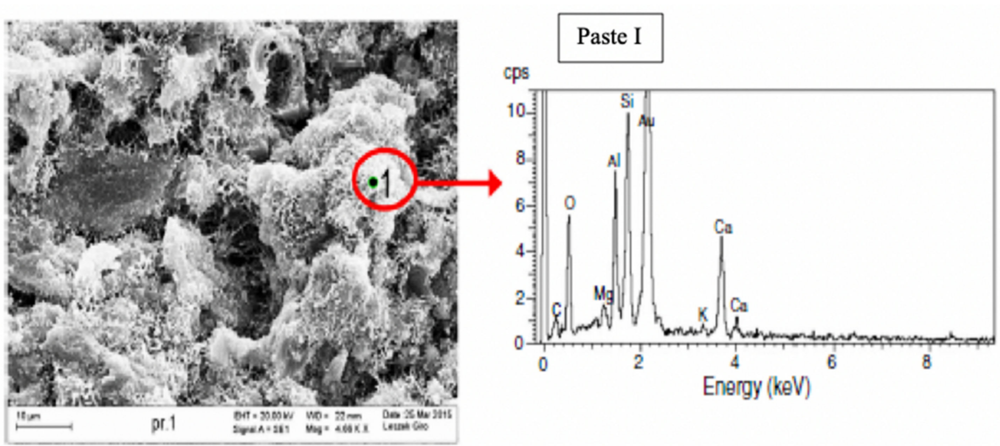


Figure 5. *Cont.*

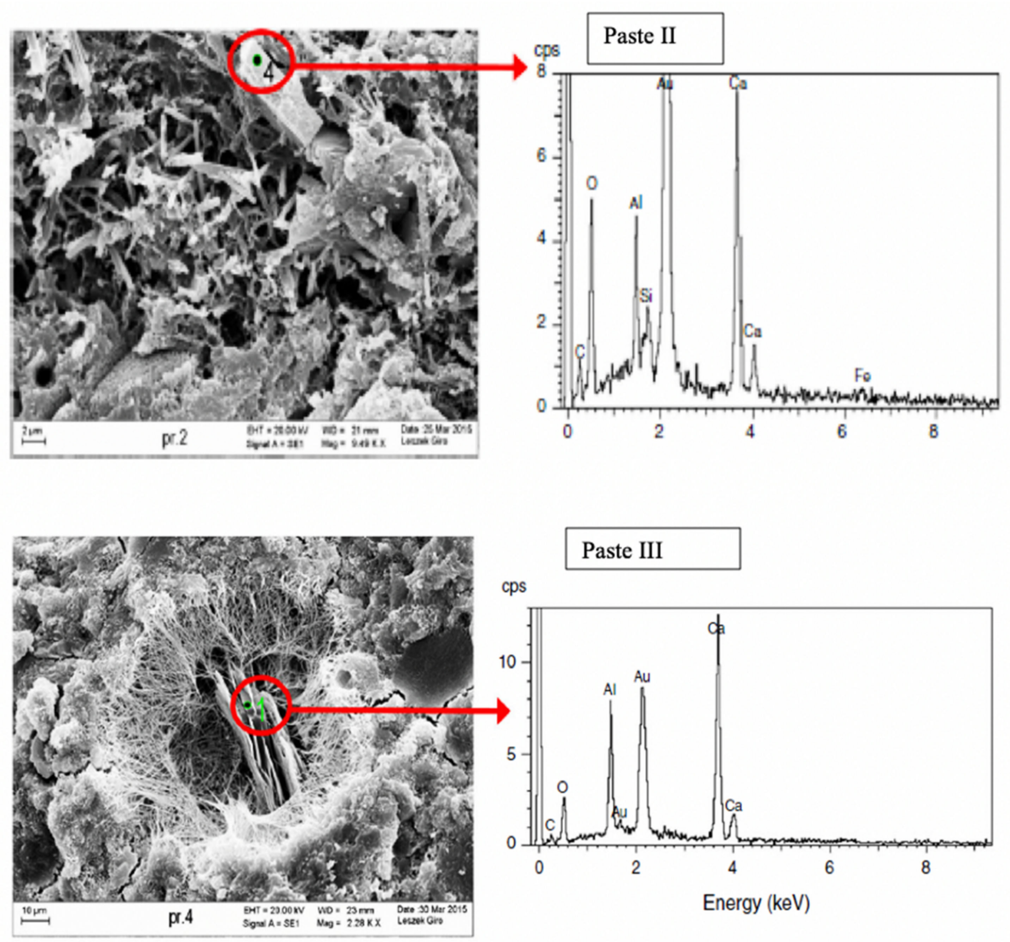


Figure 5. SEM-EDS analysis for various forms of hydration products of cement. Adapted from [53].

