

(RESEARCH ARTICLE)



## Effect of waste type and activator content on alkali-activated pumice-slag foam concrete: Evaluation of physical, mechanical, and embodied energy properties

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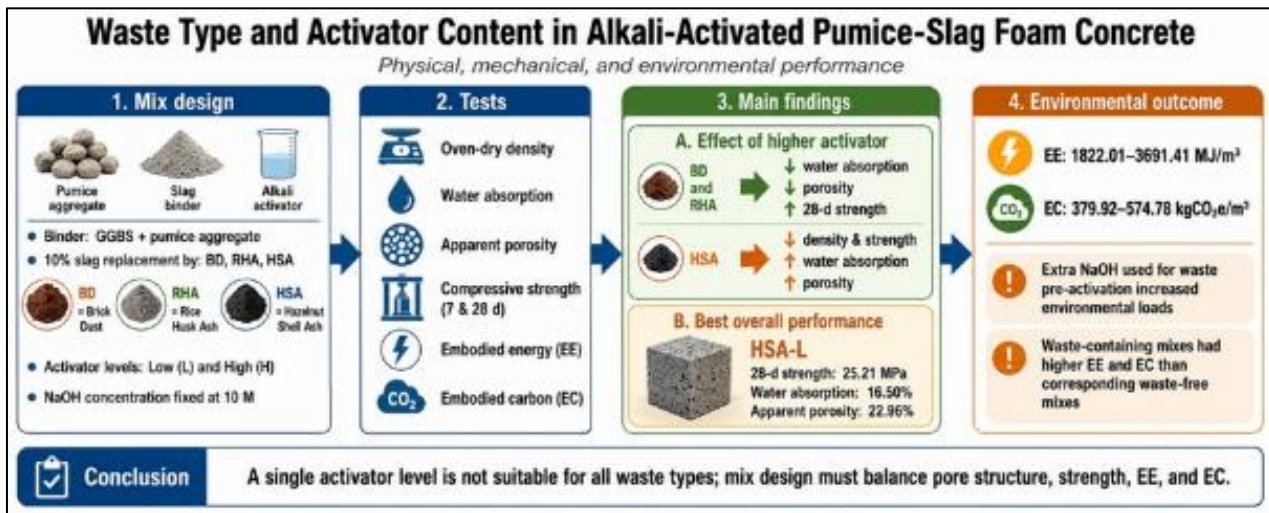
### Abstract

This study investigated the effects of brick dust (BD), rice husk ash (RHA), and hazelnut shell ash (HSA) on the physical, mechanical, and environmental performance of alkali-activated pumice – slag foam concrete. Ground granulated blast-furnace slag was replaced by each waste at 10% by mass, and mixtures were produced at two activator levels while maintaining a constant 10 M sodium hydroxide concentration. Oven-dry unit weight, water absorption, apparent porosity, 7- and 28-day compressive strength, embodied energy, and embodied carbon were evaluated. The results showed that activator content affected each waste differently. Increasing the activator level reduced water absorption and porosity and markedly improved 28-day strength in BD- and RHA-containing mixtures, whereas it reduced unit weight and compressive strength and increased water absorption and porosity in HSA mixtures. HSA at the low activator level achieved the best overall physical and mechanical performance, with a 28-day compressive strength of 25.21 MPa, water absorption of 16.50%, and apparent porosity of 22.96%. Total embodied energy and embodied carbon ranged from 1822.01 to 3691.41 MJ/m<sup>3</sup> and from 379.92 to 574.78 kgCO<sub>2</sub>e/m<sup>3</sup>, respectively. The additional sodium hydroxide used for waste pre-activation outweighed the environmental benefit obtained from slag replacement, resulting in higher environmental loads for waste-containing mixtures than for the corresponding waste-free mixtures. Overall, the findings demonstrate that a single activator level cannot be universally applied to different waste-derived precursors and that mixture design should jointly consider pore structure, strength development, embodied energy, and embodied carbon.

**Keywords:** Alkali-activated foam concrete; Pumice aggregate; Brick dust; Rice husk ash; Hazelnut shell ash; Embodied energy and carbon

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## Graphical abstract



## 1. Introduction

Building and construction have significant environmental impacts due to their high consumption of energy and natural resources. A major portion of this impact stems from Portland cement production, which is reported to account for approximately 5-8% of global CO<sub>2</sub> emissions [1, 2]. High temperatures required for clinker production and the calcination of limestone increase the carbon intensity of cement. For this reason, the development of alternative binders that reduce dependence on Portland cement while maintaining adequate engineering performance, as well as the utilization of industrial or agricultural waste in construction materials, has become increasingly important [2-4].

Alkali-activated binders are produced by activating precursors rich in aluminosilicate or calcium silicate – such as fly ash, metakaolin, and ground granulated blast furnace slag (GGBS) – with alkali solutions [2, 4, 5]. GGBS, which has a high calcium content, promotes the formation of calcium-aluminate-silicate hydrate reaction products that contribute to strength development [2, 5]. However, the environmental performance of these binders cannot be explained solely by the fact that they do not contain cement or that they use waste-based precursors. The type of precursor, activator composition, energy source, transport distance, and production conditions all influence the overall environmental impact [4]. In particular, the energy and emissions associated with commercial sodium silicate and sodium hydroxide may limit the environmental benefits that can be achieved compared to Portland cement [4, 6].

Foam concrete is a low-density construction material in which a cellular void structure is formed within the binder matrix. Its physical and mechanical properties depend on the pore volume, size, distribution, and connectivity, as well as the binder composition and mix density. Increased porosity generally reduces density and compressive strength, while interconnected voids increase the tendency to absorb water [1, 7]. For this reason, a balance must be struck between low unit weight and adequate mechanical performance in the design of foam concrete. The use of agricultural and industrial waste as additives or binding agents can alter this balance and the material's environmental impact [3, 8].

Due to its low density and high internal porosity, pumice is used as an aggregate in lightweight concrete and helps reduce the unit weight [1, 7]. However, its porous structure can affect its water requirements, water absorption behavior, total porosity, and mechanical properties [1, 9]. The use of pumice in conjunction with its foam-formed cellular structure requires a comprehensive evaluation of the relationship between density, water absorption, apparent porosity, and compressive strength.

The use of industrial and agricultural waste in construction materials contributes to the circular economy by reducing the consumption of natural resources and the need for landfills [5, 8–12]. Brick dust, a ceramic waste product containing silica and alumina, can be used as a filler or partial precursor in cement-based and alkali-activated systems [4, 5, 13]. Similarly, studies on ceramic-powder-containing alkali-activated slag mortars have shown that the mechanical and durability performance of ceramic waste depends strongly on the replacement ratio, activator composition, water-to-binder ratio, and curing conditions [14]. Its effect depends on the amount of the amorphous phase, particle fineness, substitution ratio, and the activator system.

Rice husk ash (RHA) is an agricultural byproduct rich in silica. Under appropriate burning and grinding conditions, its high content of amorphous silica confers on RHA properties suitable for pozzolanic and alkali activation [2, 8, 13]. Its reactivity is influenced by its combustion temperature, combustion time, carbon content, particle size, and specific surface area [2, 15]. Previous research on alkali-activated slag-fly ash mortars has shown that RHA contents of up to 7.5% can contribute positively to compressive strength; however, the magnitude of this contribution depends on the precursor proportions, activator composition, and thermal-curing conditions [16]. Although it can increase compressive strength and reduce water absorption and porosity at appropriate replacement rates, high replacement rates can lead to adverse results due to increased liquid demand and insufficient reaction [7]. For this reason, the effect of RHA should be evaluated based on the properties of the binding system in which it is used.

Hazelnut shell ash (HSA) is a biomass-derived waste product obtained by burning hazelnut shells. Although hazelnut shells and similar shell-based wastes have been studied in cement-based composites [8, 10], research on the use of HSA in alkali-activated binders is more limited compared to that on RHA and brick dust. Other biomass-derived ashes, such as forest-industry waste ash, have been incorporated into slag-based alkali-activated mortars; however, their mechanical contribution has been shown to depend on the replacement level and curing conditions [12]. Current studies indicate that the chemical composition, fineness, and usage rate of HSA may affect its physical and mechanical properties [8]. However, it is not appropriate to directly apply the results from other shell-based waste or biomass ash to HSA.

The type and amount of the alkali activator are among the key variables that determine the dissolution of the precursors, the formation of reaction products, and the physical and mechanical properties of the binder [2, 4]. Although an increase in the amount of activator may promote reaction and strength development in some systems, the result depends on the properties of the precursor and the waste used. Amounts above the optimum level may not provide additional mechanical benefits; they may adversely affect the pore structure and fresh-state properties [4]. In addition, the use of commercial sodium silicate, in particular, increases the mixture's embodied energy and environmental impact [4, 6].

For this reason, environmental assessment should not be based solely on energy consumption per unit volume or mass; engineering performance must also be taken into account. A lower activator content can reduce total embodied energy; however, if it causes a disproportionate loss in mechanical performance, the overall environmental – engineering balance may not improve. Linking embodied energy and CO<sub>2</sub> emissions to mechanical performance can enable more meaningful comparisons between different mixtures [4, 17].

