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Sustainable Concrete from Industrial and Agricultural By-Products: Performance and Life-Cycle Assessment of Slag-Bagasse Blends in Treated Recycled Aggregate Concrete

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Abstract

Developing sustainable concrete from industrial and agricultural by-products addresses environmental challenges of cement production and construction waste. The research focuses on the synergistic effects of incorporating ground granulated blast furnace slag (GGBS) and sugarcane bagasse ash (SCBA) as partial cement replacements in concrete made with 33% treated recycled concrete aggregates. Mix designs were prepared with varying SCBA (0%, 5%, 10%) and GGBS (0%, 25%, 50%) contents. The SCBA was characterized using X-ray diffraction (XRD) and scanning electron microscopy (SEM) to confirm its reactivity. The aggregates were treated using a three-stage method involving sodium silicate and silica fume (SF), the latter also being included in the concrete matrix. The performance of these sustainable mixes was evaluated through compressive strength test, rapid chloride permeability test (RCPT), a comprehensive life cycle assessment (LCA), and an economic feasibility study. Based on the findings, the mix with 50% GGBS and no SCBA achieved the best balance of mechanical properties, economic benefit, and a lower environmental impact, with notably a 19.6% reduction in CO_2 emissions for every 25% increment of GGBS compared to the control mix with 0% GGBS (R-S0-B0). Replacing 20% of the remaining cement with SCBA in this optimal mix further enhanced durability, reducing chloride ion permeability by over 67%, although it incurred a slight strength reduction and higher cost. The critical role of SF was demonstrated, as its omission severely compromised chloride resistance. Moreover, the significant potential of tailored GGBS and SCBA combinations in producing high-performance, sustainable recycled aggregate concrete is confirmed.

Keywords

Recycled Aggregate Concrete
Ground Granulated Blast Furnace Slag (GGBS)
Sugarcane Bagasse Ash (SCBA)
Life Cycle Assessment (LCA)
Sustainable Construction
Waste Valorization
Chloride Permeability

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1. Introduction

Concrete, a key construction material, is favored for its rather acceptable strength, durability, and maintenance cost [1,2]. However, the environmental impact of using Portland cement (PC) in concrete is a growing concern [3]. The production of PC consumes high energy and natural resources, emitting approximately one ton of CO_2 per ton of cement [4,5]. Aggregate use in concrete also poses environmental issues, including habitat damage and landscape alteration, which contribute to biodiversity loss and soil erosion [6]. These impacts highlight the urgent need for sustainable materials and methods in concrete production.

The adoption of recycled aggregates (RA) in concrete production is a key strategy for sustainable construction, contributing to reduced consumption of non-renewable resources and lower greenhouse gas emissions [7]. RA, sourced from construction and demolition waste, serve as sustainable alternatives to virgin materials, cutting production costs, and repurposing construction waste as aggregates [8-10]. Two primary methods exist for aggregate recycling in concrete: mechanical grinding and the two-stage mixing approach [11]. Mechanical grinding, which uses abrasion to remove mortar, is well-studied for its simplicity [12,13]. The two-stage mixing method, aimed at surface modification, has received less attention but shows potential to improve recycled aggregate quality [14,15].

Minimizing cement consumption is crucial due to its environmental impact. Using minerals and waste materials from agricultural and industrial sources offers a promising alternative [16,17]. Sugarcane bagasse ash (SCBA), rich in amorphous silica, can effectively replace cement, improving concrete's durability and strength [18-21]. v [22-24]. Annually, over 1.5 billion tons of sugarcane present an opportunity to reuse bagasse waste in concrete [5,25]. This method not only utilizes waste for environmental benefits but also boosts concrete durability and performance. In the steel industry, the Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) produce steel slag, a valuable byproduct [26,27]. GGBS, derived from steel slag, offers environmental and economic benefits by reducing waste and energy use [28-30]. It also enhances concrete strength and durability [31,32]. While the benefits of SCBA and GGBS in binary blended natural aggregate concrete are documented [33,34], their combined use for sustainable recycled concrete needs further investigation [35]. This highlights a promising direction for eco-friendly concrete through multi-material substitutions.

While previous studies have established the individual merits of GGBS and SCBA as supplementary cementitious materials, and some have explored binary blends in conventional or recycled aggregate concrete, a significant research gap exists concerning their synergistic effects within a system employing chemically treated recycled aggregates. Furthermore, comprehensive assessments that simultaneously evaluate mechanical performance, durability, environmental impact (via LCA), and economic viability for such a multi-component sustainable concrete are scarce. To address this gap, this study investigates the combined use of GGBS and SCBA as partial cement replacements in recycled aggregate concrete (RAC) made with aggregates treated by a novel three-stage method involving sodium silicate and silica fume (SF). A range of concrete mixes with varying proportions of GGBS (0%, 25%, 50%) and SCBA (0%, 5%, 10%) were produced. Their performance was rigorously evaluated through compressive strength tests, rapid chloride permeability tests (RCPT), and microstructural analysis (XRD/SEM). Crucially, this work integrates these technical findings with a comprehensive life cycle assessment (LCA) and a detailed cost analysis, providing a holistic view of the feasibility and sustainability of the proposed concrete mixes for practical application in the construction sector.

This research embarks on an investigation into the combined use of GGBS and SCBA as partial replacements for cement in recycled aggregate concrete (RAC). Setting this study apart from existing literature, it introduces a detailed examination of the combined effects of these additives and a three-stage mixing method on the properties of sustainable concrete containing treated recycled aggregates and silica fume (SF), addressing a system that has received less attention compared to studies on binary blends or individual SCMs in RAC [22-24, 33-35]. A mixing method enhanced with pozzolanic materials, such as SF and sodium silicate (SS), was employed to improve the properties of sustainable concrete. By incorporating varying proportions of GGBS and SCBA as partial cement replacements, a range of concrete samples was produced. The investigation evaluated compressive strength, supplementary material reactivity (activity index), microstructural characteristics, and resistance to chloride ion penetration, which are critical indicators of concrete performance. Additionally, this study incorporates a life cycle assessment (LCA) to assess the environmental impact spanning from raw material extraction to recycling, coupled with a cost analysis to establish the economic viability of the proposed mixes, collectively and innovatively providing a comprehensive multi-criteria evaluation that underscores the potential for their broader application in the construction sector.

