Use of processed biomass ash as a sustainable pozzolana

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The industrial waste generated from sugar production, i.e. bagasse is further used as a biofuel. This generates a huge amount (44,000 tonnes/day) of waste in the form of sugarcane bagasse ash (SCBA). As-received boiler SCBA shows lower performance in terms of pozzolanic characteristics. In this study, the role of mechanical and thermal treatment in improving the pozzolanicity of SCBA has been examined. The preliminary characterization of SCBA was done using laser granulometry, SEM, XRF, XRD and TG analysis. The four methods were adopted to quantify the pozzolanic behaviour, viz. reactive silica determination, pozzolanic activity index, electrical conductivity drop and Chapelle activity. Further, the experimental data were analysed using ANOVA. The coefficient of regression (0.86–0.99) reflects effective and significant logarithmic models. The study concludes that the adopted processing of SCBA is highly effective in improving the pozzolanicity. Thus the processed SCBA is a sustainable solution to the cement industry.

Keywords: Biofuel, cement industry, sugarcane bagasse ash, sustainable pozzolana.

DEVELOPING countries like India generate a significant amount of solid waste from agro-industries. The sugarcane biomass is one of the most generated solid wastes in India, viz. 91.262 MT/annum (refs 1, 2). This accumulated biomass is generally used as biofuel for generating heat energy to run various industrial operations. It provides abundant amount of waste (sugarcane biomass ash; SCBA), i.e. 44,000 tonnes/day. The cement industry contributes to 5% of global CO_2 emissions, of which 50% is released from the chemical decomposition of calcium carbonate and 40% is from the burning of conventional fossil fuels to generate heat energy. Unlike coal, the use of biomass as a fuel does not contribute to CO_2 emissions due to the cogeneration neutralization reaction[3]. Implementation of cleaner production practices using alternative raw waste-based materials will make the cement industry sustainable[4,5].

The SCBA available from different industrial sources in the environment shows inconsistent behaviour of pozzolanic characterization and physio-chemical properties. This is due to variation in crop origin, soil conditions, weather conditions of a crop region and industrial combustion conditions[3,6]. The uncontrolled combustion conditions in the sugar industry lead to the formation of crystalline phases of silica, which affects the pozzolanicity. It happens mainly because of the insufficient amount of oxygen in the boiler and higher rate of heating[7]. The reduction of the residence time of sugarcane biomass in the boiler results in the generation of bulk amount of unburnt carbonaceous matter in its ash. The as-received SCBA particles from the industry have irregular size (coarse and fine) and shape (round, angular, cellular, prismatic and fibrous). The finer SCBA has a higher specific surface area responsible for the early hydration of cement[8,9]. The pore spaces between the transition zone of aggregate and cement paste get filled by the microstructured particles of SCBA. This densification restricts the entry of water and protects the reinforcement steel against corrosion, and makes the structure more durable[8–13]. Hence it is necessary to treat the as-received SCBA mechanically and thermally.

The present study examined the effect of processing treatments like milling and calcination on particle size and mineralogical phases, which have a direct impact on pozzolanicity. The study was focused on finding the optimum conditions of mechanical (milling operation) and thermal treatment. The quantification of pozzolanic behaviour was carried out using a pozzolanic activity index, electrical conductivity drop, Chapelle activity and the amount of reactive silica. In addition, results of pozzolanic characterization were analysed using mathematical models (analysis of variance; ANOVA). The statistical correlation of pozzolanic properties was developed.

Materials

The residual SCBA was provided by the Wainganga Sugar Mill, M/s Manas Group of Industries, Maharashtra, India. In the sugar industry, residual sugarcane biomass was burnt in the temperature range 300–600°C under uncontrolled conditions.

A wide range of particle sizes was observed in the granulometric distribution. The D10, D50 and D90 of the as-received SCBA were found to be 10.33, 55.00 and 126.58 μm respectively.

The X-ray fluorescence method presented the chemical composition dominated by the percentage of silicon

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dioxide (SiO_2) (79.50) and loss on ignition (LOI) value was found to be 4.95%. The crystalline mineral phases of silica (cristobalite and quartz) and calcium carbonate (calcite) present in the as-received SCBA (AR-SCBA) were identified using X-ray diffractometer.

Ordinary Portland cement (53-grade) conforming to BIS 12269: 2013 and natural river sand was used in the making of cement mortar blocks for the analysis of pozzolanic activity index[14]. The saturated solution of calcium hydroxide [$Ca(OH)_2$] was used for performing electrical conductivity test. Distilled water and chemically pure calcium oxide were used for Chapelle activity measurements.

Method adopted

The physical characterization of raw SCBA, i.e. AR-SCBA was carried out by testing its consistency, setting time, soundness, lime reactivity, drying shrinkage, specific gravity, moisture content and bulk density.

Consistency (BIS 4031 (Part 3): 1968 (reaffirmed 2000)), setting time (BIS 4031 (Part 5): 1968 (reaffirmed 2000)) and soundness test (by autoclave method; BIS 4031 (Part 3): 1968 (reaffirmed 2000)) were carried out using the respective procedures, except that instead of cement a mix of AR-SCBA and cement was used for the analysis[15,16]. The ratio of AR-SCBA : cement was taken as $0.2N : 0.8$, where N is the ratio of the specific gravity of AR-SCBA and cement.

Lime reactivity and drying shrinkage of AR-SCBA were measured according to BIS 1727: 2004 (ref. 17). Specific gravity (using the Le Chatelier method) and moisture content were measured in accordance with BIS 1727: 2004, and bulk density according to BIS 2720 (Part 28): 2010 (refs 17, 18).

