

Compressive Strength and Sustainability Assessment of Mortar Incorporating Rice Husk Biochar as a Sustainable Cement Replacement

Lobat Hosseinzadeh ^a, Morteza Jamshidi ^{a*} , Mehdi Dehestani ^b , Seyed Farhad Nabizadeh ^a

^a Department of Civil Engineering, Cha. C, Islamic Azad University, Chalus, Iran

^b Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran

ARTICLE INFO

Article history:

Received 07 July 2026

Revised 09 August 2026

Accepted 21 September 2026

Available online 01 July 2027

Keywords:

Rice husk

Supplementary cementitious materials

Cement mortar

Compressive strength

Strength development

Life cycle assessment (LCA)

Sustainability

ABSTRACT

The cement industry is a major contributor to global CO₂ emissions, highlighting the need for sustainable supplementary cementitious materials (SCMs) capable of reducing cement consumption while maintaining mechanical performance. This study investigated the effects of raw rice husk (SH), rice husk biochar (BSH), and calcined rice husk ash (CSH) as partial replacements for ordinary Portland cement. Mortar mixtures incorporating 3%, 5%, and 8% of each material were evaluated in terms of workability, compressive strength, normalized compressive strength, and strength development up to 28 days. In addition, a cradle-to-gate life cycle assessment (LCA) was performed to quantify greenhouse gas (GHG) emissions, cumulative energy demand (CED), and environmental impacts using the ReCiPe endpoint method. The results showed that the processing method of rice husk significantly influenced both mechanical and environmental performance. Among the investigated materials, CSH improved workability because of its filler effect and fine particle size. The mixture containing 3% CSH and BSH achieved the highest 28-day compressive strength (43.4 and 41.1 MPa, respectively), corresponding to 143.6% and 136.0% of the reference mixture's compressive strength (i.e., a 43.6% and 36.0% increase), respectively. Biochar enhanced long-term strength through internal curing, whereas SH exhibited slower early-age strength development but substantial later-age strength gain. The LCA results indicated that replacing 8% of cement with RH reduced CO₂ emissions, cumulative energy demand, and the overall ReCiPe endpoint impact by 7.7%, 6.7%, and 4.8%, respectively, compared with the control mixture, while CSH also provided considerable environmental benefits. Overall, SH-derived materials offer an effective strategy for producing low-carbon cementitious mortars. The 3% CSH mixture delivered the best mechanical performance, whereas the 8% SH mixture achieved the greatest environmental benefits, demonstrating the importance of balancing engineering performance and sustainability.

How to cite this article: Hosseinzadeh, L., Jamshidi, M., Dehestani, M., Nabizadeh, S. F. Compressive Strength and Sustainability Assessment of Mortar Incorporating Rice Husk Biochar as a Sustainable Cement Replacement. Civil Engineering and Applied Solutions. 2027; 3(3): 22–37. doi:10.22080/ceas.2026.32347.1122.

1. Introduction

Rice is one of the world's major agricultural products, with an annual production exceeding 750 million tons. Alongside this production, approximately 150 million tons of rice husk (SH) are generated as a by-product of rice processing [1-3]. In many rice-producing regions, including northern Iran, this residue is still predominantly managed through open-field burning or accumulation on agricultural lands. Such practices not only contribute to air pollution and particulate emissions but also remove a significant

* Corresponding author.

E-mail address: morteza_jamshidi@iau.ac.ir (M. Jamshidi).



<https://doi.org/10.22080/ceas.2026.32347.1122>

ISSN: 3092-7749/© 2027 The Author(s). Published by University of Mazandaran.

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<https://creativecommons.org/licenses/by/4.0/deed.en>)

economic opportunity from the production cycle [4]. In recent years, the concept of the bio-circular economy has gained increasing attention as a framework for recovering value from agricultural residues. Consequently, SH is no longer regarded as a worthless waste material but rather as a valuable feedstock capable of being transformed into a wide range of products for the energy, agricultural, and construction sectors [5, 6].

Among the industries utilizing agricultural residues, the construction sector represents one of the primary destinations for such by-products due to its extensive consumption of raw materials and substantial contribution to greenhouse gas emissions. Portland cement, the most widely used binder in mortar and concrete, remains the most consumed manufactured material worldwide because of its compatibility, low maintenance requirements, and abundant raw material availability. However, it is also responsible for approximately 7-8% of global anthropogenic carbon dioxide emissions [7, 8]. It has been reported that the production of one ton of Portland cement clinker releases approximately 0.8 tons of CO₂ into the atmosphere [9]. This environmental concern has driven researchers toward the development of supplementary cementitious materials (SCMs), which can partially replace cement while maintaining or even enhancing the mechanical performance and durability of the final product [10-12]. Owing to their abundance, renewability, and relatively low production cost compared with other cement replacement materials such as metakaolin or blast furnace slag, agricultural waste-derived products have emerged as attractive SCM candidates [13].

SH, in particular, has long been recognized as a promising source for the production of supplementary cementitious materials due to its naturally high silica content. However, the conversion of this raw agricultural residue into a cementitious material can be achieved through different thermochemical pathways, each yielding products with distinct physicochemical characteristics and performance mechanisms. The most common route is calcination (controlled combustion in the presence of oxygen), which produces calcined rice husk ash (CSH). The pozzolanic quality of CSH is highly dependent on the calcination temperature, as processing parameters such as temperature, duration, and atmospheric conditions directly influence the amount of amorphous silica, specific surface area, and particle morphology of the resulting ash [14]. Previous studies have demonstrated that combustion within a temperature range of approximately 500-700°C preserves silica predominantly in its amorphous form and results in the highest pozzolanic activity. In contrast, higher temperatures promote the gradual crystallization of silica (forming cristobalite), leading to a reduction in pozzolanic reactivity [15-17].

Conversely, pyrolysis conducted under oxygen-limited or oxygen-free conditions produces rice husk biochar (BSH) instead of ash. BSH is a carbon-rich, porous, and stable material that, in addition to its well-established applications in soil amendment and carbon sequestration, has recently attracted attention for use in cementitious composites [18, 19]. Unlike CSH, whose contribution is primarily pozzolanic, the role of biochar within the cement matrix is largely physicochemical. Its influence is exerted through mechanisms such as particle-filling effects, internal curing resulting from water absorption and gradual release, and serving as nucleation sites for hydration products, thereby affecting both the microstructure and mechanical properties of mortar [20, 21].

Numerous studies have independently investigated the mechanical performance of these two rice husk-derived products; however, the reported findings remain relatively scattered and, in some cases, contradictory due to differences in processing conditions, particle size, and replacement levels. For CSH, several studies have reported compressive strength increases exceeding 50% at replacement levels of 15-25%, attributed to the formation of additional C-S-H and C-A-S-H gels, microstructural densification, and improvement of the interfacial transition zone (ITZ) [22]. Similarly, for rice husk biochar, a range of results has been documented in the literature, varying from approximately 12-14% improvements in compressive strength at replacement levels of 5-10%, attributed to filler effects and reduced pore connectivity [18], to strength reductions in mixtures characterized by high porosity or low contents of reactive silicon and aluminum oxides [23]. This variability indicates that the selected thermochemical processing route for rice husk plays a decisive role in determining its effectiveness as a cement replacement material. In addition to its mechanical and environmental performance under ambient conditions, rice husk ash-modified concrete has also been shown to exhibit favorable behavior under thermal exposure, with water re-curing partially recovering strength losses following exposure to elevated temperatures of 300-700°C [24].

Although numerous investigations have focused on the mechanical and durability performance of rice husk-derived supplementary cementitious materials, structural performance alone is insufficient to determine their overall sustainability. For instance, recent studies have shown that rice husk ash-modified concrete exhibits favorable resistance to thermal degradation, with water re-curing partially recovering strength losses following exposure to elevated temperatures [24], and a complementary life cycle assessment of the same material further confirming its favorable environmental profile under such exposure conditions [25]. The thermochemical conversion routes required to produce rice husk ash and rice husk biochar differ considerably in terms of energy demand, process emissions, and resource consumption, which may significantly influence their environmental benefits despite comparable engineering performance. In recent years, life cycle assessment (LCA) has become one of the most widely accepted methodologies for quantifying the environmental impacts of construction materials throughout their life cycle, enabling comprehensive comparisons of alternative materials based on indicators such as global warming potential, cumulative energy demand, and damage to human health, ecosystems, and natural resources. Consequently, integrating mechanical performance with life cycle assessment provides a more reliable basis for identifying sustainable cement replacement strategies and supports decision-making toward low-carbon construction materials [26-29].

Despite the growing body of literature addressing SH or BSH individually [17, 19, 21], no study has yet simultaneously compared all three thermochemical processing routes of SH (SH, CSH, and BSH) within a unified experimental and environmental framework. The novelty of the present study lies in this three-way comparison combined with an integrated mechanical-environmental assessment: by evaluating compressive strength development at multiple curing ages alongside a cradle-to-gate LCA for each

processing route, this study identifies not only which material performs best mechanically, but which replacement level and processing route offers the most balanced trade-off between structural performance and environmental sustainability. This integrated approach, rather than either aspect alone, provides a more practical basis for material selection in low-carbon cementitious design. Therefore, this study aims to comparatively investigate the compressive strength development of mortar incorporating CSH and BSH as partial cement replacements at different curing ages. In addition, a cradle-to-gate life cycle assessment is conducted to quantify the environmental impacts associated with each processing pathway and to identify the more sustainable alternative considering both mechanical performance and environmental criteria.

