Valorization of Sugarcane Bagasse Ash as an Alternative SCM: Effect of Particle Size, Temperature-Crossover Effect Mitigation & Cost Analysis

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Abstract: The construction industry faces increasing pressure to reduce its environmental impact while meeting the growing demand for infrastructure. One approach to achieving this goal is the use of industrial waste as a replacement for traditional supplementary cementitious materials (SCMs). This study investigates sugarcane bagasse ash (SCBA), addressing the future scarcity and increased cost of other commonly used SCMs. Despite existing literature, the use of SCBA is hindered by several unknowns. This research evaluates SCBA's performance in mortars, focusing on the effects of curing temperature and particle size variation. Mortar samples were prepared with SCBA replacements from 0% to 30% by mass of cement and cured at 21 °C and 45 °C for 7, 28, and 90 days. The results suggest potential for SCBA replacement up to 30%, emphasizing its sustainability and economic benefits. A cost analysis was also conducted, demonstrating the economic viability of SCBA as an alternative to traditional cement for practical applications.

Keywords: sugarcane bagasse ash; cement mortar; curing temperature; crossover effect; strength activity index; supplementary cementitious materials

1. Introduction

The construction sector is challenged by the need to minimize the depletion of natural resources, energy consumption and carbon dioxide (CO_2) emissions, yet the demand for Portland cement grows every year due to the development of civil infrastructure across the world [1]. As a consequence, tons of raw natural resources are consumed annually for the manufacture of cement. Therefore, the reduction in ordinary Portland cement (OPC) in cementitious composites is imperative to reducing the environmental burden and carbon footprint derived from the manufacturing chain, which requires a substantial amount of energy and resources [2]. In this context, the development of more sustainable cementitious composites with the inclusion of industrial and agricultural by-products or waste as supplementary cementitious materials (SCMs) serves as a way to reduce the usage of raw naturally mined materials and to decrease the volume of waste landfilled [2]. An opportunity, driven by the ongoing issue of waste management, has been seen in biomass combustion ashes [3]. Among others, sugarcane bagasse ash (SCBA), a solid agro-industrial waste produced from the combustion of bagasse for energy generation, has been shown to have potential as an SCM in cement-based composites [4]. Although SCBA is a promising SCM, there are some limitations to its use in cement-based composites. One of the primary

challenges is the variability in the chemical composition and physical properties of SCBA, which can vary depending on the source and processing (e.g., combustion process) methods used. The most significant component of SCBA is silica (SiO_2), often in the amorphous form, followed by other oxides such as calcium oxide (CaO), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3). Therefore, SCBA can react with the calcium hydroxide formed during the hydration of the cement and water to form additional cementitious compounds, such as calcium silicate hydrate and calcium aluminate hydrate [5–9]. This may result in an enhancement of the strength and durability of the composite material [4].

Thus far, the main studied aspects are chemical composition, loss on ignition (LOI), calcination, particle size reduction and, to a lesser extent, the curing conditions. ASTM 618 [10] determines that class N pozzolans must have a minimum percentage of 70% in the sum of pozzolanic oxides $SiO_2 + Al_2O_3 + Fe_2O_3$. For class F and C, the minimum is 50%. The amount of pozzolanic oxides present in the biomass ashes depends on factors such as the characteristics of the soil, the environment surrounding the plantation, and the quality of calcination in the mills [4,8,11]. These variations can alter the concentrations of key pozzolanic oxides like SiO_2, Al_2O_3, and Fe_2O_3, thereby influencing the effectiveness as an SCM. For instance, differences in combustion temperatures can result in varying levels of amorphous versus crystalline silica, with higher temperatures promoting crystallization, which in turn reduces the ash's reactivity [5,12]. Additionally, impurities such as unburnt carbon may negatively impact the strength activity index (SAI), water demand, and the long-term durability of the mortar [6,13]. While some researchers have reported the use of ashes with good chemical characteristics obtained directly from mills [8,14], other investigators have documented very low-quality ashes, so they developed various methods to increase the pozzolanic oxides in the ash [15–17] such as grinding, (re)calcination, or chemical processing. The recalcination of SCBA has been studied by evaluating different temperatures and durations to improve chemical properties, thus increasing the percentages of pozzolanic oxides [15,18–21]. Moreover, this approach generates a lower carbon content, which correlates with lower LOI. The recalcination of SCBA burned at temperatures between 600 and 700 °C caused an improvement in the compressive strength of concretes [5]. Although the time in the ash furnace varied between 20 min and 6 h in each investigation, in general, the higher the temperature, the lower the time the ash needs to be in the furnace, and vice versa [5]. In addition, it was evidenced that temperatures higher than 700 °C favor a crystallization of the particles, decreasing the reactivity of the ash [4]. Previous studies have shown that SCBA grinding (i.e., particle size) can influence the compressive strength of concrete and mortar samples [15,21–24]. A bigger particle size of the ash reduces the strength values, compared to the values of reference samples without cement replacement. Furthermore, with particle sizes similar to or smaller than the cement used, better results were obtained compared to the reference samples [6,23,25]. One of the reasons is that the extra fine grinding can reduce the crystalline phases, ultimately benefiting the ash reactivity [4].

Additionally, curing conditions are an important factor affecting the development of mechanical properties in a hydrated cement paste [26]. The effect of curing temperature on Ordinary Portland Cement mortars and concretes has been extensively studied [27–30]. The partial replacement of cement with supplementary cementitious materials (SCMs) and their exposure to different temperatures and curing processes have been shown to increase compressive strength and reduce permeability [31–33]. However, there has been limited investigation into the influence of different curing temperatures when incorporating SCBA as a cement substitute, despite its significance in optimizing the mechanical properties and durability. Murugesan et al. [34] analyzed the effects of eight different curing methods on concrete specimens containing SCBA, including accelerated curing in hot water at 100 °C for the first 24 h. Their results indicate that normal water curing has better effects on the strength and durability of concrete. Accelerated curing in hot water yielded values close to normal curing. However, the fineness of the SCBA, which is a key factor for its pozzolanic activity in concrete, was not considered in their study. Rajasekar et al. [35] investigated

an ultra-high-strength concrete (UHSC) with SCBA replacements treated by grinding and incineration. Three different curing systems were evaluated, (i) normal water curing at 27 °C ± 2 °C, (ii) steam curing for 24 h at 90 °C, and (iii) heat curing for 24 h at 160 °C. After the second and third curing methods, the samples were cooled and immersed in normal water. The study reported that the optimum replacement of cement by SCBA was 15%, and that UHSC improved its strength with an increasing percentage of SCBA replacement, with a better performance observed under heat curing.

