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Environmental Benefits of Using Activated Sugarcane Bagasse Ash in Cementitious Materials

Environmental Benefits of Using Activated Sugarcane Bagasse Ash in Cementitious Materials.

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In this research, a comprehensive environmental-based approach is applied to evaluate the effectiveness of biomass ashes processing methods to produce cementitious materials. Efforts are put in research to obtain new low-carbon cementitious materials by incorporating waste, such as sugarcane bagasse ash (SCBA). Processing methods are commonly used to counteract the drawbacks linked to the nature of ashes and boost their benefits, but the energy needed to do this, can jeopardize their environmental interest and is commonly disregarded by researchers. This research investigates the benefits of processing SCBA by mechanical activation in the production of mortars and its environmental impact. It was found that treated ashes outperforms when substituting fine aggregates, increasing the compressive strength (CoS) of plain mortars by 62%. Despite the higher embodied carbon (EC) per cubic meter, treated SCBA in substitution of fine aggregates result in higher eco-strength efficiency, +32%. This enables the reduction of structural elements' sections diminishing the material use and the ultimate EC, named in this research as *specific embodied carbon*, up to 40%.

Key Words: Mineral admixtures, Embodied Carbon, Waste, Service Life

Introduction

Building materials and construction sector emissions entail up to 11% of annual global greenhouse gas (GHG) emissions. With a growing population and the demand of construction materials expected to double in the years to come, it is mandatory to act to reduce i) the exploitation of natural resources, ii) the CO_{2e} emissions, and iii) the waste landfilling, (Beiser, 2018; UNEP, 2016; WWF, 2018). Waste is also forecasted to escalate due to an increase in the living standards. In this scenario, waste is presented as a potential source of alternate materials to traditional natural resources. In the case of cementitious materials, the use of waste as cement or aggregate replacement, can enhance the mechanical and durability properties extending the service life of structures.

Some waste such as ashes resulting from industrial processes can show hydraulic or pozzolanic activity, promoting the generation of phases such as calcium silicate hydrates (CSH), (Cordeiro, Toledo Filho, Tavares, & Fairbairn, 2008; Pan, Tseng, Lee, & Lee, 2003). This refines the porous structure making the material less permeable to external harmful species, thus extending the service life of structures. In the case of artificial pozzolans, such as SCBA, the reactivity depends on the presence and quantity of amorphous particles, the oxides content (SiO_2, Al_2O_3 and Fe_2O_3, hereafter SAF) and the fineness (British Standard Institution, 2012b). However, industrial ashes may show important drawbacks that limit or hinder their use as pozzolans in concrete production as per to BS EN 450-1 requirements (British Standard Institution, 2012b). Some of these are i) high content in undesirable particles (organic matter, harmful substances, salts, porous and light particles), ii) an insufficient content of SAF (below 70%) or iii) a higher water demand due to the increased fineness or higher porosity. This makes researchers to treat ashes to boost the pozzolanicity to exceed the minimum strength activity index (SAI) required (75%) (British Standard Institution, 2012b).

Since emissions of cement are 185 times higher than those of aggregates (Jones, 2019), most of research is focused on using ashes in cement substitution (cs). The optimum substitution rate (sr*)* was established in 15-20% for ultra-treated ashes (Chusilp, Jaturapitakkul, & Kiattikomol, 2009; Rajasekar, Arunachalam, Kottaisamy, & Saraswathy, 2018). On the other hand, few researchers used SCBA in fine aggregate substitution (as) formulations, which optimum sr is not clear, (Modani & Vyawahare, 2013; Sales & Lima, 2010). However, the environmental impact of treatments, increasing the EC of the final product, is not commonly reported.

This research studies the environmental benefits of mortars containing treated SCBA (T-SCBA). To do this, comparisons were stablished with plain mortars and mortars containing untreated SCBA (Ut-SCBA). The influence of substitution of cement and fine aggregate was also investigated.

Materials and methods

Raw materials

Industrial SCBA from a 30MW energy plant in Dominican Republic was used. The combustion temperature was 750-800˚C. Ut-SCBA were ground, to mechanically activate the resulting ashes, labelled as T-SCBA. The grinding regime was the optimum one found previously as a part of the same research project. Ordinary Portland Cement (OPC), CEM I 52.5 and local commercial sand for construction purposes were used. The physical and chemical basic data of cement, sand and Ut-SCBA are shown in **Error! Reference source not found.**table 1.