2. Matrials and Methods

2.1 Materials

This study examined the combined impact of treated RA, GGBS, SF, and SCBA on green concrete. Natural fine aggregates (NFA) were sand with a water absorption rate of 3.30% and a specific gravity of 2.62 g/cm³, as per ASTM C128 [36]. Natural Coarse aggregates (NCA) had a maximum size of 19 mm, a water absorption rate of 1.99%, and a specific weight of 2.68 g/cm^3, as per ASTM C127 [37]. Recycled coarse aggregates (RCA) from a demolished residential building in Qom, Iran, were treated with SS, using distilled water from Qatran Shimi Tajhiz company. The concrete was processed using a compression rod and a laboratory crusher. Fig. 1 demonstrates that both natural and treated recycled aggregates (RCA) comply with ASTM C33 [38] grading limits. The RCA's water absorption (2.93%) and specific gravity (2.65 g/cm³) were within typical ranges for concrete applications, as per ASTM C127.

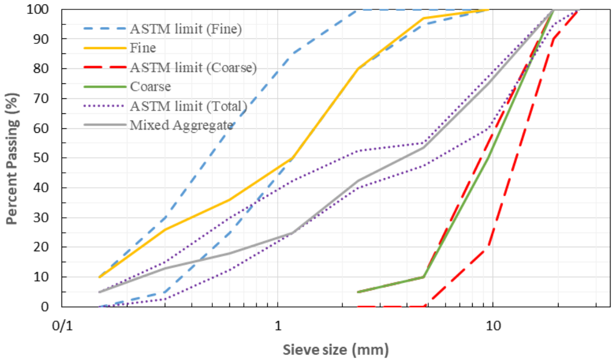


Fig. 1 Grading curves for natural and treated RA used in this study

The main binder utilized in this study was PC Type I, manufactured by Delijan Cement Company in Iran, and it complied with all the specifications of ASTM C150 [39]. The PC had a specific surface area of 3230 cm^2/g according to ASTM C204 [40]. The initial and final setting times were recorded at 115 and 235 minutes, respectively. The 28-day compressive strength of the cement mortar was found to be 47 MPa. In addition to PC, a combination of other binders was used in some concrete samples. GGBS and SF were obtained from Kavir Kashan Cement Company and Iran Ferrosilice Company, respectively. Sugar Cane Bagasse Ash (SCBA) was produced in the laboratory using bagasse provided by Karun Agro Industries Incorporated in Iran. Table 1 presents the chemical composition, Loss of ignition (LOI), and specific surface area of the binders used in this study. To enhance workability, the polycarboxylate ether-based superplasticizer (SP), i.e., Super Plasticizer 163-New, manufactured by Namikaran Company in Tehran, Iran, was used. The dosage was based on the water-to-binder ratio and targeted slump value per ASTM C494 [41].

Table 1 Chemical composition, Loss of Ignition, specific surface, specific gravity of PC, SCBA, SF, and GGBS used in this study.

Chemical Composition (%)	PC	SCBA	GGBS	SF
SiO_2	20.4	79.6	37.88	90.7
AL_2O_3	4.58	4.5	13.29	1.1
CaO	64.01	3.3	36.76	2.15
MgO	1.09	1.0	7.63	0.55
Na_2O	0.54	0.2	0.62	0.35
K_2O	0.74	2.4	0.76	0.7
TiO_2	-	-	1.52	-
Fe_2O_3	4.28	4.9	0.54	1.2

SO_3	1.74	0.7	0.2	-
other	2.62	3.4	0.8	3.25
Loss of Ignition (LOI)	2.6	4.6	-	1.2
Specific surface (cm^2 /gr)	3230	3950	4600	1450
Specific gravity (gr/cm^3)	3.08	2.22	3.22	2.2

Unprocessed sugarcane bagasse does not effectively react with cement hydration products and requires thermal activation. To observe the physical changes in SCBA, a set of samples was heated to 550 °C. As shown in Fig. 2, the unsieved samples exhibited a noticeable color change after approximately 60 min. The sieved SCBA produced at 550 °C exhibited a low LOI of 4.6% (Table 1), confirming effective carbon removal.

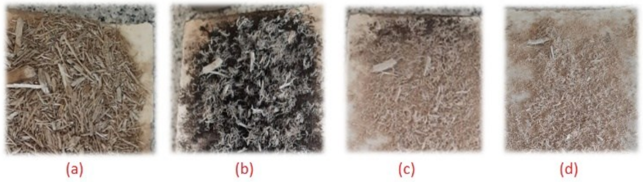


Fig. 2 Unsieved Sugarcane bagasse exposed to a temperature of 550°C: (a) raw materials, (b) after 30 minutes, (c) after 60 minutes, (d) after 120 minutes

To produce large quantities of SCBA under conditions more or less similar to free combustion of bagasse in sugarcane fields, the cylinder-shaped gas furnace shown in Fig. 3 was used. The special geometry of this 250-liter furnace facilitated the flow of hot air and consequently created a near-constant temperature throughout its interior. Within an hour, the furnace temperature was raised from ambient temperature to about 550 °C. Consequently, to penetrate heat into the depth of the bagasse mass, the temperature was kept constant for 3 hours. After cooling freely in the air, the remaining product was removed from the furnace and passed through the sieves to remove unburned particles and gravel debris. To ensure that the furnace was not choked, a few rows of refractory bricks were arranged around the pile of materials.

Fig. 3 (a) Furnace used to produce SCBA (b) inside the furnace before combustion (c) inside the furnace after combustion

2_2Mix proportion

Table 2 outlines the mix proportions for all concrete samples, categorized into control (1), main (2-10), and supplementary (S1-S2) groups. The main categories explore the effects of SCBA in samples 2-4, GGBS in samples 2, 5, and 8, and a combination of SCBA and GGBS in samples 6, 7, 9, and 10 on recycled aggregate concrete. Each sample is named following a format that indicates the type of coarse aggregate and the content of SCBA and GGBS (e.g., R-S25-B10).