In the context of sustainable construction, the use of SCBA as an SCM presents both opportunities and challenges. While higher curing temperatures can expedite the hydration process leading to faster early-age strength development, it is crucial to evaluate the balance between the immediate benefits and the potential impacts on ultimate strength and long-term properties. Understanding the temperature crossover effect, whereby the optimal performance of concrete shifts at different temperatures, when using supplementary cementitious materials (e.g., SCBA) is essential for developing sustainable construction materials and practices that maximize the benefits of such substitutions, while mitigating potential drawbacks. For instance, in comparison with other SCMs, such as fly ash and silica fume, SCBA may exhibit similar or even superior pozzolanic behavior under certain conditions [4]. Fly ash, on one hand, is widely known for its ability to mitigate ASR and improve long-term strength, but it generally requires longer curing times to activate its pozzolanic properties compared to SCBA, especially when SCBA is finely ground [4,36]. Silica fume, on the other hand, reacts more quickly due to its ultra-fine particle size, but its high reactivity can lead to early-age strength improvements at the expense of longer-term performance in certain environments [4,25]. SCBA's particle size, when optimized through grinding, and its high silica content allow for a more balanced pozzolanic reaction, which is particularly beneficial in environments where both early-age strength and long-term durability are critical. This balance gives SCBA an advantage over fly ash, which may require additional activation, and silica fume, which may not perform as well in sustained high-temperature environments.

However, in the current literature, a gap is evident—the combined effects of SCBA fineness and curing temperature have not been thoroughly investigated. This study aims to bridge this gap by examining how curing temperature and particle size influence the efficacy of SCBA as a partial cement replacement in mortars. Through this research, we seek to advance the application of SCBA, as a viable and effective material in the production of sustainable cementitious composites.

2. Materials and Methods

2.1. Materials

Mortars in this study were manufactured using commercial-grade Portland cement Type I obtained from Buzzi Unicem (Green Castle, IN, USA). The measured specific gravity of the Portland cement employed was 3.12. The fine aggregate utilized was natural siliceous sand compliant with ASTM C33 [37]. The sand exhibited a fineness modulus of 2.99, an absorption value of 1.97%, and a relative density (specific gravity under saturated surface dry conditions—SSD) of 2.45. The sugar cane bagasse ash (SCBA) used in the study was sourced from a sugar plant situated in Valle del Cauca, Colombia. This is a by-product resulting from the combustion of sugarcane bagasse for energy production. The ash was black in color and its shape was irregular with some presence of coarse partially burnt organic matter.

Before mixing the ashes were prepared as follows: (i) The as-received SCBA was sieved through a 425 μm sieve to reduce the fibrous coarser and unburnt particles. The organic waste retained was about 10%. These ashes were labeled as untreated SCBA (USCBA). (ii) The as-received SCBA was ground for two minutes using a RETSCH ZM1 bench top mill (Verder Scientific, Haan, Germany) and labeled as treated SCBA (TSCBA). Figure 1 displays an overview of the study.
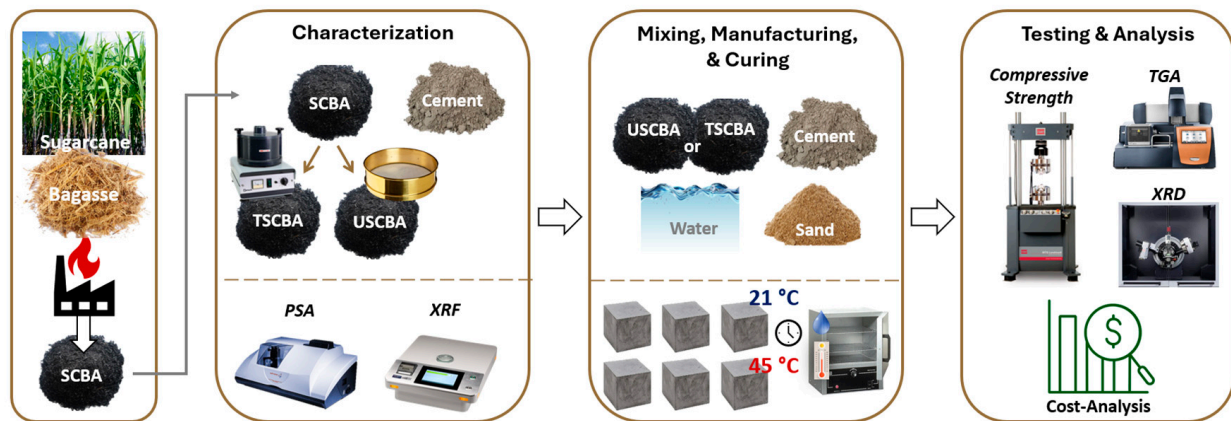
Figure 1. Overview of the experimental process.

Mix Design, Sample Manufacturing, and Curing Conditions

The reference mortar formulation was prepared with a 1:3:0.5 (cement:sand:water) weight ratio. For this study, three percentages of replacement of cement with SCBA were selected based on the previous literature. The amounts of cement replaced were 10%, 20% and 30% (by mass of cement). Water to binder (cement + ash) and binder to aggregate ratios were kept constant for all mixes at 0.5 and 3, respectively. The mix proportions of the composites are presented in Table 1.

Table 1. Mix proportions (per m^3 of mortar).

Component	Reference	10% SCBA	20% SCBA	30% SCBA
Cement (kg)	486.39	437.75	389.12	340.48
SCBA (kg)	0.00	48.64	97.28	145.92
Sand (SSD) (kg)	1459.18	1459.18	1459.18	1459.18
w/b	0.50	0.50	0.50	0.50
Water (kg)	243.20	243.20	243.20	243.20

Three groups of mixtures were manufactured for each percentage of cement replaced. A reference mortar (without SCBA), a mortar with untreated SCBA, and a mortar with treated SCBA were labeled as Ref., USCBA and TSCBA, respectively.

A total of 18 cubic specimens were cast per group of mortar. The dimensions of each specimen were 50 × 50 × 50 mm. The samples were cured for 7, 28 and 90 days. For each curing age, six specimens were cast: three were cured at 21 °C, and three at 45 °C. All samples were allowed to cure in their molds at room temperature for the first day. After demolding, each group was placed in water at its respective temperature. The specimens cured at 21 °C were stored in covered plastic containers, while those cured at 45 °C were placed in covered plastic containers within an Isotemp 637F Incubator Oven (Fisher Scientific, Hampton, NH, USA). Similarly, small paste samples (with no sand) were cast for each mixture for characterization.

Mortar preparation involved an initial step where the dry sand was mixed with its absorption water for 30 s and allowed to stand for 10 min to achieve a saturated surface dry (SSD) state. In the meantime, the binder (cement + SCBA) was introduced to the mixer, and water was added while mixing at low speed for 30 s. Then, the fine aggregate was added over a 30 s period while mixing at low speed and further mixed for 30 s at medium speed. Subsequently, the mortar was left to rest for 90 s and finally mixed for 60 s at medium speed. At each interval, any mortar adhering to the side of the bowl is promptly scraped down into the batch. All mixtures were prepared under controlled room temperature (21 ± 1 °C) and within a relative humidity range of 50 ± 5% RH.

