

Sugar Cane Wastes as Pozzolanic Materials: Application of Mathematical Model

by Ernesto Villar-Cociña, Moisés Frías Rojas, and Eduardo Valencia Morales

This paper proposes a kinetic-diffusive model that allows for determination of pozzolanic activity as related to optimum calcining temperature on the activation of wastes from sugar cane industries and their use as pozzolanic material. Research based on the reaction kinetics between lime (calcium hydroxide [CH]), sugar cane straw ash (SCSA), and sugar cane bagasse ash (SCBA) calcined at 800 and 1000 °C (1472 and 1842 °F) is described.

A pozzolanic activity method (accelerated chemical method) based on the measurement of the amount of CH reacted as the reaction proceeds is applied and the latter on the kinetic parameters are quantified by applying a kinetic-diffusive model to the process. The kinetic parameters that characterize the process (in particular, the reaction rate constant and free energy of activation) were determined with relative accuracy in the fitting process of the model. The pozzolanic activity is quantitatively evaluated according to the obtained values of the kinetic parameters.

The results show good pozzolanic properties of the sugar cane wastes between 800 and 1000 °C (1472 and 1832 °F), and no influence of the calcining temperature on the pozzolanic activity for SCSA was observed.

The correlation between the values of free energy of activation ΔG^\ddagger and the reaction rate constants K are in correspondence with the theoretical studies about the rate processes reported in the literature.

Keywords: kinetic; pozzolans; sugar cane waste; temperature.

INTRODUCTION

The reuse of waste materials for concrete production is a worldwide practice. It is known that the incessant generation of solid waste materials represents a serious problem. For that reason, it is very important to study and develop any technology, procedure, or method that may help to reuse them efficiently.

At present, pozzolanic materials are, in most cases, industrial by-products and solid waste that can be used as active additions to portland cement. This is due to their capacity for reacting with calcium hydroxide (CH) produced during the hydration of portland cement. It is well known that the compounds formed during this pozzolanic reaction improve the performance of young cements.¹⁻⁵

In recent years, the use of solid waste derived from agriculture as pozzolans in the manufacture of blended mortars and concrete has been the focus of new research.⁶⁻¹⁰ In fact, the addition to concrete of ashes from combustion of agricultural solid waste is, at present, a frequent practice because of the pozzolanic activity of the ashes toward lime. One of the most interesting materials is the ash obtained from the combustion of sugar cane solid wastes (sugar cane straw and sugar cane bagasse).

In Cuba, significant amounts of sugar cane are processed, generating high volumes of solid waste. These wastes are disposed and burnt in open landfills, negatively impacting the environment. Some studies have been carried out for

characterizing the sugar cane solid waste as pozzolanic material.¹¹⁻¹⁴ Baguant¹⁴ found that bagasse ashes from a furnace operating in the 1000 to 1100 °C (1832 to 2012 °F) range showed very poor pozzolanic reactivity. On the other hand, Payá et al.¹¹ reported ashes of bagasse and coal (9:1 mass ratio) at 800 °C (1472 °F) that presented high pozzolanic reactivity. Sing et al.¹² also stated that good pozzolanicity of bagasse ash occurred when mixed with portland cement but, in this case, the calcining temperature was not specified.

For the case of sugar cane wastes, the experimental results are still scarce. Recently, research regarding the pozzolanic behavior of sugar cane straw has been made, mixing the sugar cane straw with clay and calcining the mixture, showing good pozzolanic properties.^{15,16}

Accordingly, further study and evaluation of these sugar cane wastes as pozzolanic materials is needed. The methods for evaluating pozzolanic activity used in the aforementioned research were, in the majority of the cases, focused on the qualitative aspect of the behavior of the pozzolanic materials rather than the quantitative aspect of the lime-pozzolan reaction, with the latter regarding computation of kinetic coefficients.

At present, researchers are beginning to focus on known kinetic coefficients as an acceptable and rigorous criterion for evaluating the pozzolanic activity of the materials. With this propose, several traditional mathematical models have been applied to the pozzolanic reaction in recent years. Khangaonkar et al.¹⁷ proposed a mathematical model for the kinetic study of the hydrothermal reaction between lime and rice husk ash silica. This model involves the mechanisms of nucleation and growth, phase boundary interaction, and diffusion. An equation for each mechanism is proposed. The application of the model was satisfactory only for early ages of the reaction.

Subsequently, Cabrera and Frías^{18,19} applied the kinetic model of Jander²⁰ to describe the mechanism of reaction in metakaolin-lime systems at different curing temperatures.

Kondo et al.²¹ modified the Jander equation to depend on the mechanism (reaction or diffusion) that controls the reaction process. They studied the reaction kinetics in a lime-quartz-water system.