2. Methodology

2.1. Materials

In the present study, Type II Portland cement produced by Mazandaran Cement Company was used as the primary binder. A recycled rice husk-derived material was introduced as a SCM in three different forms, namely SH, BSH, and CSH, for the production of low-carbon cement (Fig. 1). As shown in Fig. 1, the three forms of rice husk-derived material exhibit visibly distinct physical characteristics: raw rice husk retains its fibrous, light-tan appearance; the biochar exhibits a dark black, porous texture resulting from carbonization under oxygen-limited conditions; and the calcined ash presents a fine, light-gray powder consistent with the removal of carbonaceous material during high-temperature oxidation. The chemical compositions of the Portland cement, raw rice husk, rice husk biochar, and calcined rice husk ash used in this study are presented in Table 1. Chemical compositions were determined by X-ray fluorescence (XRF) spectroscopy, and loss-on-ignition (LOI) values were obtained by heating samples at 1100°C for 2 hours and measuring the resulting mass loss. The SH employed in this research were obtained from Tarom rice cultivated in the Sarbaz region of Gilan Province, representing one of the common rice varieties available in northern Iran. As shown in Table 1, the SiO₂ content increased progressively from SH (78.8%) to BSH (87.2%) and CSH (91.0%), reflecting the progressive removal of organic matter and volatile compounds during thermal treatment. The relatively high K₂O content observed in BSH (4.7%) compared with the other materials should be noted, as elevated alkali content can potentially influence the risk of alkali-silica reaction (ASR) when used at higher replacement levels. The low CaO content across all three SH-derived materials (0.6–1.8%), in contrast to Portland cement (63.2%), confirms their primarily pozzolanic (rather than hydraulic) nature, consistent with their role as reactive silica sources rather than independent binders. The CSH was subjected to thermal treatment at a temperature range of 500–550°C for one hour. This calcination temperature was selected to prevent incomplete combustion, eliminate residual organic matter, and obtain an amorphous silica-rich structure, since the presence of amorphous silica is the primary factor governing effective pozzolanic reactions at later curing ages [30]. Calcination temperatures below the optimum range may result in the retention of unburned carbon and consequently reduce pozzolanic activity, whereas excessively high temperatures can promote silica crystallization and diminish its reactivity. After calcination at 500–550°C for one hour, the resulting ash was ground and sieved to pass through a 75 µm (No. 200) sieve, consistent with the particle fineness applied to the biochar and comparable to that of Portland cement, to ensure comparable reactivity and particle-filling behavior among the three processing routes.

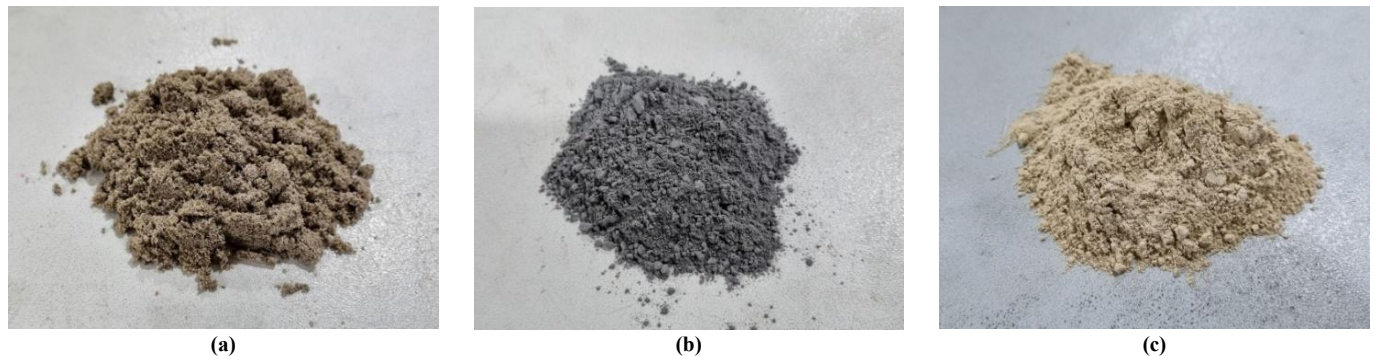


Fig. 1. Physical appearance of the three RH-derived materials: (a) SH; (b) BSH; and (c) CSH.

Table 1. Cementing materials' chemical compositions.

	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	SO ₃	TiO ₂	LOI
Cement	21.3	63.2	4.9	3.4	1.2	0.3	0.6	2.3	-	2.5
Raw rice husk (SH)	78.8	0.6	0.2	0.5	0.3	0.05	2.1	0.1	0.02	16.9
Rice husk biochar (BSH)	87.2	1.8	0.9	1.4	0.5	-	4.7	0.15	0.23	3.03
Calcined rice husk (CSH)	91.0	0.8	1.1	1.3	0.2	-	0.9	-	-	-

BSH was produced through a controlled pyrolysis process in a muffle furnace under oxygen-limited conditions at approximately 450–500°C for about 1–2 hours, with a heating rate of approximately 10°C/min. After pyrolysis, the biochar was ground and sieved to pass through a 75 µm (No. 200) sieve to achieve a fineness comparable to that of Portland cement. Owing to its porous structure, high specific surface area, and the presence of surface functional groups, this material can influence not only the filler effect but also the microstructure of the cement paste and the paste-aggregate ITZ. These SH-derived materials were utilized as partial cement replacements for the development of low-carbon cement and concrete. Their primary functions within the cementitious system include particle packing and filler effects, nucleation of hydration products, and, in the case of CSH, pozzolanic reactions with the calcium hydroxide released during the cement hydration process.

2.2. Mortar mix designs

The details of the reference sand-cement mortar mixture and the mortars incorporating SH in its raw, biochar, and calcined forms are presented in Table 2. In these mixtures, SH-derived materials were used as partial cement replacements at replacement levels of 3%, 5%, and 8% by weight of the cementitious binder. These replacement levels were selected to maintain adequate workability while enabling a systematic evaluation of the progressive effects of cement substitution on the mechanical performance and microstructural characteristics of the mortar. The selected dosage range also allowed the investigation of both the beneficial and potential adverse effects associated with increasing levels of SH-derived materials within the cementitious matrix. In all mix designs, the water-to-cementitious materials ratio was kept constant at 0.42, and the sand-to-cementitious materials ratio was fixed at 2.0. Maintaining these proportions ensures that the observed variations in mortar properties are primarily attributed to the presence and type of SH-derived material rather than changes in the fundamental mix design parameters. This approach enables a more accurate evaluation of the roles of filler effect, pozzolanic reaction, and microstructural changes induced by the SH. Keeping the sand content constant also helps control the influence of rheological variations in the cement paste and maintain consistency in experimental conditions. This is particularly important because fine rice husk particles, especially in calcined and biochar forms, can increase specific surface area and consequently affect the water demand of the mixture. The particle size distribution of the sand used in this study was determined in accordance with ASTM C136 [31] (sieve analysis), and the particle size distribution curve is presented in Fig. 2. The curve indicates a well-graded distribution of particles, which can lead to improved particle packing and a reduction in capillary porosity in mortar.

Table 2. Mix design of mortar samples.

Mix ID.	Cement	SH	BSH	CSH	Water	Sand	Density
	(g)						(kg/m ³)
C ₁₀₀	1000	-	-	-	420	2000	2481
C ₉₇ SH ₃	970	30	-	-	420	2000	2093
C ₉₅ SH ₅	950	50	-	-	420	2000	2180
C ₉₂ SH ₈	920	80	-	-	420	2000	2254
C ₉₇ BSH ₃	970	-	30	-	420	2000	2300
C ₉₅ BSH ₅	950	-	50	-	420	2000	2288
C ₉₂ BSH ₈	920	-	80	-	420	2000	2336
C ₉₇ CSH ₃	970	-	-	30	420	2000	2315
C ₉₅ CSH ₅	950	-	-	50	420	2000	2260
C ₉₂ CSH ₈	920	-	-	80	420	2000	2285

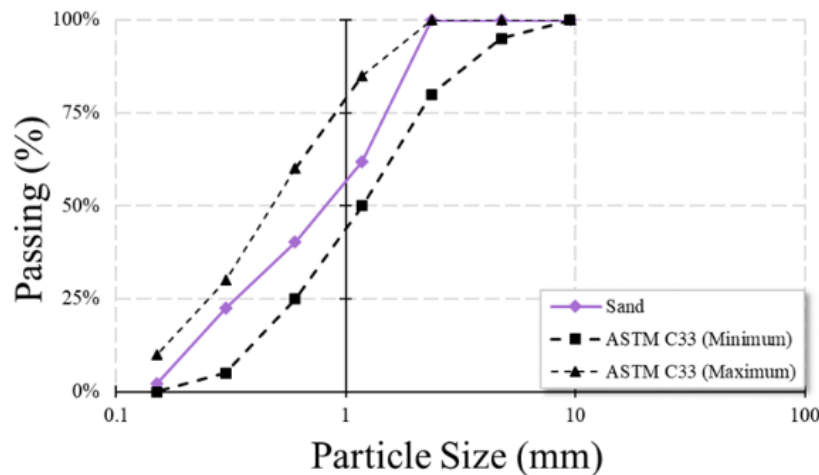


Fig. 2. Particle size distribution.

2.3. Preparation, casting, and curing of mortar specimens

Mortar mixing was performed in accordance with ASTM C305 [32]. To prepare the sand-cement mortar specimens according to Table 2, all materials were mixed using a 10-liter laboratory mixer available in the Concrete Technology Laboratory at Babol Noshirvani University of Technology. First, all cementitious materials, including cement and SH-derived material (raw, biochar, or calcined), were dry-mixed to achieve a homogeneous blend. Subsequently, the calculated amount of water was added to the mixer to form the cement paste. Then, the sand was introduced into the cement paste, and mixing was continued for one minute. When necessary, a superplasticizer was added within 20 to 30 seconds of mixing to achieve the desired workability. A polycarboxylate ether (PCE)-based superplasticizer was used, at dosages adjusted per mix (as % of binder mass) to achieve comparable workability. Superplasticizer was required only for SH mixtures (0.5%, 1.5%, and 2.25% at 3%, 5%, and 8% replacement, respectively), reflecting the higher water demand of untreated, fibrous SH. No superplasticizer was needed for BSH or CSH mixtures, indicating that thermal processing reduced water/admixture demand relative to SH. The workability of the fresh mortar mixtures was evaluated

using the Flow Table test in accordance with ASTM C230 [33]. According to ASTM C511 [34], curing of mortar specimens is a process during which moisture loss is prevented, and an appropriate temperature is maintained. In this study, 24 hours after casting, the specimens were demolded and immediately placed in a water tank maintained at laboratory ambient temperature to preserve surface moisture. The samples were then cured in this tank for 7, 14, and 28 days (Fig. 3). For each mix design, two cubic specimens with dimensions of $50 \times 50 \times 50$ mm were cast and tested at each curing age (a total of six specimens per mix design), and the average value is reported. Compressive strength tests were carried out in accordance with ASTM C109 [35], using an ELE compression testing machine with a capacity of 200 kN. Prior to testing, the bearing surfaces of each specimen were wiped clean to remove any loose material or surface irregularities, ensuring uniform load distribution during testing. Fig. 3a illustrates the casting of fresh mortar into oiled steel molds, and Fig. 3b illustrates the subsequent water curing of demolded specimens, carried out in accordance with the curing protocol described above.