Although studies exist on the use of brick dust, RHA, and HSA in cement-based or alkali-activated systems, there are few studies that directly compare these materials within the same pumice-slag-based foam concrete matrix, at equal replacement ratios and two activator levels. In particular, there is limited data on the behavior of HSA in alkali-activated foam concrete. Some previous studies have combined the mechanical evaluation of waste-containing alkali-activated materials with production-cost analysis [12]. However, comparatively fewer studies have examined the effects of waste type and activator content on embodied energy and embodied carbon within the same experimental framework. Therefore, the interaction between waste type and activator content must be examined collectively in terms of physical, mechanical, and environmental performance.

In this study, the effects of brick dust, RHA, and HSA on GGBS-based, pumice-aggregate-containing, alkali-activated foam concrete were compared at two different activator levels. The NaOH concentration was kept constant at 10 M; oven-dry unit weight, water absorption, apparent porosity, and compressive strengths at 7 and 28 days were determined. Furthermore, the mechanical performance of the mixtures was evaluated in conjunction with embodied energy and embodied carbon results to elucidate the interaction between waste type and activator content.

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## 2. Materials and methods

### 2.1. Materials Used

Fine pumice sourced from Nevşehir, Türkiye, was used as lightweight aggregate. Before being used in the mixtures, the pumice was sieved through a 2-mm mesh sieve, and only the fraction that passed through the sieve was used. The use of fine aggregates instead of coarse aggregates in the production of foam concrete is important for maintaining the stability and cellular structure of low-density mixtures [18].

Granulated blast furnace slag (GGBS), supplied in ground form by KARÇİMSA, was used as the main binder. Brick dust (BD), rice husk ash (RHA), and hazelnut shell ash (HSA) were sourced from the Turkish market, ground, and sieved through a No. 230 sieve with a 0.063 mm mesh size. In the mixtures containing waste, 50 kg/m<sup>3</sup> of the 500 kg/m<sup>3</sup> GGBS was replaced with the relevant substitute material, resulting in a 10% by mass substitution based on the GGBS content.

Commercial aluminous cement sourced from the Turkish market was also used in the mixtures. Aluminous cement was added at a rate of  $10 \text{ kg/m}^3$  to all mixtures except the initial reference mixture. The powdered materials used are shown in Figure 1.

The alkali activator system consists of a commercial sodium silicate solution with a silica modulus ( $M_s=3$ ) and a 10 M sodium hydroxide solution. Tap water that meets the requirements of EN 1008 was used as the mixing water [19]. A commercial foaming agent supplied by Fatsa Kimya San. ve Tic. Ltd. Şti. was used in the preparation of the preformed foam.



**Figure 1** Materials used: (A) Pumice (B) Brick Dust (C) Hazelnut Shell Ash (D) Aluminous Cement (E) Blast Furnace Slag (F) Rice Husk Ash

## 2.2. Experimental Design and Mixing Ratios

The experimental program consisted of an initial reference mixture without aluminous cement and eight comparison mixtures prepared at two different activator levels. Low and high activator levels are denoted by the letters L and H, respectively. REF-0 represents the initial reference mixture containing no aluminous cement; the P groups represent mixtures containing aluminous cement but no waste substitute; and the BD, RHA, and HSA groups represent mixtures in which 10% by mass of the GGBS has been replaced with the respective substitute material.

Aluminous cement was not used in the REF-0 mixture. In all other mixtures, the total amount of pumice, GGBS, and/or substitute materials was kept constant at  $1000 \text{ kg/m}^3$ , and  $10 \text{ kg/m}^3$  of aluminous cement was added to this amount. Accordingly, the total dry material content of the REF-0 mixture was  $1000 \text{ kg/m}^3$ , while that of the other mixtures was  $1010 \text{ kg/m}^3$ .

The total mass of the mixing water, commercial sodium silicate solution, and the 10 M NaOH solutions used was kept constant at  $500 \text{ kg/m}^3$  in all mixtures. In mixtures with low activator levels,  $40 \text{ kg/m}^3$  of sodium silicate and  $30 \text{ kg/m}^3$  of NaOH solution were used, while in mixtures with high activator levels, these amounts were 80 and  $60 \text{ kg/m}^3$ , respectively.

In mixtures containing BD, RHA, or HSA, a 10 M NaOH solution at a concentration of  $50 \text{ kg/m}^3$  was also used to pre-activate the replacement material. To keep the total liquid volume constant, the amount of water in these mixtures was reduced by  $50 \text{ kg/m}^3$ . The experimental mixture ratios are given in Table 1.

**Table 1** Experimental mixture ratios (kg/m<sup>3</sup>)

| Mixture | Pumice | GGBS | HSA | BD | RHA | AC | Water | SS  | 10 M NaOH, Stage 1 | 10 M NaOH, Stage 2 |
|---------|--------|------|-----|----|-----|----|-------|-----|--------------------|--------------------|
| REF-0   | 500    | 500  | —   | —  | —   | —  | 430   | 40  | 30                 | —                  |
| L       | P      | 500  | 500 | —  | —   | —  | 10    | 430 | 40                 | 30                 |
|         | HSA    | 500  | 450 | 50 | —   | —  | 10    | 380 | 40                 | 30                 |
|         | BD     | 500  | 450 | —  | 50  | —  | 10    | 380 | 40                 | 30                 |
|         | RHA    | 500  | 450 | —  | —   | 50 | 10    | 380 | 40                 | 30                 |
| H       | P      | 500  | 500 | —  | —   | —  | 10    | 360 | 80                 | 60                 |
|         | HSA    | 500  | 450 | 50 | —   | —  | 10    | 310 | 80                 | 60                 |
|         | BD     | 500  | 450 | —  | 50  | —  | 10    | 310 | 80                 | 60                 |
|         | RHA    | 500  | 450 | —  | —   | 50 | 10    | 310 | 80                 | 60                 |

SS refers to a commercial sodium silicate solution; AC refers to aluminous cement; and NaOH Stage 2 refers to the 10 M NaOH solution used in the pre-activation of substitute materials.

### 2.3. Pre-Activation of Substitute Materials

BD, RHA, and HSA were pre-activated before being added to the main mixture. For this purpose, 50 kg/m<sup>3</sup> of replacement material was mixed in a separate container with 50 kg/m<sup>3</sup> of 10 M NaOH solution until a homogeneous mixture was obtained. The prepared pre-activated mixture was added to the mixer along with the liquid components; this process was not applied in the REF-0 and P groups.

### 2.4. Preparation of the Foam

The pre-formed foam method was used in the production of foam concrete [18, 20]. The foam solution was prepared by mixing a commercial foaming agent with water at a mass percentage of 2.5%. The resulting foam was used at a rate of 5% of the total fresh mixture volume and was added to the main mixture immediately after production, without being allowed to stand.

### 2.5. Mixing and Sample Preparation

The mixtures were prepared using a laboratory-type mortar mixer that complies with the specifications set forth in TS EN 196-1 [21]. Pumice, GGBS, and aluminous cement were dry-mixed at low speed for 2 minutes. Then, mixing water, a commercial sodium silicate solution, a NaOH solution, and the pre-activated replacement material from the relevant groups were added to the mixer, and the mixing process continued for another 5 minutes.

**Figure 2** Sample production process

The pre-formed foam was added to the mixture at a low speed and gradually to limit the coalescence and collapse of air bubbles. Mixing continued at a low speed until the foam was evenly distributed [18, 20].

The freshly prepared mixtures were placed into cube molds with internal dimensions of 50x50x50 mm. Three cube specimens were prepared for each test age to determine the compressive strength of each mixture at 7 and 28 days. The



production process is shown in

Figure 2.

The prepared specimens were cured in their molds at 60 °C and 90% relative humidity for 48 h. Thermal curing is commonly employed to promote early reaction and strength development in alkali-activated systems, although its effectiveness depends on precursor composition, curing temperature, and duration [22]. After the initial cure, the specimens were removed from the molds, stored under laboratory conditions until they reached the required test age, and subjected to physical and mechanical tests at 7 and 28 days.

### 3. Experimental Methods

#### 3.1. Dry Unit Weight, Water Absorption, and Porosity

Tests for dry unit weight, water absorption, and porosity were conducted in accordance with ASTM C642 [23]. The oven-dried mass ( $W_d$ ), the surface-dry mass after water saturation ( $W_s$ ), and the suspended mass in water ( $W_{sub}$ ) of the samples were determined. Water absorption by mass, apparent porosity, and dry unit weight were calculated using Equation (1), Equation (2), and Equation (3), respectively.

$$WA(\%) = \frac{W_s - W_d}{W_d} * 100 \quad (1)$$

$$AP(\%) = \frac{W_s - W_d}{W_s - W_{sub}} * 100 \quad (2)$$

$$\rho_{dry} = \frac{W_d}{W_s - W_{sub}} * \rho_w \quad (3)$$

Here,  $\rho_w$  represents the density of water at the experimental temperature.