2.2. Methods

2.2.1. Binders

- Particle size analysis (PSA)

Cement, USCBA and TSCBA particle sizes were analyzed with a PSA 1090 Series (Anton Paar, Austria), which uses laser diffraction (with two lasers) to determine the particle size and particle size distribution of the sample. Isopropanol alcohol was used as a carrier liquid for the wet measurement. For the optimal dispersion of the ashes, ultrasound and medium stirring and pumping speed were used. The final result is the average of 3 repetitions on the same sample.

- X-ray fluorescence (XRF)

The chemical composition of the raw materials was obtained using the Lab X500 XRF analyzer (Hitachi, Tokyo, Japan). Additionally, a literature review was conducted to obtain and compare the XRF analysis results obtained for the binders used in this study with other commonly used supplementary cementitious materials.

- Specific gravity and Loss on ignition (LOI)

The specific gravity of the cement and ashes used for this study was determined following the ASTM C188 [38]. Besides this, the ASTM C311 [39] standard was followed in the determination of moisture content and loss on ignition (LOI) for the as-received SCBA, the USCBA, and the TSCBA.

2.2.2. Pastes

- Thermogravimetric analysis (TGA)

Small paste samples were prepared for thermogravimetric analyses and tested after 28 days. TGA was carried out on a 2050 Thermogravimetric Analyzer (TA Instruments, New Castle, DE, USA). The tested samples had an amount of 20–40 mg of grounded powder and were placed in a platinum pan. The test was run in nitrogen atmosphere with a pressure of 20 psi and a 60 mL/min purge flow. Initially, samples were kept for 2 min in isothermal conditions, then heated up to 900 °C at a 10 °C/min rate, and the mass loss versus temperature was recorded. Before the test, samples were pretreated to remove free water [40]. First, they were roughly ground, and approx. 5 g of sample was soaked in 50 mL of isopropanol. After fifteen minutes, the isopropanol was removed, and specimens were dried in a laboratory oven for 10 min at 40 °C to remove the excess solvent. Finally, the samples were ground with a mortar and pestle and then sieved through a No. 200 sieve (75 μm).

- X-ray powder diffraction (XRD)

X-ray powder diffraction was employed to characterize the ash and analyze and compare the crystallographic structure of the mixes. Tests on paste samples were performed after 28 days. A Siemens D500 diffractometer instrument with a 50 kV voltage and a 30 mA current was used for the analysis. The 2θ-range of the scan was 5–70° at a 0.02°/s scanning rate. Tested samples were prepared in the same way as the ones used for the TGA. The results were analyzed with the open source Profex software 5.2 [41].

2.2.3. Mortars

- Compressive strength

Compressive strength tests were performed on the $50 \times 50 \times 50$ mm cubes according to the ASTM standard C349 [42]. An MTS (Eden Prairie, MN) machine with a load capacity of 300 kN under a displacement control of 0.05 mm/s was used. Tests were conducted at 7, 28 and 90 days for each mixture design set.

- Modified Strength Activity Index (MSAI)

Strength activity index (SAI) is an indirect method commonly used to determine if fly ash or natural pozzolan results in an acceptable level of strength development when used as a partial cement replacement in cementitious composites. In the standard procedure of ASTM C311 [39], 20% of the cement of the control mixture is replaced by the test sample, which is then tested at 7 and 28 days. In this study, the SAI procedure was adapted and computed also for 10% and 30% replacement levels. In addition, ASTM C618-22 [10] was employed to determine whether the investigated SCBA is suitable for replacing cement based on whether the specimens achieved the 75% minimum SAI requirement.

- Cost Analysis

A cost analysis was carried out to measure the economic impact of using SCBA as a partial replacement of cement in mortars in real-world applications. For the cost analysis, the mixture designs of this research's experimental campaign were used. Table 2 lists the raw materials' cost per unit weight (in USD). The total cost of each mixture was obtained by multiplying the unit prices by the weight of each material used per 1 m^3 unit volume.

Table 2. Raw materials' unit price.

Compound	Cost (USD)	Source [43,44]
Cement	130.00/ton	US Geological Survey, 2023
Natural aggregate	11.00/ton	US Geological Survey, 2023
Water	1.25/ton	EPA WaterSense, 2021
SCBA	30/ton	See Results and Discussion

3. Results and Discussion

3.1. Binders

3.1.1. Particle Size Analysis (PSA)

The particle size distribution curves of the cement, the USCBA, and the TSCBA (ground) are reported in Figure 2a. Three measurements were taken for each material. As shown in the graph, the curves of the USCBA and TSCBA are shifted to the right with respect to those of the cement, indicating a higher particle size overall, with a greater difference in the lower range indicating a broader distribution of smaller particles. Figure 2b displays the results of the particle size analysis (wet measurement) for the cement, and the untreated and treated ashes. The mean particle size of the untreated bagasse ash was 37.62 μm. After grinding, the SCBA's mean particle size was reduced to 23.55 μm, close to the one of cement, which was 19.99 μm. The ground SCBA had a specific gravity of 1.6, which is almost half of that of cement. The laser diffraction particle size distribution of the USCBA showed a D_{90} of 71.5 μm, a D_{50} of 32 μm, and a D_{10} of 8 μm. On the other hand, just 2 min of grinding in the rotary mill reduced the particles size almost by half, with TSCBA showing a D_{90} to 47.5 μm, a D_{50} of 19 μm, and a D_{10} of 4 μm. The particle size reduction is crucial, as it increases the surface area, improving pozzolanic activity.
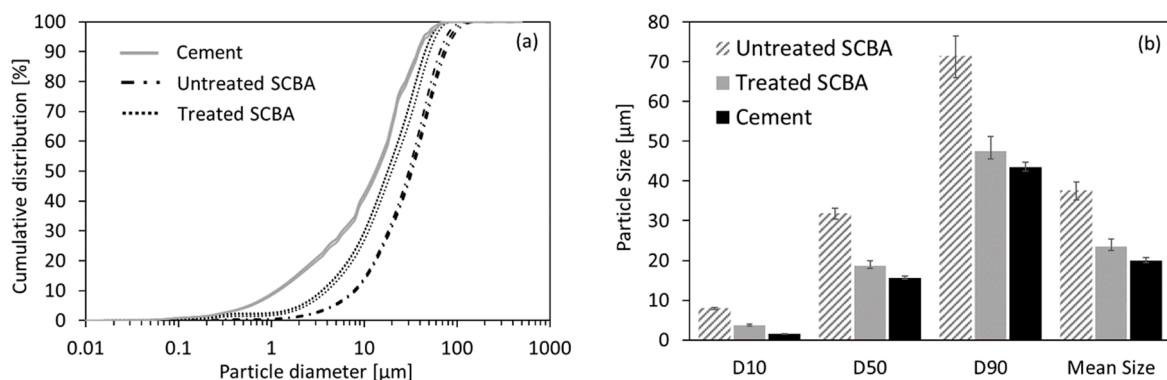

Figure 2. Particle size distribution (**a**) and size (**b**) of the binders used in this study.