With an aim of obtaining higher specific surface area, the AR-SCBA was ultra-milled mechanically in a vibrating cup mill for four different durations, viz. 0.5, 5, 10 and 15 min. The respective samples were designated as SCBA-M0.5, SCBA-M5, SCBA-M10 and SCBA-M15, where M represents the mechanical treatment. The principle behind the milling operation of the vibrating cup mill is based on the motion of the cylindrical core placed in the system of two empty cylinders. Vibrations of smaller amplitude and higher frequency, responsible for the milling were created by the movement of the cylindrical core away from the centre of the system and towards the circumference of the outer cylinder. As SCBA is a soft material, sliding action (friction force) efficiently reduces the particle size instead of collision (impact force). So, the vibrating cup mill was selected for the study over the ball mill.

In case of thermal treatment, the samples, viz. AR-SCBA, SCBA-M0.5, SCBA-M5, SCBA-M10 and SCBA-M15 were burnt in a muffle furnace at an optimum temperature of 800°C for 2 h duration. The heating rate was maintained at 10°C/min. The respective thermally treated samples were designated as AR-SCBA:T, SCBA-M0.5T, SCBA-M5T, SCBA-M10T and SCBA-M15T, where T represents the thermal treatment. After combustion and cooling in the muffle furnace, the samples were taken out for further examination.

The laser granulometric analysis was carried out using a laser particle size analyser (Saturn Digitizer model 5205, Jawaharlal Nehru Aluminium Research Development and Design Centre, Nagpur, India). Distilled water was used as a dispersant. The distribution of particle sizes was analysed by D10, D50 and D90 values. The surface texture of the carbon-coated sample particles was studied using scanning electron microscope (JSM-6380A, Visvesvaraya National Institute of Technology, Nagpur, India) at a potential difference of 5 kV. The quantitative X-ray fluorescence analysis (PANalytical PW2403 MagiX, Indian Bureau of Mines, Nagpur, India) was carried out to check the chemical compositions of the respective samples. X-ray diffraction (PANalytical X'Pert Pro; at 40 kV and 30 mA) was used for mineralogical phase analysis. The scanning range was 10.0–64.9 with a degree of 2θ (step of 0.04) being maintained. Copper was utilized for X-ray diffraction. Thermogravimetric (TG) analysis was done to check the mass change with respect to temperature (Diamond TG, PerkinElmer, Jawaharlal Nehru Aluminium Research Development and Design Centre, Nagpur, India). It determines the thermal stability of the material.

The pozzolanic behaviour was studied using pozzolanic activity index, electrical conductivity drop, Chapelle activity and amount of reactive silica. The correlation was developed between pozzolanic behaviour of the mechanically treated and thermally treated SCBA samples.

In accordance with BIS 2250: 2000, the mortar blocks (70.5 mm × 70.5 mm × 70.5 mm) were prepared to test the pozzolanic activity index[19]. This index was calculated as the percentage ratio of 28 days compressive strength of sample block to that of a control block. The sample blocks were prepared by replacing 35% (by volume) of cement by the respective treated SCBA[20].

The electrical conductivity test gives a measure of the pozzolanic activity of the mineral admixture. First, the electrical conductivity of 200 ml saturated $Ca(OH)_2$ solution was measured at 40°C. Next, 5 g of the respective treated SCBA sample was added to the saturated solution of calcium hydroxide. The solution was stirred continuously and electrical conductivity was measured again. The drop in electrical conductivity gives a measure of pozzolanic activity[21].

Chapelle activity gives the pozzolanic reactivity in terms of reacting $Ca(OH)_2$. First, 250 ml of distilled water was mixed with the 1 g of mineral admixture (i.e. treated SCBA samples) and 1 g of calcium oxide powder.

After magnetic stirring of the solution, it was kept in the oven at 90°C for 16 h duration. The solution was allowed to cool and then titrated against 1N HCl acid using phenolphthalein indicator at room temperature. The titre values give the amount of reacted $Ca(OH)_2$ (ref. 22).

The reactive silica of the treated SCBA samples was determined by acid washing technique. The treated SCBA sample was weighted in an analytical weight balance. One gram of the sample was boiled in concentrated acid solution. The solution was then filtered through Whatman filter paper No. 40. The filtrate was washed with distilled water and dried in a furnace at 900°C for 1 h duration. The percentage loss in weight gives the amount of non-reactive silica[23].

The effect of mechanical treatment and thermal treatment on pozzolanic reaction kinetics of SCBA was studied and correlation was developed between the various pozzolanic properties.

Results and discussion

Table 1 shows the physical characterization of AR-SCBA. The consistency of the control cement paste was found to be 31%. According to BIS 12269: 2013, ordinary Portland cement (53-grade) has consistency in the range 30–32%. The presence of fibrous and porous particles increases the water requirement of AR-SCBA-blended cement to achieve the required consistency. The setting times were observed to be higher because of the same reason. Lower values of specific gravity (1.95) and bulk density (0.302 kg/l) of AR-SCBA were observed due to the presence of light-weight fibrous carbonaceous matter. A minor expansion (0.082%) and drying shrinkage (0.132%) were observed in the autoclave soundness test and the drying shrinkage test respectively. Lime reactivity depends upon the reaction product of reactive silica (present in AR-SCBA) and hydrated lime. It was observed to be less than the permissible limit because AR-SCBA has the crystalline phases of silica as well as unburnt carbonaceous matter, which makes it non-reactive.

