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Investigation of Pozzolanic Properties of Sugarcane Bagasse Ash for Commercial Applications

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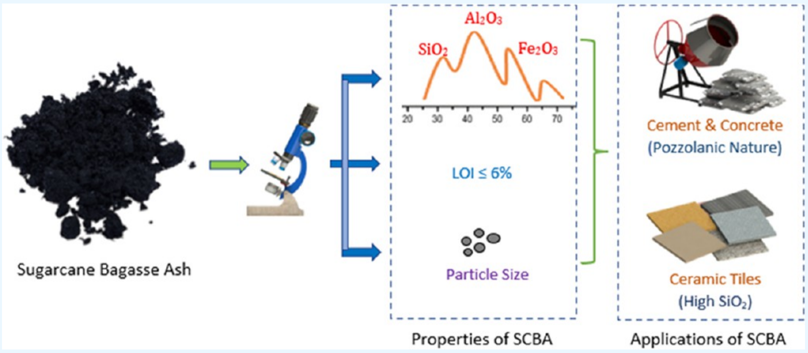

ABSTRACT: The ideal climatic and environmental conditions for sugarcane cultivation are present all year round in the tropical island of Sri Lanka. Given the annual sugar consumption of the nation, a significant amount of sugarcane bagasse ash (SCBA), a by-product with no intended commercial use but potential environmental and health risks, is produced. Numerous studies have been conducted recently to assess the viability of using SCBA as a pozzolanic material in structural applications. The purpose of this study is to evaluate the microstructure of SCBA samples from three sugar manufacturing facilities in Sri Lanka to identify the pozzolanic capacities. Several quantitative and qualitative characterization techniques have been utilized for the investigations. While maintaining the American Society for Testing and Materials (ASTM) 618 specification as the standard for pozzolanic properties, a comparative investigation of the attributes of samples from each location was conducted. Beyond that, the relationship between the SCBA generation process parameters and their impact on the properties of SCBA have been identified. Finally, the SCBA source of the Pelwatte unit has been identified as the ideal source for the pozzolanic material from the three locations, considering quality and the extent of additional treatments required before use. Other prospective areas of research on SCBA and its potential applications have been recognized.

1. INTRODUCTION

Numerous researchers have concentrated on agricultural waste generation in an effort to minimize negative environmental effects and to explore the possibilities for such waste to be repurposed and reused. Because landfills are frequently utilized as dumpsites, which undermine their commercial value, disposing of agricultural waste has been a significant problem.[1−6] In addition, dangerous substances and particles pollute the environment surrounding dumpsites, endangering the health of nearby residents.[7] The purpose of this line of research is to investigate the microstructural characteristics of sugarcane bagasse ash (SCBA), a by-product of the sugar industry to evaluate the possibility of utilizing SCBA in commercial applications. One of the main applications of SCBA that is frequently mentioned in the literature is related to its pozzolanic characteristics. To evaluate this behavior; samples were collected from three of Sri Lanka's largest sugar production facilities. Furthermore, by incorporating SCBA into commercial items including concrete, ceramic tiles, earth blocks, and biofertilizers, negative environmental and health concerns will be minimized.[8−12]

According to the American Society for Testing and Materials (ASTM) C618-08a specification, the distinctive chemical composition of SCBA can be generally characterized as a

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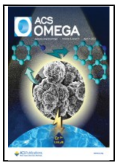

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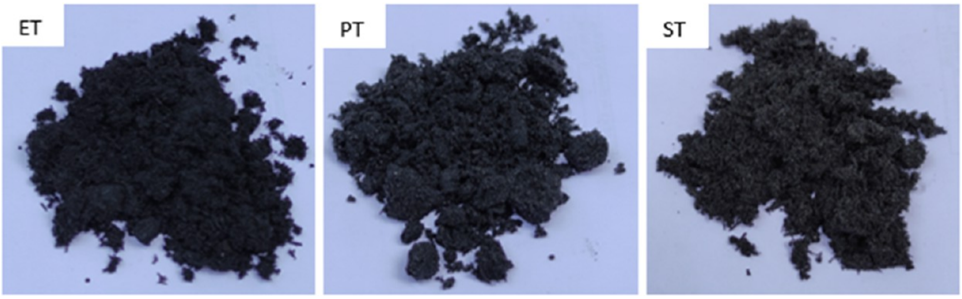

Figure 1. Top ash samples: ET, Ethimale top ash; PT, Pelwatta top ash; and ST, Sewanagala top ash.

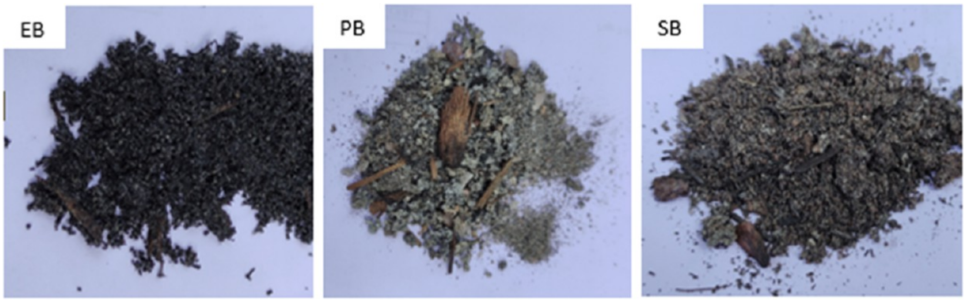

Figure 2. Bottom ash samples: EB, Ethimale bottom ash; PB, Pelwatta bottom ash; and SB, Sewanagala bottom ash.