Table 2 **Detailed proportions of concrete mix components expressed in kg/m^3**

		Aggregate				Binder				
Sample	Mix ID	NCA	Non-Treated RCA	Treated RCA	NFA	W	PC	GGBS	SCBA	SF
1	NR-S0-B0*	865	0	0	848	203.65	407.3	0	0	20.36
2	R-S0-B0	577	0	287	857	199.56	399.12	0	0	19.96
3	R-S0-B5	577	0	287	857	199.56	379.16	0	19.96	19.96
4	R-S0-B10	577	0	287	857	199.56	359.21	0	39.91	19.96
5	R-S25-B0	577	0	287	857	199.56	299.34	99.78	0	19.96
6	R-S25-B5	577	0	287	857	199.56	279.38	99.78	19.96	19.96
7	R-S25-B10	577	0	287	857	199.56	259.43	99.78	39.91	19.96
8	R-S50-B0	577	0	287	857	199.56	199.56	199.56	0	19.96
9	R-S50-B5	577	0	287	857	199.56	179.60	199.56	19.96	19.96
10	R-S50-B10	577	0	287	857	199.56	159.65	199.56	39.91	19.96
S1	R-S0-B0-WT**	577	287	0	857	199.56	399.12	0	0	19.96
S2	R-S0-B0-WSF-WT+	577	287	0	857	199.56	399.12	0	0	0

*NR: with No RCA. **WT: Without Treatment of RCA (by SS and SF). +WSF: Without SF in mix design.

2.3 Treatment of Recycled Concrete Aggregates (RCA)

The treatment process of the crushed RCA, schematically illustrated in Fig. 4, consisted of three stages:

(I) As shown in Fig. 4a, the RCA were immersed in a sodium silicate (SS) solution with a concentration of 12.5 wt% (SiO_2/Na_2O mass ratio of 3.0) for 1 h. The immersion was conducted at a solution-to-aggregate mass ratio of 0.5.

(II) After immersion, the aggregates were drained and spread in a thin layer, as depicted in Fig. 4b. This stage lasted 3 h under ambient laboratory conditions (20 ± 2 °C) to achieve a saturated surface-dry (SSD) state.

(III) In the final stage (Fig. 4c), the SSD-conditioned aggregates were uniformly coated with SF powder. The SF content was fixed at 2% of the total binder mass (cement + GGBS + SCBA). This was achieved by mixing the aggregates with SF powder in a rotary mixer for 5 min to ensure complete coating. The coated aggregates were then left undisturbed for 4 h to facilitate the formation of additional C–S–H gel [42].

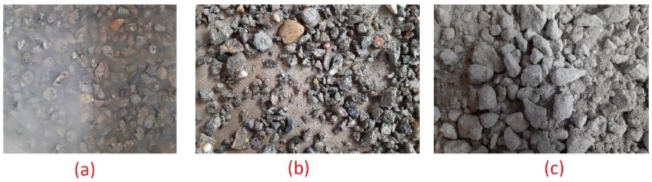


Fig. 4 **Preparation of crushed aggregates: (a) pre-soaked in SS (b) air dried (c) soaked in SF powder**

Note that the treated RCAs were used in concrete mixing within 24 hours of treatment to prevent any significant moisture loss.

2.4 Fabrication of RCA samples

Fabrication of treated RCA samples was conducted in two steps:

(I) The materials were mixed using a three-stage method [43]. Initially, 1.2 times the total water needed for aggregates to reach the SSD state was added. Next, GGBS and SCBA content were added and blended. Finally, all the required cement and SP dissolved in water residue were successively added, followed by additional mixing.

(II) Fresh concrete was poured into the molds. The sample surface was covered to prevent evaporation of the concrete water.

2.5 Experimental program

Compressive strength tests were performed on three cubic specimens with dimensions of 100×100×100 mm^3 for each of the mix designs #1 to #10 and at the ages of 7, 28, and 91 days [44]. Rapid Chloride Permeability Test (RCPT) was carried out on 7 series of 90-day cylindrical samples in accordance with ASTM C1202 [45]. They were related to samples lacking slag-bagasse combination (#1,#2), with GGBS but without SCBA (#5,#8), containing the highest amount of slag-bagasse replacement (#10), and supplementary mix designs S1 and S2. Moreover, the reactivity of the available GGBS and produced SCBA was measured in accordance with ASTM C989 [46] and ASTM C311 [47]. The fresh density of concrete mixtures immediately after the completion of mixing was determined according to ASTM C138 [48].

2.6 Life Cycle Assessment and Cost Analysis

The product life cycle encompasses all stages of a product's existence, from the extraction of raw materials through production, use, and eventual disposal or recycling. LCA is a valuable tool for evaluating the environmental impact of products or systems throughout their entire life cycle, including the production, use, and disposal or recycling stages [49]. In the construction industry, LCA plays a critical role in evaluating the environmental impact of materials such as concrete, steel, and wood, and in developing strategies to reduce this impact using sustainable materials or changes to the production process. Sustainable construction materials are becoming increasingly important for reducing environmental impacts and improving sustainability [50]. Additionally, green building certification programs require the use of LCA in the evaluation of construction materials. By evaluating construction materials using LCA, the industry can identify areas for improvement, promote sustainable development, and meet certification requirements.

Concrete production significantly impacts the environment because of its high greenhouse gas emissions, highlighting the need for sustainable alternatives and practices to reduce its impact and promote a more sustainable future [51]. LCA is a crucial tool for evaluating the environmental impact and resource utilization of concrete production [52]. By collecting data on the environmental impacts of concrete production, including raw materials, energy consumption, waste management, water use, and greenhouse gas emissions, LCA allows for the comparison of different concrete mixtures and assessment of the potential benefits and drawbacks of using sustainable additives, leading to more sustainable concrete production practices that benefit both the industry and the environment. LCA applies three types of boundary conditions for concrete production: cradle-to-gate, cradle-to-grave, and cradle-to-cradle [53]. The cradle-to-gate approach evaluates the environmental impact of concrete from raw material extraction to its delivery from the plant. The cradle-to-grave approach assesses the impact from raw material extraction to disposal. The cradle-to-cradle approach considers concrete recycling. This study focuses on the cradle-to-gate boundary conditions since the production stage has the most significant environmental impact in concrete production.

In this study, a developed web tool package by the University of California, Berkeley, called as Green Concrete LCA [54], is used. This tool is a user-friendly tool that considers impact categories such as global warming potential, acidification potential, eutrophication potential, and ozone depletion potential, making it invaluable for identifying areas of improvement in concrete production and promoting more sustainable practices [55]. The LCA Web Tool has played a crucial role in advancing sustainable practices in the concrete industry, as it is widely used for LCA estimations of both conventional concrete [55,56] and concrete with RCA [57]. By evaluating the life cycle of various concrete mix designs using this tool, researchers and stakeholders can optimize the manufacturing process and reduce its environmental impact.

