Construction and Building Materials 172 (2018) 635–649

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Self-compacting concrete incorporating sugarcane bagasse ash

Juliana Petermann Moretti [a], Sandra Nunes [b,*], Almir Sales [a]

[a] Department of Civil Engineering, University of São Carlos (UFSCar), Via Washington Luís, km 235, São Carlos, SP 13565-905, Brazil
[b] CONSTRUCT-LABEST, Faculty of Engineering (FEUP), University of Porto, Portugal, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

HIGHLIGHTS

- Valorization of sugarcane bagasse ash generated by the Brazilian sugarcane industry.
- Sugarcane bagasse ash as a filler material in powder-type self-compacting concrete.
- Mixture design method based on statistical factorial design approach.
- Good mechanical and durability performance of tested self-compacting concretes.

ARTICLE INFO

Article history:
Received 12 December 2017
Received in revised form 29 March 2018
Accepted 30 March 2018

Keywords:
Agricultural waste
Recycling
Sugarcane bagasse ash
Self-compacting concrete
Statistical factorial design

ABSTRACT

The aim of the current study is to assess the feasibility of incorporating sugarcane bagasse ash (SBA) from the sugar and ethanol industry as a filler material in the production of self-compacting concrete (SCC). For this purpose, paste composition was designed in the first stage of this study by conducting an experimental plan at the mortar level. During the second stage, SCC mixture properties were evaluated by considering the paste mixture proportions defined in the first stage. The study at the mortar level was conducted based on a statistical factorial design approach, which offers a valid basis for developing empirical models that allow determination of optimal settings of the design variables to satisfy all performance requirements. At the concrete level, the impact of three optimised paste mixtures on SCC properties was assessed. Fresh state, mechanical, and durability properties were evaluated. Mortar and concrete test results revealed that SBA can be used successfully in powder-type SCC as a filler material, and it exhibits good self-compacting ability and strength levels, which are adequate for many current civil engineering applications.

1. Introduction

Concrete provides the foundation for the current built environment. This intensive use of concrete is expected to increase over the next decades, because of increasing global population and urbanisation rates, portending very alarming figures concerning the environmental footprint [1]. No alternative for concrete as a major global construction material currently exists that can be applied at sufficient scale. The growth of market demand for concrete and cement is developing faster than the technical potential to reduce CO_2 emissions per ton of product; hence, absolute CO_2 emissions will continue to increase. Replacing cement by other lower carbon materials with cementitious properties was identified as one of the four levers for carbon emissions reduction by the World Business Council for Sustainable Development [2]. In this regard, Miller et al. examined several material alternatives that could contribute significantly to CO_2 reductions and proposed two clinker substitution methods: calcined clay with limestone filler and engineered filler combined with dispersant [3]. Another challenge facing the construction sector concerns the need for a close-the-loop approach to managing product lifecycles through greater recycling and re-use, to reduce the environmental impacts caused by the excessive use of natural resources. The construction sector produces an enormous amount of waste, thus a large potential exists for a more efficient use and recycling of raw materials [4]. This sector also offers opportunities for industrial symbiosis, achieved by converting other industrial by-products into raw materials for the construction sector. Concrete production, in particular, allows incorporation of several industrial and agricultural wastes, either as partial surrogates of the aggregates or of cement. Comprehensive reviews on the effects of different wastes on concrete properties can be found in the literature, comprising: industrial wastes such as silica fume, fly ash, and slag [5]; waste foundry sand, coal bottom ash, cement kiln dust, and wood ash [6]; agricultural waste [7]; glass waste [8]; aggregates from construction

---

* Corresponding author.
E-mail address: snunes@fe.up.pt (S. Nunes).

https://doi.org/10.1016/j.conbuildmat.2018.03.277

demolition waste [9]; and various industrial by-products as partial replacement for fine aggregate in concrete [10].

Martinera and Monzó recently presented a review paper characterising the current state of development of technologies associated with recycling agricultural wastes as supplementary cementitious materials, identifying the main research needs and the obstacles to a widespread use of agricultural ashes [11]. Wastes mainly from the sugar and rice industries are increasingly used as alternative sources of fuel for industrial processes, mainly owing to their abundant reserves of biomass; thus, they are good candidates for massive production of vegetable ashes. These ashes, if fired under controlled temperature and residence time, might exhibit pozzolanic properties, enabling their use as cement substitutes in cementitious systems (typically in proportions between 0 and 20% by mass) [11]. Besides rice husk and sugarcane ashes, the most studied agricultural ashes, other vegetable ashes have been studied, such as corncob, wheat straw and plane leaf [12]; bamboo leaf, corn cob, and wood waste [7]; and cassava peel [13]. Nevertheless, it is recognised there is a need to better understand the extent to which these vegetable ashes should be utilised in cementitious systems based on their availability, the most appropriate processing conditions, impact on durability of concrete products, and potential to contribute to the reduction of environmental impacts on a full life cycle basis [11].