Fig. 3. Casting and curing of mortar specimens.

A complete summary of the experimental specimens, including mix designations, replacement levels, specimen dimensions, and the number of specimens tested at each curing age, is provided in Table 3. In total, 60 cubic specimens ($50 \times 50 \times 50$ mm) were cast and tested for compressive strength across the ten mix designs and three curing ages, with two specimens tested per age and the reported values representing their average. In addition, one flow spread measurement was conducted for each mix design to assess fresh-state workability.

Table 3. Specimen details.

Mix ID	Cement (%)	SH (%)	BSH (%)	CSH (%)	Specimen type/dimensions	Test	Ages/repetitions
C ₁₀₀	100	–	–	–	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₇ SH ₃	97	3	–	–	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₅ SH ₅	95	5	–	–	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₂ SH ₈	92	8	–	–	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₇ BSH ₃	97	–	3	–	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₅ BSH ₅	95	–	5	–	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₂ BSH ₈	92	–	8	–	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₇ CSH ₃	97	–	–	3	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₅ CSH ₅	95	–	–	5	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)
C ₉₂ CSH ₈	92	–	–	8	Cube, $50 \times 50 \times 50$ mm	Compressive strength	7, 14, 28 d, 2 specimens/age (6 total)

2.4. Life cycle assessment (LCA)

To evaluate the environmental impacts of replacing cement with three SH-derived materials, namely SH, BSH, and CSH, an LCA was conducted in accordance with the framework specified in ISO 14040 [26] and ISO 14044 [36] standards. The primary objective of this analysis was to compare the greenhouse gas emissions associated with the production of the different mortar mixtures and to identify the most environmentally sustainable cement replacement while considering the corresponding mechanical performance. Since the cement industry is recognized as one of the largest contributors to global carbon dioxide emissions, reducing Portland cement consumption through the incorporation of agricultural by-products has considerable potential to mitigate the environmental impacts of cementitious materials.

In this study, a cradle-to-gate system boundary was adopted, encompassing raw material extraction, transportation, and mortar production processes [37]. The use phase and end-of-life stage were excluded from the assessment, consistent with the scope commonly adopted in material-oriented mortar LCA studies. The functional unit was defined as 1 m^3 of mortar, allowing environmental impacts to be expressed in terms of $\text{kg CO}_2\text{-eq/m}^3$ and other environmental indicators [38]. The environmental assessment was carried out using SimaPro software, while the life cycle inventory (LCI) data were primarily obtained from the Ecoinvent database using global and regional datasets (GLO/RoW) [39]. Transportation impacts were estimated using the "market for" datasets available in Ecoinvent, which incorporate representative transportation distances and average vehicle emission factors based on global conditions.

The life cycle impact assessment (LCIA) was performed using the Greenhouse Gas (GHG) Protocol to quantify carbon dioxide emissions and the 100-year Global Warming Potential (GWP100). In addition, the ReCiPe impact assessment method was employed to evaluate aggregated endpoint indicators related to human health, ecosystem quality, and resource depletion [40, 41]. Furthermore, the cumulative energy demand (CED) associated with the production of each mortar mixture was quantified and reported.

Within the LCA model, SH was considered an agricultural residue. Following the cut-off allocation approach, no environmental burdens associated with rice cultivation, harvesting, or primary production were assigned to SH, since it is regarded as a by-product rather than the primary product of the agricultural system. In contrast, BSH was modeled as a product generated through the pyrolysis process. This process involves the thermochemical conversion of rice husk under oxygen-limited conditions and requires both electrical and thermal energy inputs, which were included in the life cycle inventory. Similarly, CSH was modeled by incorporating the calcination process into the production system. The thermal energy required to heat the SH and convert it into amorphous silica-rich ash was included in the inventory to accurately represent the environmental burdens associated with CSH production. For transparency, the main LCI assumptions are summarized as follows: functional unit, 1 m³ of mortar; system boundary, cradle-to-gate (raw material extraction, transportation, and mortar production); software, SimaPro; background database, Ecoinvent v3.4; impact assessment methods, the GHG Protocol (GWP100) and ReCiPe Endpoint (H/A), covering Human Health, Ecosystems, and Resources categories, alongside cumulative energy demand (CED); and allocation approach, a zero-burden (cut-off) allocation was applied to SH, consistent with its status as an agricultural residue.

3. Results

3.1. Flow table

The workability of the fresh mortar mixtures was evaluated using the Flow Table test in accordance with ASTM C230 [33], using a truncated cone mold (100 mm base diameter, 70 mm top diameter, 50 mm height) subjected to 25 drops within 15 seconds. The obtained flow spread values, expressed as a percentage increase in average base diameter, are presented in Fig. 4. The reference specimen (C₁₀₀) exhibited a flow spread of approximately 170 mm. With the incorporation of SH, the workability of the mortar was found to be dependent on the replacement level. At a replacement ratio of 3%, no significant change was observed compared to the reference mixture. However, increasing the replacement level to 5% resulted in an increase in flow spread to approximately 200 mm, indicating improved fluidity of the mixture. Nevertheless, at an 8% replacement level, the flow spread decreased to about 160 mm, becoming even lower than that of the reference specimen. This behavior can be attributed to the higher specific surface area and greater water absorption capacity of SH particles at elevated replacement levels, which reduce the amount of free water available in the mixture and consequently decrease workability. A similar trend was observed in mortars containing BSH. The incorporation of 3% biochar increased the flow spread to approximately 195 mm. However, at replacement levels of 5% and 8%, the flow spread stabilized at around 180 mm. The porous structure of biochar promotes the absorption of a portion of the mixing water; nevertheless, its surface roughness and particle morphology may improve particle distribution and fluidity at low replacement levels. At higher contents, the water absorption effect becomes dominant, limiting any further enhancement in workability. The highest flow spread values were obtained in mixtures containing CSH. Replacing 3% of cement with CSH increased the flow spread to approximately 235 mm, while replacement levels of 5% and 8% further increased it to about 250 mm. This remarkable improvement can be attributed to the fine particle size of the ash, its favorable particle size distribution, and the filler effect. The ultrafine particles of calcined rice husk ash fill the voids between cement grains, thereby reducing internal friction within the mixture and facilitating the movement of the cement paste. Furthermore, the relatively more uniform particle shape of CSH compared with SH and BSH plays a significant role in enhancing mortar fluidity.

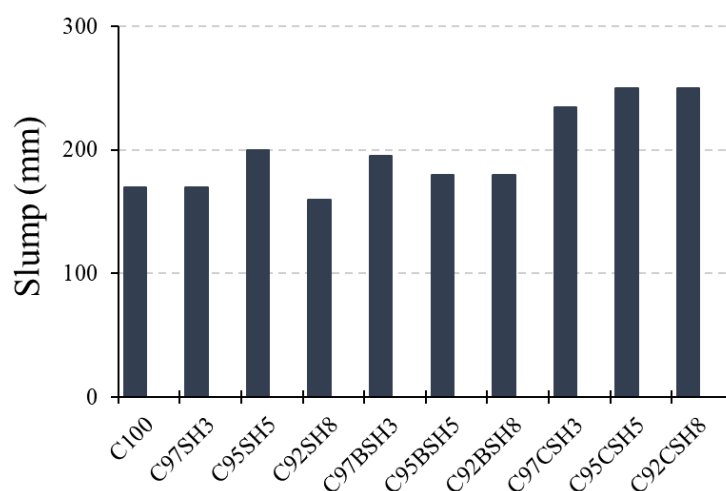


Fig. 4. Flow table test results.

Overall, in terms of workability performance, the materials can be ranked as follows: CSH > BSH > SH. Specifically, CSH increased the flow spread by approximately 38–47% compared to the control specimen, whereas BSH resulted in a modest increase of about 6–15%. In contrast, SH exhibited satisfactory performance only at the 5% replacement level, while an 8% replacement led to a reduction in workability. The Flow Table test results demonstrated that the processing method of SH has a decisive influence on mortar workability. While the use of SH and BSH provided only limited improvements in mixture fluidity, CSH significantly

enhanced the flow spread. This behavior is primarily attributed to the filler effect, improved particle size distribution, and reduced internal friction within the mixture. It was also observed that increasing the replacement level of SH beyond the optimum value reduced mortar workability due to its higher water absorption capacity and larger specific surface area. Overall, from the perspective of fresh-state performance, the incorporation of 5-8% CSH provided the most favorable workability among all investigated mixtures.