As shown in Figure 6, the SEM morphology for the hydration products of FC, with the selected pozzolan, was examined. The specimen containing FA exhibited homogeneous foam bubbles with CSH gel located closely together. Conversely, the SEM image of the specimen without FA revealed more and larger pores, with more calcium hydroxide crystals that exhibited a large crystal structure and hexagonal prism [54]. A similar trend was observed in the specimen with nano SF, with the microstructure containing fewer microstructural pores than the specimen without SF due to increased calcium hydroxide crystals with a large crystal structure, and a hexagonal prism in the specimen without SF [55]. The microstructure of the specimen with POFA appeared to contain small pores, with the surface almost completely covered by CSH gel. The amount of CH was greater in the specimen without POFA [56], indicating that the incorporation of POFA and other PA as partial cement replacement in FC leads to densification of the concrete's internal structure through pozzolanic reaction, resulting in a decrease in the quantity of CH crystal and an increase in additional CSH gel, ultimately leading to an increase in the strength of FC. In line with the microstructure, previous studies have also reported that the pore structure of cementitious material affects the strength and durability of concrete [57].

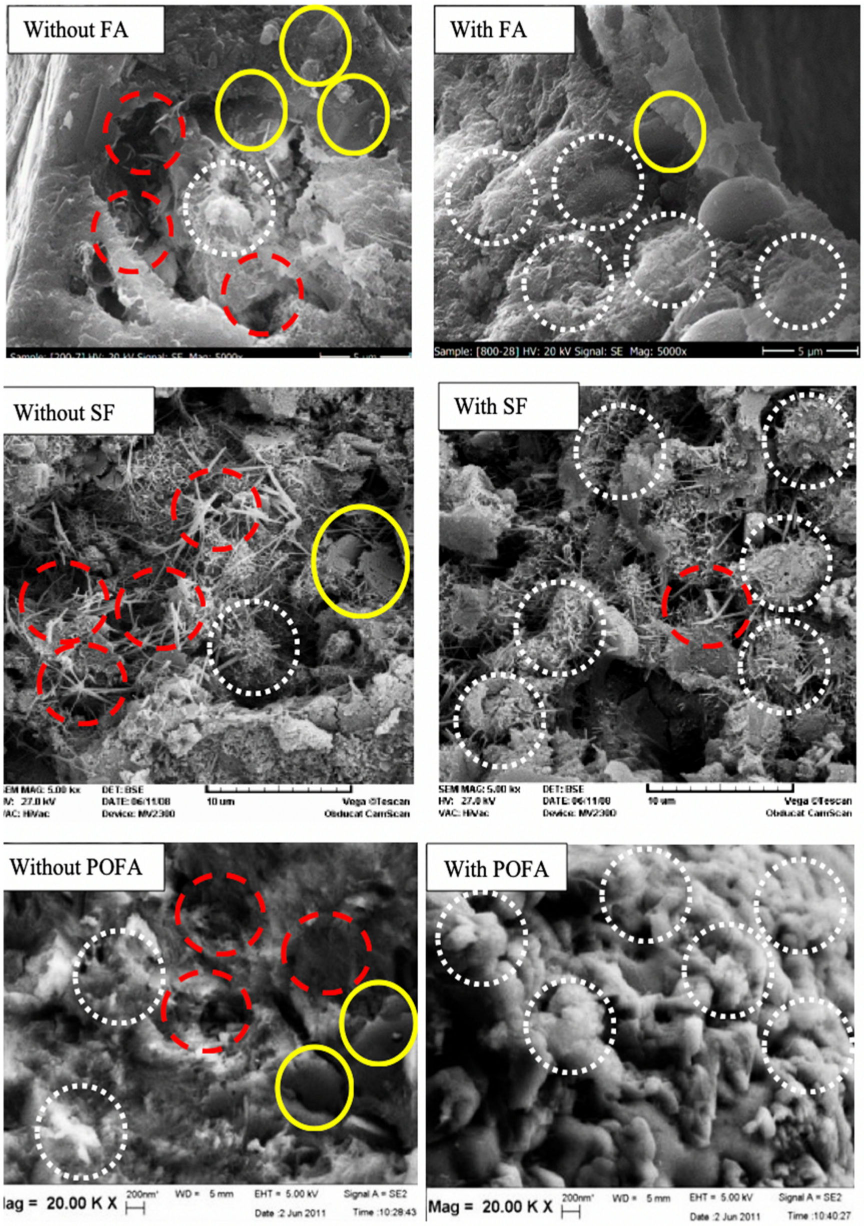


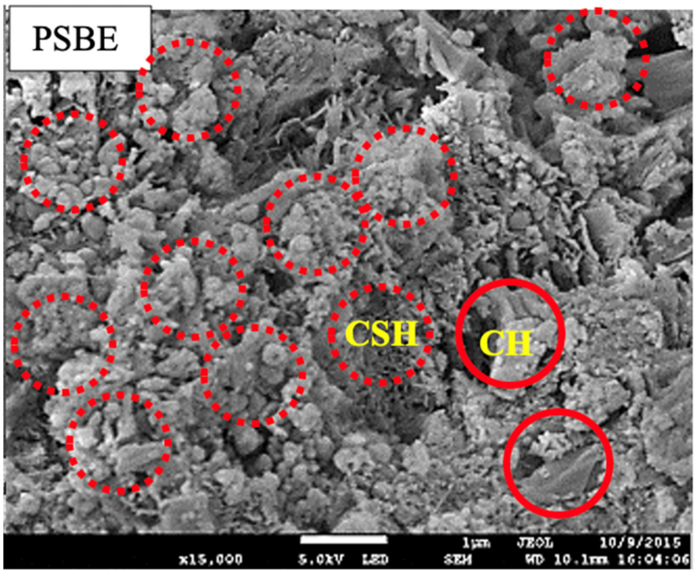
Figure 6. SEM of FC with pozzolan alternatives.

3. Compressive Strength of FC with Pozzolan Alternatives

The compressive strength of FC is an important factor in determining its suitability for various applications. In order to determine the compressive strength of FC, 100 mm cubes were tested using a universal testing machine (UTM) in accordance with ASTM C513-11 [58]. The compressive strength of FC is affected by a variety of factors such as density, age, curing method, and mix proportion components. The base mix and foam used also play a role in determining the compressive strength of FC [59]. Previous studies have found that the compressive strength of FC with densities ranging from 800–1000 kg/m^3 is between 1–8 N/mm^2, which is adequate for its intended purposes such as void filling, highway reinstatement, and other underground works [60]. If FC is to be used for structural applications, however, a compressive strength of at least 25 N/mm^2 is necessary [61]. The compressive