class F pozzolan material. This classification is made possible by the main fact that SCBA is 70%, consisting of SiO_2, Al_2O_3, and Fe_2O_3 compounds. Because of its capability, many researchers have reported the potential of SCBA to replace ordinary portland cement (OPC) in certain applications.[13−16]

While sugarcane crops account for 80% of all sugar production worldwide, they are regarded as the crop with the highest global production rates.[17] Other industries that have a direct relationship to the cultivation and production of sugar include bioethanol, alcoholic beverages, yeast, and paper.[17,18] Only about 10% of Sri Lanka's annual sugar requirement, which was over 590,000 MT in 2019 has been domestically produced.[19]

Remaining sugarcane bagasse is usually used inside the boilers as a biofuel to produce steam to generate electricity and to power the steam engines inside the production plant after sugar and other significant by-products from sugarcanes have been produced. The final waste product in the processing of sugar is SCBA, which is produced in the subsequent stage of the steam generation process. After being burned in boilers, one ton of sugarcane bagasse yields about 4% (or 40 kg) of SCBA.[20,21]

Ethimale Plantation (Pvt) Ltd is one of the sugar manufacturing plantations in Sri Lanka situated in the Monaragala district. The manufacturing operation of this facility commenced in 2017. It has the capacity to produce 25,000 MT of sugar annually and planning to produce 15,000 L of alcohol per day. The plant uses sugarcane bagasse, which is produced as the primary by-product, to generate steam, which produces an electrical output of around 4 MW. That is sufficient to power the entire operation alongside steam engines. Throughout the process of burning sugarcane bagasse, the internal temperature of a boiler is maintained between 700 and 800 °C. SCBA is collected from two distinct locations of the process. Dense SCBA, also known as bottom ash, is gathered inside the boiler unit where the collected sugarcane bagasse is burned. Before the exhaust gas is released into the environment, dust particles are captured in the electrostatic precipitator unit, producing top ash, which is lighter and finer than bottom ash.

Lanka Sugar Company (Pvt) Ltd., Pelwatta is another sugar manufacturing facility, which is also located in the same district as Ethimale plantations. For the manufacturing of sugar, this plant has the capability of crushing 115 MT of sugarcane per hour. Two boiler units used in the sugarcane bagasse calcination process are kept at a temperature between 1000 and 1300 °C while in use. Bagasse burns inside the boiler for a relatively short time due to the high temperature that is maintained. Bottom ash is collected from inside the boiler whereas top ash is collected from the flue gas transporting through cyclone separators and water injectors. Finally, the top ash is collected as a slurry via settling tanks. Therefore, the top ash has a higher moisture content when it is collected. For the time being, there is no value addition or intended use for the volumes of collected ash.

Since 1986, the Sewanagala plant of Lanka Sugar Company (Pvt) Ltd has been operating on the border of the Monaragala district of Sri Lanka with a daily production capacity of 1250 MT of crushed sugarcane. Depending on the season and the type of processed sugarcane utilized, the amount of sugar produced is approximately 6% of the mass of crushed sugarcane. The factory's two working bagasse boilers are maintained at an average temperature of 600 °C and they can reach a maximum temperature of 850 °C. Bagasse is continuously supplied to the boilers, which then use it to produce 25 tons of steam per hour for the steam engines and for the production of electricity. During the dry weather season, 2.5 MW of electricity is generated, which is sufficient to meet the entire energy need of the operation. Soot scrapers are used to remove the bottom ash from the boiler, while cyclone separators are used to collect the top ash from top ash filters. Sand and soil get contaminated with sugarcane bagasse during the harvesting process and when the boilers are loaded with crushed bagasse. Sugarcane from the fields contains a