Browsers and Van Eijk²² proposed a shrinking core model for analyzing the pozzolanic reactivity of fly ash. This model considers the pozzolanic particle composed by two regions

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(outer hull and inner region). The thermodynamic properties of the fly ashes were derived.

Recently, Villar-Cociña et al.^{23,24} proposed a new kinetic-diffusive model that allows characterizing the pozzolanic activity of sugar cane waste mixed with clay for all ages of the reaction by computing the kinetic coefficients (reaction rate constant, fundamentally) of the CH/sugar cane-clay ash reaction. The results obtained showed a good correlation between the experimental and theoretical data.

In this research, the characterization of sugar industry solid wastes as pozzolanic materials was carried out. Sugar cane straw ash (SCSA) and sugar cane bagasse ash (SCBA) samples calcined at 800 and 1000 °C (1472 and 1832 °F) were analyzed. Chemical composition, X-ray diffraction (XRD) patterns, and the computing of the kinetic parameters (reaction rate constant and free energy of activation) of the pozzolanic reaction by applying a kinetic-diffusive model underpinned the study.

RESEARCH SIGNIFICANCE

The incorporation of some agricultural wastes, calcined at high temperature, producing pozzolans of high activity, have been studied with positive results in the manufacture of blended cements.

The knowledge of the kinetic coefficients is a good criterion for evaluating the pozzolanic activity of the materials in lime (or cement)/pozzolan systems. In the literature, reported values of the kinetic and thermodynamics parameters that reflect the pozzolanic reactivity of the materials are scarce.

In the present paper, a mathematical model published previously by the authors is applied. The fitting of the model allows the computation of the kinetic and thermodynamics parameters (reaction rate constant, diffusion coefficient, and free energy of activation) for the pozzolanic reaction in sugar cane waste/lime systems, which are not reported in the literature that the authors are aware of. This allows the characterization of

the pozzolanic activity of these wastes. Also, the influence of the calcining temperature on the activation of these materials is analyzed.

EXPERIMENTAL

Materials

The pozzolanic ashes obtained were two types of biomasses. The sugar cane straw (SCS) and sugar cane bagasse (SCB) were recollected in the vicinity of the sugar factory J. P. Carbó in Placetás, a province of Villaclara, Cuba.

Sugar cane straw ashes and bagasse ashes were obtained in an electric furnace at two different temperatures of calcination: 800 and 1000 °C (1472 and 1832 °F) for a 20-minute duration. Once calcined, the ashes were ground and sieved to < 90 μm (3.5 mil), fineness similar to portland cement. Table 1 shows the samples used in this paper and their designations.

The chemical compositions (refer to Table 2) of the ashes were determined by an X-ray fluorescence (XRF) technique.

The main oxide present in SCSA and SCBA ashes is SiO₂, followed by CaO. Other oxides such as Al₂O₃, Fe₂O₃, P₂O₅, and K₂O are present in smaller amounts. The sum of these oxides exceeds 90% of the total value.

Figure 1(a) and (b) show the XRD patterns for the starting ashes. The SCSA samples show a very low crystallinity. A wide band is observed between 15 and 35 (2 theta), which implies the presence of vitreous matter. For the SCSA1 sample, the XRD patterns suggest the presence of calcite as the main crystalline compound, whereas the XRD patterns for SCSA2 suggest the alpha cristobalite as the main crystalline compound. Other minor compounds such as iron oxides, quartz, and carbon are present. For SCBA samples (Fig. 1(b)), quartz is detected as the main crystalline compound.

The lime used in the ashes/calcium hydroxide system was an analytical grade calcium hydroxide (95% of minimum purity, 4.8% of maximum magnesium and alkaline salts content, and 0.5% of maximum insoluble substance content).

Test methodologies

Pozzolanic activity method—The pozzolanic activity was studied by using an accelerated chemical method that followed the material-calcium hydroxide reaction over time. The test consisted of putting the pozzolanic material (1 g [0.032 oz]) in contact with a saturated lime solution (75 mL [0.019 gal.]) in individual double cap polyethylene flasks of 100 mL (0.026 gal.) capacity and maintained in an oven at 40 ± 1 °C (104 ± 2.6 °F) for 1, 7, 28, and 90 days (two flasks per period). At the end of each period, the solution was filtered and the chemical determination of CaO in the remaining solution was quantified by using 20 mL (0.005 gal.) of filtered solution and ethylenediamine tetra-acetic acid (EDTA) (0.0178 mol/L [0.068 mol/gal.] concentration) and calcein as chemical reagents for titration. The fixed calcium hydroxide (mmol/L) was obtained as the difference between the original concentration of a solution of saturated calcium hydroxide and the CaO found in the solution in contact with