Table 1. Physical characterization of as-received sugarcane biomass ash (AR-SCBA)

Physical properties	Results	Permissible limit (BIS 3812 (Part 1): 1981)[25]
Consistency (%)	36.5	–
Setting time (min)		–
Initial	190	
Final	275	
Specific gravity	1.95	–
Lime reactivity (N/mm^2)	2.6	Min 4.5
Drying shrinkage (%)	0.132	–
Soundness by autoclave (%)	0.082	–
Moisture content (%)	6.0	–
Bulk density (kg/l)	0.302	–

The porous and cellular nature of particles increases the water absorption capacity of AR-SCBA, resulting in the natural moisture content of 6%.

Figure 1 shows the cumulative particle size distribution of AR-SCBA and mechanically treated samples (SCBA-M0.5, SCBA-M5, SCBA-M10 and SCBA-M15). Due to the vibratory and sliding action of the cylinders, reduction in particle size was observed. A significant reduction in particle size of the AR-SCBA sample was seen after the milling duration of only 30 sec. Faster particle breakage kinetics was observed in the vibrating cup mill. The results of the mechanical treatment indicate that the increase in milling time reduces particle size. The range of D10 and D90 values of the mechanically treated samples was observed to be 1.172–0.807 μm, and 23.309–12.093 μm respectively, while AR-SCBA presented D10 and D90 values of 10.334 and 126.581 μm respectively.

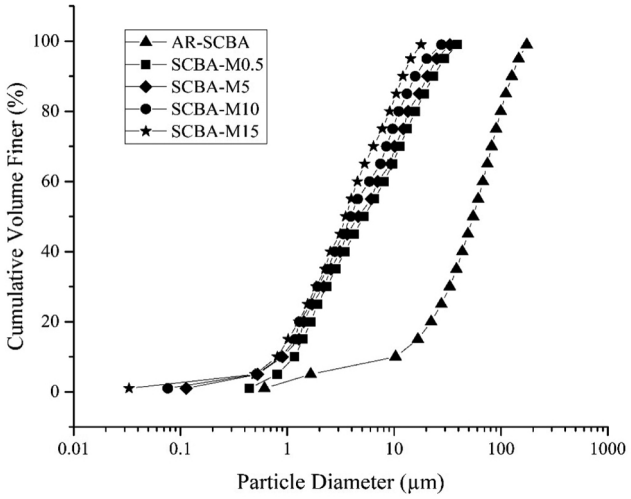

Figure 1. Particle size distribution curves of as-received sugarcane biomass ash (AR-SCBA) and mechanically treated SCBA samples.

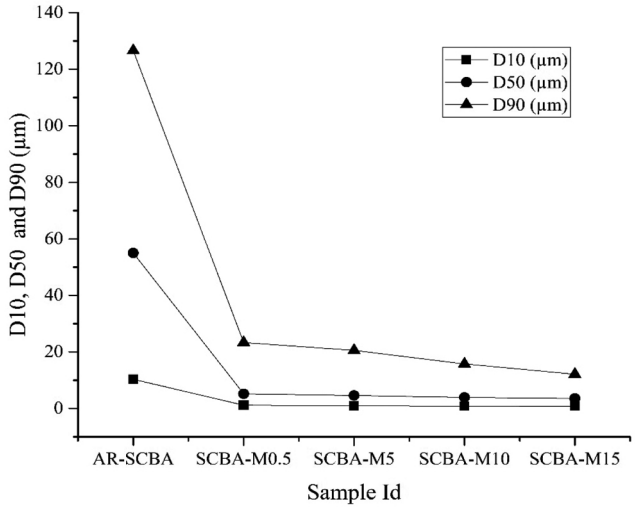

Figure 2. Distribution of D10, D50 and D90 (μm) of AR-SCBA and mechanically treated SCBA samples.

Table 2. Chemical characterization of AR-SCBA

Oxides	SiO_2	LOI	P_2O_5	CaO	MgO	Fe_2O_3	Al_2O_3	MnO_2	Na_2O
Percentage	79.50	4.95	3.20	3.14	2.07	1.12	1.03	0.13	0.12

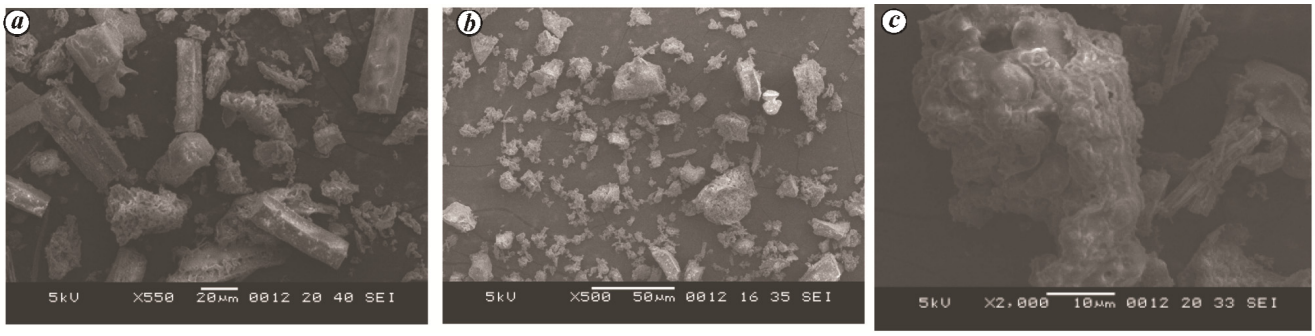

Figure 3. Microstructure of (***a***) AR-SCBA and (***b***) SCBA-M15T. (***c***) Magnified SCBA-M15T.