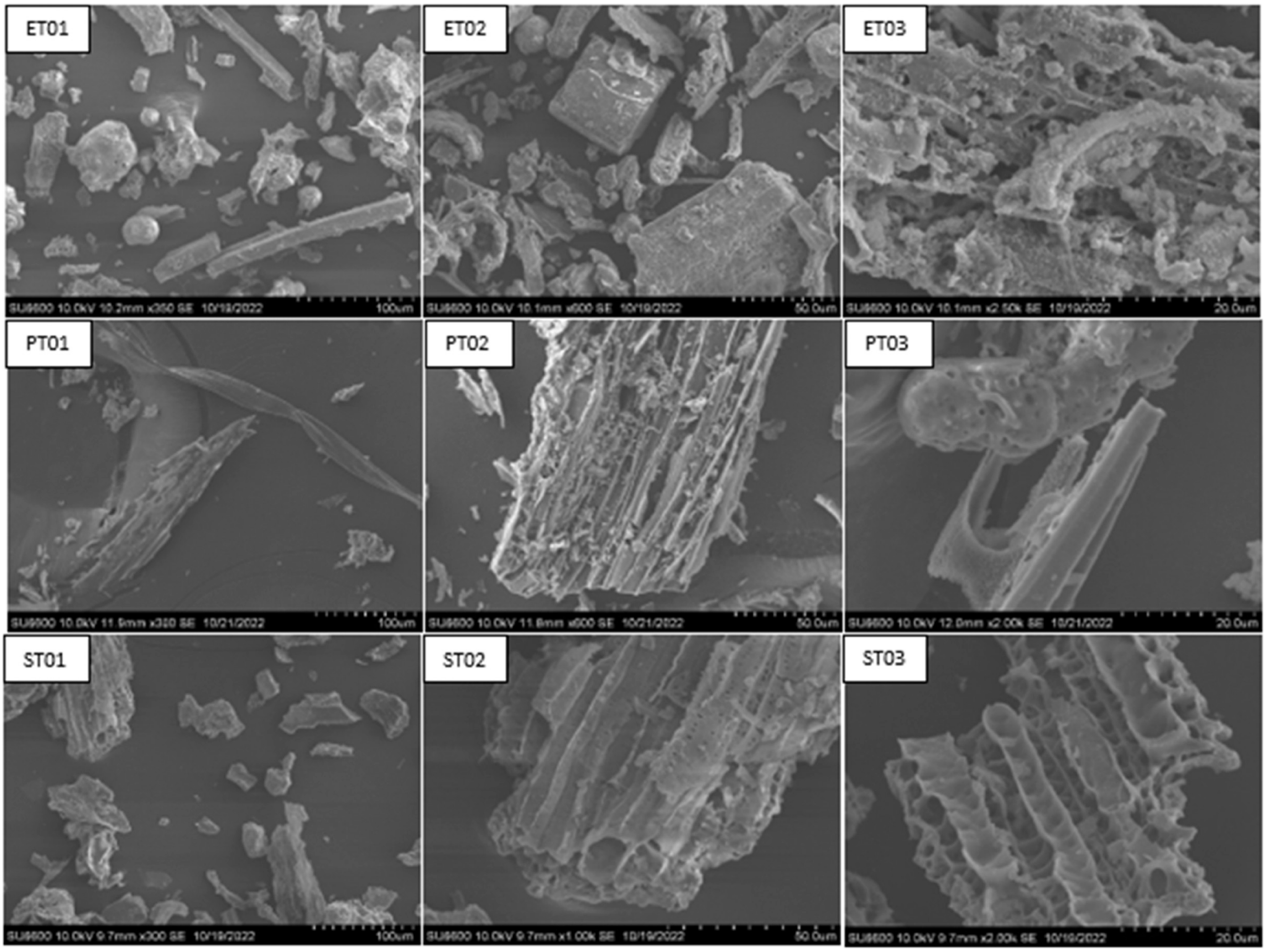

Figure 3. SEM images of top ash samples: ET01, ET02, and ET03—Ethimale top ash; PT01, PT02, and PT03—Pelwatta top ash; and ST01, ST02, and ST03—Sewanagala top ash.

significant amount of mud and soil, this is particularly acute during the wet season. In the Sewanagala plant, the burning of 1 MT of bagasse produces roughly 16 kg of top ash and 26 kg of bottom ash. Around 180 MT of top ash and 300 MT of bottom ash are produced from the boiler during an average month of operation. The produced SCBA is transported to the dumpsites and partially used as fertilizer in neighboring farmland.

Provided information about the above processes has been gathered by referring to production/plant records and by on-site observations. Scientific research work on the properties of SCBA samples from the mentioned sugar manufacturing facilities is yet to be conducted to identify to assess if they have the potential to be used in commercial applications. This study aims to bridge that specific research gap and reveal additional possible SCBA-related research fields.

2. EXPERIMENTAL SECTION

Ethimale Plantation (Pvt) Ltd, Monaragala; Lanka Sugar Company Ltd, Pelwatte; and Lanka Sugar Company Ltd, Sewanagala are the leading sugar manufacturing facilities in Sri Lanka, six SCBA samples were collected for characterization purposes. For comparative characterization, random top ash samples (Figure 1) and bottom ash samples (Figure 2) were gathered from each location. These samples were produced on the same day of sugarcane crushing. Sample preparation was carried out to conduct scanning electron microscopy (SEM), X-ray diffraction (XRD), particle size distribution, X-ray fluorescence (XRF) spectroscopy, and differential scanning calorimetry−thermogravimetric analysis (DSC-TGA).

A 2.36 mm standard sieve was used to filter out large unburned particles before selecting three bottom ash SEM samples. Three top ash samples did not require this filtering procedure because they were readily comprised of relatively finer particles. After that, the samples were heated in an oven at 105 °C for 3 h to achieve a constant weight by removing moisture. Six SCBA samples were examined using a "Hitachi SU6600" scanning electron microscope to examine the morphologies of the grains. Samples were sprayed on carbon tape and then gold coated. A 10 kV acceleration voltage and a 2.3 A emission current from secondary electron signals were used to capture the images.

For XRD examination, three samples of top ash were obtained. Moisture was eliminated from each top ash sample by processing them in a drying oven set to 105 °C for 3 h, until the sample's weight remained constant. Then, the fine powder samples were developed by grinding. A "Bruker D8 Focus" diffractometer (Cu Kα radiation) was used to obtain XRD data. Diffraction patterns for 2θ angle between 5 and 90° were