#### 3.2. Compressive Strength

Compressive strength tests were conducted on 50x50x50 mm cubic specimens at 7 and 28 days of age. Three specimens were tested for each mix and test age, and the results were evaluated as mean values and standard deviations. A compression testing machine with a capacity of 20 metric tons was used in the tests. The loading principles defined in TS EN 196-1 were adapted for 50 mm cubic specimens, and the tests were conducted at a constant loading rate of 2.2 kN/s [21]. The compressive strength was calculated using Equation (4).

$$f_c = \frac{P_{max}}{A_y} \quad (4)$$

Here,  $f_c$  represents the compressive strength (MPa),  $P_{max}$  represents the maximum load at the point of failure (N), and  $A_y$  represents the surface area over which the load is applied (mm<sup>2</sup>).

#### 3.3. Assessment of Embodied Energy and Embodied Carbon

The environmental performance of the mixtures was evaluated using a comparative calculation approach based on the embodied energy (EE) and embodied carbon (EC) coefficients of the materials and production inputs used. In the calculations, the functional unit was defined as 1 m<sup>3</sup> of foam concrete. The system boundary includes the environmental impacts arising from the production of mixture components – such as pumice, GGBS, substitute materials, aluminous cement, alkali activators, water, and foaming agents – as well as the production energy input defined in Table 2. The

transportation of raw materials to the construction site or laboratory, the production of equipment and forms, the use of testing equipment, the use phase, and end-of-life operations were excluded from the assessment.

The unit embodied energy and embodied carbon coefficients for the mixture components were obtained from the Inventory of Carbon and Energy database, relevant literature, and product environmental declarations [24–31]. For components such as pumice, HSA, BD, and aluminous cement – for which no product-specific environmental data is available – proxy coefficients representing similar materials or production processes were used. The values used as proxies are indicated by an asterisk in Table 2. Therefore, the calculations represent the comparative environmental performance of mixtures prepared under the same system boundaries and calculation principles, rather than a detailed and comprehensive life cycle assessment.

**Table 2** The EE and EC coefficients used in the embodied energy and embodied carbon calculations (the coefficients for material inputs are expressed in MJ/kg and kgCO<sub>2</sub>e/kg, respectively, while those for production energy are expressed in MJ/kWh and kgCO<sub>2</sub>e/kWh)

| Abbreviation                     | EE     | EC       | Value Type                                   | Ref.     |
|----------------------------------|--------|----------|----------------------------------------------|----------|
| Pumice                           | 0.72   | 0.03*    | Substitute value for natural fine aggregate  | [25]     |
| Slag/GGBFS                       | 0.857  | 0.3360   | Literature-based value                       | [26]     |
| HSA                              | 0.243* | 0.0027*  | RHA-based biomass ash substitute value       | [25]     |
| BD                               | 0.083* | 0.0110*  | Substitute value for processed mineral waste | [25]     |
| RHA                              | 0.243  | 0.0027   | Literature-based value                       | [26]     |
| AC                               | 4.530* | 0.9050   | ISIDAÇ40 EPD, A1–A3                          | [27]     |
| Na <sub>2</sub> SiO <sub>3</sub> | 5.370  | 1.2220   | Literature-based value                       | [26, 28] |
| NaOH                             | 20.500 | 1.9150   | Literature-based value                       | [26]     |
| Water                            | 0.010  | 0.000168 | Tap water coefficient                        | [29, 30] |
| Foam                             | 18.1   | 2.05     | Literature-based value                       | [31]     |
| Energy                           | 9.28   | 0.4261   | Literature-based value                       | [31]     |

In the calculations of embodied energy and embodied carbon, the material quantities given in Table 1 for 1 m<sup>3</sup> of mixture were used as the basis. In the REF-0 and P mixtures, which do not contain waste substitutes, only the NaOH solution used in Stage 1 was included in the calculation. For mixtures containing BD, RHA, and HSA, the total amount of NaOH was calculated as the sum of the NaOH solution added to the main mixture in Step 1 and the 50 kg/m<sup>3</sup> NaOH solution used for the pre-activation of the substitute material in Step 2. Accordingly, a total of 80 kg/m<sup>3</sup> of NaOH solution was evaluated for the L mixtures containing waste, and a total of 110 kg/m<sup>3</sup> for the H mixtures.

The total embodied energy per unit volume for each mixture was calculated using Equation (5).

$$EE_V = \sum_{i=1}^n q_i * e_i \quad (5)$$

Here, EE<sub>V</sub> represents the total embodied energy per unit volume of the mixture (MJ/m<sup>3</sup>); q<sub>i</sub> represents the amount of the relevant material or production input in 1 m<sup>3</sup> of the mixture; and e<sub>i</sub> represents the unit embodied energy coefficient for that input. For mass-based material inputs, q<sub>i</sub> is expressed in kg/m<sup>3</sup>, and the embodied energy contribution of each component is determined by multiplying the relevant quantity by the unit coefficient.

An electricity consumption of 20 kWh/m<sup>3</sup> was assumed for the production and curing process. The embodied energy and embodied carbon contributions of the production energy were calculated by multiplying the assumed electricity consumption by the coefficients of 9.28 MJ/kWh and 0.4261 kgCO<sub>2</sub>e/kWh, respectively. The embodied energy contribution of water was considered negligible and taken as 0.010 MJ/m<sup>3</sup> in the calculations; the embodied carbon contribution was determined by multiplying the amount of water in the mixtures by the relevant EC factor.

The total embodied carbon per unit volume of each mixture was determined using Equation (6).

$$EC_V = \sum_{i=1}^n q_i * c_i \quad (6)$$

Here,  $EC_V$  represents the total embodied carbon value per unit volume of the mixture ( $\text{kgCO}_2\text{e/m}^3$ ), while  $c_i$  represents the unit embodied carbon coefficient used for the relevant input. Embodied carbon values are expressed in carbon dioxide equivalents, taking into account the global warming potentials of different greenhouse gases.

To demonstrate the effect of differences in dry unit weight on environmental indicators, the total embodied energy and embodied carbon values per unit volume were divided by the dry unit weight to calculate the indicators per unit mass. The embodied energy and embodied carbon values per unit mass were determined using Equation (7) and Equation (8), respectively.

$$EE_m = \frac{EE_V}{\rho_d} \quad (7)$$

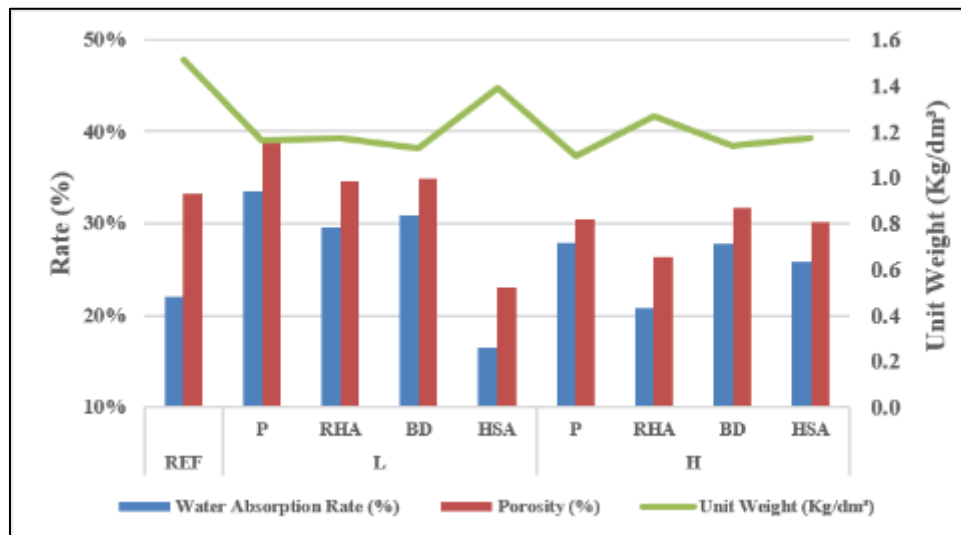
$$EC_m = \frac{EC_V}{\rho_d} \quad (8)$$

Here,  $EE_m$  represents the embodied energy per unit mass ( $\text{MJ/kg}$ );  $EC_m$  represents the embodied carbon per unit mass ( $\text{kgCO}_2\text{e/kg}$ ); and  $\rho_d$  represents the dry unit weight of the mixture ( $\text{kg/m}^3$ ).