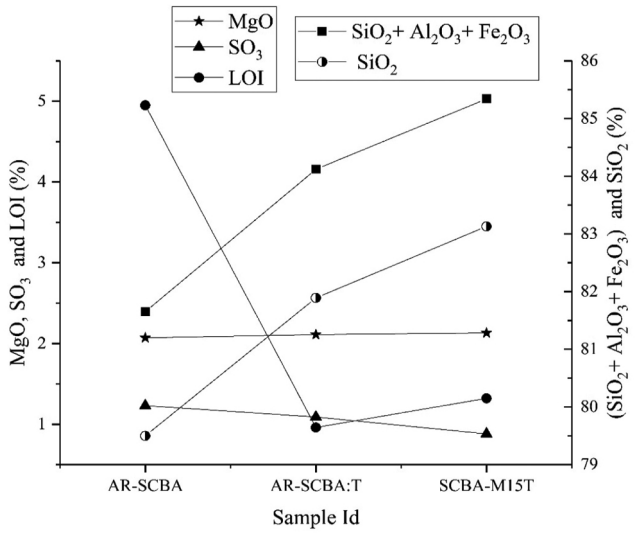

Figure 4. Oxide composition of AR-SCBA, thermally treated (AR-SCBA:T) and combinedly treated sample (SCBA-M15T).

The average particle size (i.e. D50 = 55.009 µm) of AR-SCBA was found to reduce to 3.521 µm (sample SCBA-M15) (Figure 2).

Figure 3 shows the microstructure of AR-SCBA and combinedly treated SCBA sample. The sugarcane biomass fibre mainly consists of cellulose, pentosane and lignin. The burning of sugarcane biomass causes the decomposition of lignin and volatilization of cellulose, leading to rapid weight loss of biomass. Figure 3 *c* shows the porous structure of SCBA. Cellular, prismatic and irregular-shaped particles in a variety of sizes were observed in AR-SCBA (Figure 3 *a*). The particle size was reduced due to mechanical treatment (Figure 3 *b*). Change in particle shape was observed due to the combustion process. The spherical and prismatic-shaped particles were found to be rich in silica.

The chemical characterization of AR-SCBA was dominated by silica (SiO_2) (79.50%). The addition of $SiO_2 + Al_2O_3 + Fe_2O_3$ was calculated to be 81.65% (Table 2), which is greater than the permissible limit of 70% as specified in BIS 3812 (Part 1): 1981. The LOI value and MgO percentage were below 12 and 5 respectively. SO_3 value was 1.23%, i.e. less than 3% (Table 2). It shows the favourable conditions for using SCBA as a pozzolanic material. All the permissible chemical composition limits are given in BIS 3812: 1981. Figure 4 compares the effect on chemical oxide composition by thermal treatment and the combined (mechanical plus thermal) treatment. Thermal treatment increased the ($SiO_2 + Al_2O_3 + Fe_2O_3$) content from 81.65% to 84.12%, while the combination of both treatments increased it further to 85.34%. In case of SiO_2 content, thermal treatment improved it from 79.50% to 81.89%. While the combined effect of both the treatments increased it up to 83.13%. No significant changes were observed in the MgO and SO_3 contents. Thermal treatment reduced the LOI value considerably, due to the combustion of unburnt/or partially burnt carbon particles (from LOI of 4.95% (AR-SCBA) to 0.96% (AR-SCBA:T)).

Figure 5 presents X-ray diffractograms of AR-SCBA and the combinedly treated SCBA (SCBA-M15T). AR-SCBA had the mineral phases namely calcite ($CaCO_3$), cristobalite (SiO_2) and quartz (SiO_2), while SCBA-M15T was completely in the amorphous phase. A decrease in maximum intensity of the diffractogram was observed after the combined (mechanical and thermal) treatment. The maximum intensity of AR-SCBA and SCBA-M15T was observed to be 650 and 374 respectively. Higher intensity and narrower peaks were converted to minimum

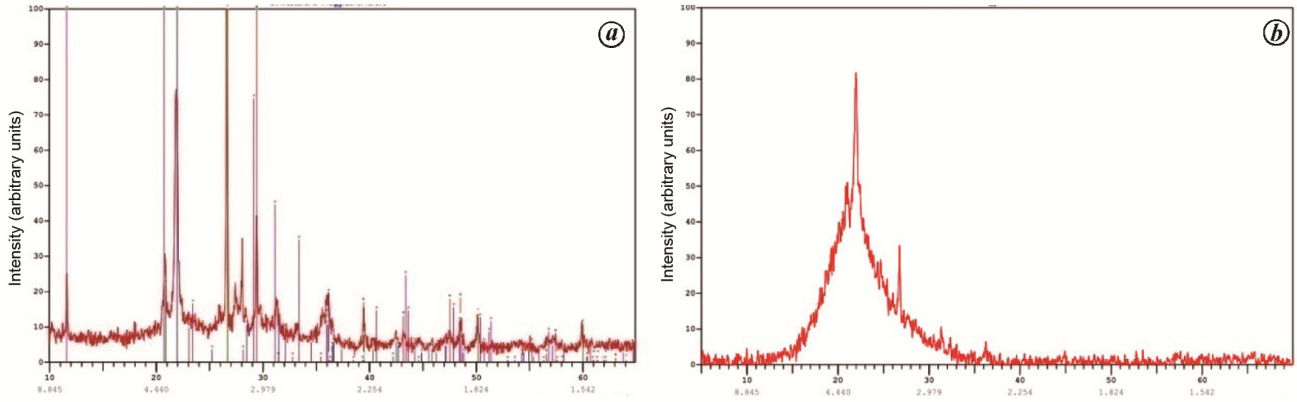

Figure 5. X-ray diffractograms of (***a***) AR-SCBA; (***b***) SCBA-M15T.