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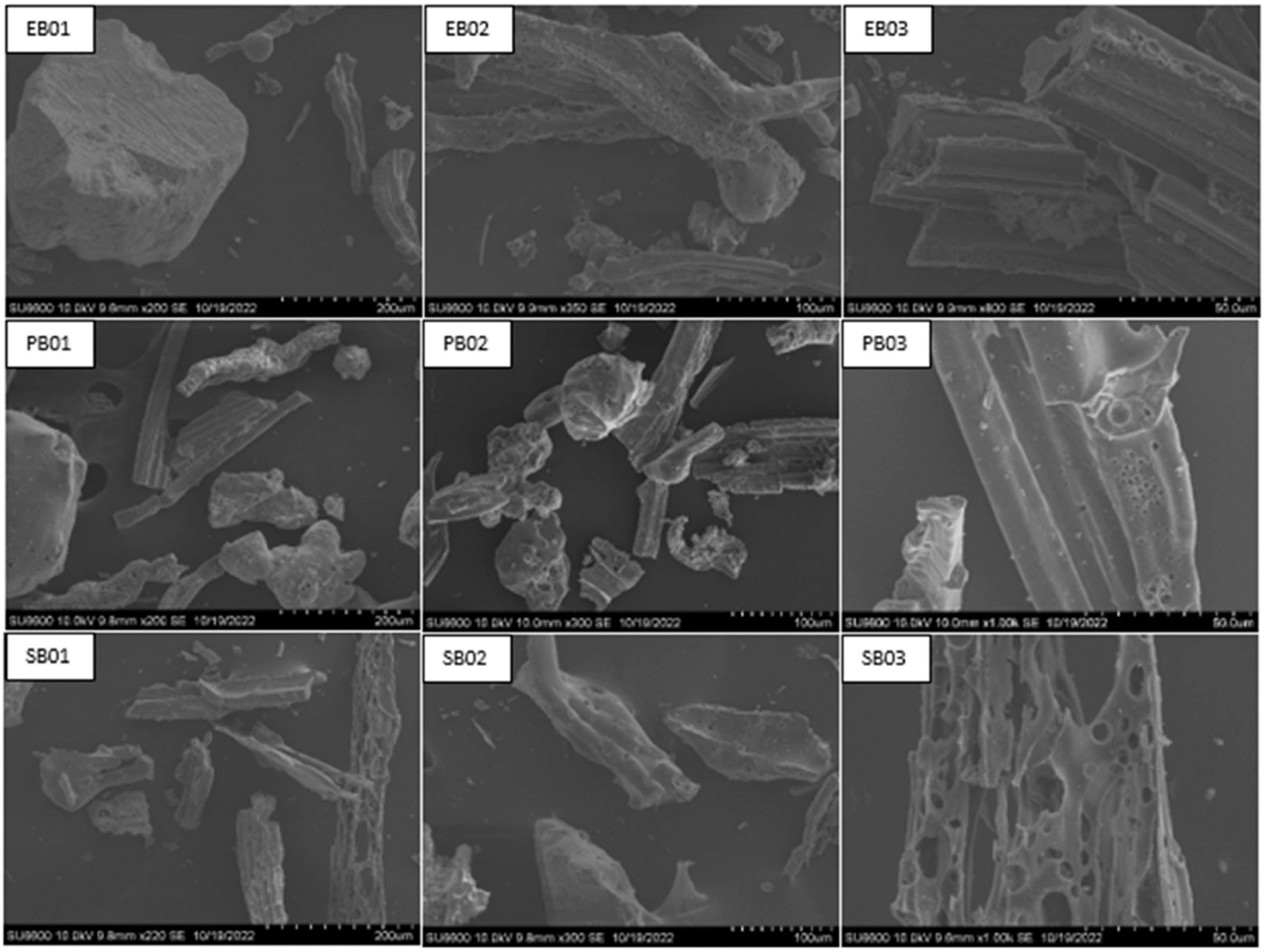

Figure 4. SEM images of bottom ash samples: EB01, EB02, and EB03—Ethimale bottom ash; PB01, PB02, and PB03—Pelwatta bottom ash; and SB01, SB02, and SB03—Sewanagala bottom ash.

examined. The step size was 0.019939° and the time per step was 19.200001 S.

The chemical composition of three top ash samples was investigated using the XRF characterization technique. A representative sample from each source was first mounted on the sample stage using double tapes. Investigations were carried out for six distinct locations of each sample. A "HORIBA Scientific XGT—5200 X-Ray Analytical Microscope" was utilized with an XTG diameter of 100 μm, an X-Ray tube voltage of 50 kV, processing time—P4, and Live time 300 s for characterization.

The "Fritsch-Analysette 22 Nano Tec" particle size analyzer with a measuring range of 0.01−2100 μm was used to determine the particle size of top ash samples. To determine the size distribution of the original SCBA from factories, three top ash samples were dried in an oven at 105 °C for 3 h. Grinding was not performed on the samples. For each top ash sample, the test was repeated four times, and the average results were computed.

DSC-TGA analysis was conducted using "SDT Q600 V20.9 Build 20" thermal gravimetric instrument. Top ash samples between 5 and 10 mg were studied at a heating rate of 19.8 °C/min under an N2 atmosphere.

3. RESULTS AND DISCUSSION

3.1. Microscopic Morphology of SCBA.

3.1.1. Top Ash Samples. SEM images of top ash samples are depicted in Figure 3. Images labeled as ET01, PT01, and ST01 respectively represent the 100 μm scale of Ethimale, Pelwatte, and Sewanagala SCBA samples. The Ethimale top ash sample, ET01 depicts both elongated prismatic particles and small spherical particles while Pelwatte top ash, PT01 indicates the presence of coarse fibrous particles which could be due to unburnt organic materials present in the Pelwatte SCBA sample. Prismatic particles with sharp edges possibly indicate the availability of crystalline materials. Sewanagala top ash sample, ST01 contains both prismatic and fibrous noncrystalline particles in its microstructure. ET02, PT02, and ST02 are magnified images at the 50 μm scale where crystalline particles of Ethimale top ash are further highlighted while fibrous particles in Pelwatte top ash and Sewanagala top ash are visible. Scaled-down images at 20 μm; ET03, PT03, and ST03 provide more information about the porous characteristic of SCBA samples. Pores with large surface areas are revealed in Ethimale top ash and Sewanagala top ash samples in comparison to those of the Pelwatte top ash sample. Small crystalline regions of the Pelwatte sample can be identified as well.