## 4. Results and discussion

### 4.1. Dry Unit Weight, Water Absorption, and Porosity Properties

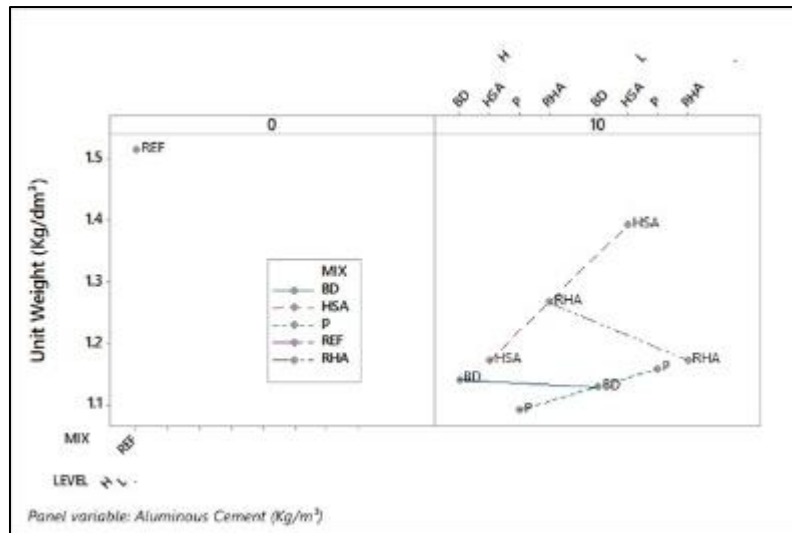
The results for the dry unit weight, water absorption rate, and porosity of the mixtures are presented together in Figure 3.



**Figure 3** Water absorption, porosity, and dry unit weight of the mixtures

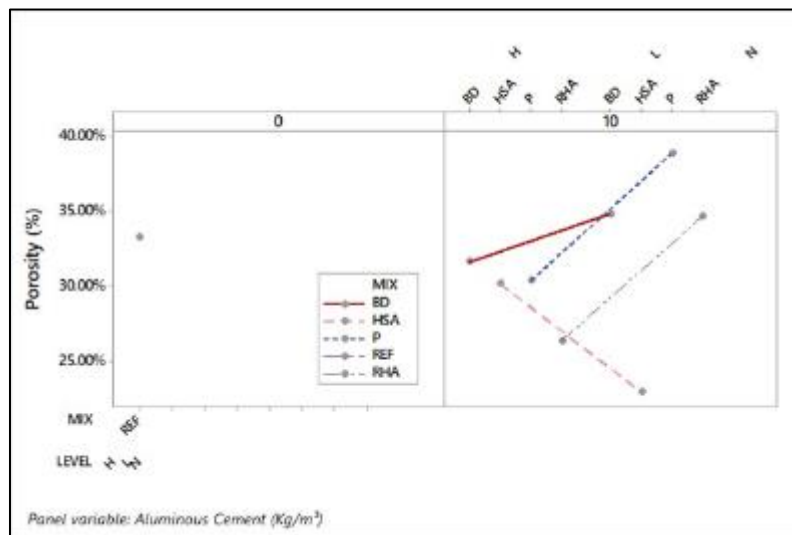
The highest dry unit weight was obtained for the REF-0 mixture, while the lowest was obtained for the P-H mixture, which contained a high activator content and no waste substitute. All mixtures fell within the low-density range reported in the literature for foamed concrete [18].

The effect of the activator level on the dry unit weight varied depending on the substitute material used. In mixtures containing HSA, increasing the activator level significantly reduced the dry unit weight; this change was accompanied by an increase in porosity and water absorption and a decrease in compressive strength. In contrast, in RHA mixtures, a high activator level increased the dry unit weight, and this change was accompanied by a decrease in porosity and water absorption, as well as an improvement in mechanical performance. In BD mixtures, however, the change in dry unit weight (Figure 4) remained relatively limited.

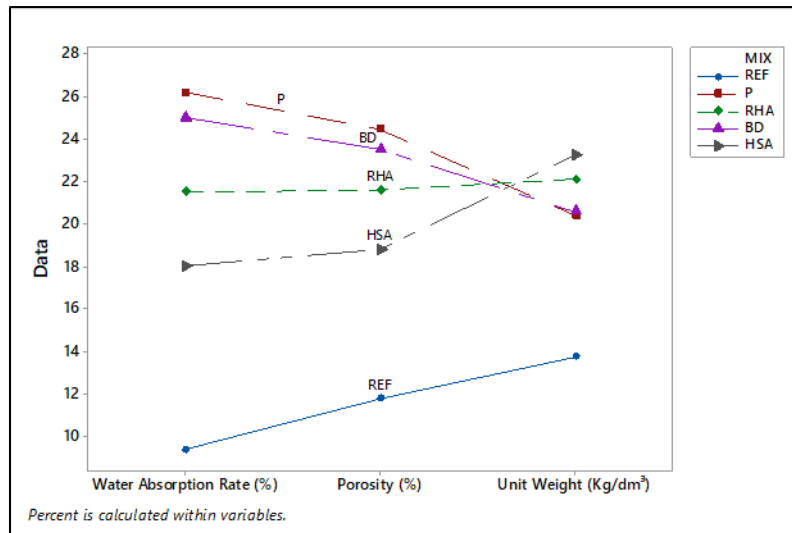


**Figure 4** Effect of activator level on dry unit weight

As shown in Figure 5 and Figure 6, the water absorption rate and porosity results generally varied in tandem. The lowest values for both properties were obtained in the HSA-L mixture, while the highest values were obtained in the P-L mixture. The fact that HSA-L also has a relatively high dry unit weight and the highest compressive strength among the mixtures supports the relationship between low interconnected pore volume and improved mechanical performance.



**Figure 5** Comparative effect of activator level on porosity values



**Figure 6** Comparative effects of water absorption, porosity, and dry unit weight

As shown in Figure 3 and Figure 5, increasing the activator level in mixtures containing BD and RHA reduced both the water absorption rate and the porosity. This trend suggests that a higher amount of activator may have promoted the dissolution of reactive components in these materials and facilitated the formation of a more cohesive binder matrix.

RHA's high silica content and fine particle size can contribute to the formation of solid reaction products and the improvement of the pore structure under appropriate activation conditions. However, the effect of RHA depends on the calcination conditions, the amorphous silica content, the particle size, and the amount of alkali used [7, 15].

The effect of BD also depends on the fineness of the material, its amorphous phase content, and its ability to react with the activator. The fact that the BD-H mixture exhibits a lower water absorption rate and porosity than BD-L suggests that high activator conditions may have increased the contribution of the ground brick dust to the binder system [5].

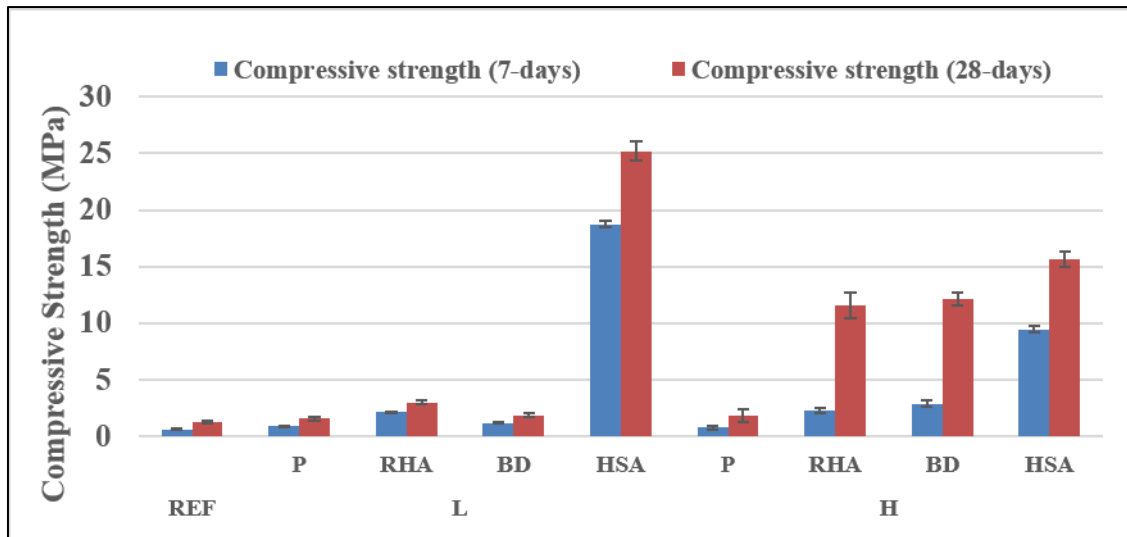
In HSA mixtures, however, the opposite behavior was observed. Increasing the activator level raised the water absorption rate and porosity, while reducing the dry unit weight and compressive strength. This result indicates that the high activator level examined did not improve the pore structure of the HSA-containing system.

This behavior in the HSA-H mixture may be related to excessive alkalinity, a different dissolution-precipitation equilibrium, the presence of unreactive components, or changes in the foam stability of the fresh mixture. However, since the chemical and mineralogical composition of HSA and the microstructure of the hardened matrix were not directly examined, it is not possible to identify any of these mechanisms as the definitive cause. The limited direct literature on the behavior of HSA in alkali-activated foam concrete also makes it difficult to generalize the results to other biomass ashes.

The water absorption rate in foamed concrete is not solely a result of total porosity. Pore size, interconnections between pores, continuity, and tortuosity also determine the movement of water within the material [20, 32]. Indeed, the fact that the improvement in compressive strength remains limited despite a decrease in porosity in the P-H mixture indicates that, while the physical pore structure is important for strength, it is not the sole determining factor. A similarly non-unique relationship between water absorption and compressive strength has been reported for alkali-activated slag-fly ash-glass powder mortars subjected to different curing conditions [22]. The degree of reaction of the binder matrix and the integrity of the solid phase must also be taken into account when evaluating mechanical performance.