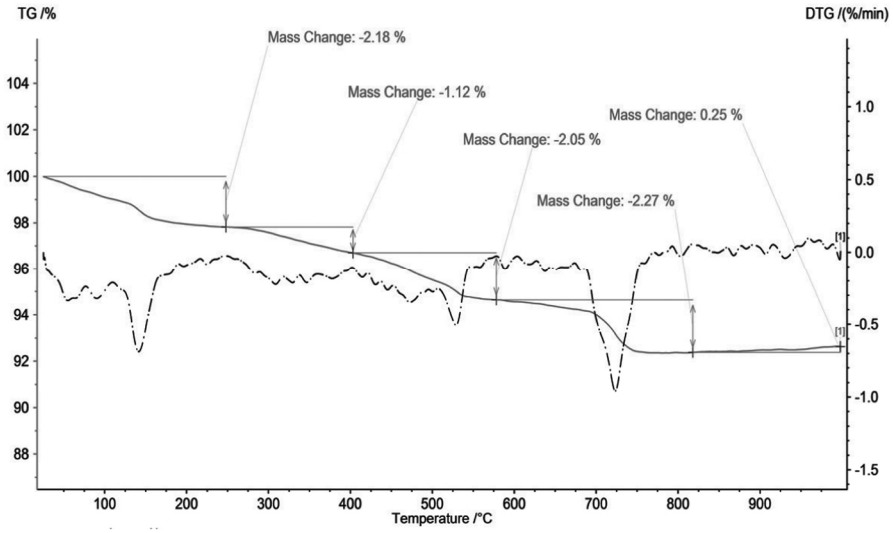

Figure 6. Thermogravimetric analysis of AR-SCBA.

number of peaks with lesser intensity scattered in a wide angular range.

The TG curve of AR-SCBA showed different regions of mass losses with respect to increased temperature when subjected to the combustion process (Figure 6). Up to 500–600°C, the water molecules present in the pores evaporated and the sample was subjected to mass loss (5.35%). Later, mass loss (2.27%) occurred at 800°C due to thermal degradation. Finally, a mass gain of 0.25% was observed because of the sintering action of the sample.

At 800°C, all the unburnt or partially burnt organic matter burnt out and resulted in the pure form. No further mass loss was observed after 800°C, and so the samples were thermally treated at the said temperature.

Figure 7 shows a plot of the behaviour of pozzolanic activity index and amount of reactive silica with respect to milling duration. Milling operation (mechanical treatment) improves both the above-mentioned properties. An increase in pozzolanic activity index and reactive silica with an increase in milling duration was observed to follow the nonlinear logarithmic curve pattern. Figure 7 also shows the equations of the curve patterns. R^2 value of the pozzolanic activity index for as-received and thermally treated SCBA samples was 0.9613 and 0.9562 respectively. While the R^2 value of reactive silica for as-received and thermally treated SCBA was 0.9029 and 0.9610 respectively. Reactive silica is the key parameter in determining the potential of pozzolanicity. Reduction in particle size significantly improved pozzolanic performance. Further improvement was observed due to the thermal treatment. So a combination of mechanical and thermal treatments was found to give much better results. Figures 8 and 9 illustrate the confidence (confidence level = 95%) and predicted curves of the pozzolanic activity index and reactive silica respectively. Predicted values were calculated using the respectively fitted curve equations. The experimental data were analysed using

Table 3. Regression analysis and statistics of pozzolanic characterization

Dependent variable	Type	Regression equation	R^2 (%)	F-value (lack of fit)	P-value
Pozzolanic activity index	As-received sample	$y = 22.12*\ln(x + 14.05)$	0.9613	4158.15	8.21E-6
	Thermally treated sample	$y = 23.55*\ln(x + 16.21)$	0.9562	4753.85	6.72E-6
	Confidence and predicted bands	$y = 0.96x + 2.47$	0.96	244.3	2.79E-7
Reactive silica	As-received sample	$y = 23.17*\ln(x + 14.04)$	0.9029	1590.8	3.46E-5
	Thermally treated sample	$y = 19.02*\ln(x + 46.05)$	0.9610	48649.49	2.05E-7
	Confidence and predicated bands	$y = 0.94x + 4.2$	0.9347	114.59	5.09E-6
Electrical conductivity drop	As-received sample	$y = 1.15*\ln(x + 9.13)$	0.8712	519.86	1.84E-4
	Thermally treated sample	$y = 1.065*\ln(x + 67.45)$	0.9388	72231.07	1.13E-7
	Confidence and predicated bands	$y = 0.98x + 0.048$	0.9795	383.59	4.80E-8
Chapelle activity	As-received sample	$y = 185*\ln(x + 4.69)$	0.9580	584.05	1.55E-4
	Thermally treated sample	$y = 197*\ln(x + 7.34)$	0.9377	762.82	1.04E-4
	Confidence and predicated bands	$y = 0.95x + 17.39$	0.957	178.11	9.49E-7

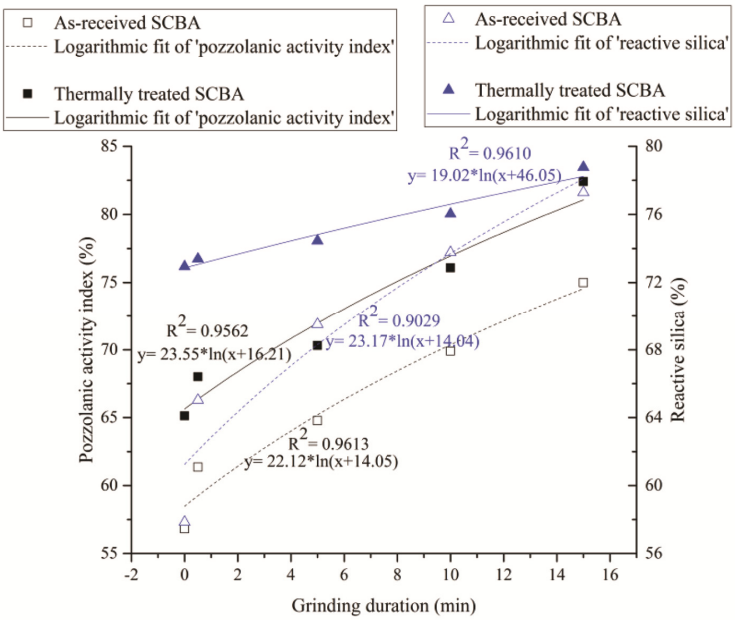

Figure 7. Relation of pozzolanic activity index and reactive silica with respect to the milling duration.