3.1.2. Chemical Composition and Loss on Ignition (LOI)

An XRF analysis was conducted for the sugarcane bagasse ash (SCBA) and Ordinary Portland Cement Type I (OPC-I) used in this study. A literature review was also conducted to obtain the typical chemical compositions of SCBA, OPC-I, Fly Ash-C, Fly Ash-F, Slag cement and Silica Fume from other sources for comparison with the raw materials used in this study. The chemical composition results are reported in Table 3. The main oxide compositions of the SCBA were SiO_2 (54.97%), Al_2O_3 (13.85%), CaO (9.98%), and Fe_2O_3 (8.57%), with a high LOI value of 18.15%, indicating the presence of unburnt or partially burnt carbonaceous particles. Unburnt carbon and other organic impurities, reflected in the high LOI value, can adversely affect both the pozzolanic activity and the durability of cementitious materials. High LOI is commonly associated with diminished compressive strength and increased water absorption, as carbonaceous particles tend to retain water. The moisture content of the original ash was 1.65%. After processing, the LOI was reduced to 13.76% and 16.55% for the USCBA and TSCBA, respectively. Nonetheless, these values are still over the 12% limit allowed for class F pozzolan by ASTM C618 [10] if either acceptable performance records or laboratory test results are made available. This suggests that additional processing steps, such as further calcination, may be necessary to decrease impurities and improve the reactivity of the ash.

Table 3. Chemical composition of materials used in this study and other common SCMs.

Compound	SCBA	OPC Type-I	SCBA [4,5] Mean (Min.–Max.)	OPC Type-I [45] Mean (Min.–Max.)	Fly Ash Type-C [2,45]	Fly Ash Type-F [2,45]	Slag Cement [2,45]	Silica Fume [2,45]
(%)								
Al_2O_3	13.85	5.08	5.37 (1.33–15.00)	5.1 (4.40–5.70)	18.0	23.0	12.0	0.4
CaO	9.98	64.60	3.54 (0.51–16.06)	63.3 (60.7–64.6)	21.0	5.0	40.0	1.6
Fe_2O_3	8.57	2.68	3.69 (0.60–10.80)	2.5 (1.3–3.6)	6.0	11.0	1.0	0.4
K_2O	1.39	0.75	2.68 (0.36–12.80)	Combined with Na_2O	0.7	2.0	0.4	2.2
MgO	2.07	2.77	1.36 (0.10–6.68)	2.3 (0.8–3.3)	-	-	-	-
Mn_2O_3	1.25	0.02	0.16 (0.05–1.23)	-	-	-	-	-
Na_2O	0.51	0.11	0.35 (0.02–1.49)	0.62 (0.3–1.0)	5.8	1.0	0.3	0.5
P_2O_5	0.21	0.10	1.05 (0.19–6.12)	-	-	-	-	-
SiO_2	54.97	21.38	63.57 (22.95–85.17)	19.8 (18.8–20.6)	35.0	52.0	35.0	90.0
SO_3	0.93	3.24	0.51 (0.03–4.38)	3.3 (2.5–4.1)	4.1	0.8	2.0	0.4
SrO	0.16	0.03	-	-	-	-	-	-
TiO_2	1.60	0.29	0.58 (0.08–3.68)	-	-	-	-	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	77.39	29.14	74.83 (27.20–91.92)	27.4	59.0	86.0	48.0	90.8
Relative density	2.16	3.12	2.12 (1.85–2.47)	3.15	2.65	2.38	2.94	2.40
LOI	13.76–16.55	2.48	7.04 (0.40–59.20)	0.0–3.3	0.3–3.5	0.2–7.2	1.0	0.0–2.8

Per ASTM C618 [10], the SCBA used in this study achieved the 70% minimum requirement for the $SiO_2 + Al_2O_3 + Fe_2O_3$ sum. The calcium oxide (CaO) also had a value of 9.98%, which falls under the class F maximum requirement. It can also be observed that the SCBA used in this study had similar results to Fly Ash-F reported in other studies.

3.2. Pastes

3.2.1. Thermogravimetric Analysis (TGA)

Powders from pastes cured for 28 days were analyzed by means of TGA. Figure 3a,b shows the thermogravimetric and differential thermogravimetric curves (first derivative) for samples with TSCBA replacements of 0, 10, and 20%, cured at 21 and 45 °C. These mixtures were chosen as they exhibited the best results in terms of compressive strength, especially as the amount of SCBA replaced increased. The TGA analysis was primarily used to quantify the amount of calcium hydroxide (CH), by determining the weight loss between 405 and 490 °C and using the tangential and modified method suggested by [40,46]. These methods subtract the amount of weight loss from the dehydration of other compounds in the same region, and consider the amount of CH that may have carbonated during sample preparation, respectively. The correction results in the quantification of the CH weight loss only. The CH content is reported in Table 4. For both curing temperatures, the CH content decreases with the increase in the substitution rate of TSCBA within the mix, which may be interpreted as a major consumption of CH in the pozzolanic reaction. Besides this, in the paste samples cured at 45 °C, the CH content was higher than that in samples cured at a lower temperature (21 °C), suggesting that the higher curing temperature led to higher CH formation. However, the increase in the amount of CH was reduced as the replacement level of SCBA increased, which indicates that the higher curing temperature also aided the pozzolanic reaction.

Table 4. Calcium hydroxide content in pastes (28 days) based on TGA.