Table 1—Designations of samples used

Samples/calcining temperature	Designations
Sugar cane straw ash/800 °C (1472 °F)	SCSA1
Sugar cane straw ash/1000 °C (1832 °F)	SCSA2
Sugar cane bagasse ash/800 °C (1472 °F)	SCBA1
Sugar cane bagasse ash/1000 °C (1832 °F)	SCBA2

Table 2—Chemical composition for SCS and SCB ashes

Samples	Oxides, %										Loss on ignition, %
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	TiO ₂	P ₂ O ₅	
SCSA1	70.20	1.93	2.09	12.20	1.95	4.10	3.05	0.50	0.02	1.40	1.81
SCSA2	70.99	2.08	2.25	12.44	2.01	4.35	3.10	0.56	0.02	1.37	0.52
SCBA1	58.61	7.32	9.45	12.56	2.04	0.53	3.22	0.92	0.34	2.09	2.73
SCBA2	59.55	7.55	9.83	12.89	2.10	0.72	3.41	0.96	0.37	2.15	0.81

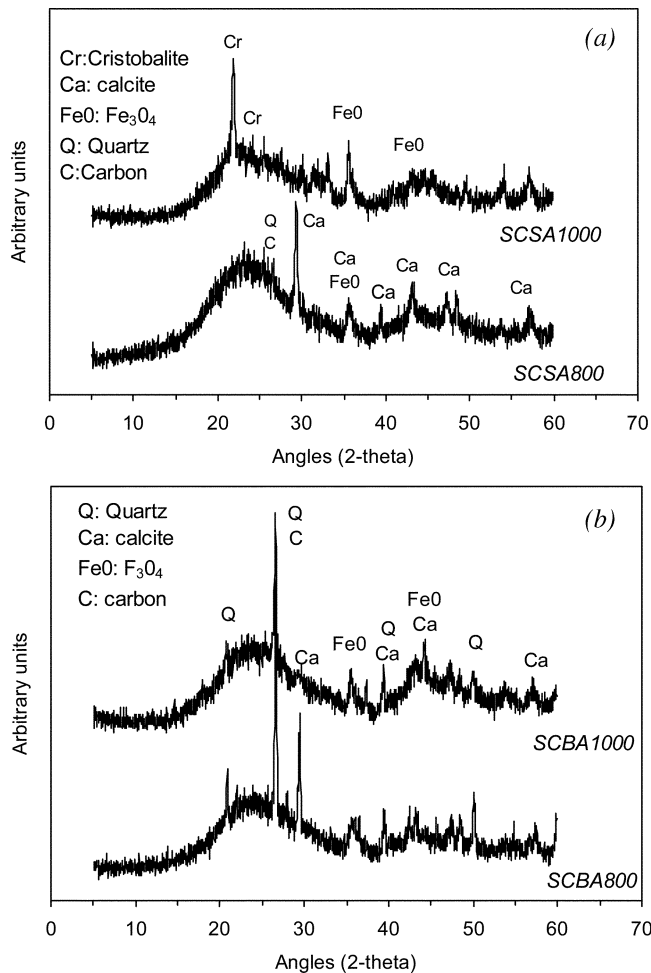
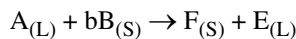


Fig. 1—Mineralogical composition for starting ashes: (a) SCSA burned at 800 and 1000 °C (1472 and 1832 °F); and (b) SCBA burned at 800 and 1000 °C (1472 and 1832 °F).

the sample, at the end of a given period. This method is a modified version of the European Standard EN 196-5, which is a pozzolanicity test for pozzolanic cement. For this reason, the determination of unreacted CaO content was valorized as described in standard (EDTA and calcein reagents for titration).

Mathematical model—It is known that the pozzolanic reaction in CH/pozzolan systems is heterogeneous and it can be considered about solid-solution type



When Solution A reacts on the surface of the solid reactant, B (with stoichiometry coefficient b), a layer of reaction products, F, is formed around the nucleus of reactant B that has not yet reacted (unreacted nucleus within), which decreases gradually. If the layer, F, is porous, the reaction take place by diffusion of A through the layer F until it is verified on the interface between F and the nucleus without reacting. $E_{(L)}$ accounts for the fluid products of the solid-solution type reaction that could be formed.

The form of the rate equation is determined by the control regime or the rate-limiting step, which can be one of the following two, principally^{25,26}: 1) diffusion through the layer of reaction product (diffusive control); and 2) chemical reaction at the surface on the unreacted nucleus (kinetic control).