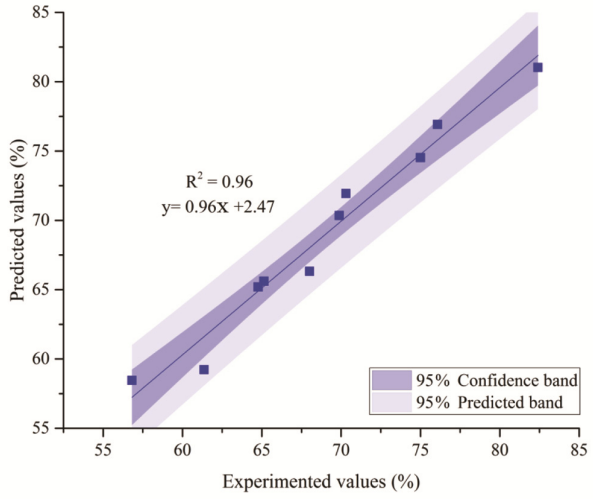

Figure 8. Confidence and predicted bands of the pozzolanic activity index.

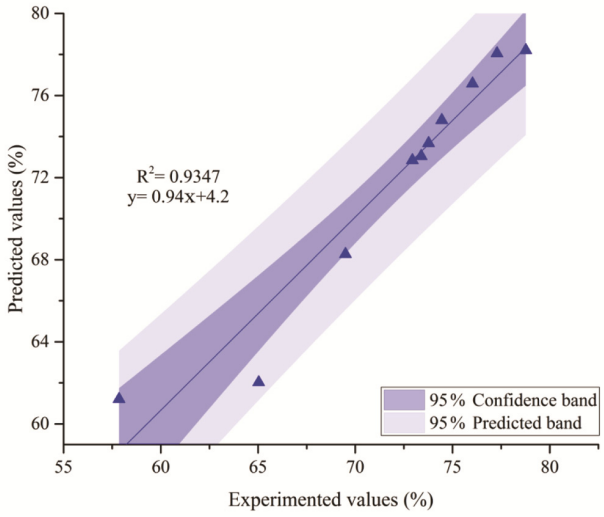

Figure 9. Confidence and predicted bands of reactive silica.

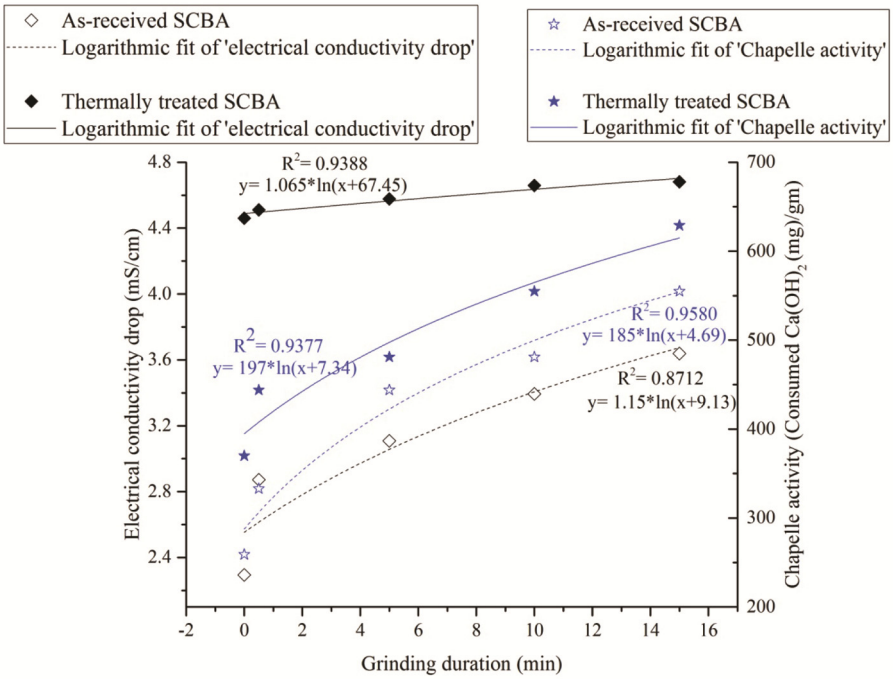

Figure 10. Relation of electrical conductivity drop and Chapelle activity with respect to milling duration.

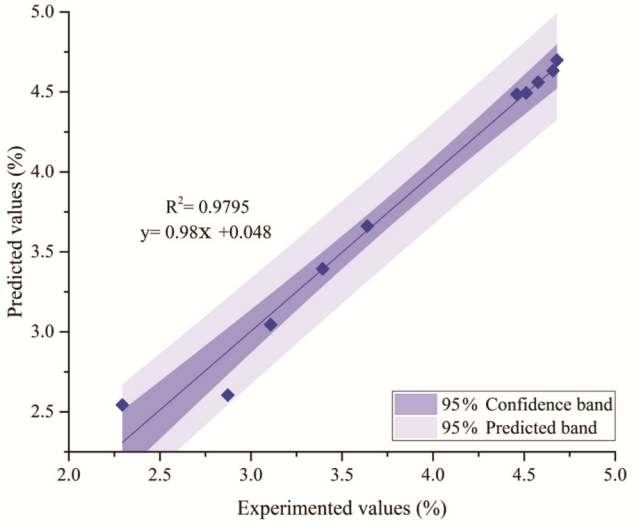

Figure 11. Confidence and predicted bands of electrical conductivity drop.