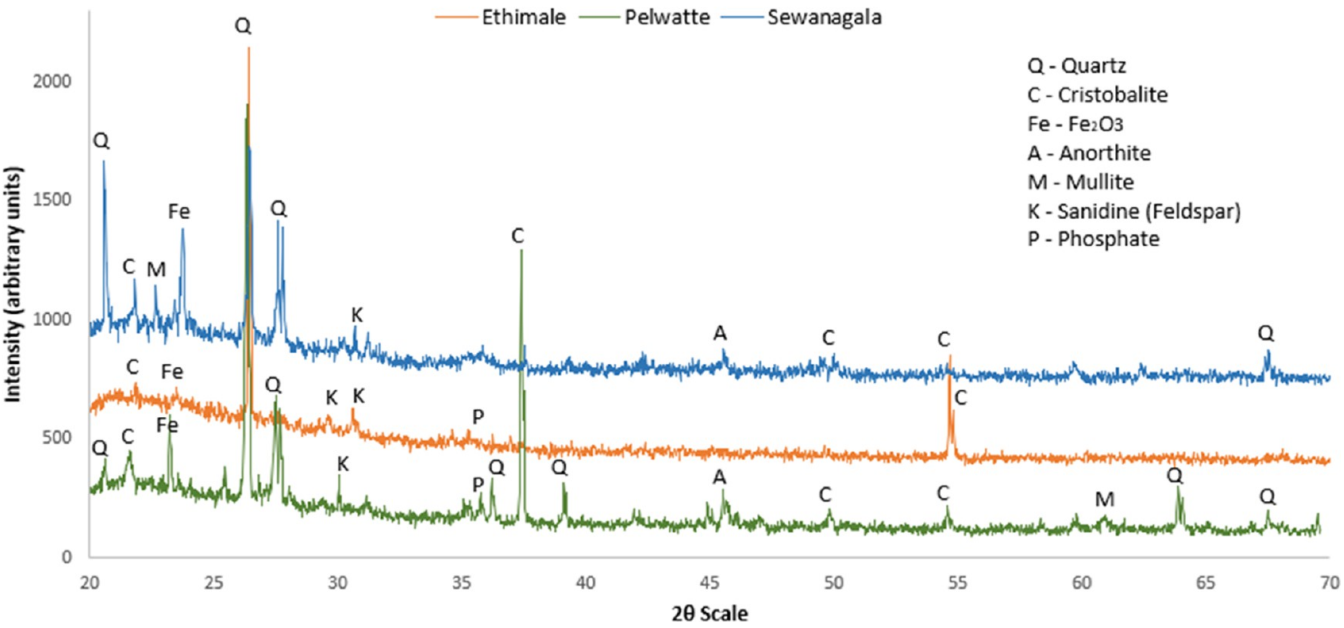

Figure 5. XRD diffractograms for top ash samples.

In general, prismatic, spherical, and irregular-fibrous particles are present in SCBA. These morphologies are similar to those observed by Torres Agredo et al.,[22] Faria et al.[2] and Natarajan et al.[23] Crystallinity of Ethimale top ash samples is prominent in SEM images than the other two top ashes. This is indicated by the frequent presence of the fully burnt particles with sharp edges. Pelwatte and Sewanagala ash samples indicate the presence of larger particles of unburnt organic material. The images indicate that the particle size of Ethimale top ash is the smallest and Pelwatta top ash contains several larger size (elongated) particles than the size of coarse particles in Sewanagala top ash. Porosity of particles is the highest in the Sewanagala top ash sample and it is the least in the Pelwatte top ash sample.

Figure 4 shows SEM images of bottom ash samples. Here EB01, PB01, and SB01 are 200 μm scale images of the three ash samples. Clearly visible large crystalline particles can be identified in all three samples which could indicate that contamination occurred due to the sand, mud, and soil particles mixed with SCBA.[24] EB02, PB02, and SB02 are the 100 μm scale images and depict the presence of large coarse and porous particles. Particle sizes vary intensively while the shapes of the particles can be considered as irregular by a large margin. This could be due to the high amount of unburnt organic matter present in all three bottom ash samples. de Aguiar et al.[25] have observed similar characteristics in raw sugarcane bagasse treated with different solutions. Some level of crystallinity can be identified in images captured at the 50 μm scale (EB03, PB03, and SB03). Generally, all bottom ash samples depicted coarse and porous particles mixed with large foreign crystalline particles. Compared to Figure 3, showing the top ash samples, more unburnt carbon material is present in the microstructure of all bottom ash samples. Particle size distributions of bottom ash samples are vivid and the particles are much larger in size in comparison to the particle size of top ash grains. As depicted in Figures 1 and 2, these characteristics were visible to the naked eye as well. Properties revealed by SEM images demonstrated a poor pozzolanic nature of the bottom ash samples. Hence, top ashes from three sugar factories show more favorable microstructures to be used in structural application as a pozzolanic material than the three bottom ash samples.[26−28]

3.2. Mineralogical Composition of SCBA.

Crystalline mineralogical phases present in three SCBA top ash samples Ethimale, Pelwatte, and Sewanagala were identified by implementing qualitative XRD tests separately on each individual sample. Later, three representative diffraction patterns were plotted in the axis system for comparison. Sharp peaks were identified between a 2θ range of 20−70° and Figure 5 presents the results with labeled peaks.

Peaks representing quartz (SiO_2), cristobalite (SiO_2), and iron oxide (Fe_2O_3) can be clearly identified in diffraction patterns of all three top ash samples. The presence of anorthite ($CaAl_2Si_2O_8$) and mullite ($Al_6Si_2O_{13}$) in the microstructure of Pelwatte top ash and Sewanagala top ash samples is indicated by the corresponding peaks. Sanidine ($KAlSi_3O_8$) and small phosphate peaks[29,30] in the XRD spectrum indicate the correlation between results of XRF techniques (Table 1) and XRD results.