3.2. Compressive strength

Table 4 presents the mean and standard deviation (SD) of compressive strength for each mix design at 7, 14, and 28 days of curing, based on two specimens per condition. Fig. 5 presents the compressive strength development of mortar specimens incorporating SH, BSH, and CSH at curing ages of 7, 14, and 28 days. As expected, all mixtures exhibited a continuous increase in compressive strength with curing time due to the progressive hydration of cement and the formation of additional cementitious products. However, the rate of strength development and the ultimate compressive strength were significantly influenced by both the form of SH utilized and its replacement level. At the age of 7 days, most modified mixtures exhibited lower compressive strengths than the control specimen, indicating that the partial replacement of cement initially reduced the amount of readily available hydraulic binder. This effect was particularly pronounced for mixtures containing SH, where the incorporation of untreated lignocellulosic particles delayed strength development due to their limited pozzolanic reactivity and relatively high-water absorption capacity. Nevertheless, mixtures containing CSH showed comparatively higher early-age strengths, suggesting that the amorphous silica generated during the calcination process contributed to early pozzolanic reactions and enhanced particle packing. A substantial increase in compressive strength was observed between 7 and 14 days for all mixtures. This improvement can be attributed to the continuation of cement hydration as well as the gradual activation of supplementary cementitious reactions.

Table 4. Standard deviations of mortar compressive strength results.

Mix ID.	Compressive strength (MPa)		SD	AVG	Compressive strength (MPa)		SD	AVG	Compressive strength (MPa)		SD	AVG
	7-days	7-days			14-days	14-days			28-days	28-days		
C ₁₀₀	23.7	22.9	0.49	23.3	28.5	27.5	0.72	28.0	32.6	27.9	3.36	30.2
C ₉₇ SH ₃	8.4	9.0	0.42	8.7	16.8	17.6	0.58	17.2	23.4	24.5	0.74	23.9
C ₉₅ SH ₅	14.3	15.9	1.16	15.1	28.7	28.4	0.26	28.5	35.8	34.6	0.84	35.2
C ₉₂ SH ₈	14.8	16.2	0.94	15.5	35.5	34.0	1.06	34.8	40.7	39.9	0.58	40.3
C ₉₇ BSH ₃	13.5	13.9	0.28	13.7	30.2	32.1	1.32	31.1	41.7	40.5	0.84	41.1
C ₉₅ BSH ₅	15.4	13.1	1.62	14.3	29.0	30.1	0.78	29.5	35.7	37.2	1.02	37.9
C ₉₂ BSH ₈	14.1	13.2	0.66	13.7	28.8	27.9	0.66	28.4	36.7	35.6	0.78	36.2
C ₉₇ CSH ₃	20.4	17.5	2.04	18.9	32.0	30.8	0.88	31.4	44.1	42.8	0.88	43.4
C ₉₅ CSH ₅	13.8	13.5	0.27	13.7	25.9	25.2	0.44	25.5	36.8	33.4	2.37	35.1
C ₉₂ CSH ₈	11.9	12.6	0.44	12.3	19.0	20.0	0.71	19.5	30.9	28.1	1.93	29.6

The strength gain was particularly evident in mixtures containing higher proportions of SH and BSH, indicating that the internal curing effect provided by the porous structure of these materials may have facilitated further hydration. In addition, the fine particles generated during the biochar production process likely acted as micro-fillers, reducing pore connectivity and contributing to matrix densification. At 28 days, distinct performance trends emerged among the investigated materials. The mixture containing 3% calcined rice husk ash (C₉₇CSH₃) achieved the highest compressive strength among all specimens, reaching approximately 43.4 MPa. This represents a significant improvement compared with the control mixture and highlights the effectiveness of CSH as a supplementary cementitious material. The superior performance of this mixture is likely attributable to the combined effects of pozzolanic activity, filler action, and microstructural refinement, consistent with mechanisms widely reported for similar supplementary cementitious materials [12, 42]. It should be noted that the mechanistic explanations discussed throughout this section, including internal curing, secondary C-S-H formation, ITZ refinement, pore refinement, and crack-bridging effects, are proposed based on established mechanisms reported in the literature for comparable materials, and are not directly verified through microstructural characterization (e.g., SEM, XRD, or mercury intrusion porosimetry) in the present study; they should therefore be regarded as plausible interpretations consistent with the observed strength trends rather than directly confirmed mechanisms. The highly reactive amorphous silica present in the ash is expected to react with calcium hydroxide released during cement hydration, potentially producing additional calcium silicate hydrate (C-S-H) gel and enhancing matrix compactness.

The mixtures containing BSH also demonstrated notable improvements in compressive strength, particularly at the 3% replacement level. The best performance among the tested biochar levels, observed for C₉₇BSH₃, is consistent with the hypothesis that a limited amount of biochar can improve hydration efficiency through internal curing and moisture retention mechanisms, although this was not directly verified in the present study. However, increasing the biochar content beyond the optimum level resulted in a gradual reduction in strength. This behavior is likely associated with the porous nature of biochar, which may increase the overall void content and reduce the effective binder concentration when used at higher dosages. A different trend was observed for SH mixtures. Although the 3% replacement level resulted in relatively low compressive strength, increasing the replacement ratio led to a substantial improvement in later-age (up to 28 days) performance, with the 8% replacement mixture achieving one of the highest strengths among the tested specimens. This behavior may be associated with the delayed contribution of finely dispersed silica and a possible gradual improvement of the ITZ over time, although this was not directly examined. It is also possible that the

fibrous morphology of SH particles contributed to crack-bridging effects and stress redistribution within the hardened matrix; however, this proposed mechanism was not directly verified in this study. Overall, the results demonstrate that the processing method of SH plays a decisive role in determining the mechanical performance of cementitious composites. Among the investigated materials, CSH exhibited the highest efficiency in enhancing compressive strength due to its strong pozzolanic reactivity, while biochar provided beneficial internal curing effects at low replacement levels. The findings indicate that optimizing both the treatment method and replacement ratio of SH-derived materials is essential for maximizing the mechanical performance of sustainable cement-based composites.

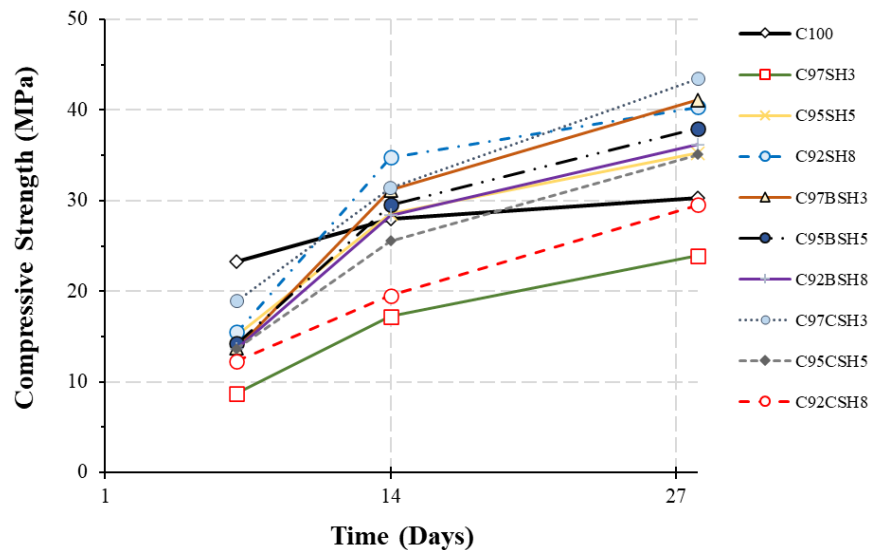


Fig. 5. Compressive strength of mortar samples.

Fig. 6 illustrates the normalized compressive strength of mortar specimens containing SH, BSH, and CSH relative to the control mixture at different curing ages. The normalization process enables a clearer comparison of the effectiveness of each replacement strategy independent of the absolute strength values. At the age of 7 days, all modified mixtures exhibited normalized strengths below 100%, indicating that the partial replacement of cement adversely affected early-age strength development. This reduction can primarily be attributed to the dilution effect caused by replacing a portion of the hydraulic binder with materials possessing lower initial reactivity. The most pronounced reduction was observed in mixture C₉₇SH₃, which retained only 37.4% of the compressive strength of the control specimen. Similarly, mixtures containing BSH and CSH exhibited normalized strengths ranging from approximately 52.8% to 81.3%. These results suggest that the beneficial effects associated with pozzolanic activity, micro-filler action, and internal curing had not yet fully developed during the first week of hydration. A markedly different trend emerged after 14 days of curing. Several mixtures surpassed the performance of the reference specimen, indicating the progressive activation of secondary strengthening mechanisms. The normalized strength of C₉₂SH₈ increased to 124.2%, while C₉₇BSH₃ and C₉₇CSH₃ achieved values of 111.2% and 112.1%, respectively. This substantial improvement reflects the continued hydration of cement and the increasing contribution of SH-derived materials to microstructural refinement. In particular, the porous structure of biochar may have promoted internal curing by gradually releasing absorbed water, thereby sustaining hydration reactions and reducing self-desiccation effects. Simultaneously, the fine particles present in CSH likely provided additional nucleation sites for hydration products, accelerating the formation of a denser cementitious matrix.

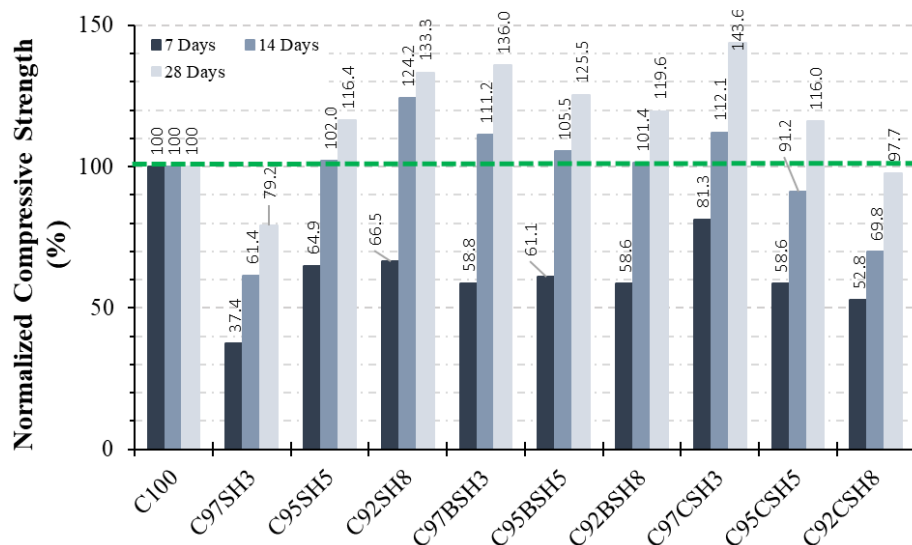


Fig. 6. Normalized compressive strength of mortar samples.