Calcium Hydroxide (%)		
	Reference	23.83
21 °C	10%	20.83
	20%	18.79
	Reference	27.74
45 °C	10%	23.23
	20%	18.91

In general, the same behavior was observed for all samples after 28 days of hydration. Peaks were observed between 35 and 180 °C, attributed to ettringite (AFt), calcium silicate hydrate (C-S-H), and aluminate ferrite monosulfate (AFm) phases of dehydration, with no significant difference. There was a significant mass loss between 400 and 480 °C due to the decomposition of CH. Finally, at temperatures above 600 °C, calcium carbonate ($CaCO_3$) decarbonation occurred in all samples.
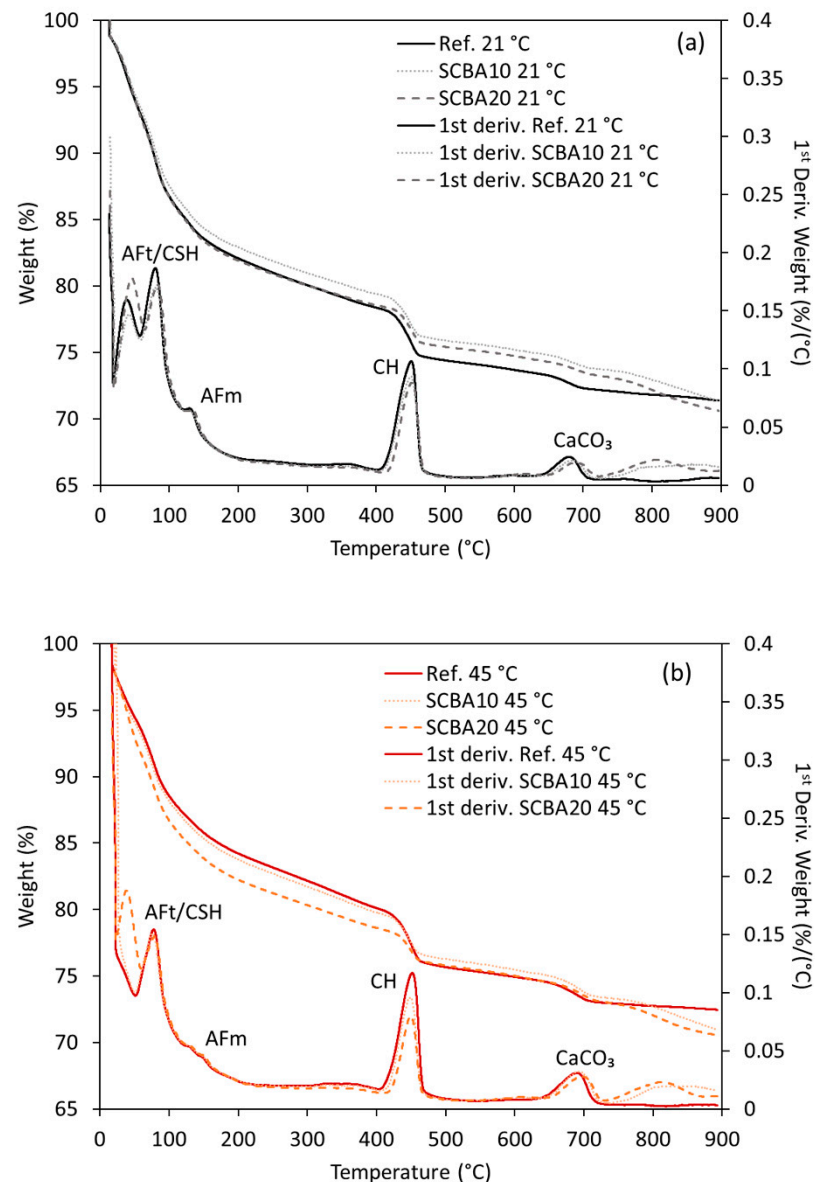
Figure 3. TGA of pastes cured for 28 days at (**a**) 21 °C and (**b**) 45 °C.

3.2.2. X-Ray Powder Diffraction (XRD)

Figure 4 displays the XRD result for the SCBA employed in this study. The mineral compositions from diffraction peaks for SiO_2, Al_2O_3, CaO, and Fe_2O_3 were identified in agreement with the oxide compositions (Table 3). The analysis confirmed that silicon oxide is the predominant mineral component in the ash. Crystalline silica in quartz form was easily noticed, with sharp peaks at 20.9 and 26.6 2θ. It can also be noticed that the SCBA presented a wide scattering band revealing the presence of amorphous phases mainly associated with silica (Cu-Kα 2θ ranging from 15 to 30°).

X-ray diffraction was explored as a qualitative method for understanding the effect of TSCBA substitution and curing temperature on the formation of hydration products. The X-ray diffraction patterns of the sample containing 0, 10, 20, and 30% TSCBA tested at 28 days are portrayed in Figure 5a (paste cured at 21 °C) and Figure 5b (paste cured at 45 °C). The XRD results indicate that CH had the highest presence in the chemical composition of all the samples. The main change can be observed in the CH peaks, which decreased in intensity with the incorporation of TSCBA as result of the consumption of the portlandite (CH) due to the pozzolanic reaction. Nevertheless, there were no significant

changes in the peak intensity of the other compounds. The peaks of calcite confirm the carbonation of all pastes to some extent. Besides this, even though a small reduction in the portlandite content was observed with the higher curing temperature, no substantial difference was observed.
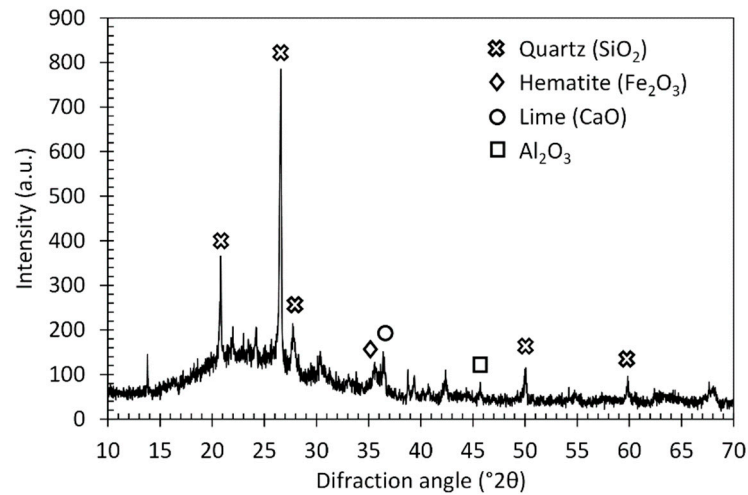