The data entered into the software for the LCA was based on conservative estimates, using default values if accurate data was not available. The primary functional unit adopted in this study is 1 m³ of concrete at 28 days, consistent with common practice in comparative concrete LCAs. To account for differences in mechanical performance among mixes, the environmental results were additionally normalized by the 28-day compressive strength, allowing comparison of impacts per unit strength (e.g., per MPa·m³). We also included data from the Ministry of Industry of Iran regarding the contribution of each source to electricity generation and the type and quantity of fuel used. The functional unit, or reference unit of the product system for which environmental impacts are evaluated, is commonly defined as the unit of volume (1 m^3) of concrete [58]. However, a smaller functional unit might be more appropriate for comparing the environmental impacts of various concrete mixes.

A list of factors affecting the concrete life cycle is presented in Table 3, including the type of Portland cement, substitute materials, additives, location of constituent materials, distance to transport materials, technology used in cement plants, and mixing processes at the concrete plant. The significance of considering multifunctional processes is also highlighted, where a single process can produce both the main product and several by-products. Allocating impacts to by-products is important to ensure that the environmental impact of a product is accurately assessed. Baseline and disposal avoidance scenarios were utilized to stabilize the results. However, no single allocation scenario is more valid than others, as the allocation coefficients depend on production processes, market value of materials, and the quality of raw material inputs. The examined LCA parameters included global warming potential (GWP) and air pollutants such as lead, volatile organic compounds (VOCs), NOX, PM10, and SO$_2$.

In this study, with respect to multifunctional processes, a cut-off allocation approach was adopted for industrial and agricultural by-products, consistent with the default methodology of the Green Concrete LCA web tool. Accordingly, by-products such as GGBS and SCBA were assigned no upstream environmental burdens from their primary production processes, and only impacts associated with processing, transportation, and incorporation into concrete were considered. This approach reflects their status as secondary materials whose utilization avoids disposal and offsets the demand for Portland cement. The same allocation principle was applied consistently across all mix designs to ensure comparability of results. We also considered the environmental impact of transportation scenarios by taking a conservative approach to the distances involved. We analyzed the locations of raw material supply sites and their distances from the concrete manufacturing facility in Kashan, Iran, as illustrated in Fig. 5.

Fig. 5 *Locations of raw material supply sites and their distances from the concrete manufacturing site*

Table 3 LCA Green Concrete web tool input assumptions in this study

Type of Materials	Assumption	
PC	Type I	
SCMs	GGBS, SCBA, SF	
admixture	SP	
constituent material	Location of Supplier	Distance to concrete plant* (km)

PC	Delijan, Iran	126
NCA&NFA	Kashan, Iran	127
SCBA	Shushtar, Iran	600
GGBS	Kashan, Iran	24
RCA	Qom, Iran	101
SP&SF	Tehran, Iran	251
Technology options for	**Type of technology selected**	
Cement raw materials prehomogenization	Dry process, Raw storing, preblending	
Cement raw materials grinding	Dry raw grinding, ball mill	
Cement raw materials blending/ homogenization	Raw meal homogenization, blending, and storage	
Clinker pyroprocessing	Preheater/Precalciner kiln	
Clinker cooling	Reciprocating grate cooler (modern)	
Cement finish milling/grinding/ blending	Roller press	
Clinker particulate materials control	Electrostatic precipitators (ESP)	
Conveying within the cement plant	Screw pump 20 m between process stations	
Concrete batching plant loading/ mixing	Truck loading (Truck mix)	
Concrete batching plant particulate materials control	Controlled w/ Fabric filter	
Fuel options used in	**Natural gas (%)**	**Distillate (diesel or light) fuel oil**
production of cement	93	7
Generation of electricity	87.3	12.7

Mode of Transportation: Truck Class 8b (Model 2005)

In addition to environmental benefits, the economic feasibility of sustainable concrete production is essential. The cost analysis compared sustainable concrete incorporating treated RCA, GGBS, SF, and SCBA with conventional concrete, focusing on raw material, transportation, processing, and labor costs to identify potential cost savings and barriers to adoption. Additionally, Life Cycle Cost Analysis (LCCA) was conducted to assess all associated costs from design to disposal, considering factors during production and service life to support cost management and informed decision-making in sustainability initiatives [59,60].

These components are branches of more detailed cost categories, and the analysis can be conducted using their subcategories or by focusing on one main category [61]. In some cases, when portions of the production process for the reference and test samples are identical, their costs can be jointly considered or excluded from the comparison. Key cost factors in concrete production include raw material costs, which encompass aggregates, cement, and additives. The use of additives such as fly ash, steel slag, and SF may increase certain raw material costs, particularly when replacing aggregates or cement. Production costs are primarily driven by energy consumption and labor. Transportation costs, although often grouped with raw material costs, warrant separate analysis due to the multi-stage nature of material transportation [4]. This granularity helps in pinpointing specific cost increases, especially when RCAs are used, which should be evaluated based on their specific applications. To determine costs, a unit price is assigned to each material used in product production, based on its percentage in the concrete mix [62]. This method converts the unit price of each product to the cost of the materials utilized in the production. Prices vary depending on the materials and their procurement methods. The incorporation of RCA introduces additional processing stages, which may alter costs based on the chosen recycling technique [8]. Using different percentages of SCBA and GGBS as substitutes for Portland cement can reduce cement costs, although these additives themselves have associated consumption costs. This necessitates a thorough price analysis to determine the optimal mix design by comparing costs with those of a reference sample [63].

3. Results

3.1 Activity index of GGBS and SCBA

To evaluate the reactivity of the available GGBS and produced SCBA, two sets of cement-based mortar samples were prepared, and their compressive strengths were measured at 7 and 28 days. In accordance with ASTM C989 [46] and ASTM C311 [47], 20% and 50% of the cement (by mass) were replaced with SCBA and GGBS, respectively. The activity index was calculated by dividing the compressive strength of the blended mortars by that of the control mortar (containing 100% cement as the binder), and the results are presented in Figure 6. The results indicate that both GGBS and SCBA exhibited acceptable reactivity. However, GGBS outperformed SCBA, achieving 92% of the 28-day compressive strength of the control specimen.