At 28 days, the superiority of selected mixtures became even more evident. The highest normalized compressive strength was recorded for C₉₇CSH₃, reaching 143.6% of the reference specimen's strength (i.e., a 43.6% increase). This remarkable enhancement

is consistent with a high pozzolanic efficiency of CSH when incorporated at moderate replacement levels. The reactive amorphous silica generated during calcination is expected to react with calcium hydroxide liberated from cement hydration, potentially producing additional secondary calcium silicate hydrate (C-S-H) gel and contributing to pore refinement, which would be consistent with the formation of a denser and mechanically stronger matrix; however, this mechanism was not directly verified through microstructural analysis in this study. Mixtures containing BSH also demonstrated favorable later-age performance (within the 28-day testing period). $C_{97}BSH_3$ and $C_{95}BSH_5$ achieved normalized strengths of 136.0% and 125.5%, respectively, while $C_{92}BSH_8$ maintained a value of 119.6%. These findings indicate that BSH can effectively enhance later-age strength when used within an appropriate dosage range. The observed improvements may be attributable to a combination of internal curing, enhanced hydration efficiency, and filler effects arising from the fine carbonaceous particles, consistent with mechanisms reported for similar carbon-based additives, although these were not directly measured in this study. Nevertheless, the gradual decline in performance with increasing replacement level suggests that excessive BSH contents introduce additional porosity and reduce the effective cement content, partially offsetting these beneficial mechanisms. The behavior of SH mixtures was particularly noteworthy. Although the incorporation of 3% SH resulted in substantial strength reductions throughout the curing period, increasing the replacement ratio to 5% and especially 8% produced significant later-age benefits. The normalized strength of $C_{92}SH_8$ reached 133.3% after 28 days, representing one of the highest values among all investigated mixtures. This result suggests that the influence of SH extends beyond simple cement replacement and may involve gradual microstructural enhancement, improved particle packing, and delayed pozzolanic interactions associated with the silica-rich composition of rice husk. In contrast, increasing the dosage of CSH beyond the optimum level resulted in a reduction in normalized strength. While $C_{97}CSH_3$ exhibited the highest performance, the normalized strength decreased to 116.0% and 97.7% for $C_{95}CSH_5$ and $C_{92}CSH_8$, respectively. This behavior indicates that the beneficial pozzolanic and filler effects become insufficient to compensate for the reduction in cement content at higher replacement ratios. Such a trend is characteristic of supplementary cementitious materials, where an optimum replacement level exists beyond which the dilution effect becomes dominant. Overall, the normalized strength analysis demonstrates that both the processing method and replacement level govern the mechanical efficiency of SH-derived materials. Among all investigated mixtures, the incorporation of 3% CSH produced the greatest enhancement in compressive strength, followed by 3% BSH and 8% SH. These findings confirm that suitable treatment of SH can transform an agricultural waste into an effective supplementary cementitious material capable of significantly improving the later-age mechanical performance of sustainable cement-based composites. Fig. 7 illustrates the typical failure pattern of mortar cube specimens under compressive loading. All specimens exhibited a typical shear-cone failure mode characteristic of cube compression tests, with diagonal cracking initiating near the loaded faces. No notable differences in failure mode were observed among the control and modified mixtures, suggesting that the incorporation of SH-derived materials did not alter the fundamental fracture mechanism, despite differences in load-carrying capacity.



Fig. 7. Failure of mortar samples under compressive test.

3.3. Compressive strength growth

Fig. 8 presents the contribution of different curing intervals (0-7, 7-14, and 14-28 days) to the overall 28-day compressive strength development of the mortar specimens. As expected, the reference mixture (C_{100}) exhibited rapid early-age strength development, with approximately 75.8% of its total 28-day strength gain achieved within the first seven days. The contribution of the subsequent curing intervals decreased considerably, accounting for only 16.7% and 7.5% during the 7-14 and 14-28 days periods, respectively. This behavior is characteristic of ordinary Portland cement, where the rapid hydration of clinker phases, particularly C_3S , governs early strength development. The incorporation of SH-derived materials significantly altered the kinetics of compressive strength development by shifting a larger proportion of strength gain from early ages to later curing periods.

Mortars containing SH exhibited a pronounced reduction in the contribution of the first seven days, while the proportions of strength development during the 7-14 and 14-28 days intervals increased markedly. This delayed strength development can primarily be attributed to the dilution effect caused by cement replacement and the limited early reactivity of untreated SH. Furthermore, the presence of lignocellulosic constituents in the SH may retard cement hydration by absorbing mixing water and interfering with the formation of early hydration products. A similar trend was observed for biochar-containing mixtures, although the redistribution of strength gain was more concentrated within the intermediate curing period. In particular, the 3% BSH mixture ($C_{97}BSH_3$) exhibited the lowest contribution from the first seven days (19.7%) and the highest contribution during the 7-14 days interval (56%). This behavior is associated with the porous microstructure and high specific surface area of BSH, which initially absorbs part of the mixing water, thereby slowing early hydration, before the gradual release of this stored water promotes internal curing during the intermediate stage, consistent with the mechanism discussed in Section 3.2.

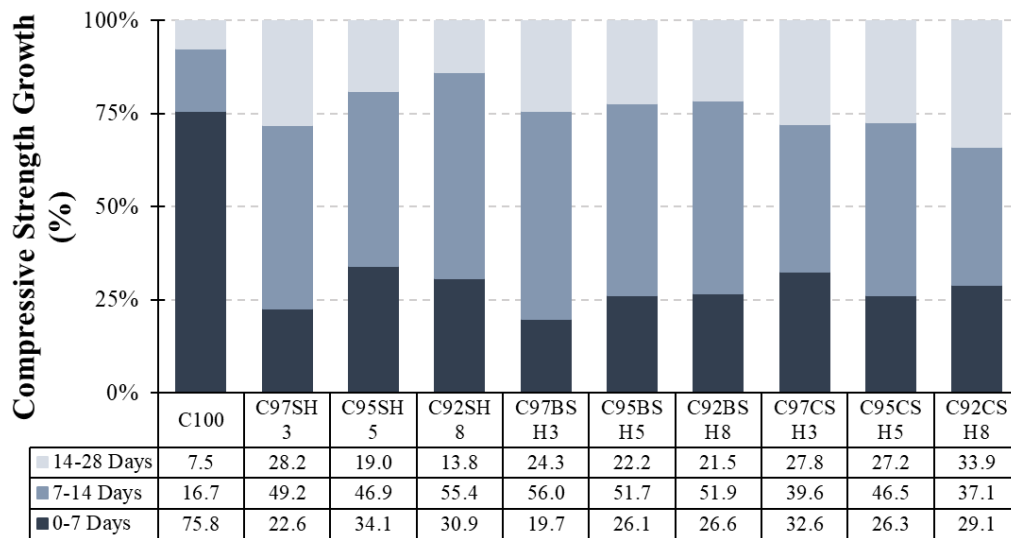


Fig. 8. Compressive strength growth of mortar samples.

Mortars incorporating CSH also demonstrated lower early-age strength contributions than the reference mixture; however, their strength development was more evenly distributed throughout the curing period. Notably, the contribution of the 14-28 days interval increased substantially, reaching 33.9% in the mixture containing 8% CSH (C₉₂CSH₈). This is consistent with the progressive pozzolanic reaction mechanism discussed in Section 3.2 for CSH. Overall, the results indicate that replacing cement with SH-derived materials modifies the mechanism of strength development rather than simply reducing or increasing compressive strength. While the reference mortar derives most of its strength during the first week, the modified mortars continue developing strength during later curing ages through a combination of ongoing cement hydration, internal curing effects (in the case of BSH), and secondary pozzolanic reactions (particularly in CSH mixtures). These findings suggest that evaluating the performance of SH-modified mortars solely based on early-age compressive strength may underestimate their strength development within the tested 28-day period; testing beyond 28 days would be required to substantiate any longer-term trajectory.

3.4. Environmental impact assessment results

An LCA was conducted to evaluate the environmental performance of mortar mixtures incorporating SH, BSH, and CSH at cement replacement levels of 3%, 5%, and 8%, using the reference mixture. The assessment considered GHG emissions, ReCiPe endpoint impact categories, and CED. These environmental analyses complement the mechanical performance results and highlight the sustainability potential of SH-derived supplementary cementitious materials.

The carbon footprint and GG emissions of the different mortar mixtures per 1 m³ are presented in Fig. 9. The total GHG emissions, expressed as kg CO₂-equivalent, decreased with increasing replacement levels for both the SH and CSH mixtures, demonstrating the clear environmental benefits of partial cement substitution. The reference mixture exhibited the highest total emissions, reaching approximately 667.27 kg CO₂-eq/m³. In contrast, the 8% SH mixture (C₉₂SH₈) produced the lowest emissions, approximately 617 kg CO₂-eq/m³, followed by the 8% CSH mixture (C₉₂CSH₈) with approximately 623 kg CO₂-eq/m³. Mixtures containing BSH exhibited comparatively higher total GHG emissions, primarily because of the additional CO₂ emissions associated with the pyrolysis process and the carbon-rich nature of biochar production. These findings confirm that low-to-moderate cement replacement levels, particularly with CSH and SH, can effectively reduce the carbon footprint while maintaining or improving mechanical performance, thereby supporting circular economy principles in sustainable construction [43].