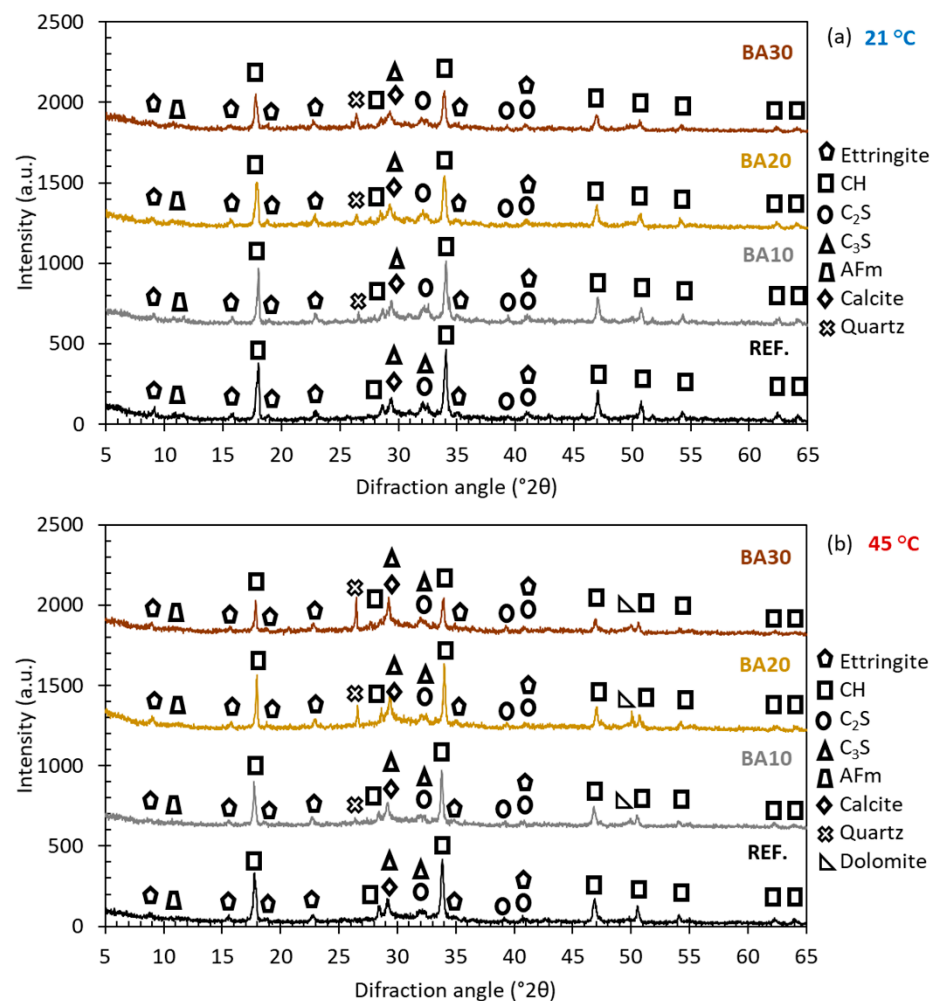**Figure 4.** X-ray diffraction pattern of the raw SCBA.

Figure 5. X-ray diffraction patterns of pastes tested after 28 days curing at (**a**) 21 °C and (**b**) 45 °C.

The presence of unreacted silica in the form of quartz in TSCBA samples is attributable to the quartz contained in the ash, as confirmed by its absence in the reference samples. Finally, the presence of C_3S (alite) and C_2S (belite) compounds around 2θ—32° in the samples indicates the incomplete hydration of blended cement at the age of 28 days.

3.3. Mortars

3.3.1. Compressive Strength of Mortars

Figure 6 represents the compressive strength results of USCBA and TSCBA mortar specimens cured at 21 °C and 45 °C, at 7, 28, and 90 days. Overall, TSCBA specimens showed a greater compressive strength than their corresponding USCBA specimens, with a higher difference as the replacement level increases. At 7 days and at a normal curing temperature of 21 °C, the replacement of 10% cement with TSCBA increased the compressive strength by 10% with respect to the plain mortar. However, with a 20 and 30% replacement, the compressive strength was reduced by 4 and 20%, respectively. Nevertheless, when cured at 45 °C, all TSCBA samples demonstrated a higher compressive strength than their reference mortar without ashes, regardless of the replacement level. Furthermore, all TSCBA samples cured at 45 °C presented higher compressive strength results with respect to the same mixes cured at 21 °C. The higher result was obtained with a 20% replacement, which recorded an increase in compressive strength of 18% compared to its reference at the same curing temperature and a 30% increase compared to the reference mortar cured at 21 °C, while mixes with 10 and 30% replacements of cement by TSCBA showed 15 and 7% increases in comparison to their reference at the same curing temperature, respectively. When USCBA was used, the trend was similar, with all mixes cured at 45 °C showing increased compressive strength with respect to the same mixes cured at 21 °C. Thus, when using SCBA in mortar, a higher curing temperature (up to 45 °C) is beneficial for the compressive strength at early ages.

After 28 days of curing, the compressive strength decreased as the SCBA replacement level increased. Nevertheless, all specimens containing SCBA cured at 45 °C had either similar or higher compressive strengths to their corresponding specimens cured at 21 °C. However, when no ashes were used, the mortar cured at 45 °C exhibited significantly lower compressive strength than the mortar cured at 21 °C, and the mortars containing SCBA regardless of the replacement level. This can be explained by the cross-over effect, and will be discussed in the following section. Notably, the high curing temperature of 45 °C was most beneficial for a high replacement volume of SCBA. The highest improvement in compressive strength at 45 °C compared to the same mixture cured at 21 °C was obtained when cement was replaced with 30% of SCBA. At 90 days, the disparity between the reference mortar and TSCBA samples cured at 21 °C diminished. Among the specimens incorporating SCBA and cured at 45 °C, all except those with a 30% SCBA replacement exhibited either comparable or superior compressive strength compared to their counterparts cured at 21 °C.
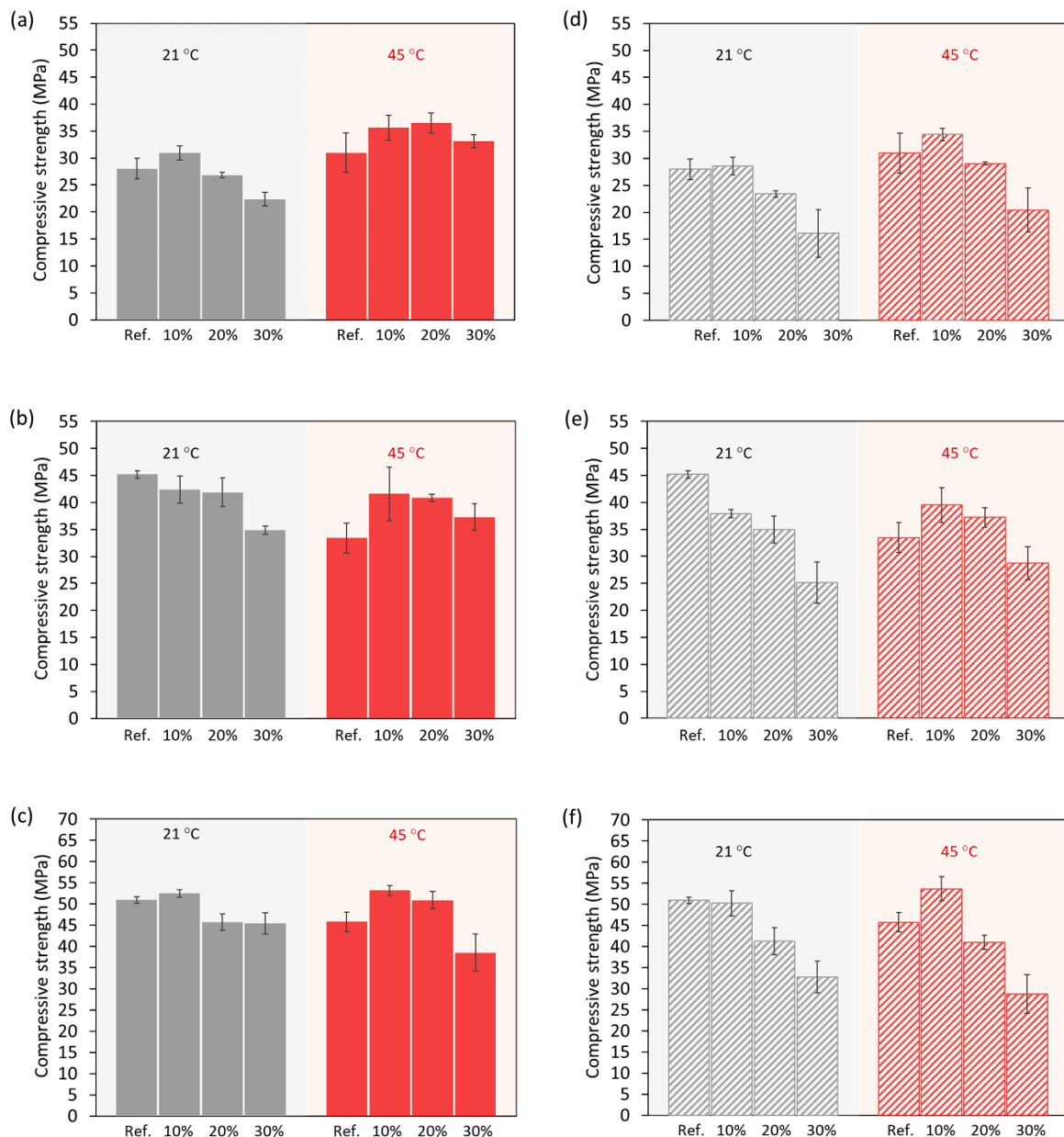
Figure 6. TSCBA compressive strength results at (**a**) 7 days, (**b**) 28 days and (**c**) 90 days and USCBA compressive strength results at (**d**) 7 days, (**e**) 28 days, and (**f**) 90 days.