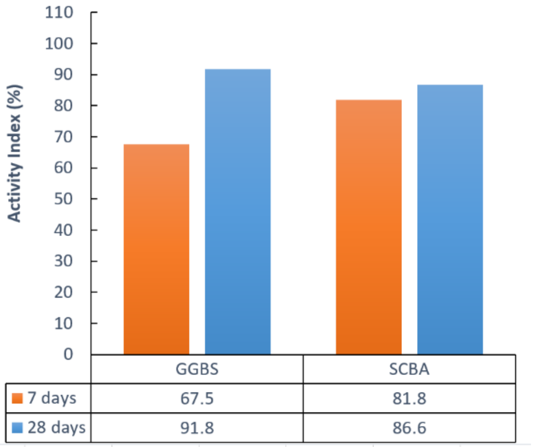
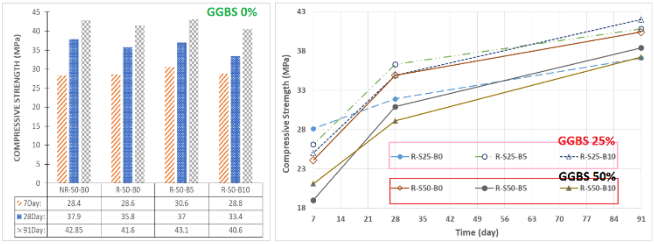


Fig. 6 Activity index of the available GGBS and produced SCBA

3.2Compressive strength and fresh density of concrete samples

For the comparison of compressive strength among different designs, the comparison could be conducted in two separate sections based on the treatment of RCA, treated and untreated [7]. Testing was conducted on samples containing treated RCA, with the treated RCA content kept constant across all mixtures, while the percentages of additives were varied. The mixture designs summarized in Table 2 include SCBA at 0%, 5%, and 10% and GGBS at 0%, 25%, and 50%. The control sample consisted of natural aggregates without additives, except for SF, which was evaluated separately. Compressive strength was measured at curing ages of 7, 28, and 91 days. The results are presented in two complementary graphs (Fig. 7) to distinguish the effects of the additives. Figure 7a focuses on the effect of SCBA (0%, 5%, 10%) in mixes without GGBS, including the control samples with natural (NR) and recycled (R) aggregates. Figure 7b illustrates the synergistic effects over time for mixes containing both GGBS and SCBA, where dashed and solid lines represent mixes with 25% and 50% GGBS, respectively.

As shown in Fig. 7a, it is observed that within the RCA samples excluding GGBS, 5% bagasse usage yields the highest compressive strength at any age. The obtained 7 and 91-day compressive strength of R-S0-B5 excels that of the non-recycled control sample, showing the effectiveness of the treatment method. However, with the addition of 25% GGBS (samples #6 to #8), a decrease in compressive strength with an increase in bagasse percentage is observed, especially in the 7-day interval (see dashed lines in Fig. 7b).



(a) (b)

Fig. 7 Compressive strength development: (a) Effect of SCBA content (0%, 5%, 10%) in mixes without GGBS; (b) combined effects of GGBS and SCBA over time.

It is observed that in the 7-day interval, at different percentages of GGBS (0%, 25%, 50%), the compressive strength of the samples generally diminishes as the SCBA content increases. However, sample R-S0-B5 showed a 7.7% increase in compressive strength compared to the control sample at the 7-day mark. At the 28-day mark, all designs exhibited a decrease in compressive strength. Sample R-S0-B5 also showed better results in this interval compared to other samples, with approximately a 2.4% reduction in compressive strength compared to the control sample. In the 91-day interval, Samples R-S0-B5 and R-S25-B10 also show the best results, with compressive strengths more than 98% of the control sample, while the other samples demonstrate a modest decline in compressive strength of up to approximately 13.4%.

The fresh density of concrete mixtures was measured immediately after mixing, and the results are presented in Table 4. The values ranged from 2308 to 2435 kg/m³, indicating that the substitutions influenced the initial volumetric characteristics of the mixes.

Table 4 Fresh density of concrete samples

	NR-S0-B0	R-S0-B0	R-S0-B5	R-S0-B10	R-S25-B0	R-S25-B5	R-S25-B10	R-S50-B0	R-S50-B5	R-S50-B10
Fresh Density (kg/m^3)	2321	2336	2381	2416	2322	2367	2402	2308	2353	2435

3.3 RCPT results

Fig. 8 compares the passed charge through a selection of main mix designs at the age of 90 days as an indication of resistance against chloride ion attack. The findings show that the application of GGBS in RAC caused a considerable reduction in the RCPT results compared to the sample R-S0-B0. i.e., by substituting half of PC with GGBS, the passed charge decreases to less than 45% of its initial value. The best performance is related to mixes R-S50-B10, where RCPT results are even less than one-third of the control specimen.

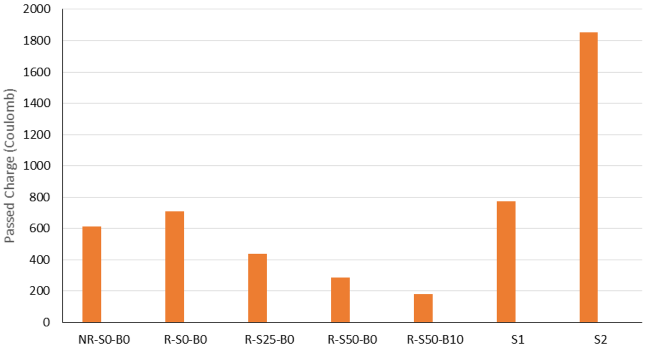


Fig. 8 Comparison of the passed charge in different samples after 90 days

To further investigate the effects of SF in mix design and aggregate treatment with SS on specimen R-S0-B0, an RCPT test was conducted on two supplementary mixes: one without treatment (S1) and one without SF in the mix design (S2). The passed charge in S1 was only 9.3% higher than that of R-S0-B0, illustrating the limited impact of SS treatment. However, the RCPT result of sample S2 was 2.4 times greater than that of S1, highlighting the critical importance of incorporating SF in recycled aggregate concrete (RAC).