Villar-Cociña et al.^{23,24} proposed a kinetic-diffusive model for describing the pozzolanic reaction in sugar cane straw-clay ash/CH systems. The model is

$$\xi = \frac{C_0 - C_t}{C_0} = 1 - \frac{0.23 \exp\left(\frac{-3t}{\tau}\right) \left(-1 + \exp\left(\frac{t}{\tau}\right)\right) \frac{1}{\tau}}{C_0 D_e r_s} \quad (1)$$

$$+ \frac{0.23 \exp\left(\frac{-t}{\tau}\right) \frac{1}{\tau}}{C_0 K r_s^2}$$

where D_e is the effective diffusion coefficient of A through the porous layer of product F; K is the reaction rate constant; C_0 is the initial concentration of the solution; and τ is a constant of time (time interval in which the radius of the nucleus of pozzolan diminish to 37% of its initial radius r_s). The initial radius r_s of the pozzolan particles was taken as 0.090 mm (0.004 in).

The dimensionless magnitude $\xi = (C_0 - C_t)/C_0$ represents the relative loss of lime concentration, and C_t represents the absolute loss of lime concentration with time for the pozzolan/lime system.

As the pozzolanic reaction develops in stages, it is possible that the rate-limiting stage corresponds with the diffusion through the layer of reacting product or with the chemical reaction at the surface on the unreacted nucleus.

For that reason, it is possible in certain cases to have different behavior: diffusive (described by the second term of Eq.(1)); kinetic (third term); and kinetic-diffusive (both terms). Further explanations about the model can be found in Villar-Cociña et al.^{23,24}

For the case of SCSA/CH and SCBA/CH systems, a correction term was added to the model (Eq. (1)) to account for the remainder concentration of CH that is not consumed in the reaction. In some systems, the CH is not consumed completely. The corrected model is

$$\xi = \frac{C_0 - C_t}{C_0} = 1 - \frac{0.23 \exp\left(\frac{-3t}{\tau}\right) \left(-1 + \exp\left(\frac{t}{\tau}\right)\right) \frac{1}{\tau}}{C_0 D_e r_s} \quad (2)$$

$$+ \frac{0.23 \exp\left(\frac{-t}{\tau}\right) \frac{1}{\tau}}{C_0 K r_s^2} - C_{corr}$$

The fitting of this model allows determining the kinetic parameters (effective diffusion coefficient and reaction rate constant) and, therefore, a rigorous characterization of the process.

RESULTS AND DISCUSSION

Pozzolanic activity

Figure 2 shows the influence of calcining temperature on the pozzolanic behavior—fixed lime content (mmol/L [3.84 mmol/gal.]) versus reaction times (days) of different ashes.

In SCSA samples, there was little influence of calcining temperature under the experimental conditions applied (Fig. 2(a)). The pozzolanic behavior was maximized

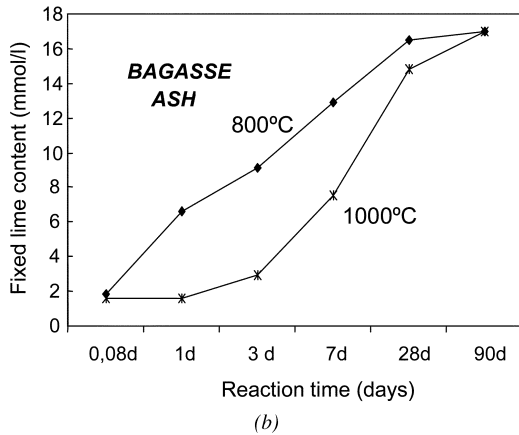
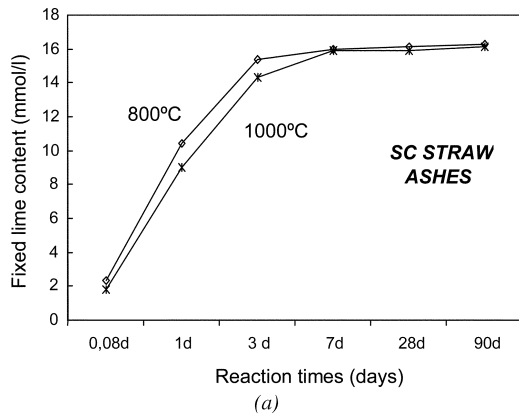


Fig. 2—Pozzolanic activity for sugar cane waste samples (fixed CaO content over time): (a) SCSA burned at 800 and 1000 °C (1472 and 1832 °F); and (b) SCBA burned at 800 and 1000 °C (1472 and 1832 °F).

between 3 to 7 days of curing, as inferred from the rapid consumption of the available lime. Therefore, at 1 day of reaction, the partial consumption of lime was 59% for SCSA1 and 51.2% for SCSA2. By 7 days, lime consumption exceeded 90% for both ashes. Beyond 7 days, calcining temperature was not influential on apparent pozzolanic activity. Some 92% of lime had reacted with both ashes at the end of testing (90 days).