#### 4.2. Compressive Strength

The 7-day and 28-day average compressive strengths and standard deviations of the mixtures are shown in Figure 7.



**Figure 7** 7- and 28-day compressive strengths of the mixtures

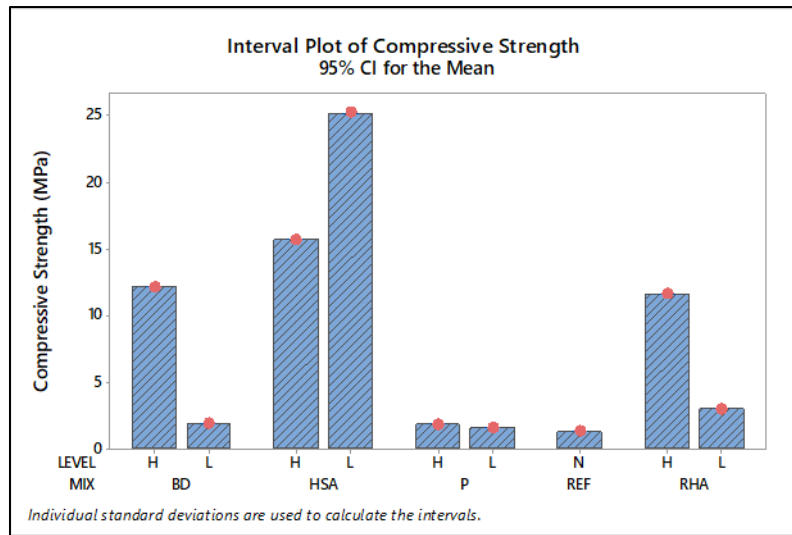
Examining Figure 7, it can be seen that the 28-day compressive strength of all mixtures is higher than the 7-day strength. However, the extent of strength development varied significantly depending on the substitute material used and the activator level. Previous research has similarly shown that the strength development of alkali-activated mortars depends on the combined effects of precursor composition and curing conditions [22]. The REF-0 mixture exhibited low compressive strength at both test ages. In the P-L mixture, only a limited increase in strength was achieved with the addition of aluminous cement. However, the fact that the water absorption and porosity of this mixture were higher than those of REF-0 indicates that the binding contribution provided by the aluminous cement does not necessarily result in a structure with lower porosity.

The 28-day compressive strength ranking at low activator levels was HSA-L > RHA-L > BD-L > P-L. HSA-L clearly stood out from the other low-activator mixtures, exhibiting high strength even at an early age. This indicates that a significant portion of the strength development in HSA-L occurs at an early age. The simultaneous achievement of a low water absorption rate and porosity, along with a relatively high dry unit weight in the same mixture, suggests that the high strength may be associated with a hardened structure that is more cohesive and contains fewer interconnected voids.

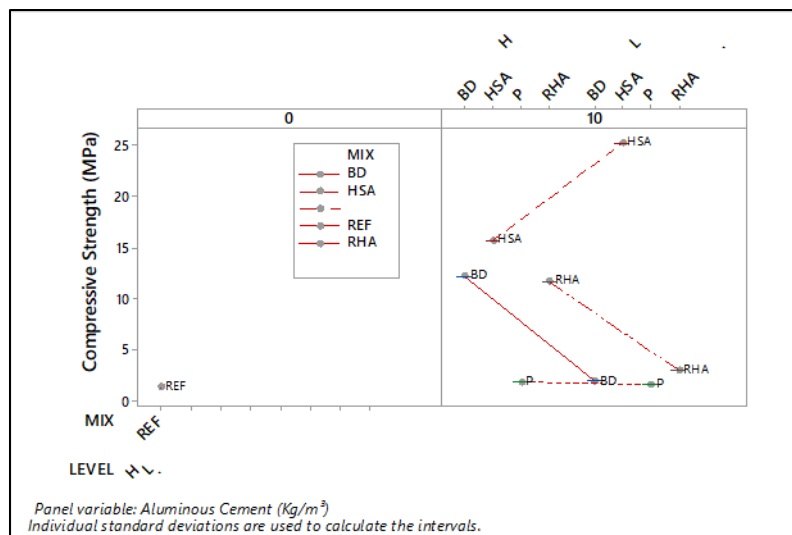
The 28-day strength ranking at high activator levels was as follows: HSA-H > BD-H > RHA-H > P-H. The low strength of the P-H mixture indicates that a high activator level alone does not provide sufficient mechanical performance. In contrast, mixtures containing BD and RHA benefited significantly from the high activator conditions.

A significant increase in strength was observed in the BD-H and RHA-H mixtures over the 7–28-day period. This trend suggests that, at high activator levels, the siliceous and aluminosilicate phases in BD and RHA may have contributed more to the binding reactions over time. While the amount and composition of the alkali activator affect the dissolution of the precursors and the formation of reaction products, the results obtained are closely related to the chemical composition and reactivity of the precursor [2]. When Figure 7 is evaluated as a whole, it can be seen that HSA-L stands out distinctly from the other mixtures at both early and later ages, while BD-H and RHA-H exhibit strong strength development, particularly during the 7–28-day period. The fact that HSA-H performs worse than HSA-L confirms that the increase in activator does not produce a positive mechanical effect in the HSA-containing system.

Upon examining Figure 8, it is clear that the average strength and confidence interval of HSA-L stand out distinctly from those of the other mixtures. Although the average strengths of the BD-H, RHA-H, and HSA-H mixtures are higher than those of the P-L, BD-L, and RHA-L mixtures, the fact that their confidence intervals approach or overlap in some regions indicates that the differences between them should not be considered statistically significant based solely on visual assessment. The wide confidence interval in the P-H mixture is also consistent with the high variability in results observed in this group. Due to the limited number of samples, Figure 8 has been evaluated as a descriptive tool illustrating the distribution of results and the uncertainty of the means.

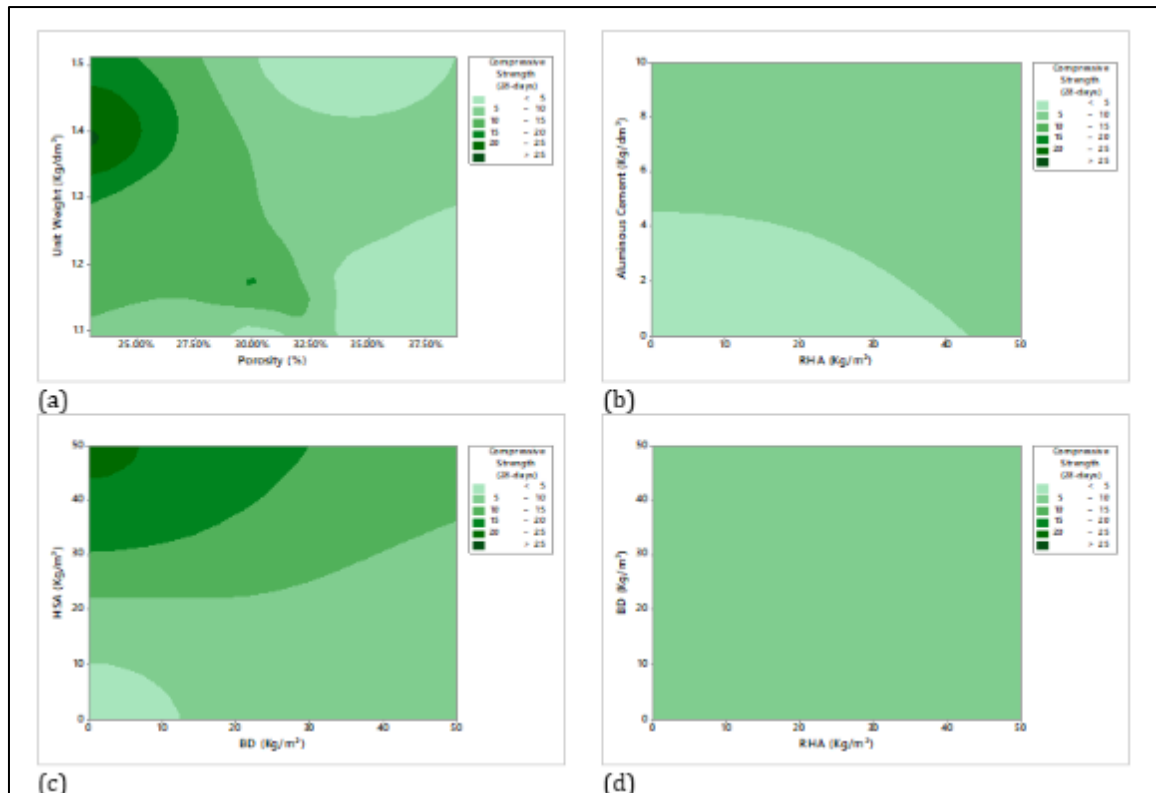


**Figure 8** Mean compressive strengths and 95% confidence intervals (H: high activator; L: low activator; N: normal level)



**Figure 9** The interaction between mixture type and activator level on compressive strength

Figure 9 shows that the mechanical response to the activator level changes in both direction and magnitude depending on the type of mixture. The transition from level L to level H resulted in significant increases in strength in the BD and RHA mixtures, while it led to only a limited improvement in the P group. In the HSA mixture, however, strength decreased, unlike in the other groups. The fact that the line in the P group runs approximately horizontal indicates that the increase in activator level has a limited effect on the strength of this mixture. In contrast, the opposite slope of the HSA line reveals that the effect of the activator varies depending on the substitute material used. However, for this pattern to be interpreted as statistically significant, it must be supported by an appropriate factorial analysis.