3.4 Assessing Environmental Impacts through LCA Results

The life cycle assessment of sustainable concrete samples was carried out by quantifying pollution production in kilograms. Each sample's pollutant load was then compared to that of the control mix (NR-S0-B0) by calculating the percentage change. The outcomes, depicted in Fig. 9, indicate a discernible reduction in the emissions of carbon monoxide, lead, and volatile organic compounds with increased concentrations of SCBA and GGBS. Notably, sample R-S50-B10 led to a substantial decrease in pollutant levels by approximately 60%. Conversely, levels of PM_{10} and SO_2 saw an increase. In sample R-S0-B0, neither considerable exacerbation nor mitigation of these pollutants was observed.

The concentration of NO_x pollutants in the concrete samples varied minimally, with changes capped at 10%. Notably, sample R-S50-B0 demonstrated a 9.9% reduction in NO_x levels. To identify the optimal sample-the one that yields the most significant reduction in pollutant emissions- it is crucial to consider factors such as the overall decrease in pollution production [4]. However, the production amount of some pollutants in the production of a sample is low, and the decrease or increase in their production is slight. Therefore, this factor is also taken into account in the comparison. Considering the points mentioned, the reduction in CO pollutant is very tangible, while the other pollutants have much smaller changes compared to CO, ranging from approximately 30 to 600 grams. Sample R-S50-B0, with a reduction of approximately 50% in the amounts of CO, lead, and VOC pollutants, and a 9.9% reduction in NO_x, along with an increase of 19.4% and 43% for PM10 and SO_2, respectively, which translates to an increase of 26 and 34 grams, respectively. Although these increases are small in absolute terms compared to the substantial reductions observed in other impact categories, they represent an environmental trade-off that should be acknowledged in a life-cycle assessment. From a holistic LCA perspective, the overall environmental performance of mix R-S50-B0 remains favorable; however, these results highlight the importance of evaluating multiple impact categories simultaneously when assessing sustainable concrete alternatives.

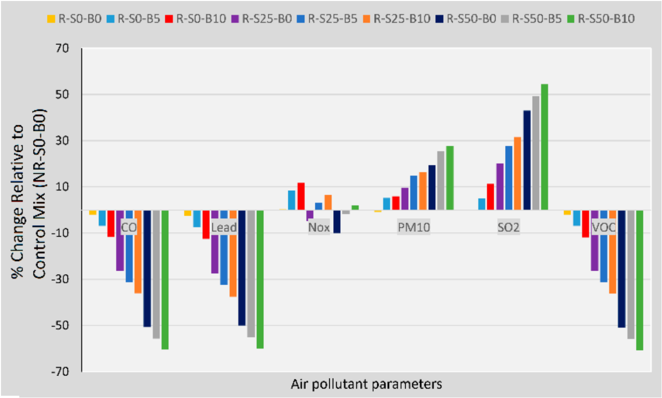


Fig. 9 Relative Change in air pollutant emissions for different concrete Mixes

In addition to the previous assessments, the carbon dioxide emissions associated with each concrete mix design were critically analyzed [50]. Figure 10 presents the CO_2 emissions for each mix, highlighting the environmental impact of cement and concrete production. Incorporation of treated RCA alone led to only a 1.7% reduction in CO_2 emissions. However, a strategic reduction in cement content combined with increased use of SCBA and GGBS significantly lowered CO_2 emissions associated with cement, despite a slight increase from concrete production. This increment is minimal compared to the reductions achieved in cement-related emissions. Overall, the total CO_2 footprint of the mix designs was substantially reduced, with mixes containing high proportions of slag-bagasse—particularly the R-S50 series—demonstrating the most favorable outcomes.

In fact, every 25% increase in GGBS resulted in a 19.6% reduction in CO_2 production (compared to the control mix with 0% GGBS), whereas every 5% increase in SCBA caused an approximately 3% reduction in CO_2 production. As a result, the combined utilization of RCA, SCBA, and GGBS significantly decreased pollutant emissions, especially CO_2.

It should be noted that to account for the differences in mechanical performance among the investigated mixes, the environmental impacts were additionally normalized by the 28-day compressive strength, expressed as impact per unit strength (MPa·m³). This performance-based normalization does not alter the relative ranking of the mixes observed using the volumetric functional unit (1 m³ of concrete). Mixes incorporating higher proportions of GGBS, particularly R-S50-B0 and R-S50-B10, continue to exhibit the lowest environmental burdens per unit strength, confirming that the reductions in CO_2 emissions and air pollutants are not solely a result of reduced cement content but are achieved without compromising structural efficiency. This consistency between volumetric and strength-normalized comparisons demonstrates the robustness of the LCA conclusions and supports the validity of the recommended optimal mix designs.

The findings from the analyses demonstrate that using SCBA and GGBS in concrete significantly reduces environmental impacts. Notably, mixes such as R-S50-B10 and R-S50-B0 excel in reducing pollutants like CO, lead, VOCs, and NO_x, with only minor upticks in PM10 and SO_2. Additionally, these optimized mix designs significantly lower CO_2 emissions, highlighting their potential for enhancing both the sustainability and environmental performance of concrete.