Table 1. Chemical Composition of Top Ash Samples

(w/w)%	Sewanagala	Pelwatte	Ethimale
Fe_2O_3	2.83	2.49	1.90
Al_2O_3	4.45	2.95	0.56
SiO_2	62.02	68.02	62.41
P_2O_5	0.00	2.86	2.08
K_2O	6.84	6.65	7.14
CaO	3.80	6.38	4.25
TiO_2	0.43	0.14	0.16
MnO	0.20	0.21	0.42
MgO	0.32	0.36	1.40
BaO	0.00	0.01	0.00
Sm_2O_3	0.00	0.03	0.00
Cr_2O_3	0.00	0.00	0.01
ZnO	0.00	0.00	0.06
LOI	19.11	9.88	19.61

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The presence of silica in free quartz form can be due to several reasons. Contamination of soil and sand particles in SCBA while sugarcanes were harvested, uncontrolled incineration process, and absorption of silica through the roots of sugarcane plants are some of the reasons mentioned by researchers.[3,31] A relatively low number of quartz and other sharp peaks are present in the diffraction patterns of the Ethimale top ash sample compared with Sewanagala and Pelwatte top ash samples. Rather a broad hump is present at a 2θ range between 26 and 55° that corresponds to amorphous contents.[20,32] This indicates that the crystalline properties which hinder pozzolanic properties of SCBA are the least in Ethimale top ash. A number of sharp peaks appear and their distribution in the diffraction pattern in Pelwatte and Sewanagala top ash samples are approximately the same, which could indicate the crystalline nature of the two samples is more similar to each other than to the Ethimale top ash sample. Some of the other chemical compounds mentioned in the literature that were not identified in this research are graphite, gibbsite, and calcite.[4,22,33,34] Overlapping of peaks within the diffraction patterns and low concentrations of such elements are possible reasons for not identifying some of the compounds.

3.3. Chemical Composition of SCBA.

Results of chemical composition analysis are shown in Table 1 and they are the average values of six individual results in six distinct locations of a sample. Values indicated are calculated considering loss on ignition (LOI) correction of XRF results.[20]

SiO_2, Al_2O_3, and Fe_2O_3 cumulative weight percentage of SCBA samples, which is responsible for pozzolanic properties are 69.30% for Sewanagala top ash, 73.46% for Pelwatte top ash, and 64.87% for Ethimale top ash. Therefore, based on ASTM C618 specification, the Pelwatte top ash sample satisfies the compositional classification of class F pozzolans while Ethimale and Sewanagala top ash samples only satisfy the classification under class C pozzolans.

LOI values are critical to the water requirement and rheological properties of concretes and mortars. SCBA with high LOI values is not desirable in cement composites as they hinder fluidity during the mixing process. The compressive strength of high LOI cement composites has shown slight reductions.[35] The highest LOI values recorded in this experiment are 19.61% for Ethimale top ash and 19.11% for Sewanagala top ash (Table 1). Neither of the mentioned two top ash samples satisfies the standard requirement for LOI, which is specified in ASTM C618 under class N, class F, or class C pozzolan material.[36−38] But the Pelwatte top ash sample has an LOI value under 10% which makes it compatible with LOI requirement of ASTM C618 for a class N natural pozzolan that can be utilized in concretes with average strengths. Therefore, the chemical compositions of the three top ash samples reveal the aptness of a secondary burning process to further enhance the desired properties before utilizing the ashes as pozzolanic materials. An increase in pozzolanic materials percentage and a reduction of the LOI value are the expected outcomes of this secondary burning process.

It is mentioned that the formation of small spherical particles, such as the ones observed in SEM images of Figure 3 can be attributed to the melting of miner components observed in the XRF spectrum, including Mg, P, Ca, Zn, and Fe.[13,39] Furthermore, Cordeiro et al.[39] have observed that the pozzolanic activity index increased until the calcination temperature of SCBA reached a certain value (600 °C). This increasing behavior is due to carbon removal and then it reduces as the crystalline content of SCBA increased further with increasing temperatures. Therefore, valid research work can be conducted on the relationship between pozzolanic activity and calcination temperature of SCBA in Sri Lankan sugar factories to identify an optimum calcination temperature.

3.4. Particle Size Distribution of SCBA.

It can be identified that particle size and size distribution of three SCBA top ash samples are fairly different. As listed in Table 2,

Table 2. Particle Size Distribution of Top Ash Samples

	10% (D10)	50% (D50)	90% (D90)
sample ID	average (μm)	average (μm)	average (μm)
Ethimale	8.37 (±0.25)	46.71 (±2.49)	117.43 (±14.86)
Sewanagala	12.99 (±1.10)	57.89 (±1.96)	179.70 (±19.71)
Pelwatte	9.19 (±0.66)	51.40 (±2.47)	206.66 (±29.47)

Ethimale top ash consists of the smallest particles in its microstructure (90% of particles having an average size of 117.43 μm), which is more favorable in enhancing the pozzolanic activity of SCBA. Cordeiro et al.[40] have observed a similar value in their unprocessed SCBA (115.7 μm). Average size distribution from the smallest to the largest particles of the Ethimale top ash sample is approximately 109.06 μm and it is the narrowest range from the three top ash samples as well (size distribution of Pelwatte top ash is 197.47 μm and size distribution of Sewanagala top ash is 166.71 μm).