**Figure 10** Contour plots of the mixtures: (a) dry unit weight–porosity, (b) aluminous cement–RHA, (c) HSA–BD, and (d) BD–RHA interactions

Figure 10-(a) shows that the high-strength region is generally concentrated in the direction of low porosity and high dry unit weight. This region largely reflects the effect of the HSA-L mixture, which simultaneously provides low porosity, relatively high dry unit weight, and high strength. In contrast, the fact that some mixtures with similar dry unit weight or porosity properties exhibit different strengths demonstrates that mechanical performance cannot be explained solely by physical void characteristics.

The contour distributions in Figure 10-(b)-(c)-(d) descriptively show that the region where HSA is present is associated with higher strength, while the effects of BD and RHA vary depending on the activator conditions. However, since no intermediate mixtures combining BD, RHA, and HSA were produced, the contour surfaces are based on mathematical interpolation between experimental data points. Therefore, the graphs should not be interpreted as evidence of optimal material quantities, continuous dose–response relationships, or actual binary interactions between substitute materials.

When Figure 7 and Figure 10 are evaluated together, it can be seen that compressive strength is not controlled solely by the amount of activator or total porosity. While HSA provides high early-age strength, low water absorption, and low porosity at low activator levels, the mechanical contribution of BD and RHA becomes more pronounced at high activator levels and at advanced ages. These results indicate that the amount of activator should be determined based on the properties of the replacement material used.

#### 4.3. Embodied Energy and Embodied Carbon

The component coefficients used in the embodied energy and embodied carbon calculations are presented in Table 2, while the environmental impacts per unit volume and mass of the mixtures are presented in Table 3 and Table 4, respectively. Since proxy coefficients were used for some components – such as HSA, BD, and pumice – for which direct, product-specific environmental data is unavailable, the results obtained represent the comparative environmental performance of mixtures prepared within the same system boundaries rather than a detailed and comprehensive life cycle assessment. Therefore, in addition to absolute results, the assessment took into account relative changes depending on the activator level, the type of substitute material, and the dry unit weight values.

**Table 3** Calculation of the embodied energy (EE) of mixtures

| LEVEL | GROUP | PUMICE EE contribution (MJ/m <sup>3</sup> ) | SLAG EE contribution (MJ/m <sup>3</sup> ) | HSA EE contribution (MJ/m <sup>3</sup> ) | BD EE contribution (MJ/m <sup>3</sup> ) | RHA EE contribution (MJ/m <sup>3</sup> ) | AL- CEMENT EE contribution (MJ/m <sup>3</sup> ) | Na <sub>2</sub> SiO <sub>3</sub> EE contribution (MJ/m <sup>3</sup> ) | NaOH EE contribution (MJ/m <sup>3</sup> ) | Water EE contribution (MJ/m <sup>3</sup> ) | Foam EE contribution (MJ/m <sup>3</sup> ) | Energy | Embodied Energy (MJ/m <sup>3</sup> ) | Unit Weight (kg/m <sup>3</sup> ) | Embodied Energy (MJ/kg) |
|-------|-------|---------------------------------------------|-------------------------------------------|------------------------------------------|-----------------------------------------|------------------------------------------|-------------------------------------------------|-----------------------------------------------------------------------|-------------------------------------------|--------------------------------------------|-------------------------------------------|--------|--------------------------------------|----------------------------------|-------------------------|
| Ref-0 | Ref-0 | 360.00                                      | 428.50                                    | 0.00                                     | 0.00                                    | 0.00                                     | 0.00                                            | 214.80                                                                | 615.00                                    | 0.010                                      | 18.100                                    | 185.60 | 1822.01                              | 1513.73                          | 1.20                    |
| L     | P     | 360.00                                      | 428.50                                    | 0.00                                     | 0.00                                    | 0.00                                     | 45.30                                           | 214.80                                                                | 615.00                                    | 0.010                                      | 18.100                                    | 185.60 | 1867.31                              | 1157.75                          | 1.61                    |
|       | RHA   | 360.00                                      | 385.65                                    | 0.00                                     | 0.00                                    | 12.15                                    | 45.30                                           | 214.80                                                                | 1640.00                                   | 0.010                                      | 18.100                                    | 185.60 | 2861.61                              | 1171.96                          | 2.44                    |
|       | BD    | 360.00                                      | 385.65                                    | 0.00                                     | 4.15                                    | 0.00                                     | 45.30                                           | 214.80                                                                | 1640.00                                   | 0.010                                      | 18.100                                    | 185.60 | 2853.61                              | 1128.36                          | 2.53                    |
|       | HSA   | 360.00                                      | 385.65                                    | 12.15                                    | 0.00                                    | 0.00                                     | 45.30                                           | 214.80                                                                | 1640.00                                   | 0.010                                      | 18.100                                    | 185.60 | 2861.61                              | 1391.74                          | 2.06                    |
| H     | P     | 360.00                                      | 428.50                                    | 0.00                                     | 0.00                                    | 0.00                                     | 45.30                                           | 429.60                                                                | 1230.00                                   | 0.010                                      | 18.100                                    | 185.60 | 2697.11                              | 1090.60                          | 2.47                    |
|       | RHA   | 360.00                                      | 385.65                                    | 0.00                                     | 0.00                                    | 12.15                                    | 45.30                                           | 429.60                                                                | 2255.00                                   | 0.010                                      | 18.100                                    | 185.60 | 3691.41                              | 1265.81                          | 2.92                    |
|       | BD    | 360.00                                      | 385.65                                    | 0.00                                     | 4.15                                    | 0.00                                     | 45.30                                           | 429.60                                                                | 2255.00                                   | 0.010                                      | 18.100                                    | 185.60 | 3683.41                              | 1140.23                          | 3.23                    |
|       | HSA   | 360.00                                      | 385.65                                    | 12.15                                    | 0.00                                    | 0.00                                     | 45.30                                           | 429.60                                                                | 2255.00                                   | 0.010                                      | 18.100                                    | 185.60 | 3691.41                              | 1171.17                          | 3.15                    |

When Table 3 and Figure 11 are examined together, it can be seen that the embodied energy values of the mixtures vary, particularly depending on the total amount of NaOH used. In mixtures containing waste, replacing 10% by mass of GGBS with BD, RHA, or HSA provided a limited energy advantage due to the reduction in the amount of GGBS. However, the energy load from the additional 50 kg/m<sup>3</sup> of NaOH solution used in the pre-activation of the substitute materials exceeded the reduction achieved through the GGBS substitution. Consequently, the mixtures containing waste yielded higher total embodied energy values compared to the P mixtures at the same activator level.

The total embodied energy values of the mixtures ranged from 1,822.01 to 3,691.41 MJ/m<sup>3</sup>. The lowest total embodied energy value, 1,822.01 MJ/m<sup>3</sup>, was obtained for the REF-0 mixture, which did not contain aluminous cement, followed by the P-L mixture at 1,867.31 MJ/m<sup>3</sup>. The highest values were determined in the RHA-H and HSA-H mixtures at 3,691.41 MJ/m<sup>3</sup>; the BD-H mixture yielded a result of 3,683.41 MJ/m<sup>3</sup>, which was very close to those of these mixtures.

While the total embodied energy value of the P-L mixture at a low activator level was 1,867.31 MJ/m<sup>3</sup>, values of 2,853.61 MJ/m<sup>3</sup> were obtained for BD-L, and 2,861.61 MJ/m<sup>3</sup> for RHA-L and HSA-L. Accordingly, the total embodied energy values of waste-containing mixtures with low activator levels were approximately 52.8–53.2% higher than those of P-L. The fact that BD-L yields slightly lower values than RHA-L and HSA-L is due to the proxy EE coefficient used for BD being lower than the coefficients for RHA and HSA.

The total embodied energy value of the P-H mixture at a high activator level was determined to be 2,697.11 MJ/m<sup>3</sup>. The BD-H mixture had an embodied energy value of 3,683.41 MJ/m<sup>3</sup>, while the RHA-H and HSA-H mixtures had embodied energy values of 3,691.41 MJ/m<sup>3</sup>. The total embodied energy values of the high-activator mixtures containing waste were found to be approximately 36.6–36.9% higher than that of the P-H mixture. This result demonstrates the decisive effect of the additional NaOH solution used in the pre-activation of the substitute materials on the total energy load.