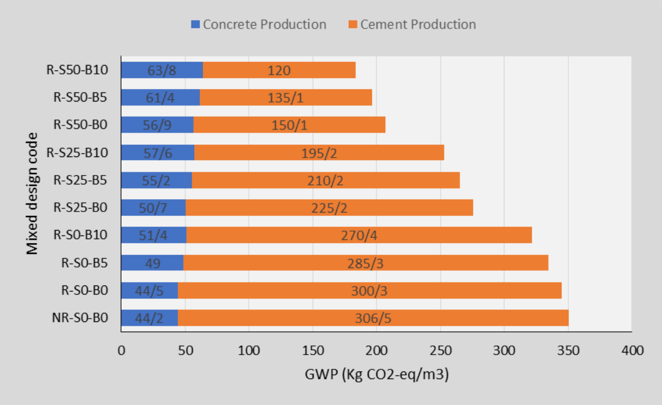


Fig. 10 Carbon dioxide emissions in different mixing plans

3.5 Economic Comparison of Concrete Mixes Using Cost Analysis

The cost analysis of each concrete mix varies based on the materials used and their respective proportions [4]. Table 5 provides a detailed overview of the unit costs for each material, expressed in dollars per ton. These unit costs are then integrated with the percentage utilization of materials and aggregates detailed in Table 2 to calculate the total costs for each design, including the control sample. The use of RCA introduces additional costs related to transportation and labor, which are not incurred by the control sample. These costs, however, are offset by the reduced cost of NA when RCA is utilized. Fig. 11 illustrates a comparative analysis of the costs, factoring in the different percentages of additives used. In terms of specific materials, the costs associated with water, SF, SP, and fine aggregate remain relatively constant compared to the control sample. Although the use of RCA necessitates higher expenditures for transportation and labor, these are included in the total cost of RCA, alongside the cost of SS solution used for treating RCA, which remains unchanged across all samples. Economically, employing RCA leads to approximately a 30% reduction in aggregate costs. Furthermore, adjusting the percentages of GGBS and SCBA has varying impacts on the cost structure. Increasing the SCBA content generally results in higher costs, while augmentations in GGBS content contribute to more substantial cost savings. Specifically, incorporating 25% and 50% GGBS into the mixes results in cost reductions of 12% and 17%, respectively. Among the various samples, R-S50-B0, which utilizes 50% GGBS without SCBA, shows a significant cost advantage, highlighting the potential for both environmental and economic benefits.

Table 5 Unit costs of construction materials per ton in USD

NCA	RCA*	NFA	W	PC	GGBS	SCBA	SF	SS	SP
16.7	1.67	11.11	2	60	36	133.33	40	230	1100

* includes: Breaking Concrete + Delivery of Waste

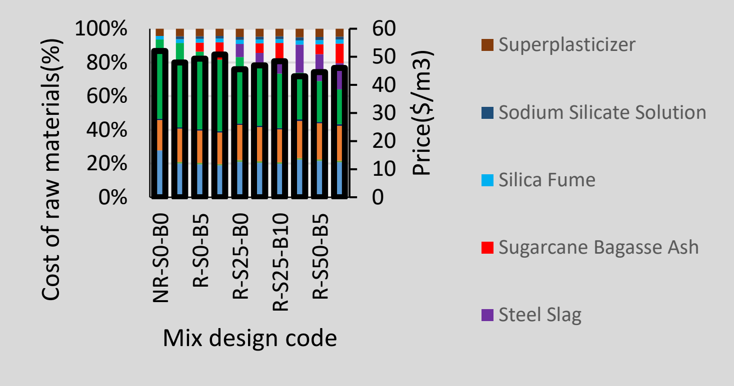


Fig. 11 Comparative analysis of component costs and per m3 material expenses across all mixtures

3.6. Microstructure

Figure 12 shows scanning electron microscope (SEM) image of the produced SCBA. Presence of spherical and porous particles, relatively high specific surface area (3950 cm²/g) along with reasonable activity index (as stated in section 3.1), justifies its suitability as a supplementary cementitious material.

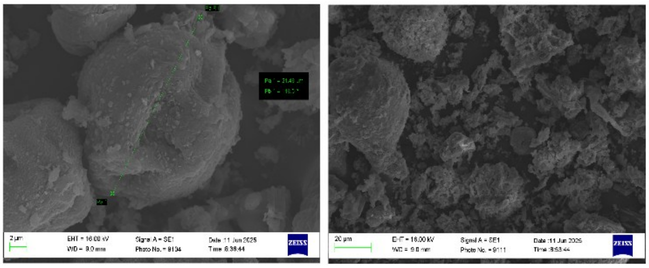


Fig. 12 SEM image of SCBA

Figure 13 presents the comparative XRD patterns at 90 days of hydration for RS25-B5 and RS0-B5. The X-ray diffraction analysis identified quartz (SiO_2, PDF# 01-079-1906), anorthite ($CaAl_2Si_2O_8$, PDF# 00-041-1486), and portlandite ($Ca(OH)_2$, PDF# 01-072-0156). The comparative patterns show significantly reduced intensity of the portlandite peaks at ~18° and ~34° in RS25-B5 compared to RS0-B5. These XRD patterns also demonstrate more complete consumption of SiO_2 in RS25-B5.

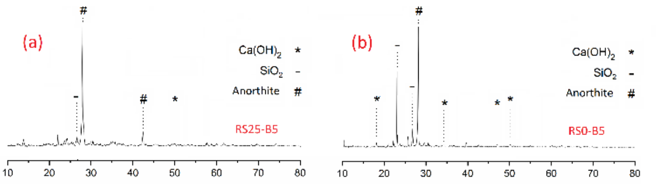


Fig. 13 *XRD patterns of concrete samples: (a) RS25-B5, (b) RS0-B5*

5. Discussion

The experimental results indicate that the incorporation of recycled concrete aggregate (RCA) into concrete mixtures significantly influences their mechanical performance, as evidenced by the reduction in compressive strength observed at 28 and 91 days. This decrease is commonly attributed to the higher porosity and greater water absorption capacity of RCA, which negatively affect the cement hydration process essential for strength development. [64,65]. Normally, the basic compounds of cement, such as dicalcium silicate (C_2S) and tricalcium silicate (C_3S), react with water to form C-S-H gel, progressively enhancing compressive strength over time. The existence of additives in the concrete mix modifies these chemical reactions. For instance, initially replacing 5% of the cement with SCBA resulted in increased compressive strength at all ages compared to the control sample (R-S0-B0), likely due to SCBA's ability to fill the voids within RCA [16,66]. However, increasing the SCBA to 10% led to a decline in strength, possibly due to the non-uniform distribution of SCBA, the coarseness of its particles, or the need for its more complete processing [21,67]. This indicates that while a 5% replacement facilitates complete and beneficial chemical reactions, a 10% replacement does not fully support the cement-strengthening reactions, thus reducing compressive strength.

The use of ground granulated blast-furnace slag (GGBS) as a partial replacement for 25% or 50% of cement affected the compressive strength in different ways. An initial reduction in strength, particularly observed at 7 days for the R-S50-B0 mixture, is attributed to the high level of cement replacement with GGBS, which results in limited early-age C–S–H formation. Over time, however, the amorphous silicate phases in GGBS react with calcium hydroxide to generate additional C–S–H, thereby compensating for the early-age strength loss.