The current work focuses on the use of sugarcane bagasse ash (SBA) to produce self-compacting concrete (SCC). Brazil leads the world's sugarcane production, and in the 2015/16 harvest, 665 million tons of sugarcane were produced [14]. Among the wastes generated in sugarcane processing, bagasse stands out owing to its utilisation as biomass. Through the burning of bagasse, the sugarcane industry generates electricity for its own consumption and for sale to electric power concessionaires. During this process, both bottom ash (from co-generation boilers) and fly ash (from filters) are produced. It is estimated that the bagasse corresponds to 25% of the sugarcane production and approximately 24 kg of ashes per tonne of bagasse burned are produced [15]. By considering the Brazilian 2015/16 sugarcane harvest, one can estimate a generation of 4 million tons of sugarcane bagasse ashes. These ashes are commonly deposited in landfills [16] or used as fertiliser in crops, although they do not provide enough nutrients to be applied for this purpose [17].

The main compound of SBA is SiO_2. Thus, researchers have explored the potential for SBA as a pozzolan in cementitious materials [18–26], aiming to reduce CO_2 emissions into the atmosphere [27]. In the pozzolanic reaction, the amorphous silica reacts with the calcium hydroxide to form compounds with binding properties. The bagasse processing, carbon content, mineralogical composition and particle size are the main characteristics that influence the ash's reactivity. Table 1 presents the characteristics of several SBA analysed in different studies. From this table, it can be concluded that ashes produced under controlled temperatures and grinding procedures can present significant pozzolanic activity [18–23,26]. Accordingly, studies showed that SBA can be used to produce high-strength concrete [24] or even to improve the mechanical properties and durability of recycled aggregate concrete [28]. In general, if the material is fired at temperatures around 600–700 °C, it presents amorphous silica, low loss on ignition (LOI), and considerable pozzolanic activity. If the temperature exceeds 700 °C, silica crystallization is observed [18], whose phase composition depends on the calcination temperature and the cooling conditions. Montakarntiwong et al. [26] reported on two SBAs combusted at a controlled temperature of 800–1000 °C which exhibited strength activity indices below 75% at 7 and 28 d; however, after grinding to increase fineness, these SBAs presented strength activity indices above 90%, although one SBA had high LOI (20.4%). Table 1 also presents that, in general, ashes from the

Table 1
Characteristics of several SBA analysed in different studies.

Ref.	Origin	Processing	Particle size (μm)	SiO_2 (%)	LOI* (%)	Pozzolanic activity	Recommended use
[16]	Disposal area	As received	$D_{50} = 107.9$	65.3	15.3	–	Aggregate
[17]	Boiler + filter	Grinding	$D_{max} = 600.0$	62.7	16.3	–	Aggregate
	Boiler	Grinding	$D_{max} = 1200.0$	93.5	0.3		
[18]	Raw bagasse burned in the laboratory	Heating (~400 °C)	$D_{50} = 12.2$	–	84.5	Insufficient – 28% (NBR 5752)	–
		Heating (~500 °C)	$D_{50} = 11.3$	–	14.0	Insufficient – 73% (NBR 5752)	–
		Heating (~600 °C)	$D_{50} = 11.6$	61.0	5.7	Appropriate – 77% (NBR 5752)	Pozzolan
		Heating (~700 °C)	$D_{50} = 12.3$	–	3.0	Insufficient – 63% (NBR 5752)	–
		Heating (~800 °C)	$D_{50} = 10.1$	–	1.3	Insufficient – 69% (NBR 5752)	–
[19]	Raw bagasse burned in the laboratory	Heating (~800 °C)	$D_{50} = 12.0$	69.4	1.6	High – fixed 94% of lime at 90 d	Pozzolan
	Filter	Heating (~300 °C)	$D_{50} = 12.0$	56.0	18.0	Low/medium – fixed 42% of lime at 90 d	Pozzolan
	Boiler	Heating (~800 °C)	$D_{50} = 18.0$	66.6	4.3	Very low – fixed 11% of lime at 90 d	Inert material
[20]	Landfill	Heating (~700 °C)	$D_{50} = 20.0$	56.4	10.5	–	Pozzolan
[21]	Boilers	As received	$D_{80} = 199.0$	78.34	0.42	49.5	–
		Grinding 960 min tumbling mill	$D_{80} = 27.2$			84.1	–
		Grinding 240 min vibratory mill	$D_{80} = 5.4$			103.0	Pozzolan
[22]	–	Grinding	$D_{50} = 10.0$	64.88	8.16	113%	Pozzolan
[23]	Filter	As received	$D_{10} = 300$	72.95	21.0	72%	–
		Heating (700 °C)			14.0	86%	Pozzolan
[24]	–	Grinding	$D_{50} = 16.4$	65.0	10.5	–	Pozzolan
[25]	Boiler	As received	–	63.2	6.9	Free lime in pastes with ash was lower than reference paste (modified Franke method)	Pozzolan
[26]	Wet scrubber system	Heating (800–1000 °C); Grinding	$D_{95} = 45.0$	76.8	20.4	102%	Pozzolan
	Multi cyclone system			67.1	3.3	101%	Pozzolan
[29]	Boiler	–	$D_{50} = 12.2$	72.3	1.52	Low	Inert material
[30]	Boiler	As received	$D_{50} = 40.0$	73.5	–	Low	Filler-material
[31]	Boiler	Grinding	$D_{max} = 1180.0$	80.2	0.8	–	Aggregate
[32]	Boiler	Grinding	$D_{max} = 1200.0$	80.8	0.7	Low – fixed 48 mg of CaO/g of ash (modified Chapelle test)	Aggregate

[*] Loss on ignition.