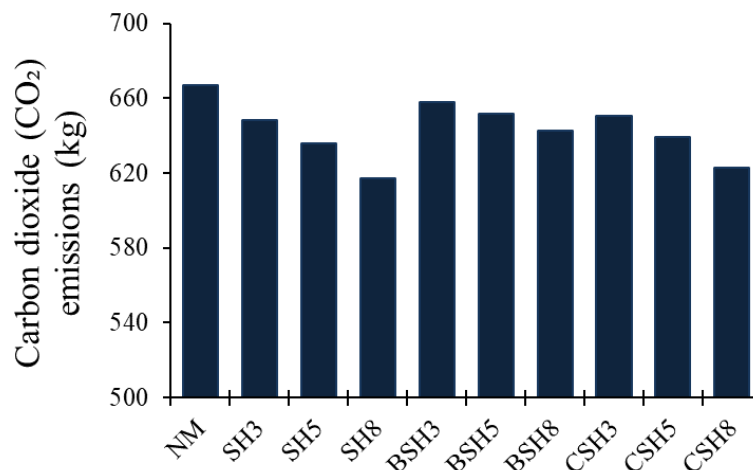


Fig. 9. Greenhouse gas (GHG)-based carbon dioxide emission results.

Similar trends were observed using the ReCiPe endpoint impact assessment method (Fig. 10), which aggregates environmental impacts into the three endpoint categories of Human Health, Ecosystems, and Resources. The control mixture exhibited the highest

overall environmental impact, with a total score of 6.22 points, mainly attributable to impacts on human health. All mixtures incorporating rice husk-derived materials demonstrated reductions in total endpoint scores, with the greatest improvements observed for the 8% SH and 8% CSH mixtures. Biochar-containing mixtures showed slightly higher overall endpoint scores because of increased ecosystem and resource impacts associated with the pyrolysis process. Nevertheless, these mixtures still offer significant environmental advantages through long-term carbon sequestration. Ecosystem damage decreased slightly in mixtures containing SH and CSH, while resource depletion followed a trend similar to that of GHG emissions owing to the reduced consumption of clinker and Portland cement. These findings are consistent with previous LCA studies on agricultural waste-derived SCMs, which have reported reductions in human toxicity, fossil resource depletion, and overall environmental burdens through partial cement replacement. Overall, the analysis demonstrates that SH-derived materials not only reduce direct GHG emissions but also provide broader environmental benefits across multiple endpoint categories [44].

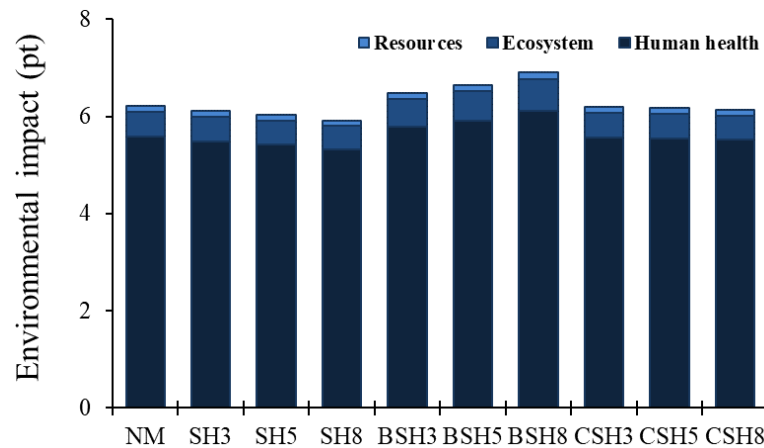


Fig. 10. Environmental endpoint impact categories of the investigated mixtures based on the ReCiPe.

The CED of the investigated mixtures is presented in Fig. 11. The lowest total fossil energy demand was obtained for mixtures containing higher replacement levels of SH and CSH, with $C_{92}SH_8$ and $C_{92}CSH_8$ requiring approximately 2795 MJ/m³ and 2864 MJ/m³, respectively, compared with 2996 MJ/m³ for the control mixture. This reduction is primarily attributed to the lower energy requirement associated with clinker production when cement is partially replaced by SH and CSH. In contrast, the BSH mixtures exhibited higher cumulative energy demands, reaching 3056 MJ/m³ for $C_{92}BSH_8$, mainly because of the non-renewable energy and biomass energy consumed during the pyrolysis process. Overall, the CED results further demonstrate the feasibility of utilizing SH-derived SCMs to reduce the embodied energy of cementitious mortars, with CSH and SH showing the greatest potential for sustainable construction applications [45].

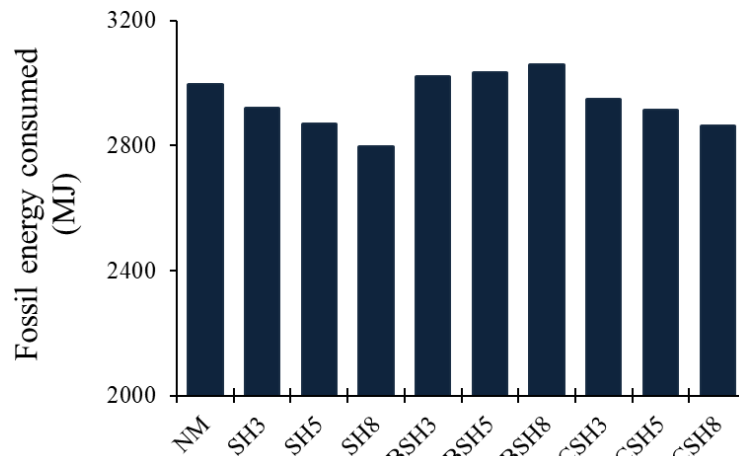


Fig. 11. Cumulative energy demand (CED) results of the investigated mixtures.

Overall, the LCA results indicate that replacing 8% of Portland cement with SH provided the greatest environmental benefits among all investigated mixtures. Compared with the reference mixture, $C_{92}SH_8$ reduced CO₂ emissions by 7.7%, the overall ReCiPe endpoint impact by 4.8%, and the cumulative energy demand by 6.7%. Likewise, the $C_{92}CSH_8$ mixture achieved reductions of 6.8%, 1.3%, and 4.4%, respectively. Although the $C_{92}BSH_8$ mixture reduced GHG emissions relative to the reference, its overall environmental performance was less favorable because of the additional energy consumption associated with the pyrolysis process.

A sensitivity analysis was performed on four key LCA assumptions: (I) the allocation approach applied to SH, (II) the pyrolysis energy input for BSH production, (III) the calcination energy input for ash production, and (IV) transport distances. The relative ranking of mixtures ($SH_8 > CSH_8 > BSH_8$, in order of decreasing environmental benefit) remained robust across all tested scenarios, although absolute GHG emissions and energy demand values were most sensitive to the pyrolysis and calcination energy inputs. The zero-allocation assumption for SH had a negligible effect (< 2%) on the overall results, since the primary environmental benefit derives from cement replacement rather than from the allocation method itself, while transport distance variations produced a moderate effect (3–5%). These findings support the robustness of the comparative conclusions drawn in this study, while absolute

values remain dependent on the underlying model assumptions. It should also be noted that background LCA data were sourced from global and rest-of-world (GLO/RoW) Ecoinvent datasets, including default "market for" transport distances based on global trade patterns; while Ecoinvent v3.4 provides robust and widely accepted background data, these datasets represent global average conditions rather than Iran-specific conditions, and a fully regionalized assessment would require site-specific inventory data. Finally, although the mechanical testing in this study did not extend beyond 28 days, biochar-amended mixtures are expected to provide an additional, longer-term environmental benefit through carbon sequestration within the biochar's stable carbon structure, independent of its mechanical performance.

3.5. Comparison with previous studies

To further evaluate the effectiveness of the proposed SH-derived supplementary cementitious materials, the 28-day compressive strength obtained in the present study was compared with representative results reported in previous investigations (Table 5). The comparison indicates that the mortar incorporating 3% CSH ($C_{97}CSH_3$) achieved the highest compressive strength (43.4 MPa) among all mixtures evaluated in the present work, followed closely by the 3% BSH mixture ($C_{97}BSH_3$) with a compressive strength of 41.1 MPa. Both mixtures exhibited substantial improvements over the control mortar (30.3 MPa), corresponding to strength increases of approximately 43.6% and 35.6%, respectively. Compared with previous studies employing agricultural or industrial waste materials as SCM, the proposed mixtures demonstrated competitive and, in several cases, superior mechanical performance.

Table 5. Comparison of 28-day compressive strength with previous studies.

References	Composition of powder materials	Compressive strength (MPa)
Current Study	100OPC	30.3
	97OPC + 3BSH	41.1
	97OPC + 3CSH	43.4
Alamian et al. [42]	100OPC	32.4
	65OPC + 20RC + 15GG	29.3
	65OPC + 25RC + 10GG	28.0
Ramezaniapour et al. [46]	100OPC	49.3
	70OPC + 30CC1	47.3
	70OPC + 20CC1 + 10LS	44.9
	70OPC + 30CC2	44.6
	70OPC + 20CC2 + 10LS	38.4
Dhandapani and Santhanam [47]	100OPC	62.1
	70OPC + 30FA	46.6
	55OPC + 30CC + 15LS	43.0
Mishra et al. [48]	100OPC	38.8
	55OPC + 30CC + 15LS	36.2

Note: OPC: ordinary Portland cement; BSH: rice husk biochar; CSH: calcined rice husk ash; RC: recycled calcined clay; GG: ground granulated blast furnace slag; CC1/CC2: calcined clay (type 1/type 2); LS: limestone; FA: fly ash. Subscripts denote replacement percentage by mass of binder.