3.3.2. Cross-Over Effect

Traditional cementitious composites, when undergoing cement hydration at higher curing temperatures, may experience a phenomenon known as the cross-over effect (COE) [47]. This effect is characterized by an initial acceleration of the hydration process that leads to rapid strength development at early ages, followed by a reduction in mechanical properties at later stages [47]. This phenomenon is primarily due to the rapid consumption of calcium hydroxide (CH) at higher temperatures, which limits the ongoing hydration and formation of calcium silicate hydrate (C-S-H). Due to its high silica content, SCBA plays a crucial role in mitigating this effect through its pozzolanic reaction. This reaction is slower than the initial hydration of Portland cement, which is advantageous in high-temperature curing environments where rapid CH formation can lead to strength reduction over time. As shown in Figure 6, specimens cured for 28 and 90 days containing 10% and 20% TSCBA reported a lower reduction in compressive strength (f'(c)) when cured at a higher temperature (45 °C) versus a lower temperature (21 °C), compared to the reference sample without

TSCBA. Therefore, the results indicate that replacing cement with SCBA may mitigate the cross-over effect due to high curing temperature.

A plausible explanation for this phenomenon may be attributed to the inherent reactivity of SCBA within the cementitious matrix. The gradual consumption of CH by SCBA through pozzolanic activity allows for the continued formation of C-S-H even after the initial hydration peak has passed, which offsets the rapid hydration caused by high-temperature curing. Besides this, the increase in curing temperature may act as a catalyst for pozzolanic reaction. When using SCBA, higher curing temperatures could accelerate the formation of CH, and the subsequent reaction of the CH with the SCBA to form C-S-H, thereby leading to improved mechanical properties in the long term.

3.3.3. Modified Strength Activity Index (MSAI)

Figure 7 displays the modified strength activity index for the investigated mortars. The MSAI was computed for both USCBA and TSCBA cured at 20 °C and 45 °C for all replacement values at 7 and 28 days. The obtained results indicate that all SCBA mixtures achieved the SAI 75% minimum requirement, apart from the 30% USCBA samples at 7 days cured at 21 °C and 45 °C, and the 30% USCBA samples at 28 days cured at 21 °C. However, when 30% USCBA samples were cured at 45 °C, they were able to meet the SAI minimum requirement of 75% after 28 days. On the other hand, all TSCBA samples met the SAI requirement regardless of the replacement level.
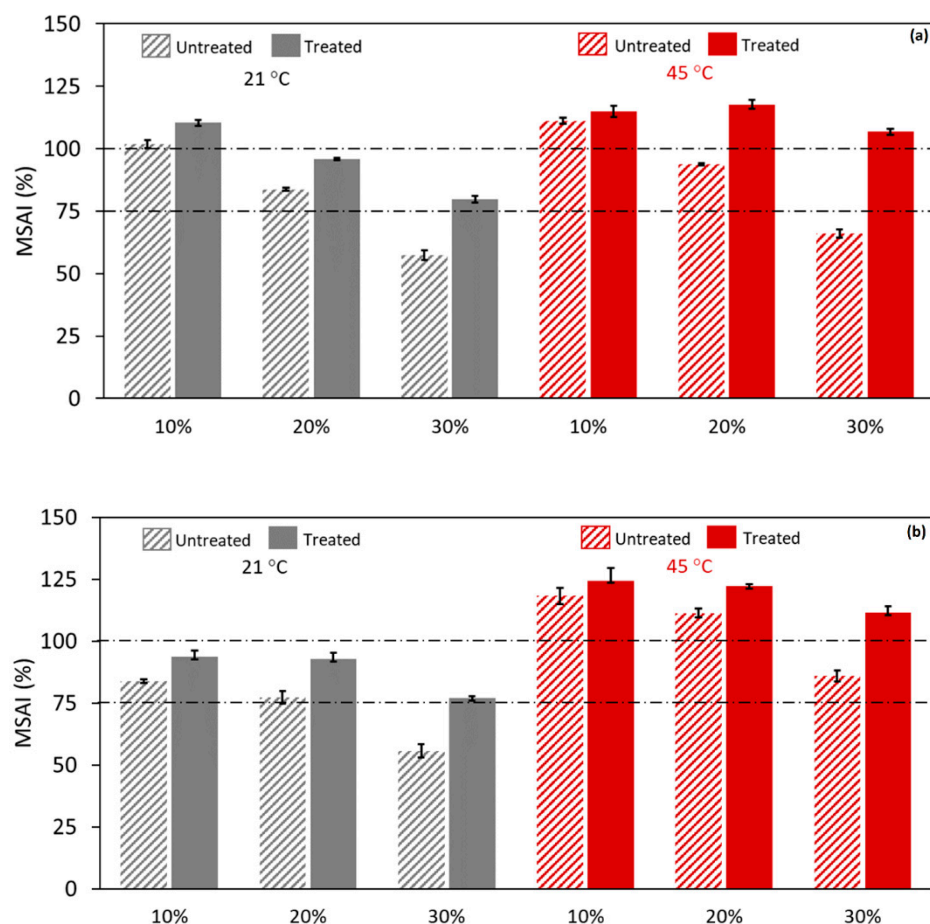

Figure 7. Modified strength activity index at (**a**) 7 days and (**b**) 28 days.