The transition from the L level to the H level increased the total embodied energy value of the P mixture by approximately 44.4%. The same transition resulted in an increase of approximately 29.0% in the RHA and HSA mixtures and approximately 29.1% in the BD mixture. The fact that the proportional increase in mixtures containing waste was

lower than that in the P group is due to the 50 kg/m<sup>3</sup> NaOH solution used in the pre-activation process remaining constant at both the L and H levels. However, all mixtures at the H level yielded higher total embodied energy values than their counterparts at the L level.

The embodied energy values per mass, calculated based on dry unit weight, ranged from 1.20 to 3.23 MJ/kg. The REF-0 mixture yielded the lowest value at 1.20 MJ/kg, followed by P-L at 1.61 MJ/kg. Among the low-activator mixtures containing waste, HSA-L had the lowest energy content per unit mass at 2.06 MJ/kg, while RHA-L and BD-L yielded values of 2.44 and 2.53 MJ/kg, respectively.

At high activator levels, the energy content per unit mass of the P-H, RHA-H, HSA-H, and BD-H mixtures was determined to be 2.47, 2.92, 3.15, and 3.23 MJ/kg, respectively. Although HSA-L has a similar energy load per unit volume to RHA-L and BD-L, its lower MJ/kg value is related to HSA-L's higher dry unit weight. In contrast, BD-H yielded the highest energy content per unit mass because it has one of the lowest dry unit weights among the high-activator mixtures containing waste.

**Table 4** Calculation of embodied carbon (EC) in mixtures

| LEVEL | GROUP | PUMICE EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | SLAG EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | HSA EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | BD EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | RHA EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | AL-CEMENT EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | Na <sub>2</sub> SiO <sub>3</sub> EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | NaOH EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | Water EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | Foam EC contribution (kgCO <sub>2</sub> e/m <sup>3</sup> ) | Energy | EC-(GHG) --- kgCO <sub>2</sub> e/m <sup>3</sup> | Unit Weight (kg/m <sup>3</sup> ) | EC-(GHG) --- kgCO <sub>2</sub> e/kg |
|-------|-------|--------------------------------------------------------------|------------------------------------------------------------|-----------------------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------|-------------------------------------------------------------|------------------------------------------------------------|--------|-------------------------------------------------|----------------------------------|-------------------------------------|
| Ref-0 | Ref-0 | 15.00                                                        | 168.00                                                     | 0.00                                                      | 0.00                                                     | 0.00                                                      | 0.00                                                            | 48.88                                                                                  | 57.45                                                      | 0.07                                                        | 82.00                                                      | 8.52   | 379.92                                          | 1513.73                          | 0.25                                |
| L     | P     | 15.00                                                        | 168.00                                                     | 0.00                                                      | 0.00                                                     | 0.00                                                      | 9.05                                                            | 48.88                                                                                  | 57.45                                                      | 0.07                                                        | 82.00                                                      | 8.52   | 388.97                                          | 1157.75                          | 0.34                                |
|       | RHA   | 15.00                                                        | 151.20                                                     | 0.00                                                      | 0.00                                                     | 0.14                                                      | 9.05                                                            | 48.88                                                                                  | 153.20                                                     | 0.06                                                        | 82.00                                                      | 8.52   | 468.05                                          | 1171.96                          | 0.40                                |
|       | BD    | 15.00                                                        | 151.20                                                     | 0.00                                                      | 0.55                                                     | 0.00                                                      | 9.05                                                            | 48.88                                                                                  | 153.20                                                     | 0.06                                                        | 82.00                                                      | 8.52   | 468.47                                          | 1128.36                          | 0.42                                |
|       | HSA   | 15.00                                                        | 151.20                                                     | 0.14                                                      | 0.00                                                     | 0.00                                                      | 9.05                                                            | 48.88                                                                                  | 153.20                                                     | 0.06                                                        | 82.00                                                      | 8.52   | 468.05                                          | 1391.74                          | 0.34                                |
| H     | P     | 15.00                                                        | 168.00                                                     | 0.00                                                      | 0.00                                                     | 0.00                                                      | 9.05                                                            | 97.76                                                                                  | 114.90                                                     | 0.06                                                        | 82.00                                                      | 8.52   | 495.29                                          | 1090.60                          | 0.45                                |
|       | RHA   | 15.00                                                        | 151.20                                                     | 0.00                                                      | 0.00                                                     | 0.14                                                      | 9.05                                                            | 97.76                                                                                  | 210.65                                                     | 0.05                                                        | 82.00                                                      | 8.52   | 574.37                                          | 1265.81                          | 0.45                                |
|       | BD    | 15.00                                                        | 151.20                                                     | 0.00                                                      | 0.55                                                     | 0.00                                                      | 9.05                                                            | 97.76                                                                                  | 210.65                                                     | 0.05                                                        | 82.00                                                      | 8.52   | 574.78                                          | 1140.23                          | 0.50                                |
|       | HSA   | 15.00                                                        | 151.20                                                     | 0.14                                                      | 0.00                                                     | 0.00                                                      | 9.05                                                            | 97.76                                                                                  | 210.65                                                     | 0.05                                                        | 82.00                                                      | 8.52   | 574.37                                          | 1171.17                          | 0.49                                |

The total embodied carbon values of the blends ranged from 379.92 to 574.78 kgCO<sub>2</sub>e/m<sup>3</sup> (Table 4). The lowest total embodied carbon value, 379.92 kgCO<sub>2</sub>e/m<sup>3</sup>, was obtained for the REF-0 mixture, followed by P-L at 388.97 kgCO<sub>2</sub>e/m<sup>3</sup>. The highest value, 574.78 kgCO<sub>2</sub>e/m<sup>3</sup>, was determined for the BD-H mixture, while both the RHA-H and HSA-H mixtures had a value of 574.37 kgCO<sub>2</sub>e/m<sup>3</sup>.

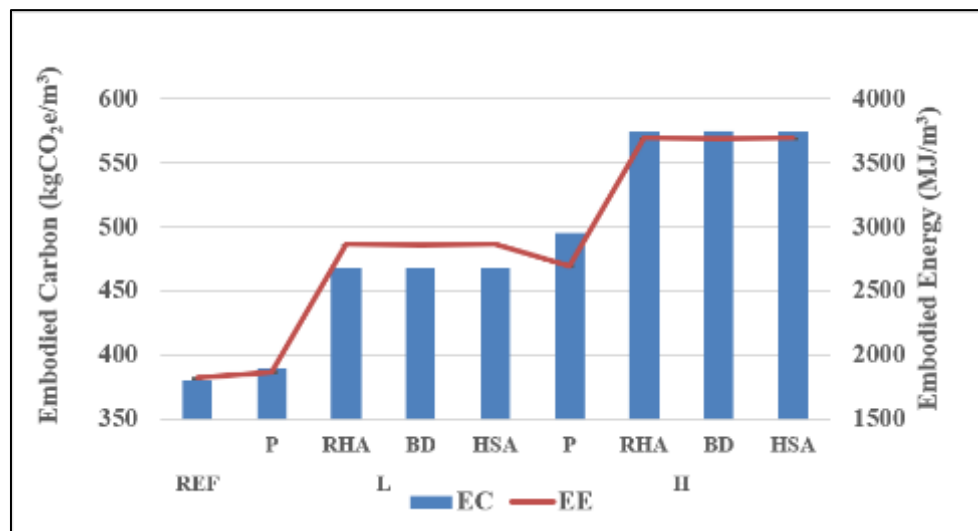
The total embodied carbon values for the RHA-L and HSA-L mixtures at low activator levels were determined to be 468.05 kgCO<sub>2</sub>e/m<sup>3</sup>, while the value for the BD-L mixture was 468.47 kgCO<sub>2</sub>e/m<sup>3</sup>. These values are approximately 20.3–20.4% higher than those of the P-L mixture. Therefore, although replacing a portion of the GGBS with waste-based materials reduced the slag-derived carbon load to a limited extent, it was insufficient to offset the carbon load from the additional NaOH solution used in the pre-activation process.

The total embodied carbon value of the P-H mixture at a high activator level was calculated to be 495.29 kgCO<sub>2</sub>e/m<sup>3</sup>. The RHA-H and HSA-H mixtures yielded values of 574.37 kgCO<sub>2</sub>e/m<sup>3</sup>, while the BD-H mixture yielded a value of 574.78 kgCO<sub>2</sub>e/m<sup>3</sup>. Accordingly, the total embodied carbon values of the high-activator mixtures containing waste were approximately 16.0% higher than that of the P-H mixture.

The transition from level L to level H increased the total embodied carbon value by approximately 27.3% in the P mixture, approximately 22.7% in the RHA and HSA mixtures, and approximately 22.7% in the BD mixture. Thus, increasing the activator level raised both the total embodied energy and the total embodied carbon load in all mixtures.