Alamian et al. [42] reported compressive strengths ranging from 28.0 to 32.4 MPa for mortars incorporating recycled calcined clay and ground granulated blast furnace slag, indicating that relatively high replacement levels (30%) resulted in a noticeable reduction in strength due to the dilution effect. Similarly, the mortars developed by Mishra et al. [48] achieved a maximum compressive strength of 38.8 MPa, which remained lower than that obtained for both optimized mixtures in the present study. The results reported by Ramezaniapour et al. [46] and Dhandapani and Santhanam [47] reached higher absolute compressive strengths, with maximum values of 49.3 MPa and 62.1 MPa, respectively. However, these studies were conducted using different binder systems, replacement materials, mixture proportions, and water-to-binder ratios, making direct numerical comparisons inappropriate. More importantly, increasing the replacement ratio in those studies generally resulted in a gradual reduction in compressive strength, whereas the present study demonstrated that carefully optimized low replacement levels (3%) can not only compensate for the reduction associated with cement replacement but also produce a significant improvement in mechanical performance. The superior performance of the optimized mixtures can be attributed to the synergistic interaction of several mechanisms. In the case of CSH, the high content of amorphous silica promotes secondary pozzolanic reactions, potentially leading to additional C-S-H formation, pore refinement, and a denser cementitious matrix. Meanwhile, BSH may contribute through internal curing, enhanced hydration, and heterogeneous nucleation of hydration products. These proposed mechanisms, consistent with those reported for comparable materials in the literature (though not directly verified in this study through microstructural characterization), may collectively help explain why the best-performing mixtures outperformed many previously reported sustainable cementitious composites. Overall, the comparison presented in Table 5 demonstrates that the strategy adopted in this study, combining low replacement levels with appropriate SH processing techniques, is more effective than simply increasing the replacement ratio. The findings suggest that optimizing the physicochemical characteristics of SH-derived materials is more critical than maximizing their dosage, providing an efficient pathway for producing sustainable cement-based materials with enhanced mechanical performance.

4. Conclusions

This study evaluated the effects of SH, BSH, and CSH as partial cement replacement materials on the fresh and mechanical properties of mortar. The results demonstrate that the processing method of SH plays a decisive role in determining the performance of cementitious composites by influencing both hydration behavior and microstructural development.

- Among the investigated materials, CSH exhibited the most beneficial overall performance. Its incorporation significantly improved mortar flowability owing to its fine particle size and filler effect, while also producing the highest 28-day compressive strength. The mortar containing 3% CSH ($C_{97}CSH_3$) achieved approximately 143.6% of the reference mixture's compressive strength (i.e., a 43.6% increase), consistent with the combined effects of pozzolanic reactivity, nucleation, particle packing, and pore refinement, which are proposed as plausible contributors to the observed mechanical performance, although not directly verified in this study.
- Although all SH-derived materials reduced the proportion of early-age strength development compared with the reference mixture, they promoted a more sustained strength gain at later curing ages. This finding confirms that replacing cement with SH-derived materials modifies the hydration kinetics and shifts strength development from rapid early hydration toward progressive reactions at later ages (within 28 days). The contributions of secondary pozzolanic reactions, continued hydration, and, in the case of BSH, internal curing is proposed to become increasingly significant as curing progresses, consistent with mechanisms reported for similar materials, though not directly measured here.
- Biochar proved to be an effective supplementary cementitious material at low replacement levels. In particular, the mixture containing 3% BSH ($C_{97}BSH_3$) exhibited favorable later-age mechanical performance (within 28 days), suggesting that a limited amount of BSH can improve hydration efficiency through internal curing while promoting a denser cementitious matrix. However, increasing the BSH dosage beyond the optimum level diminished these benefits because of the dilution effect and increased porosity.
- The SH mixtures exhibited the slowest early-age strength development but continued to gain strength throughout the curing period. Notably, the mixture containing 8% SH ($C_{92}SH_8$) showed one of the greatest late-age strength growth rates, demonstrating that untreated SH can contribute to continued strength development at later ages within the tested 28-day period. Nevertheless, its overall mechanical performance remained inferior to that of the best-performing CSH mixture ($C_{97}CSH_3$) among the tested levels.
- The LCA demonstrated that incorporating SH-derived materials substantially improved the environmental performance of mortar by reducing GHG emissions, CED, and overall environmental impacts. Among the investigated mixtures, the 8% SH mixture ($C_{92}SH_8$) exhibited the greatest environmental benefits, achieving reductions of approximately 7.7% in CO_2 emissions, 4.8% in the ReCiPe endpoint score, and 6.7% in CED compared with the reference mixture. Similarly, the 8% CSH mixture ($C_{92}CSH_8$) also showed considerable environmental improvements, whereas the BSH mixtures exhibited comparatively higher embodied impacts because of the additional energy required during the pyrolysis process. Nevertheless, BSH remains an attractive low-carbon supplementary cementitious material owing to its long-term carbon sequestration potential and favorable mechanical performance at low replacement levels.

Overall, the findings demonstrate that SH-derived materials offer an effective strategy for simultaneously improving the sustainability and engineering performance of cementitious mortars. Among the investigated mixtures, $C_{97}CSH_3$ delivered the best overall mechanical performance, whereas $C_{92}SH_8$ achieved the greatest reduction in environmental impacts. Consequently, the optimum replacement level should be selected according to the primary design objective, prioritizing low CSH contents for mechanical performance and higher SH contents for environmental sustainability. These results provide a practical basis for designing low-carbon cementitious materials with reduced clinker consumption while maintaining satisfactory engineering performance. The findings should, however, be interpreted in light of two limitations. First, compressive strength was determined from two specimens per mixture at each curing age, limiting the statistical robustness of the comparisons. Second, the proposed mechanisms are supported by established literature rather than direct experimental evidence, as no microstructural characterization (XRD, SEM, BET/Blaine surface area, TGA, and MIP/porosity) or particle size analysis was performed. Future research should incorporate comprehensive microstructural analyses and a larger number of test specimens to validate the proposed mechanisms and enable more rigorous statistical evaluation. In addition, a constant water-to-binder ratio (0.42) was applied across all mixtures without correction for the water absorption of the rice husk-derived materials or pre-saturation of these materials prior to mixing. As a result, the effective water available for cement hydration may have varied between mixtures in an uncontrolled manner, which should be considered when interpreting the reported strength differences. Future studies should incorporate water absorption measurement and corresponding mixing water adjustment (or material pre-saturation) to isolate this effect.

Statements & Declarations

Author contributions

Lobat Hosseinzadeh: Conceptualization, Idea, Methodology, Investigation, Visualization, Writing - Original Draft, Formal analysis.

Morteza Jamshidi: Conceptualization, Methodology, Supervision, Project administration, Validation, Writing - Review & Editing.

Mehdi Dehestani: Conceptualization, Methodology, Supervision, Project administration, Validation, Writing - Review & Editing.

Seyed Farhad Nabizadeh: Data curation, Methodology, Validation, Writing - Review & Editing.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Declarations

The data presented in this study will be available on interested request from the corresponding author.

Data availability

The authors declare no conflict of interest.

References

- [1] Rukzon, S., Shindaprasirt, P. Strength and chloride resistance of blended Portland cement mortar containing palm oil fuel ash and fly ash. *International Journal of Minerals, Metallurgy, and Materials*, 2015; 16: 475–481. doi:10.1016/S1674-4799(09)60083-2.
- [2] Kordi, M., Farrokhi, N., Pech-Canul, M. I., Ahmadikhah, A. Rice husk at a glance: from agro-industrial to modern applications. *Rice Science*, 2024; 31: 14–32. doi:10.1016/j.rsci.2023.08.005.
- [3] Thomas, B. S. Green concrete partially comprised of rice husk ash as a supplementary cementitious material—A comprehensive review. *Renewable and Sustainable Energy Reviews*, 2018; 82: 3913–3923. doi:10.1016/j.rser.2017.10.081.
- [4] Kacho, H. A., Samadi, M. T., Niazi, S., Leili, M. Human Health Risk Assessment of Atmospheric Pollutant Emissions from Open Field Burning of Rice Residues. *Water, Air, & Soil Pollution*, 2026; 237: 319. doi:10.1007/s11270-025-08934-8.
- [5] Duque-Acevedo, M., Lancellotti, I., Andreola, F., Barbieri, L., Belmonte-Ureña, L. J., Camacho-Ferre, F. Management of agricultural waste biomass as raw material for the construction sector: an analysis of sustainable and circular alternatives. *Environmental Sciences Europe*, 2022; 34: 70. doi:10.1186/s12302-022-00655-7.
- [6] John, K. I., Adeleye, A. T., Munsif, S., Odusina, B. O., Omorogie, M. O. Perspectives on circular economy and efficient resource utilization of valorized value-added material for sustainable development. *Circular Economy and Sustainability*, 2026; 6: 17. doi:10.1007/s43615-026-00837-y.
- [7] Dunant, C. F., Joseph, S., Prajapati, R., Allwood, J. M. Electric recycling of Portland cement at scale. *Nature*, 2024; 629: 1055–1061. doi:10.1038/s41586-024-07338-8.
- [8] Chaudhury, R., Sharma, U., Thapliyal, P., Singh, L. Low-CO2 emission strategies to achieve net zero target in cement sector. *Journal of Cleaner Production*, 2023; 417: 137466. doi:10.1016/j.jclepro.2023.137466.
- [9] Antunes, M., Santos, R. L., Pereira, J., Rocha, P., Horta, R. B., Colaço, R. Alternative clinker technologies for reducing carbon emissions in cement industry: a critical review. *Materials*, 2021; 15: 209. doi:10.3390/ma15010209.
- [10] Ahmed, A. Assessing the effects of supplementary cementitious materials on concrete properties: a review. *Discover Civil Engineering*, 2024; 1: 145. doi:10.1007/s44290-024-00154-z.
- [11] Raghav, M., Park, T., Yang, H.-M., Lee, S.-Y., Karthick, S., Lee, H.-S. Review of the effects of supplementary cementitious materials and chemical additives on the physical, mechanical and durability properties of hydraulic concrete. *Materials*, 2021; 14: 7270. doi:10.3390/ma14237270.
- [12] Alamian, M., Mousavi, S. S., Dehestani, M. Development of a low-clinker GGBFS calcined clay cement using waste ceramic tile. *Journal of Materials in Civil Engineering*, 2025; 37: 04025312. doi:10.1061/JMCEE7.MTENG-20525.
- [13] Chandru, U., Bahurudeen, A., Senthilkumar, R., Vijay, T. Evaluating the availability and carbon footprint of agricultural waste ashes: a strategy for achieving sustainable cement production in India. *Innovative Infrastructure Solutions*, 2024; 9: 482. doi:10.1007/s41062-024-01736-7.
- [14] Ji, J., Li, L., Quan, L., Tian, B., Zhang, P., Li, S. The Effects of Calcination Process Parameters on RHA Reactivity and Mortar Mechanical Properties. *Materials*, 2025; 18: 3129. doi:10.3390/ma18133129.
- [15] Nair, D. G., Fraaij, A., Klaassen, A. A., Kentgens, A. P. A structural investigation relating to the pozzolanic activity of rice husk ashes. *Cement and Concrete Research*, 2008; 38: 861–869. doi:10.1016/j.cemconres.2007.10.004.
- [16] Shen, J., Liu, X., Zhu, S., Zhang, H., Tan, J. Effects of calcination parameters on the silica phase of original and leached rice husk ash. *Materials Letters*, 2011; 65: 1179–1183. doi:10.1016/j.matlet.2011.01.034.
- [17] Chen, W.-H., Magdaraog, B. J. P., Ubando, A. T., Felix, C. B., Lin, K.-Y. A., Conejos, S. Sustainable cementitious materials: A comprehensive review on rice husk biochar-Portland cement blends. *Case Studies in Construction Materials*, 2025; 23: e05087. doi:10.1016/j.cscm.2025.e05087.
- [18] Mahmoud, A. A., El-Sayed, A. A., Fathy, I. N., Fawzy, S., Alturki, M., Elfakharany, M. E., Abouelnour, M. A., Mahmoud, K., Dahish, H. A., ElTalaawy, S. M. Evaluation of rice husk biochar influence as a partial cement replacement material on the physical, mechanical, microstructural, and radiation shielding properties of ordinary concrete. *Scientific Reports*, 2025; 15: 27229. doi:10.1038/s41598-025-11987-8.