Overall, the TSCBA cured at 45 °C had the greatest performance, regardless of the replacement level. The results suggest that TSCBA can be used up to 30% replacement without compromising the strength, when the curing temperature is higher.

3.3.4. Cost-Analysis

Table 5 presents the cost analysis results for the mixtures used for this experimental campaign, and the cost reduction of the cementitious mixture (Δ$) as a function of the amount of cement replaced with SCBA. Equation (1) was used to compute the mixture cost per m^3 of mortar.

$$C_M = \sum(a * b)_i \tag{1}$$

where a = material quantity in metric ton; b = material cost per ton of material (presented in Table 2); i = i-th material compound of the mixture; C_M is the cost of the mixture in USD.

Table 5. Cost of studied mixtures.

SCBA Replacement (%)	Cement	SCBA	Sand	Water	Cost of Mixture (per m^3)	(Δ$)
		(metric ton)				
0	0.49	0.00	1.46	0.24	$ 79.59	-
10	0.44	0.05	1.46	0.24	$ 74.68	−6.16%
20	0.39	0.10	1.46	0.24	$ 69.78	−12.32%
30	0.34	0.15	1.46	0.24	$ 64.88	−18.48%

As displayed in Table 5, the cost of the mixtures decreases with the replacement of cement with SCBA. The analysis shows that the cost of final mixture can be reduced by up to 18% when an SCBA replacement of 30% is employed, while still having an acceptable compressive strength. The main reason is that SCBA is regarded as a waste and is yet considered a commodity, meaning it does not hold any economic value hitherto. Besides this, SCBA is often relegated to landfill disposal, which sustains specific costs. These disposal costs, combined with the environmental burden of waste accumulation, present a dual challenge that can be leveraged by reusing the SCBA waste. Therefore, even in a scenario where SCBA may not be freely available, the offset of landfill fees can result in net savings. In 2020, the Environmental Research & Education Foundation (EREF) reported that the national average landfill tipping fee in the United States was USD 53.72/ton, with a standard deviation of USD 29.62 [48]. These numbers highlight a significant potential cost burden for companies dealing with SCBA as a waste. By diverting SCBA from landfills and repurposing it as a cement replacement, these companies can avoid substantial landfill fees. This not only represents a direct cost-saving measure, but also aligns with broader environmental sustainability goals.

While SCBA can be considered an industrial waste byproduct and may be available at no direct cost, several associated costs need to be considered to provide a more comprehensive cost analysis. In this study, the costs analysis for SCBA includes transport and processing. Collecting the ash and transporting it to cement production facilities incurs logistical costs, which may vary depending on the distance between the sugar mill (where the SCBA is generated as a byproduct of energy generation) and the cement plant or construction site. For this calculation, the average distances between all of the major sugar mills and cement plants in Louisiana and Florida were considered, which account for over 90% of the total U.S. sugarcane production area. The average distance was approximately 200 km and the cost for transport was calculated at USD 0.039 per ton per kilometer. Additionally, as discussed in the manuscript, SCBA often requires further processing to meet specific standards, such as particle size requirements or quality, for use as an SCM. Processing involves burning the SCBA and grinding it into a fine powder, which demands both energy and infrastructure. Based on the available data [49], the cost of burning and grinding SCBA was estimated, using a total energy consumption of 1000 kWh, an average U.S. retail electricity price of USD 0.07 per kWh, and an electrical consumption for grinding of 77 kWh per ton. This resulted in costs of approximately USD 70.00 for burning and USD 5.39 for grinding per ton. Thus, on average, the combined transport and processing costs are estimated to be as high as USD 82 per ton, which aligns with estimates

from other studies on similar materials [50]. However, when accounting for cost savings from diverting SCBA from landfills (based on the national average landfill tipping fee in the U.S.), the total estimated net cost for SCBA is approximately USD 30 per ton. While our cost estimates account for additional processing, such as burning and grinding, it is important to note that the extent of this step may vary depending on the efficiency of the sugar mill's boiler and its combustion process. In some cases, SCBA may already meet the required quality standards without further treatment, which could reduce overall costs. This approach allows for a more focused evaluation of the unique cost-saving benefits of utilizing SCBA, emphasizing its potential as a sustainable alternative to traditional cement.

4. Conclusions

This investigation focused on the valorization of SCBA as a partial replacement for cement. Its adoption offers a dual advantage: it mitigates the financial burden of waste disposal for producers while contributing to the development of more sustainable construction practices.

The incorporation of SCBA in mortar can lead to similar or even increased compressive strength compared to traditional cement, especially for high curing temperatures up to 45 °C. The results suggest that the optimum percentage of replacement of cement with SCBA is between 10 and 20%. However, even a substitution of up to 30% of cement with SCBA can yield favorable results when a finer particle size and higher curing temperature are employed, as revealed by the 7- and 28-days SAIs, which exceeded 100%. The fineness of the ashes is key for a higher performance. As the amount of SCBA increases, the beneficial effect of smaller particle size is more significant. Additionally, the findings indicate that SCBA mitigates the cross-over effect, where the early-age strength is accelerated, but long-term strength remains unaffected due to the continuous pozzolanic reaction.

The economic analysis revealed that using SCBA as a cement replacement can lead to substantial cost savings. At 30% replacement, the total cost of the mixture was reduced by up to 18.5%. The reuse of SCBA also presents a sustainable alternative to landfilling, reducing both environmental and economic burdens.

Overall, the use of SCBA in cement-based composites can yield a good performance even with replacement values up to 30%. The potential benefits of using SCBA as an alternative to traditional SCMs include improved mechanical properties, increased durability, and reduced cost and environmental impacts. However, ongoing research is essential to optimize its performance and ensure consistent quality for broader application in the construction industry. To address the variability in SCBA composition and its influence on mechanical performance, the application of consistent processing techniques, including optimized combustion and potentially further calcination, is recommended. These methods can reduce LOI and enhance the uniformity of the ash's pozzolanic characteristics. Continued research should aim at refining these processes to ensure the production of consistent, high-quality SCBA for use in cementitious composites, and increased market acceptance.

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