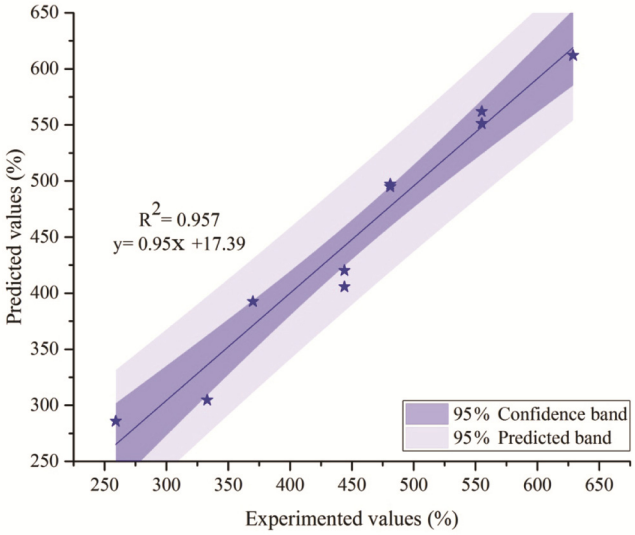

Figure 12. Confidence and predicted bands of Chapelle activity.

ANOVA. Table 3 presents the *F*-values and *P*-values of the analysis. The *F*-values of the pozzolanic activity index and reactive silica models ranged between 114.59 and 48649.49. The *P*-values of all the respective fitted models were less than 0.0500, which implies that the fitted models are statistically significant and effective (Table 3).

Figure 10 shows the relation of electrical conductivity drop and Chapelle activity with respect to milling duration. A drop in electrical conductivity of the saturated calcium hydroxide solution was observed due to the fixation of dissolved calcium hydroxide on the surface of the respective pozzolana. The greater the loss of electrical conductivity, the more is the pozzolanic reactivity of the sample. The increasing pattern of drop in electrical conductivity of both the as-received and thermally treated samples followed a nonlinear logarithmic curve. The respective R^2 values were 0.8712

