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Sugar cane bagasse ash from a high-efficiency co-generation boiler as filler in concrete

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HIGHLIGHTS

- Pozzolanic activity of these bagasse ashes is low and most beneficial as filler-materials.
- As a filler material the concrete compressive is increased by ≈20% over controls.
- Increases in sulphuric acid resistance as strength and reduced spalling are displayed.
- Acid resistance is from either pore-filling and/or cement chemistry shifts from C3A, to C2S.
- Rapid chloride permeability tests suggest increased permeability.

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ABSTRACT

Bagasse ashes from high efficiency co-generation boilers have dominant filler effect in concrete from a greatly reduced pozzolanic activity because of quartz polymorph phase changes to α-quartz, rather than the often-reported α-cristobalite for bagasse derived silica. Sugar cane bagasse ash used as filler in concretes provided substantial improvements to compressive strengths at up to ≈20%. These combined filler effect and limited pozzolanic activity improved the acid resistance as measured by both mass loss and compressive strength tests. Improved acid resistance suggests pore filling and lowered permeability from the filler effects, whereas the limited pozolanic may be sufficient to shift cement chemistry to more acid resistant silicates mineral systems compared to aluminate minerals (e.g., C_3A to C_2S). Similarly, drying shrinkage improved. However, in contrast the rapid chloride permeability tests indicate increased chloride ingress, suggesting increased permeability, but these maybe possibly misleading results generated from the superplasticizer.

1. Introduction

Sugar-cane bagasse ash SCBA) is mostly fine particulate silica with minor alumino-silicates, produced when bagasse is burnt for co-generation of heat and electricity at a sugar mill. Australia cultivates over 30 million tonnes of sugar-cane annually [1], resulting in approximately 4 million tonnes of bagasse and approximately 30 thousand tonnes of SCBA per year [2]. Brazil, the world's largest cultivator of sugar-cane, produces as much as 2.5 million tonnes of SCBA annually [3]. Unfortunately, limited utilisations of this silica-rich ash occurs at present with the primary methods of disposal being either placement in landfill, or use as a soil stabilizer on the growing fields [4]. However there are environmental concerns, which limit the use of the ash on fields [5]. Particularly there is concern that field disposal presents a risk of re-suspension of airborne silica particles of respirable size [6]. Thus finding value added alternative utilisations could alleviate potential hazards, while benefiting the sugar-cane industry; one potential utilisation is use as silica-rich filler in concrete.

Aggregate makes up the bulk volume and mass of concrete and comprise of a combination of coarse (>4.75 mm) and fine (<4.75 mm) aggregates [7]; filler materials are fine aggregate, defined as the material <0.063 mm [8]. A well graded aggregate size distribution sets to achieve the maximum density possible by reducing potential concrete matrix voids [9]. In particular, filler materials by nature fill the small voids between fine aggregates increasing the density of concrete, and consequently can enhance concrete strength and durability via the filler effect [10–12]. Fillers

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provide increased nucleation sites for cement hydration reactions, and, therefore may indirectly increase the calcium silicate hydrate (CSH) content of the concrete, which provides additional strength gains [13]. Furthermore, filler materials may improve the workability of concretes when particles are spherical thus exerting a ball bearing effect [13]. However, most traditional fillers are sourced from river sand or crushed rock, which given the environmental concerns of mining finite natural resources finding alternatives is desirable [14]. Consequently, increased research interest in waste materials as fillers including: coal bottom ash [15]; glass wastes [16]; red mud [17]; and rice husk ash [18] among others [19] has occurred. Consequently, SCBA may be suitable as a filler material as it is a fine particulate, high in quartz silica, similar to natural sand.

SCBA in concrete research has mostly focused on its use as a supplementary cementitious material due to the high silica content [2,20–28]. This is because materials containing silica also have the potential to undergo the pozzolanic reaction and replace cement in concrete. However, the silica for pozzolanic reactions to occur has to be in high solubility forms to be sufficiently reactive with portlandite [29]. Consequently, because SCBA is produced under uncontrolled high temperatures (>800 °C), the silica content readily undergoes phase transitions to low solubility crystalline forms, e.g., α-quartz [24,29,30]. We have shown that uncontrolled burning resulted in the SCBA having high α-quartz content but low pozzolanic activity [31,32]. Despite the lack of pozzolanic activity of some supplementary materials, many authors often report concrete property improvements because of the filler effect [20,21,26]. Whilst there is considerable research into the pozzolanic potential of SCBA in concrete, there has been limited research into the use of SCBA as a sand replacement in concretes and its filler effects [33,34].

Sales and Lima [34] investigated the use of a SCBA with high silica contents, but low pozzolanic activity as a sand replacement in both concretes and mortars, where pre-treatments of the SCBA included both sieving and grinding. In mortars with a constant w/c ratio increasing SCBA content increased compressive strengths by up to 25% of controls, while mortar workability was not greatly affected [34]. Furthermore, optimal SCBA sand replacement concentrations for the mortars was between 30% and 50% by mass [34]. Similar replacement concentrations in concrete showed the workability was minimally affected, and 30 MPa compressive strengths were attainable for the concretes. Modani and Vyawahare [33] also investigated SCBA utilisation as a partial sand replacement, but in contrast to Sales and Lima [34], the SCBA was used in the 'as received' state and workability of concretes decreased as SCBA content increased [33]. In addition, concrete tensile strength decreased as SCBA content increased, but the compressive strength increased up to 10% by volume sand replacement with SCBA, but then decreased at higher replacement volumes [33]. Hence, a 20% by volume optimum replacement level was reported, that produced concretes with both satisfactory strengths and workability. The two studies highlight the affects that preprocessing such as sieving and grinding have in utilizing waste materials. Grinding in particular has large effects, because this fractures crystal lattices exposing reactive bonds, and increasing reactive surface areas [22,24]; both sieving and/or grinding will add further costs in waste utilisation.