Table 1

Physicochemical properties of raw materials

	CaO %	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	SAF %	Cl^-_{ws} %	SAI %	D_{50} kg/m^3	ρ_r kg/m^3	ρ_b kg/m^3	SSA m^2/kg
OPC	76.5	18.7	3.3	3.1	25.0	-	-	39.6	3150	1400	163.5
Sand	0.3	7.6	3.2	0.3	-	-	-	476	2420	1635	36
Ut-SCBA	13.1	48.1	6.1	5.9	60.1	0.18	51	130.8	2449	718	442.8
T-SCBA	13.9	53.2	7.1	6.0	66.3	0.24	83	10.4	2551	928	817.1

ρ_b: bulk density; ρ_r: real density

Methodology

Preparation and curing of mortars

Mortars prisms (40x40x160mm) and cylinders (100x200mm) were casted as per BS EN 196-1 (British Standard Institution, 2016) by incorporating Ut-SCBA and T-SCBA in the substitution of cement/fine aggregate. The water to binder -the sum of cement and ash- ratio was adjusted to get the same flow value of control samples (w/b= 0.5). The sr were 0% (control) and 20% -as reported to be the optimal *one*-, (see table 2). Mortars were demolded after 24h and cured in tap water until testing date.

Table 2

Mix composition of mortars

ID	Description	CEM (kg)	Ash (kg)	Sand (kg)	w/b
Con	Control specimen	1	0	3	0.5
Ut-SCBA(cs)	Untreated ashes. Cement substitution	0.8	0.2	3	0.625
T-SCBA(cs)	Treated ashes. Cement substitution	0.8	0.2	3	0.525
Ut-SCBA(as)	Untreated ashes. Fine aggregates substitution	1	0.6	2.4	0.525
T-SCBA(as)	Treated ashes. Fine aggregates substitution	1	0.6	2.4	0.346

Testing of mortars performance

Fresh density of mortars was obtained as per BS EN 1015-6 (Bristish Standards Institution, 1999). The compressive strength (CoS) and total open porosity (OP) were obtained according to BS EN 196-1:2016 (British Standard Institution, 2016) and BS EN 1936:2006 (British Standard Institution, 2006), respectively, at 3, 7 and 28 days. Then, non-steady state migration values at 28 days, $D_{nssm-28}$ were obtained by means of rapid chloride migration test as per NT BUILD 492 (NORDEST, 1999) on control samples and Ut-SCBA and T-SCBA in *as* regime, since showed better mechanical performance.

Environmental assessment of mortars

Embodied carbon, EC. In this research the embodied carbon of mortars were calculated from the EC of raw materials as per equation (1).

$$CO_{2e} = \sum_{i=1}^{n}(CO_{2e-i} \; x \; W_i) \quad (1)$$

The EC of cement, fine aggregates and water were obtained from the references shown in table 3. The EC of Ut-SCBA and T-SCBA were estimated. Since SCBA is a waste from another industrial activity, in agreement to Sinoh et al. (2021), the resulted EC was that from transport and treatments. Transport was estimated under two scenarios: i) local use (in Dominican Republic) and ii) the exportation to United Kingdom (UK). In the first hypothesis, a round trip of 100 km (200 km) is covered by an average diesel heavy goods vehicle and average load. The second hypothesis contemplates a cargo ship and a distance of 6,836 km (one way). Additionally, the emissions due to treatments needed to obtain T-SCBA were calculated based on the laboratory machine characteristics. When scaling this up to industrial machines, more efficient results could be achieved.

Table 3

Embodied carbon of raw materials

Material				EC ($kgCO_{2e}/kg$)		Source
Average CEM I OPC				0.912		(Jones, 2019)
Fine aggregates				0.00493		(Jones, 2019)
Water				0.000149		(Government, 2022)
	Material processing	**Transport Import**	**Transport Local**	**Total Import**	**Total Local**	
Ut-SCBA (as)	0	0.11	0.024	0.11	0.024	Estimated
T-SCBA (as)	0.35	0.11	0.024	0.46	0.374	Estimated

Eco-strength efficiency, ES_{CO2e}. This ratio assesses the emissions (CO_{2e}) against the strength capacity (CoS) as per equation (2). Including an additional functional unit facilitates the comparison between different materials performance. The carbon intensity is measured in $MPa/kgCO_{2e}$ so the higher the value, the more efficient the composition is.

$$ES_{CO2e} = \frac{CS}{CO_{2e}} \quad (2)$$

Specific embodied carbon, EC'. This concept, previously introduced by Torres de Sande et al. (2022b), meets the Structural Sustainable Design principles (Danatzko & Sezen, 2011) and evaluates the EC of a material considering the potential material reduction. This is obtained by defining a load acting on a specific geometry, in this case a cube (see figure 1). The minimum cube needed is then obtained considering a reduction factor of 1.5. Finally, the EC' of the cube can be obtained.