According to ASTM 618-12a classification, to be considered as an acceptable pozzolanic material, fineness of the material/the amount retained when wet-sieved on a 45 μm (No. 325) sieve (or the percentage of particles larger than 45 μm) has to be no more than 34% by weight.[37] Figures corresponding to any of the top ash samples in Table 2 do not satisfy this requirement. Therefore, each top ash sample requires a particle size reduction process before it can be used as pozzolanic materials.

In Figure 6 (PT), some larger particles or agglomerations of particles are indicated in the particle size distribution pattern (see the circled region) of the Pelwatte top ash sample. This result aligns with the observations made in SEM characterization of the Pelwatte top ash sample in Figure 3. The reason could be the low burning time of bagasse inside the boilers in the Pelwatte unit. It is possible that some of the bagasse, which did not get fully decomposed during this limited time period, reaches the top ash chambers. Unburnt or half-burnt bagasse particles which enter the flue gas are larger in size and they could act as centers for other SCBA particles to adhere onto. This is one reason for the deviation of the particle size distribution pattern of the Pelwatte top ash sample. The color of the Pelwatte top ash sample is black [see Figure 1 (PT)] rather than gray. This could be an indication that the top ash sample collected from the flue gas has reached a lower temperature compared to the average temperature inside the boiler.[31,41] Soares et al.[42] have also mentioned the calcination temperature and the air-flow conditions to be the governing factors of particle size of laboratory SCBA samples prepared in similar calcination periods. Another probable reason for this observation could be the top ash collection method in the Pelwatte unit. Because top ash is collected from the setting tank with water, agglomeration of SCBA is very much possible. Hence, the particle size could be randomly increased.

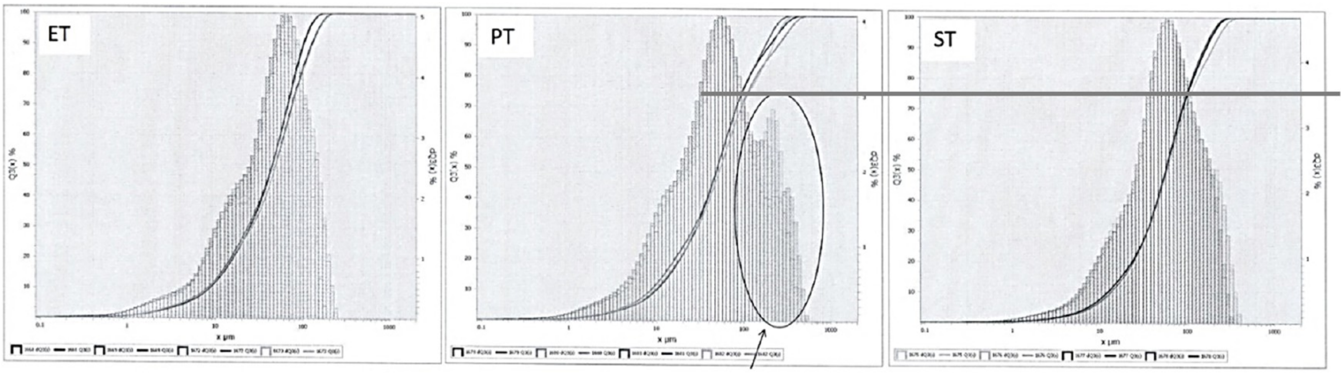

Figure 6. Particle Size Distribution: ET, Ethimale top ash; PT, Pelwatta top ash; and ST, Sewanagala top ash.

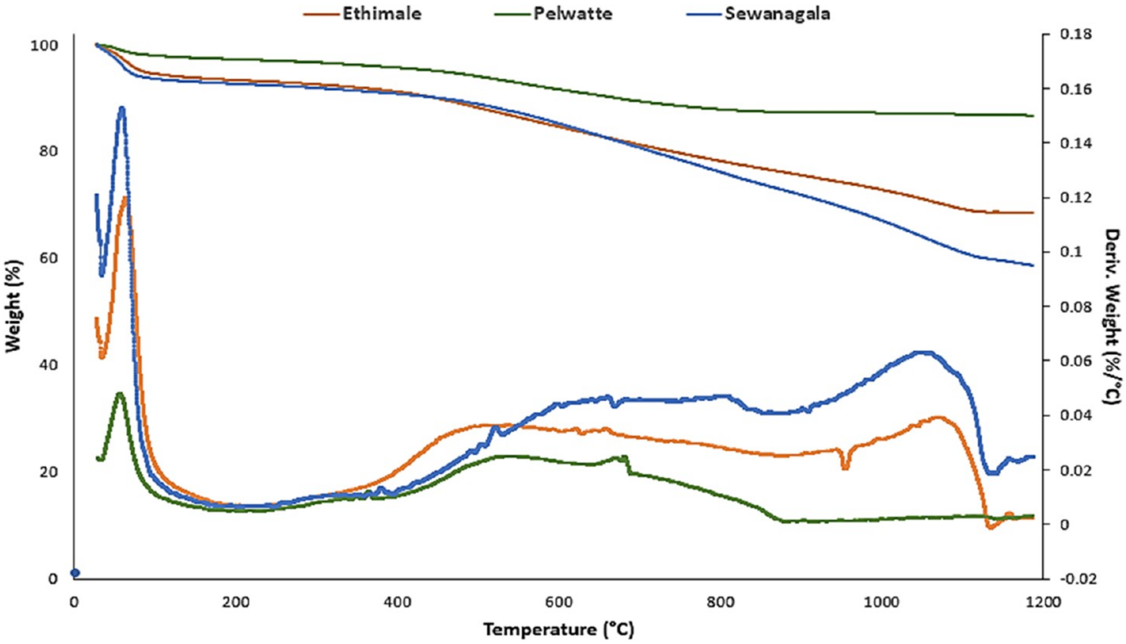

Figure 7. DSC (below) and TGA (above) for Top ash samples.