strength of FC is influenced by various factors, including density, cement type and content, pozzolan alternative material type and content, water-cement ratio, foaming agent type, and curing regimes [62–64]. The relationship between compressive strength and dry density was reported by [65], which found that an increase in density results in an increase in compressive strength. The water content of the mixes also significantly affects the compressive strength of FC. It has been found that compressive strength increases with the use of a suitable water content [66]. In addition, the compressive strength of FC increases with time. It has also been found that the optimum ash/cement ratio increases with increasing age. These findings suggest that the use of suitable mix proportions, curing methods, and pozzolan alternative materials can contribute to the densification of the concrete internal structure through the pozzolanic reaction, resulting in an increase in compressive strength of FC.

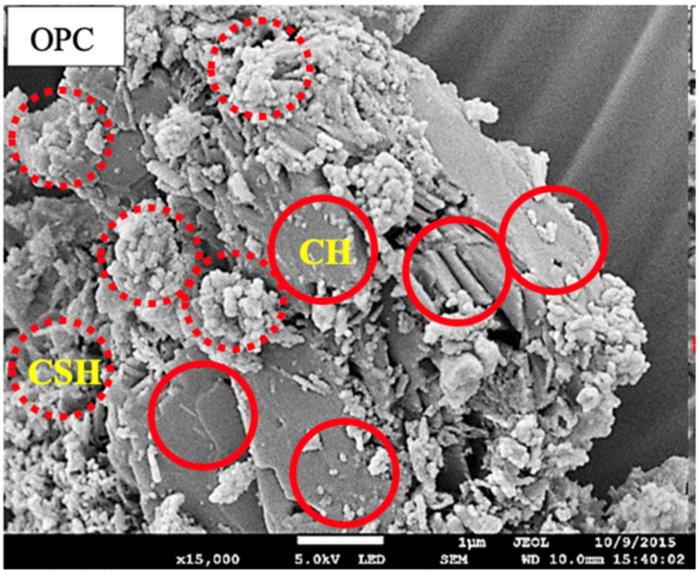
According to [67], the compressive strength of normal concrete increases with higher cement content, and this pattern is similar in FC. However, [68] reported that the strength increase is minimal above a cement content of 500 kg/m^3. In addition to cement, the use of PA such as fly ash, GGBS, silica fume, and POFA also influences the compressive strength and other properties of FC. Zhang et al. [69] found that fly ash can be used to achieve an ultimate strength of more than 50 MPa in higher density FC at 1500 kg/m^3. Similarly, a study by [70,71] reported that high calcium fly ash can increase the compressive strength of FC, and the optimal fly ash content for maximum strength after one year is nearly 60% of the cementitious material content. The type of foaming agent used also affects the compressive strength of FC, with protein-based foams increasing the strength through the creation of a closed cell network. It is important to note that when comparing the properties of FC, only mixes with the same type of foaming agents should be examined [7,71]. The foaming agent's dilution ratio also has a significant impact on the compressive strength and flexural strength of FC [72], with an optimal dilution ratio of 1:60. Additionally, the foam dosage should be carefully determined during the pre-formed foam stage, as the variation of foam dosage can affect the plastic density and, thus, the compressive strength of FC.