- [19] Samarajeewa, P., Buddika, S., Yapa, H., Gunasekara, C., Law, D. W. Rice husk ash and nanomaterial-blended cement composites: a review. *Environmental Science and Pollution Research*, 2026; 33: 717–735. doi:10.1007/s11356-025-37361-9.
- [20] Room, S., Bahadori-Jahromi, A. Hydration kinetics of biochar-enhanced cement composites: A mini-review. *Buildings*, 2025; 15: 2520. doi:10.3390/buildings15142520.
- [21] Yin, X., Rahman, M. M., Sun, Y., Zhao, Y., Wang, J. Sustainable soil–cement composites with rice husk ash and silica fume: a review of performance and environmental benefits. *Materials*, 2025; 18: 2880. doi:10.3390/ma18122880
- [22] Ullah, M. F., Tang, H., Ullah, A., Ahmad, S., Alzlfawi, A., Ahmad, M., Tóth, Z. Modeling and optimization of sustainable ternary concrete incorporating rice husk ash and extracted micro silica. *Scientific Reports*, 2026; 16: 5063. doi:10.1038/s41598-026-35983-8.
- [23] Liu, W., Tan, S., Qing, L., Li, Y. Pozzolanic activity of biochar with high carbon content and its influence on comprehensive strength-emission performance of biochar-cement composite paste. *Construction and Building Materials*, 2025; 478: 141427. doi:10.1016/j.conbuildmat.2025.141427.
- [24] Nazari, A., Toufigh, V. Effects of elevated temperatures and re-curing on concrete containing rice husk ash. *Construction and Building Materials*, 2024; 439: 137277. doi:10.1016/j.conbuildmat.2024.137277.
- [25] Farrokh, G. H., Nazari, A. Prediction of rice husk ash-based SCC compressive strength: Data-driven Framework. *Civil Engineering and Applied Solutions*, 2025; 1: 17–28. doi:10.22080/ceas.2025.29625.1025.
- [26] International Organization for Standardization (ISO). ISO 14040: Environmental management — Life cycle assessment — Principles and framework. Geneva (CH): ISO; 2006.
- [27] Guinée, J. B. Handbook on life cycle assessment: operational guide to the ISO standards. 1st ed. Berlin (DE): Springer Science & Business Media; 2002. doi:10.1007/0-306-48055-7.
- [28] Environment, U., Scrivener, K. L., John, V. M., Gartner, E. M. Eco-efficient cements: Potential economically viable solutions for a low-CO₂ cement-based materials industry. *Cement and Concrete Research*, 2018; 114: 2–26. doi:10.1016/j.cemconres.2018.03.015.
- [29] Akintayo, B. D., Babatunde, O. M., Akintayo, D. C., Olanrewaju, O. A. Transforming Industrial Waste into Low-Carbon Cement: A Multi-Criteria Assessment of Supplementary Cementitious Materials for Sustainable Concrete Design. *Recycling*, 2025; 10: 211. doi:10.3390/recycling10060211.
- [30] Avet, F., Scrivener, K. Investigation of the calcined kaolinite content on the hydration of Limestone Calcined Clay Cement (LC3). *Cement and Concrete Research*, 2018; 107: 124–135. doi:10.1016/j.cemconres.2018.02.016.
- [31] American Society for Testing and Materials (ASTM). ASTM C136/C136M-25: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. West Conshohocken (PA): ASTM International; 2025. doi:10.1520/C0136_C0136M-25.
- [32] American Society for Testing and Materials (ASTM). ASTM C305-20: Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. West Conshohocken (PA): ASTM International; 2020. doi:10.1520/C0305-20.
- [33] American Society for Testing and Materials (ASTM). ASTM C230/C230M-23: Standard Specification for Flow Table for Use in Tests of Hydraulic Cement. West Conshohocken (PA): ASTM International; 2023. doi:10.1520/C0230_C0230M-23.
- [34] American Society for Testing and Materials (ASTM). ASTM C511-21: Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes. West Conshohocken (PA): ASTM International; 2021. doi:10.1520/C0511-21.
- [35] American Society for Testing and Materials (ASTM). ASTM C109/C109M-26a: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). West Conshohocken (PA): ASTM International; 2026. doi:10.1520/C0109_C0109M-26A.
- [36] International Organization for Standardization (ISO). ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines. Geneva (CH): ISO; 2006.
- [37] Tait, M. W., Cheung, W. M. A comparative cradle-to-gate life cycle assessment of three concrete mix designs. *The International Journal of Life Cycle Assessment*, 2016; 21: 847–860. doi:10.1007/s11367-016-1045-5.
- [38] Imtiaz, L., Kashif-ur-Rehman, S., Alaloul, W. S., Nazir, K., Javed, M. F., Aslam, F., Musarat, M. A. Life cycle impact assessment of recycled aggregate concrete, geopolymers concrete, and recycled aggregate-based geopolymers concrete. *Sustainability*, 2021; 13: 13515. doi:10.3390/su132413515.
- [39] Habert, G., Billard, C., Rossi, P., Chen, C., Roussel, N. Cement production technology improvement compared to factor 4 objectives. *Cement and Concrete Research*, 2010; 40: 820–826. doi:10.1016/j.cemconres.2009.09.031.
- [40] Flower, D. J., Sanjayan, J. G. Green house gas emissions due to concrete manufacture. *The International Journal of Life Cycle Assessment*, 2007; 12: 282–288. doi:10.1065/lca2007.05.327.
- [41] Nazari, A., Toufigh, V. Prediction of ultrasonic pulse velocity and physicochemical properties of rice husk ash concrete exposed to elevated temperatures and post-fire curing. *Case Studies in Construction Materials*, 2025; 24: e05715. doi:10.1016/j.cscm.2025.e05715.
- [42] Alamian, M., Dehestani, M., Mousavi, S. S. Production of green low-carbon mortar containing recycled calcined clay from the tile factory and ground granulated blast furnace slag. *Amirkabir Journal of Civil Engineering*, 2025; 56: 1407–1430. doi:10.22060/ceej.2024.22864.8059.
- [43] Fernando, S., Gunasekara, C., Law, D. W., Nasvi, M., Setunge, S., Dissanayake, R. Life cycle assessment and cost analysis of fly ash–rice husk ash blended alkali-activated concrete. *Journal of Environmental Management*, 2021; 295: 113140. doi:10.1016/j.jenvman.2021.113140.

- [44] Wang, D., Bui, T. T. P., Reinke, B., Upadhyayula, V. K. K., Ágoston, R., Wilkinson, S., Piri, I. S., Karim, S., Das, O. Life cycle assessment of both cement and sand-replaced biochar concrete. *Resources, Conservation & Recycling Advances*, 2026; 30: 200337. doi:10.1016/j.rcradv.2026.200337.
- [45] Shaikh, S. A., Rajpurohit, K., Pandey, A. K., Bagla, H. K. Engineering Portland cement and concrete with agricultural-origin functional additives: Valorization of agro-waste. *Next Sustainability*, 2025; 6: 100173. doi:10.1016/j.nxsust.2025.100173.
- [46] Ramezaniapor, A., Yadak Yaraghi, A., Zolfagharnasab, A., Ramezaniapor, A. M. Investigation of mechanical properties and chloride ions ingress in concretes containing calcined. *Amirkabir Journal of Civil Engineering*, 2022; 54: 1119–1132. doi:10.22060/ceej.2021.19247.7117.
- [47] Dhandapani, Y., Santhanam, M. Assessment of pore structure evolution in the limestone calcined clay cementitious system and its implications for performance. *Cement and Concrete Composites*, 2017; 84: 36–47. doi:10.1016/j.cemconcomp.2017.08.012.
- [48] Mishra, G., Emmanuel, A. C., Bishnoi, S. Influence of temperature on hydration and microstructure properties of limestone-calcined clay blended cement. *Materials and Structures*, 2019; 52: 91. doi:10.1617/s11527-019-1390-5.