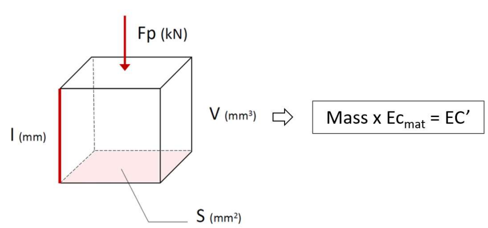

Figure 1. Specific embodied carbon approach

Service life assessment. The software Life-365 v.2.2.3.1 was used to obtained the corrosion initiation period of Control, Ut-SCBA(cs) and T-SCBA(as) samples. The diffusion of mortars at 28 days were obtained from RCMT. The concentration of chlorides at the surface of the reinforcing steel rebars to initiate the corrosion (%wt. of mortar) was calculated in 0.1% based on the commonly threshold used of 0.4% (wt. of cement). Marine tidal zone was selected as exposure condition and a cover of 50mm was defined. The supplementary cementitious materials (SCM) influence the rate of reduction in diffusivity, thus the *m*-value -that indicates the opposition of the composition to the chlorides penetration-. Since unknown, *m*-value was hypothesized by depicting two scenarios:

A. All samples have the same *m*-value (*m=0.20)*, the one calculated by the software for control samples. The software is originally designed for concretes, thus variations may occur.

B. A *m*-value of 0.60 -which is the value for fly ash (50% of wt of cement) and better represents the case of T-SCBA- to consider the influence of using SCM in the reduction in diffusivity.

Results and Discussion

Influence of Mechanical Activation in Properties of Mortars

Table 4 show the results for open porosity, compressive strength and D_{nssm} for the corresponding testing dates. The results are discussed below.

Table 4

Open porosity, compressive strength and Dnssm of mixes

	Open porosity, %			Compressive strength, MP			$D_{nssm-28d}$, $x10^{-12}m^2/s$
	3d	7d	28d	3d	7d	28d	28d
Control	21.7	19.2	17.2	23.2	29.3	36.1	26.77
Ut-SCBA(cs)	26.9	24.8	26.1	11	12.9	17	-
T-SCBA(cs)	22.9	22.5	20.8	7.4	14.9	22.4	-
Ut-SCBS(as)	28.8	26.1	25.5	13	13.3	23.7	14.23
T-SCBA(as)	17.3	13.9	11.1	33.2	40.5	58.5	2.59

Open porosity

Ut-SCBA increases the OP of mortars at 28 days by 52%(cs) and 48.2%(as*)* due to a higher water demand and the incorporation of more porous structures. T-SCBA reduces the OP of Ut-SCBA by breaking down these structures. However, only in *as* systems, T-SCBA reduces the porosity of control samples -since early ages - by 35.5% due to a major reactivity and packing effect of ashes.

Compressive strength

CoS of T-SCBA at 28 days outperformed that of Ut-SCBA by 31.7%(cs) and 147%(as) and that of control samples by 62% when substituting aggregates; however, reduced the CoS between 38% (cs) in comparison to control samples, (see table 4). T-SCBA(as) boosts the strength gain since early ages, usually delayed in mixes containing pozzolans. These improvements are attributable to a highest SSA of T-SCBA, that promotes the pozzolanic reaction, the provision of more nucleation sites, and the packing effect of unreactive fines (Torres de Sande et al. 2022a). The densification of the matrix is supported by the reduced OP of mortars containing T-SCBA, 11.1%, in comparison to the 17.2% of control samples.

Non-steady state migration, D_{nssm}.

The addition of Ut-SCBA and T-SCBA reduces the D_{nnssm} of control samples by 46.5% and by 90%, respectively. Hence, regardless the mechanical performance, the addition of SCBA can increase the chloride penetration resistance of mortars and, by extension, of concrete.

Environmental Impact of Mortars

Embodied Carbon of Mortars.