The present study observed that the inclusion of PSBE has led to a pozzolanic reaction resulting in the production of extra amounts of CSH gel and filled the voids in the foamed concrete with PSBE making the FC denser and stronger. The microstructure study has confirmed that the inclusion of PSBE also improves the internal structure of FC, making it denser than the control OPC specimen. The result is shown in Figure 7, where it may be seen that the formation of the crowded tiny cotton shapes symbolizes that the specimen containing PBSE has additional CSH that is more than that in the control OPC after 28 days. There are fewer CH crystals (hexagonal plate) and more CSH produced in the PSBE specimen, as verified through SEM analysis, which confirms its superiority.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. SEM of FC with PSBE and OPC. (**a**) FC with PSBE at 15,000× magnification, (**b**) FC with OPC at 15,000× magnification.

4. Water Absorption of FC with Pozzolan Alternatives

Water absorption is an important characteristic of concrete, as it reflects the ability of the material to absorb water. It is typically expressed as the percentage of the absorbed water to the dry mass of the specimen and is determined by measuring the specimen's constant mass, immersing it in water, and measuring the increase in mass as a percentage of dry mass. There are various methods used to measure water absorption, including 24 h immersion in water, immersion until constant mass is achieved, and vacuum saturation. However, it is important to note that different methods can produce widely different results. According to ASTM C642-13 [73], water absorption is the test used to determine the relative water absorption by the capillary uptake characteristic of mortar. In general, the water absorbed by oven-dried specimens is measured after a 48 h of immersion, or after such immersion followed by 5 h in boiling water. The ratio of the water absorbed to the dry weight is the absorption. Capillary absorption is not only affected by the water-cement ratio, but also by the paste content in the mix. As the paste content increases, the absorption also increases, and the effect is more pronounced for higher water-cement ratios [74]. It has been observed that FC has a higher water absorption value than normal concrete. The volume of water absorbed by FC is twice that absorbed by a cement paste with a similar water-cement ratio. However, the volume of water absorbed by FC appears to be insignificantly influenced by the volume of air entrained. The water absorption per unit volume of cement paste increases with increasing porosity [13]. In addition, research on other materials such as bentonite and pozzolan has shown that the water absorption rate can be influenced by factors such as the amount of the material, the curing period, and the density of the material [75,76]. Furthermore, the water absorption rate can also affect the compressive strength of the specimen. Lower water absorption rates tend to result in better compressive strength. The rate of water absorption in FC with fly ash reduces with time and becomes constant within 7 days [77]. Additionally, it is noted that water absorption decreases with increasing foam volume because the entrained pores are not interconnected. It is observed that the water absorption decreases with decreased porosity. Furthermore, the water absorption slightly increases with increased density. A study by [78,79] reported that the water absorption of a specimen produced by FC with PSBE was about 52% lower than FC produced with OPC. The positive effect of PSBE in FC is due to the decrease in the interconnected pore structure that leads to a decrease in the water absorption. Hence, only the capillary pores contribute to water absorption, which depends on the hydrated paste [57].

5. Conclusions

In this review study, the efficiency of using various types of industrial waste as a replacement for cement in foamed concrete was investigated. The results showed that certain industrial wastes demonstrated pozzolanic characteristics that meet the requirements for use as pozzolanic alternatives in construction projects. By incorporating these waste products as a replacement for cement, the construction industry can shift towards more sustainable and environmentally responsible practices. The implications of this study are significant for both the construction industry and the environment. The use of industrial waste as a replacement for cement can lead to a reduction in carbon dioxide emissions and the conservation of natural resources. The findings of this study can serve as a valuable guide for policymakers, engineers, and contractors in the construction industry for adopting sustainable construction practices. Moreover, the current research enriches the literature by providing insights into the efficiency of different types of industrial waste in foamed concrete production. The study highlights the importance of identifying the appropriate types of waste that can serve as an effective cement replacement in foamed concrete. This knowledge can be used to optimize the use of waste products in construction projects and minimize the negative impact of the construction industry on the environment. In summary, this study demonstrates that the use of PSBE as a cement replacement in foamed concrete has the potential to transform the current construction sector into a more sustainable and environmentally responsible industry. The findings provide a valuable contribution to both the literature and practice of sustainable construction.

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