Incorporating recycled coarse aggregate resulted in a slightly higher density compared to the sample NR-S0-B0, which might be attributed to the reduced air content caused by the higher water absorption of the recycled aggregates. The incorporation of GGBS or SCBA generally led to a decrease or increase in fresh density, respectively. In fact, high water absorption of SCBA particles, which reduces the effective water content and entrapped air volume, coupled with a micro-filler effect, possibly compressed the particle packing.

The microstructural differences revealed by XRD analysis provide important insights into the observed performance variations. The more complete consumption of $Ca(OH)_2$ in RS25-B5 confirms the higher pozzolanic activity expected from the slag-silica fume combination, yet this enhanced reactivity appears to create competitive conditions that limit the contribution of bagasse ash. The persistence of the amorphous silica in RS0-B5 suggests this mix achieves more effective utilization of bagasse ash components, potentially explaining its rather higher compressive strength (up to 10%). These findings highlight the complex interactions in multi-component systems where maximizing pozzolanic potential requires careful balancing of material combinations to optimize both reactivity and synergy between components. The porous and specific morphology of the processed SCBA particles, as observed in the SEM image (Fig. 12), supports the hypothesis of competitive conditions in high-pozzolan blends, where such particles may have limited space for effective contribution.

Chloride ion penetration improvement of RAC samples #8 and #10 could be attributed to the gradual formation of additional C-S-H gels over time due to GGBS and SCBA activity. Too low penetrability of main RAC samples is related to a large amount of SF used in their mix design. This result is in a good agreement with previous research [68,69]. It is noteworthy that although RCPT evaluates a key aspect of durability, it must be acknowledged that additional complementary tests will provide more comprehensive data.

From an environmental perspective, RCA has demonstrated effectiveness in reducing CO_2 emissions by 5.9 kg/m^3, underscoring its lower impact compared to cement. Increasing the percentage of SCBA from 5% to 10% leads to a more substantial reduction, demonstrating the importance of this additive in enhancing the mix's environmental performance. Similarly, GGBS significantly lowers CO_2 emissions, with each 25% replacement resulting in approximately 68 kg/m^3 reduction, illustrating its great role in promoting beneficial carbonation reactions.

Economically, the use of RCA alone leads to a cost reduction of approximately $4 per cubic meter compared to the control sample, mainly due to decreased raw material costs. This can be attributed to the transportation distance, price difference between the two products, and the availability of concrete waste. The price difference for NA extracted from quarries and RCA extracted from waste (availability of waste) can vary by country. However, in general, in Iran, disregarding transportation costs, the price of RA is lower. As for transportation, the distance has been reasonable and has not negatively impacted costs [70-73]. Increasing the SCBA content introduces additional costs due to transportation, reflecting the impact of distance on overall expenses. However, the cost benefits of using GGBS are notable, with significant reductions achieved through higher replacement percentages.

In light of the experimental data provided, our recommendations emphasize strategic substitutions to enhance both the structural integrity and environmental sustainability of concrete mixes. Substituting up to 50% of cement with GGBS proves to be a key strategy for optimizing concrete formulations. This level of substitution not only mitigates early strength loss but also facilitates significant long-term gains in compressive strength due to enhance C-S-H formation, which is crucial for the durability and load-bearing capacity of the concrete.

In summary, results show that implementing RCA, SCBA, and GGBS significantly advances environmental and economic sustainability in the construction sector. The use of these eco-friendly substitutes, especially GGBS and SCBA, illustrates a viable path to more resilient and sustainable construction practices. Continued exploration and adoption of such materials are crucial as they meet performance standards while fostering environmental stewardship and resource conservation.

5. conclusion

This study explored the synergistic effects of using slag-bagasse replacements as alternative binder materials on the performance of recycled aggregate concrete (RAC) with silica fume. A comprehensive evaluation was conducted across different concrete mix series, with varying proportions of SCBA (0%, 5%, and 10% by weight) and GGBS (0%, 25%, and 50% by weight). The assessment focused on compressive strength, resistance to chloride ion penetration, environmental impact via life cycle assessment (LCA), and cost analysis. Key findings include:

- Samples R-S0-B5 and R-S25-B10 gained more than 98% compressive strengths of the control sample at 91 days, which were higher than all other slag-bagasse replacement cases.
- Substituting half of the cement weight with GGBS (sample R-S50-B0) substantially decreased 90-day chloride ion penetration. Replacing an additional 20% of the remaining cement with SCBA (sample R-S50-B10) led to even better results, with a reduction exceeding 67%. The low penetrability of RAC samples compared to the supplementary specimen S2 confirmed the critical importance of incorporating silica fume in the RAC mix design.
- The LCA revealed that every 25% increase in GGBS resulted in a 19.6% reduction in CO_2 production compared to 0% GGBS control mix (R-S0-B0), making it more environmentally beneficial than SCBA. Additionally, every 5% increase in SCBA resulted in an approximately 3% reduction in CO_2 production. As a result, the combined utilization of RCA, SCBA, and GGBS significantly decreased pollutant emissions, especially CO_2.
- Cost reductions were achieved by reducing the percentage of cement and considering procurement methods, material costs, and transportation distances. GGBS was highly effective in reducing costs, with a 12% saving achieved per 25% by weight used as a cement replacement. In contrast, SCBA increased costs due to transportation expenses, emphasizing the importance of efficient procurement and application methods.

In synthesis, the multi-criteria analysis provides clear guidance for mix selection based on project priorities. For practitioners seeking the optimal balance of structural performance, cost-effectiveness, and environmental benefit, mix R-S50-B0 (50% GGBS, 0% SCBA) is the recommended choice. Conversely, in applications where maximizing durability and minimizing the environmental footprint are the paramount priorities, mix R-S50-B10 (50% GGBS, 10% SCBA) offers superior chloride resistance and the lowest overall impact, despite a marginal trade-off in strength and cost.

To advance these findings towards practical application, future efforts should prioritize long-term durability assessment under realistic stressors such as freeze-thaw cycles and sulfate exposure. A critical and immediate next step, as highlighted by the need to validate the competitive interactions observed in XRD analysis, is detailed microstructural investigation using SEM/EDS, with specific focus on the interfacial transition zone (ITZ) around treated aggregates. This analysis will provide the visual and chemical evidence necessary to confirm the densification mechanisms hypothesized in this study. Furthermore, the development of integrated econometric models that account for large-scale logistics and carbon policies will be essential to assess the real-world feasibility of implementing these sustainable mixes.

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