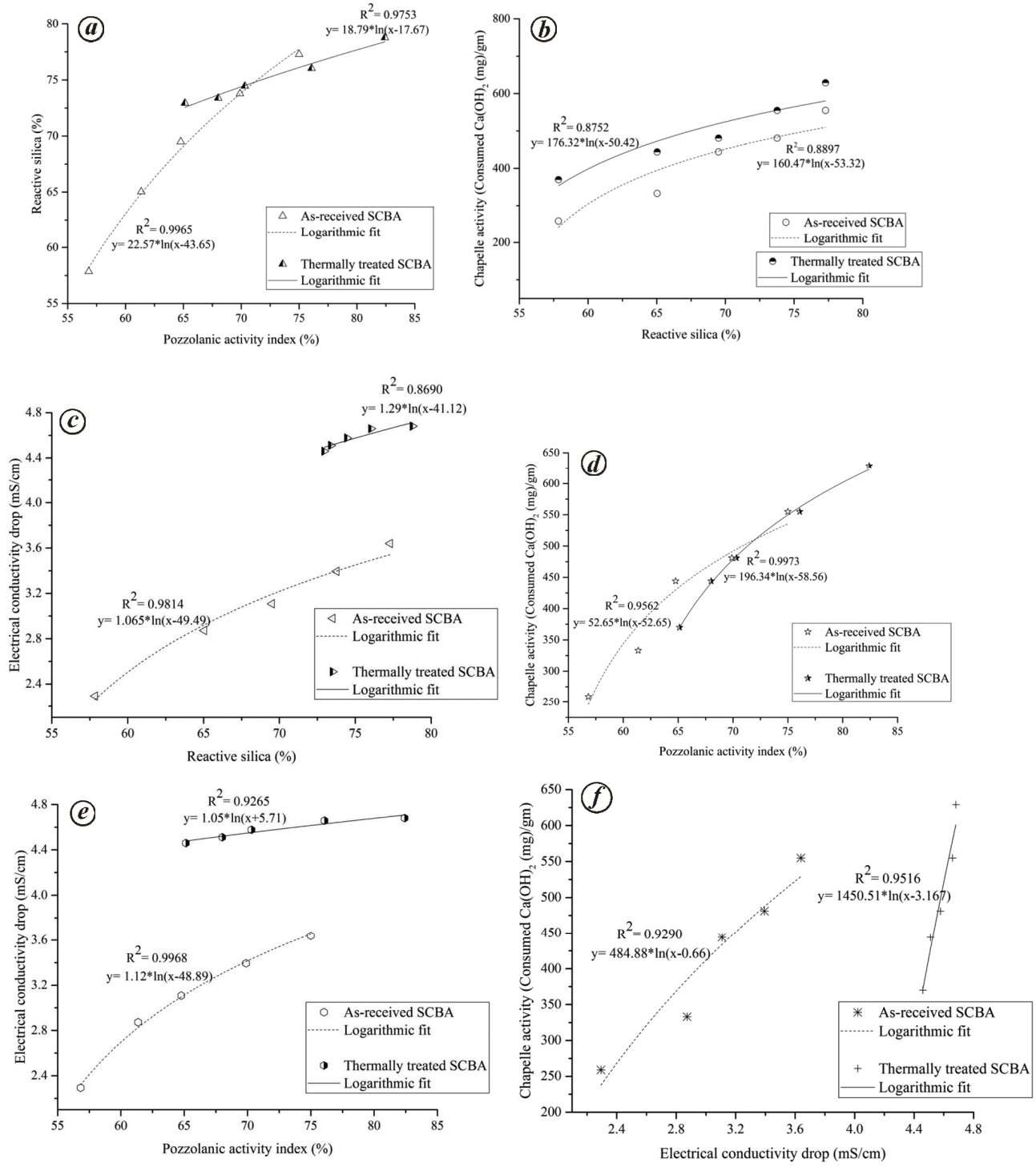

Figure 13. Relation between: ***a***, Reactive silica and pozzolanic activity index; ***b***, Chapelle activity and reactive silica; ***c***, Electrical conductivity drop and reactive silica; ***d***, Chapelle activity and pozzolanic activity index; ***e***, Electrical conductivity drop and pozzolanic activity index; ***f***, Chapelle activity and electrical conductivity drop.

and 0.9388. The results indicate that the mechanical treatment improves the specific surface area of the sample particles, indirectly improving the lime fixation rate. So, a major drop in electrical conductivity was observed in the sample milled for a duration of 15 min compared to other milling durations. The thermally treated samples showed further improved results of drop in electrical conductivity.

The Chapelle activity test was carried out at 90°C, instead of room temperature, as the pozzolanic activity reaction rate is higher at an elevated temperatures[24]. The relationship between Chapelle activity and milling

Table 4. Regression analysis and statistics of the relation between pozzolanic properties

Relation	Sample	Regression equation	R^2 (%)	*F*-value (lack of fit)	*P*-value
Reactive silica and pozzolanic activity index	As-received	$y = 22.57*\ln(x - 43.65)$	0.9965	45,309.65	2.28E-7
	Thermally treated	$y = 18.79*\ln(x - 17.67)$	0.9753	76,855.10	1.03E-7
Chapelle activity and reactive silica	As-received	$y = 160.47*\ln(x - 53.32)$	0.8897	221.17	6.59E-4
	Thermally treated	$y = 176.32*\ln(x - 50.42)$	0.8752	380.09	2.94E-4
Electrical conductivity drop and reactive silica	As-received	$y = 1.065*\ln(x - 49.49)$	0.9814	3611.86	1.01E-5
	Thermally treated	$y = 1.29*\ln(x - 41.12)$	0.8690	33,727.12	3.56E-7
Chapelle activity and pozzolanic activity index	As-received	$y = 52.65*\ln(x - 52.65)$	0.9562	560.0768	1.65E-4
	Thermally treated	$y = 196.34*\ln(x - 58.56)$	0.9973	17,690.28	9.37E-7
Electrical conductivity drop and pozzolanic activity index	As-received	$y = 1.12*\ln(x - 48.89)$	0.9968	21,004.06	7.24E-7
	Thermally treated	$y = 1.05*\ln(x + 5.71)$	0.9265	60,171.84	1.49E-7
Chapelle activity and electrical conductivity drop	As-received	$y = 484.88*\ln(x - 0.66)$	0.9290	344.7576	3.40E-4
	Thermally treated	$y = 1450.51*\ln(x - 3.167)$	0.9516	983.89	7.11E-5

duration also lead to a similar conclusion. The Chapelle activity is mainly concerned with particle size of the sample. As expected, the Chapelle activity was found to increase with an increase in milling duration. The R^2 value of Chapelle activity for the as-received and thermally treated sample was 0.9580 and 0.9377 respectively. Figures 11 and 12 illustrate the confidence (confidence level = 95%) and predicted bands of drop in electrical conductivity and Chapelle activity respectively. Table 3 shows results of ANOVA. The *F*-values of drop in electrical conductivity and Chapelle activity models ranged between 178.11 and 72231.07. All the respective *P*-values were less than 0.0500, which implies that the fitted logarithmic models are statistically effective and significant (Table 3).

Additionally, the relationships between all the pozzolanic properties (pozzolanic activity index, reactive silica, electrical conductivity drop and Chapelle activity) were developed (Figures 13 *a–f*). All the relation curves were fitted nonlinearly with the logarithmic pattern successfully. Overall a good correlation was developed, as the R^2-values varied between 0.8690 and 0.9973. This shows that all the pozzolanic properties are directly related to each other by the logarithmically fitted models. The experimental results were analysed using ANOVA. Table 4 provides a summary of the results of statistical regression analysis. The lack of fit (*F*-values) of all the logarithmic fitted models ranged between 221.17 and 76855.10. All the respective *P*-values were less than 0.0500, which implies that the fitted models are effective and significant.

Conclusion

The pozzolanic properties of SCBA can be improved either by mechanical treatment (milling the sample in a vibrating cup mill) or by thermal treatment (calcination of the sample at 800°C for 2 h duration). A combination of both treatments was observed to give improved results of pozzolanic properties.

Based on the interpretation of the XRF, XRD and SEM data, the treated sample had more reactive silica/amorphous silica, necessary for the pozzolanic activity. The TG test resulted in an optimum burning temperature (800°C) to give the pure form of silica.

The pozzolanic behaviour of SCBA samples can be quantified by measuring various properties, namely pozzolanic activity index, reactive silica, electrical conductivity drop and Chapelle activity.

Sample milled for 15 min duration in a vibrating cup mill followed by calcination at 800°C resulted in maximum pozzolanic activity.

All the above-mentioned pozzolanic properties are directly related and best-fitted by the nonlinear logarithmic model. The coefficient of multiple regression (0.86–0.99) showed that the fitted model was effective and significant.

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