The pozzolanic behavior for SCBA wastes with the reaction time is shown in Fig. 2(b). The bagasse ash obtained at 800 °C (1472 °F) shows an important amount of fixed lime during the first days of reaction. Therefore, at 1 and 28 days of reaction, the ash has fixed 37.8 and 93.3% of calcium ions (lime) respectively. From 28 days, the lime concentration in the solution is practically constant.

When the calcining temperature increases up to 1000 °C (1832 °F), the behavior of bagasse ash activity varies substantially. In the first 24 hours of reaction, the bagasse ash shows a very low pozzolanic activity, as can be seen in Fig. 2(b). Only 9.1% of the total available lime is consumed by the presence of bagasse ash. From 3 days, however, an important change on the pozzolanic evolution of bagasse ash is observed. The lime consumption increases dramatically until the final testing. At 90 days, the activity value is similar to that obtained for the bagasse ash calcined at 800 °C (1472 °F).

The pozzolanic activity of ashes (Fig. 2(a) and (b)) decreased when the calcining temperature increased. This fact could be related to the recrystallization of amorphous silica with increasing calcination temperature.^{27,28}

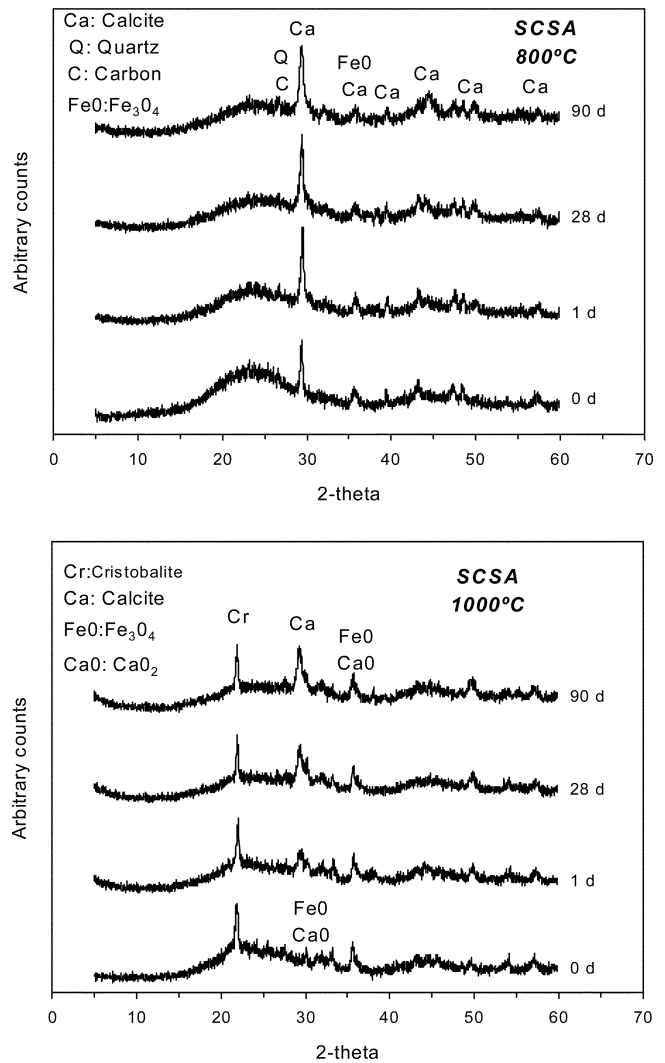


Fig. 3—X-ray diffraction patterns from pozzolanic reaction for SCSA samples burned at 800 and 1000 °C (1472 and 1832 °F).

From this data of pozzolanic activity, it is important to highlight that all samples showed pozzolanic activity but with different reaction rates. This fact can be an important aspect from the point of view of its recycling as active additions in cements. Knowing the range of reactivity has practical application in the manufacture of sugar cane waste-blended cements by allowing early determination of a desired cement/pozzolan reaction rates that, in turn, influences others properties such as heat of hydration and chemical resistance.

Reaction kinetics

X-ray diffraction analysis—The residues obtained from pozzolanicity test were characterized by XRD to identify and study the evolution of crystalline phases versus hydration time.

Figures 3 and 4 show the XRD patterns obtained for the SCSA and SCBA, respectively, calcined at two different temperatures.

Examination of XRD patterns for SCSA-lime systems with the curing times (1, 28, and 90 days) did not suggest the presence of any crystalline compounds from the pozzolanic reaction. An important decreasing of the vitreous band between 15 and 35 (2 theta) with increasing curing time, however, was observed for both ashes. This suggests the formation of noncrystalline compounds during the reaction.