In the Literature, SCBA with considerably smaller particle sizes than the particle sizes observed in this experiment has been recorded. Average particle sizes of under 14 μm were recorded by Cordeiro et al.[39] and Chindaprasirt et al.[43] Below 12 μm by Frías et al.,[4] below 10 μm by Ganesan et al.[44] and approximately 4.3 μm by de Soares et al.[45] have been mentioned. Therefore, the possibility of reducing particle sizes of the samples collected for this experiment has to be further studied.

3.5. Thermal Analysis of SCBA. Figure 7 represents the thermal analysis of three top ash samples. TGA characteristics are illustrated in the top three curves whereas the variations in derivatives of the TGA curves; DSCs are indicated by the three graphs at the bottom of Figure 7. The least weight loss with increasing temperature is exhibited in the Pelwatte top ash sample. This could be an indication of the high temperature inside boilers of the Pelwatte factory (1000−1300 °C) that results in the complete burning of the majority of organic compounds in final SCBA. TGA curves of Ethimale and Sewanagala top ash samples are almost the same, approximately up to a temperature of 800 °C. This observation is comprehensible since the boilers in the two facilities reach a similar maximum temperature of around 800−850 °C during operation.

All three samples have endothermic DSC peaks localized at about 50−150 °C, which can be attributed to evaporation of moisture in three ash samples. Again between 200 and 300 °C, second endothermic peaks corresponding to partial dihydroxylation of gibbsite present[46] in all three ash samples. The most critical weight losses occur in the temperature range from 200 to 950 °C where Ethimale, Sewanagala, and Pelwatte SCBA, respectively, have lost 19.11, 19.61, and 9.88% of their initial weights. Carbon decomposition is not isolated in this technique as the thermal analysis was conducted in an inert N_2 environment. Therefore, this weight loss could account for the decomposition of other mineralogical phases alongside decomposition of unburnt carbon materials.[4] Exothermic peaks present in Ethimale and Pelwatte ash samples between 600 and 650 °C, which can be attributed to phase transition from P_2O_5 to P_2O_7.[47] Endothermic peaks that correspond to decomposition of all crystalline phases[48] is localized about 850 °C for the Pelwatte sample. For Sewanagala and Ethimale samples, endothermic peaks of decomposition are present above 1100 °C. These observations are compatible with the operational temperatures of boilers in three manufacturing facilities.

4. CONCLUSIONS

From the findings, it can be concluded that top ash samples from the sugar plants in Ethimale, Sewanagala, and Pelwatte exhibit more favorable properties compared to the samples from bottom ash. Top ashes possess a smaller number of impurities and less amount of unburnt bagasse in their microstructures. The microstructure of top ash is more suitable for structural applications as a pozzolanic material while the secondary treatment processes are required to further enhance pozzolanic properties.

As per secondary treatments, Unburnt bagasse present in all three top ash samples tends to be larger in size in comparison to fully burnt SCBA. Therefore, the top ash samples will require a simple sieving process to partially remove coarse, unburnt, or half-burnt particles prior to application. SCBA from the boilers of Sewanagala and Ethimale have to be calcined again to reduce the LOI value below 6% and to improve the pozzolanic material content further up to 70%. But Pelwatte top ash requires a secondary burning only to reduce the LOI value (which is already below 10%) to reach the classification of class F pozzolan material. Therefore, Pelwatte top ash appears to be the ideal and most economical source of SCBA.

The average particle size of the three top ash samples from factory outlets considerably deviates from the particle size specification for pozzolanic materials. To reduce the particle size and to meet the requirements of ASTM C618 for fineness of the particles, all three top ash samples have to be subjected to grinding, milling, or other suitable mechanical treatment processes.

In this study, potential of SCBA to be used as a pozzolanic material has been identified. In addition, as a pozzolanic material, high silica content of SCBA indicates the possibility to be used as alternative silica materials in applications such as ceramic tiles as well. Value addition to waste is one of the potential advantages of this application while the possibility of safe removal of waste will be evident.

One of the major constrictions is that the majority of SCBA generated is bottom ash and it does not possess the required properties for the intended applications. Furthermore, cost factor of secondary treatment required to enhance the properties of top ash will be a concern as well.

The following potential areas of research have been identified from this study.

1. The relationships between pozzolanic activity, calcination temperature, and calcination periods of SCBA for each manufacturing facility have to be further studied. The samples collected for this study correspond only to certain calcination temperatures. Since the temperature inside bagasse boilers varies in a wide range, variation of pozzolanic properties with temperature can be studied, which would provide an idea about the optimum temperature and optimum calcination period for better SCBA for applications.
2. The amorphous material percentage in SCBA from each source has only been qualitatively studied in this research. The study can be extended to quantitative analysis of amorphous materials in SCBA, which would further extend the knowledge of the pozzolanic properties of SCBA.
3. Due to the pozzolanic nature of the studied top ash samples, the performance of composite materials with such SCBA can be investigated. There are research openings toward areas including mechanical properties and performance of concrete, ceramic tiles, and other products made with SCBA. Their microstructure and the optimum percentage of SCBA that can be utilized in such applications and cost-effectiveness of such products can be studied as well.
4. Physical properties of SCBA from each source including density and surface area have to be studied.
5. Contamination of sand has made it difficult to use bottom ash as a pozzolanic material. Since the amount of bottom ash produced is considerably higher than top ash volumes, it would be vital to study possible methods to minimize the contamination of sand and soil with SCBA.

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