The embodied carbon values per mass, calculated based on dry unit weight, ranged from 0.25 to 0.50 kgCO<sub>2</sub>e/kg. The REF-0 mixture yielded the lowest value at 0.25 kgCO<sub>2</sub>e/kg. Both the P-L and HSA-L mixtures had values of approximately 0.34 kgCO<sub>2</sub>e/kg, while values of 0.40 and 0.42 kgCO<sub>2</sub>e/kg were obtained for RHA-L and BD-L, respectively.

The embodied carbon values per unit mass of the P-H and RHA-H mixtures at high activator levels were determined to be approximately 0.45 kgCO<sub>2</sub>e/kg. The HSA-H mixture yielded the highest value at 0.49 kgCO<sub>2</sub>e/kg, while the BD-H mixture yielded 0.50 kgCO<sub>2</sub>e/kg. Although the total embodied carbon value per unit volume of HSA-L is higher than that of P-L, the fact that its value per unit mass approaches that of P-L is due to HSA-L's higher dry unit weight.



**Figure 11** Embodied energy and embodied carbon of the mixtures

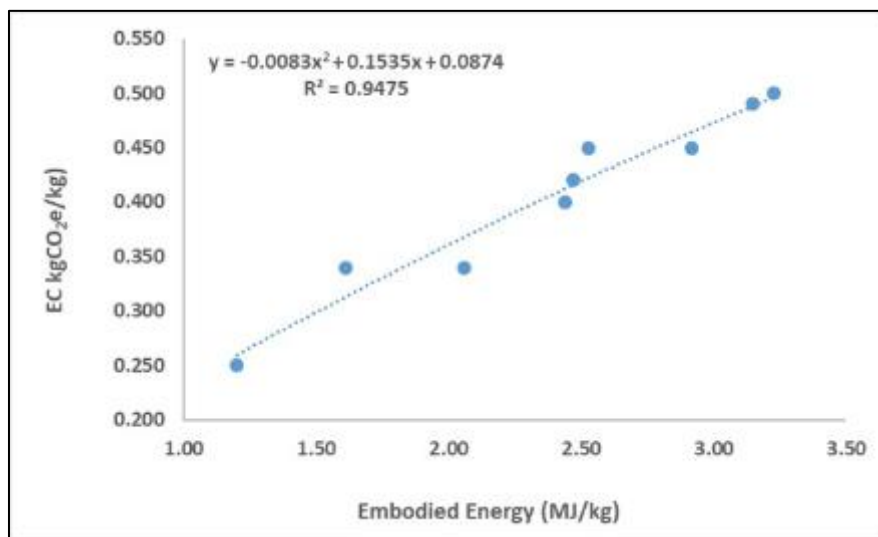
Figure 11 shows that the total embodied energy and embodied carbon values per unit volume generally increase together as a function of mixture composition and activator level. While the REF-0 and P-L mixtures fall within the lowest range for both environmental indicators, the environmental values of the L mixtures containing waste have increased significantly due to the additional NaOH solution used in the pre-activation process.

Although the total embodied carbon value of the P-H mixture was higher than that of the L mixtures containing waste, its total embodied energy value remained lower than that of those mixtures. This indicates that the embodied energy and embodied carbon coefficients of sodium silicate and NaOH do not contribute equally to these two environmental indicators. The H mixtures containing waste, on the other hand, are clustered in the highest region of the graph in terms of both EE and EC. The fact that the differences between RHA-H, BD-H, and HSA-H remain limited suggests that the total environmental load in these mixtures is determined more by the high total amount of NaOH used than by the type of substitute material.

When environmental outcomes are evaluated alongside mechanical performance, it is observed that different environmental-mechanical trade-offs emerge among the mixtures. Although the REF-0 and P-L mixtures have low environmental impacts, they are limited by their low compressive strength. In the P group, the transition from the L level to the H level increased the total embodied energy by approximately 44.4% and the total embodied carbon by approximately 27.3%, while the improvement in 28-day compressive strength remained at approximately 15.1%. Therefore, the use of additional activators in the P group did not provide a mechanical benefit proportional to the increase in environmental impact.

In the BD mixture, the transition from the L level to the H level increased the total embodied energy by approximately 29.1% and the total embodied carbon by approximately 22.7%, while the 28-day compressive strength increased by approximately 543.4%. Similarly, in the RHA mixture, the total embodied energy increased by approximately 29.0% and the total embodied carbon by approximately 22.7%, while the 28-day strength increased by approximately 289.9%. Thus, although the BD-H and RHA-H mixtures have high absolute environmental impacts, they provided a significant mechanical benefit from the high activator level.

In the HSA mixture, however, the transition from the L level to the H level increased the total embodied energy by approximately 29.0% and the total embodied carbon by approximately 22.7%, while the 28-day compressive strength decreased by approximately 37.8%. Therefore, the HSA-H mixture performed worse than HSA-L from both environmental and mechanical perspectives. Although HSA-L had higher absolute EE and EC values than REF-0 and P-L, it exhibited the highest compressive strength, the lowest water absorption and porosity, and the lowest environmental values per unit mass among the low-activator waste-containing mixtures. This combination indicates that HSA-L provided one of the most balanced physical, mechanical, and environmental performances among the mixtures examined.



**Figure 12** Second-order polynomial relationship between embodied energy and embodied carbon per unit mass

Figure 12 shows a strong, positive correlation between energy content per unit mass and carbon content per unit mass. The energy content per unit mass of the mixtures ranged from 1.20 to 3.23 MJ/kg, while the carbon content per unit mass ranged from 0.25 to 0.50 kgCO<sub>2</sub>e/kg. The second-order polynomial trend equation applied to the data is given in Equation (9), and the coefficient of determination,  $R^2$ , was calculated as 0.9475.

$$EC_m = -0.0083EE_m^2 + 0.1535EE_m + 0.0874 \quad (9)$$

The high correlation coefficient indicates that, across the nine mixtures examined, the values for embodied energy per unit mass and embodied carbon per unit mass vary largely in tandem. Within the data range examined, it is observed that as embodied energy increases, embodied carbon generally increases as well, although the rate of increase decreases somewhat as energy values rise. However, since this trend was derived from a limited number of experimental mixtures, it should not be interpreted as a general, nonlinear environmental relationship among materials.

While the REF-0 and P-L mixtures are located in the low embodied energy–low embodied carbon region of the graph, the waste-containing mixtures with low activator concentrations are clustered in the middle region, and those with high activator concentrations are generally clustered in the upper right region. This distribution supports the findings from Table 3, Table 4, and Figure 11, which indicate that an increase in the amount of activator – and particularly in the additional amount of NaOH used in pre-activation – raises both environmental indicators simultaneously. However, it should be noted that the embodied energy and embodied carbon values were calculated using the same mixture components and their corresponding environmental coefficients. Therefore, the strong correlation identified in Figure 12 should be interpreted not as an independent cause-and-effect relationship, but as the combined effect of the same mixture composition on the two environmental indicators. Furthermore, the second-order polynomial trend represents

only the nine mixtures examined and the current data range; it should not be used to estimate the environmental values of mixtures outside the experimental range or to determine optimal mixture ratios.

## 5. Conclusions

In this study, the effects of brick dust, rice husk ash, and hazelnut shell ash in the same pumice–slag-based alkali-activated foam concrete system were compared at two different activator levels. The results showed that the effect of the activator amount on the physical and mechanical properties was strongly dependent on the substitute material used. A high activator level reduced the water absorption rate and porosity in mixtures containing BD and RHA, and significantly improved compressive strength, particularly during the 7–28-day period. In contrast, in the system containing HSA, increasing the activator amount reduced the dry unit weight and compressive strength while increasing the water absorption rate and porosity. The HSA-L mixture provided the highest compressive strength along with the lowest water absorption and porosity values, yielding one of the most balanced results in terms of physical and mechanical properties among the mixtures studied.

The environmental assessment revealed that the use of waste alone does not result in lower embodied energy and embodied carbon. The environmental impact of the additional NaOH solution used for pre-activation in waste-containing mixtures outweighed the limited benefit gained from reducing the GGBS content, causing these mixtures to yield higher EE and EC values than P mixtures at the same activator level. Increasing the activator level raised the environmental impact in all mixtures; however, the engineering trade-off associated with this increase varied depending on the mixture type. In BD-H and RHA-H, the increase in EE and EC values was accompanied by a significant improvement in compressive strength, while in P-H, the mechanical gain remained limited, and in HSA-H, the increase in environmental impact was directly accompanied by a loss in mechanical performance.

Consequently, it is not appropriate to define a single activator level applicable to all types of waste in alkali-activated pumice–slag foam concretes. The amount of activator should be determined by taking into account the reactivity of the substitute material, the pore structure it creates, the strength development it provides, and the embodied energy and carbon load it generates. Although HSA-L is not the mixture with the lowest absolute environmental values, it stands out in terms of overall performance due to its high strength, improved pore characteristics, and relatively favorable environmental indicators per unit mass compared to low-activator mixtures containing waste. However, since some of the environmental coefficients used are based on proxy values, the EE and EC results should be evaluated in a comparative manner; it is recommended that future studies support the current findings with product-specific environmental data and microstructural analyses.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

The authors declare that they have no conflict of interest.

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