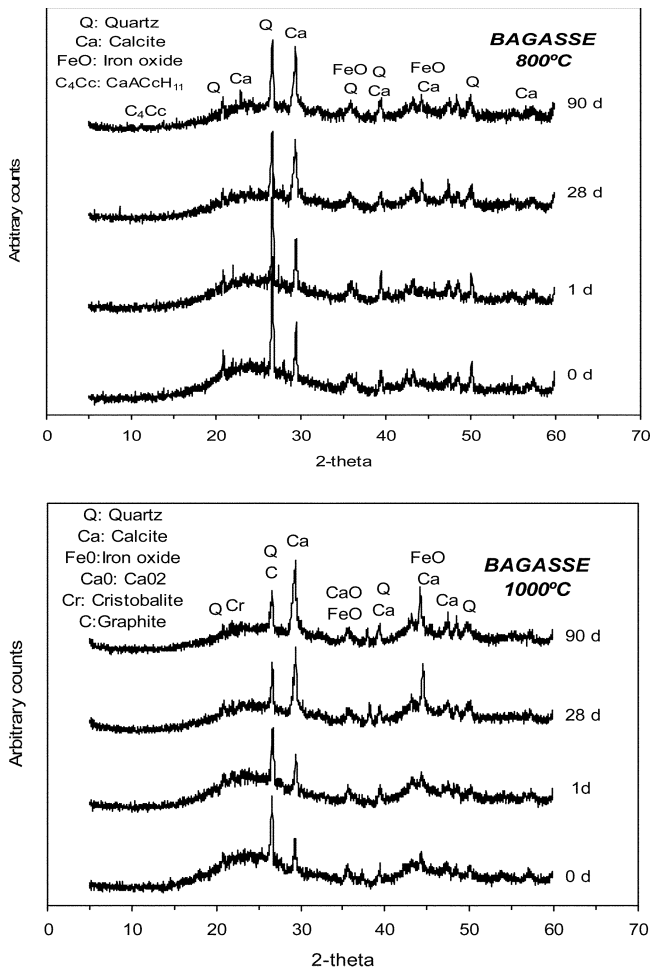
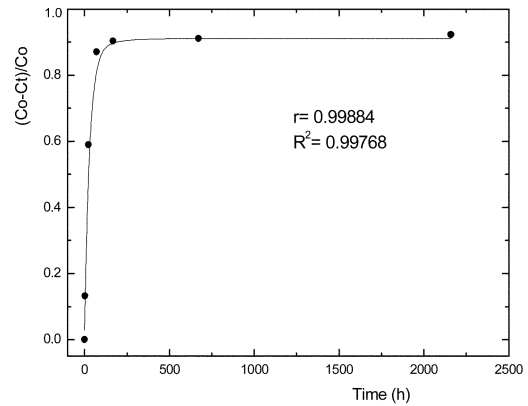


Fig. 4—X-ray diffraction patterns from pozzolanic reaction for SCBA samples burned at 800 and 1000 °C (1472 and 1832 °F).

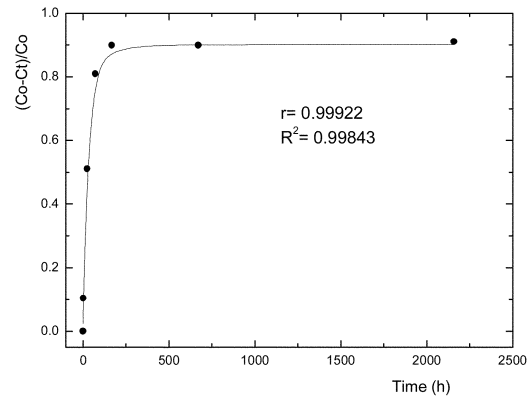
Taking into account the chemical composition of these ashes, formed mainly by SiO_2 and CaO , the compounds formed by the pozzolanic reaction will likely be calcium silicate hydrates (C-S-H) belonging to be tobermorite family. The low crystallinity of these compounds is well known and contributes to difficulty in their identification by XRD techniques.

Similarly, the study of XRD patterns for the bagasse ash-lime systems (Fig. 4) with ongoing curing time does not identify any crystalline compounds coming from the pozzolanic reaction. It is only possible to observe a decrease of vitreous band from 0 to 28 days of curing. Therefore, it is possible to conclude (in the same manner of the aforementioned case of SCSA-lime system) that the pozzolanic reaction between bagasse ash and lime produce some kind of amorphous compounds (which could be C-S-H) that are not identifiable by this technique. The thermogravimetric data (TG) carried out with these residues show weight losses in the temperature range of 100 to 400 °C (212 to 752 °F)—the decomposition range of hydrated calcium silicates and aluminates in the addition-lime system.^{29,30}

As the alumina contents are very low with respect to silica contents in these ashes, these losses could correspond mainly to the deshydroxilation of C-S-H (tobermorite). These findings would be in agreement with XRD patterns, in which calcium aluminate phases are not identified as crystalline compounds.