When used locally both, Ut-SCBA and T-SCBA, reduce the EC/m^3 of mortars when substituting cement by 19.2% and 11.6%, respectively, (figure 2). Due to the lower EC of natural aggregates in comparison to that of cement, Ut-SCBA and T-SCBA increase the EC of mortars by 1.2% and 23.9% when substituting fine aggregates. Freighting ashes from Dominican Republic to UK increases the EC of carbon up to 2.3% and 5.5% for cement and fine aggregates substitution, respectively. The difference lies in the higher amount of ashes per volumetric unit of the latter.

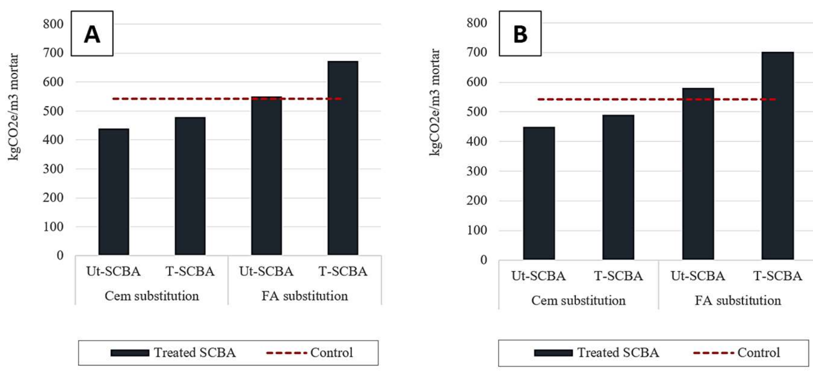

Figure 2. EC of mortar compositions when (a) using SCBA locally or (b) importing in UK.

Eco-strength Efficiency, ES_{CO2e}.

Figure 3a and figure 3b show the Eco-strength efficiencies at different ages for cement and aggregates substitution, respectively. T-SCBA(as) is the only scenario in which the efficiency outperforms that of control samples, obtaining a strength gain of 32% per kg of CO_{2e} emitted, at 28 days. In this scenario, the treatment that initially deliver mortars with higher EC, results in an increase in efficiency of 50.6% in comparison to Ut-SCBA. While the difference between using Ut-SCBA as aggregate substitute against cement substitute is 9.3%, this value turns 85% when using T-SCBA.

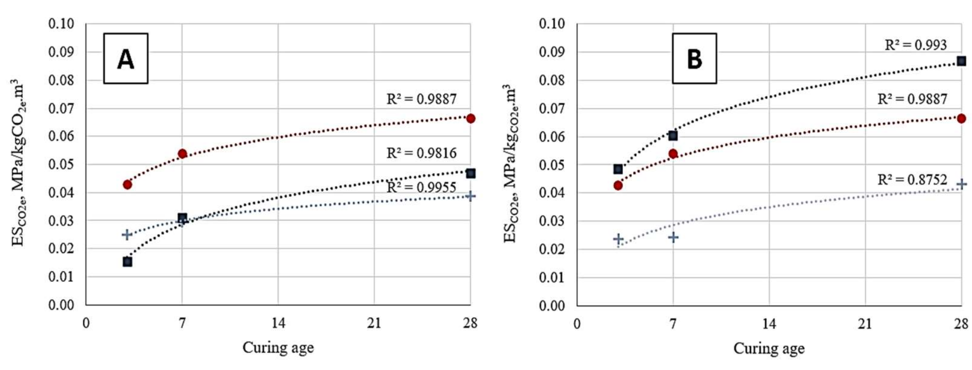

Figure 3. Eco-strength efficiency of mortars using Ut-SCBA and T-SCBA in cement substitution (a) and fine aggregates substitution (b). Local use.

Specific Embodied Carbon, EC_e.

Figure 4 shows the equivalent cubes, when using different compositions, able to bear a 100kN load and figure 5 shows the corresponding specific carbon. The volume of material needed for a cube able to bear the mentioned load when adding T-SCBA(as) is halved with respect to control mortars and one forth with respect to T-SCBA(cs).

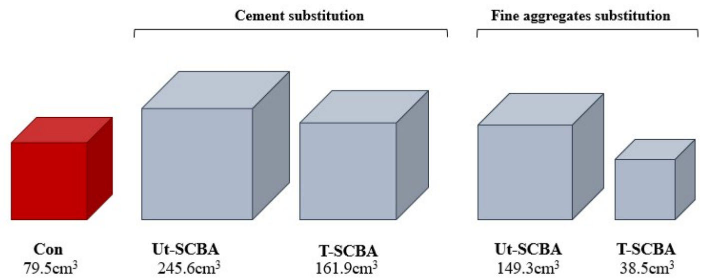

Figure 4. Specific embodied energy, $kgCO_{2e}$

When multiplying the resulting volume by the EC ($kgCO_{2e}/m^3$) of each mortar, the specific embodied carbon, EC', for each cube is obtained, (see figure 6). The EC' of T-SCBA(as) mortars is 40% lower than that of control samples, a third part of that T-SCBA(cs) mortars and a forth part of Ut-SCBA(cs) mortars. This type of approach offers a more realistic comparison among different compositions.