This paper investigates the effects of using an unprocessed SCBA from a high-efficiency co-generation boiler, high in α-quartz content and low in pozzolanic activity as a partial sand replacement in concrete. This paper further investigates the effect on workability, compressive and flexural strengths of concrete, the effect on the chloride ingress, drying shrinkage and concrete durability in acidic-environments. Results from this study will add important insights to the limited research available on the use of SCBA as a sand replacement in concrete.

2. Experimental program

2.1. Materials characterization

All experiments used a general purpose GP) ordinary Portland cement manufactured by 'Sunstate Cement' that complies with AS3972 [35]. SCBA was obtained from the Broadwater Sugar Mill Co-Generation Plant, NSW, was black in colour and used as received, except for oven drying at 105 °C to remove free water. The chemical compositions of the cement and the SCBA were determined, using a PANalytical Epsilon 3 X-ray Fluorescence (XRF. Concentrations were calculated against Omnian standards in Panalytical Epsilon3 Software; no matrix corrections were applied, and data should be considered semi-quantitative. Carbon and nitrogen concentrations were measured on a LECO 2000 Analyzer. Samples were bound with wax (9:1 and pressed as a pellet for 30 s at 20 tonnes pressure.

Specific gravity of the cement and SCBA were determined using Le Chatlier flask in accordance with AS3583.5 [36]. Particle size distributions of the SCBA and GP cement were determined using a Malvern Mastersizer 2000, with ethyl alcohol as a dispersant for 20 min ultrasonic agitation. Particle morphology of the SCBA was qualitatively determined using scanning electron microscopy (SEM) on a Phenom XL Desktop™ SEM, and was performed at an acceleration voltage of 10 kV using uncoated samples. SCBA mineralogy was determined using X-ray diffraction (XRD), where samples were milled to <10 μm prior to scanning in a Bruker D4 Endeavor XRD with a Lynxeye position sensitive detector. Cobalt $K_{\alpha 1}$ radiation (1.78897 Å) was used at 40 kV and 40 mA over a range of 5° and 80° 2θ, with a step size of 0.03572° 2θ and rest time of 1.65 s/step.

Sand used in concrete mixes was 'Easy Mix Double Washed River Sand', a natural river sand, kiln dried by 'Easy Mix' and supplied by 'Bunnings' in 20 kg sealed plastic bags. Coarse aggregate was locally derived crushed basalt supplied by 'Richmond River Sand and Gravel', which was mostly angular shape; aggregates were oven dried at 105 °C for at least 24 h. A 1:1 blend of nominal 10 mm and nominal 20 mm crushed basalt was used as the coarse aggregate; the water used for all concrete work was potable tap water. The superplasticizer used in Stage-two concretes, was "Sika Viscocrete® 20HE" sourced from Sika Australia, which is a third generation superplasticizer. Third generation superplasticizers work through steric hindrance, and the 20HE superplasticizer is specifically designed for concrete production where high water demands exist.

2.2. Mix proportions

Mix design was made using the ACI method [37] based on a normal class concrete with nominal 20 mm crushed basalt aggregate. A target compressive strength of 40 MPa and a specified 28-day strength of > 25 MPa were made. In addition, a target workability of 80 ± 10 mm slump was specified. Concrete testing occurred in two stages both of which focused on the filler effects of SCBA, by replacing sand at 0, 5, 10, 15, and 20% by weight of the cement. Previous work [31] showed that the co-generation plant SCBA had little or no pozzolanic activity resulting from high burn temperatures [32], hence this allows a simple substitution of SCBA with sand, without affecting other proportions (Table 1). In both Stage-one and -two, the water content was kept constant at a water/binder (W/B) ratio of 0.45 by cement weight. However, in Stage-one (Table 1) the specified slump was allowed to vary, whereas in Stage-two (Table 2), superplasticizer was added (by weight% of cement and SCBA), to maintain the same workability (80 ± 10 mm slump).

2.3. Manufacturing and curing of specimens

Concrete was mixed in a 70 L drum 'Creteangle®' concrete mixer with batch mixing performed by mass. The oven dried coarse aggregate was first added to the drum mixer followed by the natural sand, and the SCBA. Enough of the mix water was added at this stage to wet the SCBA, sand and coarse aggregate. For Stage-one the water contained no superplasticizer, but for Stage-two the superplasticizer was added to the mix water and stirred for 30 s prior to water incorporation with aggregate materials. Cement was then added to the mixer after a period of 30 s of mixing, before a 2 min mixing period in where remaining water was added. The concrete mix was then allowed to rest for 2 min followed by further 2 min mixing. At this time the slump was then measured and if correct the slump sample was returned, and the batch mixed for a further 2 min [38].

Concrete specimen moulding was completed within 20 min of mix cessation and slump testing. Cylindrical specimens, 100 × 200 mm) used for compressive strength and chloride ingress tests were cast by three additions, each addition was compacted by the use of a shaker table [39]. Beam specimens, for flexural strength and drying shrinkage, and cube specimens 100 × 100 mm) used for acid resistance tests, were compacted by rodding with a tamping bar. These were cast in two separate additions, with each addition tamped with 55 tamping strokes [40].

Three cylinders were cast for each mix for compressive testing at 7, 14, 28 and 56 days, totaling 108 compression test specimens. Replicate tests were conducted for each chloride ingress test for mixes CC, SPF5 and SPF10, totaling 6 chloride