(a)



(b)

Fig. 5—Relative loss of lime concentration for sugar cane straw ash burned at: (a) 800 °C (1472 °F); and (b) 1000 °C (1832 °F) (● = experimental; — = model).

Application of mathematical model: determination of the reaction rate constant and the free energy of activation—The kinetic-diffusive model (Eq. (2)) was applied to all samples. Figures 5(a) and (b) and 6(a) and (b) illustrate the relative loss of lime concentration versus reaction time for the SCSA/CH and SCBA/CH systems, respectively. The solid line represents the curve of the fitted model.

The model was fitted to the relative loss of lime concentration-time data, considering a kinetic control model, diffusive control model, and a mixed (kinetic-diffusive) control model successively.

An exhaustive analysis of the most important statistical parameters such as: correlation coefficient r , coefficient of multiple determination R^2 , residual sum of squares (RSS), 95% confidence intervals, residual scatter, residual probability, and variance analysis (that constitutes a rigorous evaluation of the fitting process of the model to the experimental data), allows one to conclude that the kinetic control regime predominates showing the best correspondence with the experimental data.

This means that the chemical interaction speed on the surface of the nucleus of the pozzolan particle is slower than the diffusion speed of the reactant through the reaction product layer formed around the nucleus. This might be due to high porosity of the reaction product layer in these ashes, which facilitates a quick diffusion process. These findings are in agreement with results published previously,^{15,31} which indicated a high porosity and slow reactivity for the sugar cane bagasse ash in pozzolan/CH systems.

Table 3—Reaction rate constants, τ parameter, free energy of activation, C_{corr} parameter, and statistical parameters for SCSA and SCBA calcined at 800 and 1000 °C (1472 and 1832 °F)

Material (ash)	τ , hours	Reaction rate constant, h^{-1}	Free energy of activation ΔG^\ddagger , kJ/mol (Kcal/mol)	C_{corr}	Correlation coefficient r	Coefficient of multiple determination R^2	Residual sum of squares
SCSA1	23.27 ± 1.86	$(8.11 \pm 0.67) \times 10^{-2}$	104.63 ± 0.19 (24.06 ± 0.43)	0.088 ± 0.012	0.9988	0.9976	0.0022
SCSA2	29.98 ± 1.91	$(6.32 \pm 0.41) \times 10^{-2}$	105.27 ± 0.15 (24.21 ± 0.34)	0.098 ± 0.010	0.9992	0.9984	0.0015
SCBA1	100.25 ± 9.83	$(1.91 \pm 0.38) \times 10^{-2}$	108.39 ± 0.47 (24.93 ± 1.08)	0.051 ± 0.038	0.9894	0.9788	0.0022
SCBA2	333.29 ± 38.63	$(5.35 \pm 0.66) \times 10^{-3}$	111.70 ± 0.28 (25.69 ± 0.64)	0.037 ± 0.024	0.9973	0.9946	0.0060

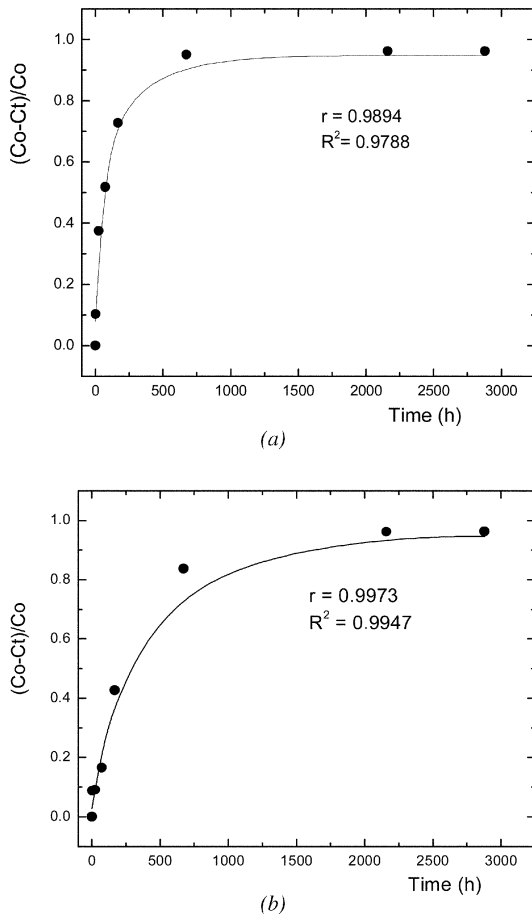


Fig. 6—Relative loss of lime concentration for sugar cane bagasse ash burned at: (a) 800 °C (1472 °F); and (b) 1000 °C (1832 °F) (● = experimental; — = model).