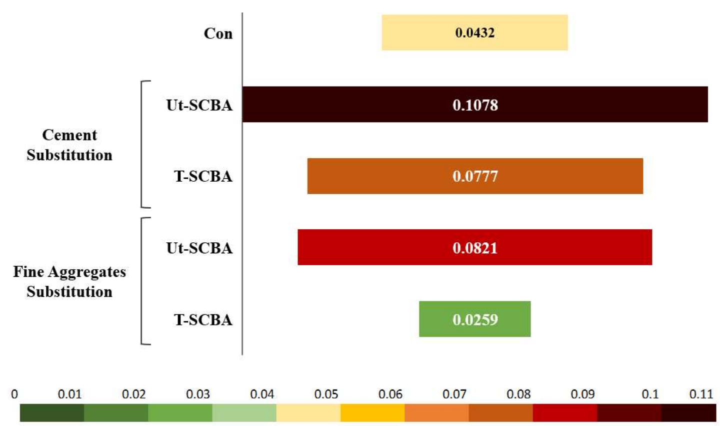

Figure 5. Specific embodied energy, $kgCO_{2e}$

Service life improvement

Figure 6(a) shows the initiation period scenarios in which the *m*-value is considered to be that provided by the software for cement composition, m=0.2. Being extremely conservatives by equaling *m*-value, the T-SCBA(as) extends the initiation period by 9 and 7 times and nine times in comparison to control samples and Ut-SCBA, respectively. When assimilating the *m*-value of T-SCBA(as) to that of mixtures containing FA, the results show an outstanding performance, being the only adequate composition for marine tidal exposure, (see figure 6(b)).

When the cover thickness is reduced by 25%, under the same parameters used above to obtained figure 6(b), the initiation period obtained was 89.3years, indicating that the potential reduction of material consumption defended when assessing the specific embodied carbon still provides higher durability properties. To obtain more accurate results and a complete life cycle assessment, electrochemical methods are needed to get a thorough understanding of the durability properties of these materials.

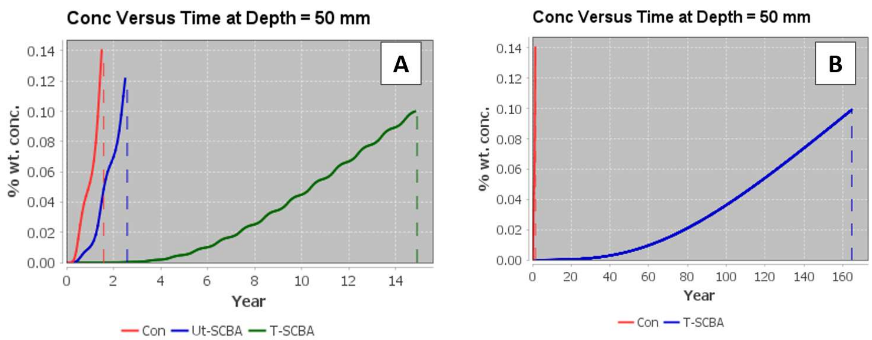

Figure 6. Initiation period when considering a) m = 0.2 and b) m = 0.6

Conclusions

The benefits of treating SCBA were investigated in different mix compositions. Additionally, the environmental impact was assessed, demonstrating the importance of the proposed approach when potential low-carbon materials are investigated. It was concluded that:

- SCBA not considered as artificial pozzolans according to the limit SAF>70%, can provide low-carbon materials when using a proper approach.

- Mechanical activation of Ut-SCBA (T-SCBA) highly improved the mechanical performance of mortars in aggregates substitution system (increase of 62% in CoS and reduction in OP by 35.5% at 28 days)

- The initial higher EC of T-SCBA(as) can be reduced if other variables are included in the evaluation as functional units, such as the CoS or the material reduction. T-SCBA(as) composition is the only one showing a higher Eco-strength efficiency than control samples. Its specific embodied carbon was reduced by 40% and the material consumption was halved.

- Based on the D_{nssm}, the initiation period of T-SCBA(as) mortars is highly extended.

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