In this current paper, only some parameters are shown (r , R^2 , SE, RSS) because the rest (mentioned previously) are related to graphic analysis and large tables that would necessitate a much longer paper.

The values of the parameters (τ and K) so obtained are given in Table 3, whereas the correlation and multiple determination coefficients r and R^2 are shown in Fig. 5 and 6.

One of the most important parameters that characterizes the reactivity of the materials is the thermodynamic parameter of activation called free energy of activation. This parameter can be calculated by using the Eyring equation of The Absolute Theory of Rate Processes cited in Reference 32.

The Eyring equation is given by

$$K = \frac{k_B T}{h} \exp\left(-\frac{\Delta G^\ddagger}{RT}\right) \quad (3)$$

where K_B is the Boltzman constant; h is the Planck constant; R is the constant of the gases; T is the temperature; K is the reaction rate constant; and ΔG^\ddagger is the free energy of activation, which characterizes the change of free energy of the system when passing from the initial state to the transition state.

It is well known that larger values of ΔG^\ddagger are correlated with stability kinetics, that is, low reactivity (small values of K). On the other hand, smaller values of ΔG^\ddagger are correlated with instability kinetics, that is, high reactivity (larger values of K). The knowledge of ΔG^\ddagger allows one to characterize how fast the reaction occurs—with larger ΔG^\ddagger values, the reaction will be slower and vice versa.

Study regarding free energy of activation in pozzolanic reactions is very scarce. Some reported values of free energy of activation, for some specific systems, can be found in References 22, 26, and 33.

For the SCSA-lime and SCBA-lime systems in the international bibliography, none have reported values of activation parameters of the pozzolanic reaction.

In the present research, the free energies of activation were calculated by substituting Eq. (3) in the model (Eq. (2)). The resultant equation was fitted to the experimental data (relative loss of lime versus reaction time) and the values of ΔG^\ddagger were determined. The values of ΔG^\ddagger obtained are given in Table 3.

The K and ΔG^\ddagger values provide a direct index of the pozzolanic activity of the materials.

According to the values of the reaction rate constant K , SCSA1 shows the highest reactivity (larger value of K) followed by SCSA2, SCBA1, and SCBA2. These results agree with the qualitative analysis carried out previously in the Pozzolanic Activity section above.

Similarly, the values of ΔG^\ddagger reflect the same tendency for the pozzolanic activity of the ashes, that is, SCSA1 shows the highest reactivity (smaller ΔG^\ddagger) followed by SCSA2, SCBA1, and SCBA2.

It is found (qualitatively and quantitatively) that the ashes diminish their reactivity as the calcination temperature increases. SCSA1 calcined at 800 °C (1472 °F) has a slightly higher reactivity in comparison with SCSA2 calcined at 1000 °C (1832 °F). Both ashes show a high pozzolanic reactivity (in the order of $10^{-2} h^{-1}$) with a similar behavior.

The bagasse ashes showed less reactivity in comparison with the SCSA ashes. The sugar cane bagasse ash calcined at 800 °C (1472 °F) shows more pozzolanic reactivity (in the order of $10^{-2} h^{-1}$) than the sugar cane bagasse ash, which calcined at 1000 °C (1832 °F) (order of $10^{-3} h^{-1}$).

CONCLUSIONS

From the results obtained in this paper, the following conclusions can be made:

1. Sugar cane wastes can be recycled as active additions when calcined in the temperature range of 800 to 1000 °C (1472 to 1832 °F);

2. The SCSAs showed a similar behavior at two different calcining temperatures and, in both cases, a high pozzolanic activity was detected. The maximum activation of this waste, however, is reached by calcining at 800 °C (1472 °C);

3. The sugar cane bagasse can become pozzolonically active in the range 800 to 1000°C (1472 to 1832 °F).

4. The sugar cane bagasse's activation rate, however, varied substantially (in the order of 10^{-2} h^{-1} for calcining temperature of 800 °C [1472 °F] and in the order of 10^{-3} h^{-1} for 1000 °C [1832 °F]);

5. Moreover, reaction products formed during pozzolanic reaction are not crystalline compounds, based on the interpretation of XRD data;

6. The values of the reaction rate constant and free energy of activation, obtained in the fitting process of the kinetic-diffusive model, show that the sugar cane straw ash calcined at 800 and 1000 °C (1472 and 1832 °F) have high and similar pozzolanic reactivity. The SCBA has less pozzolanic activity than the SCSA, and its pozzolanic reactivity varies substantially with the calcining temperature; and

7. The availability of ashes with different pozzolanic reaction rates can become an important technological advantage in the manufacture of new blended cements that include the calcined materials. The selection of one ash or another as the preferred pozzolan will depend on the characteristics needed for the building site.

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