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Rudimentary, low tech incinerators as a means to produce reactive pozzolan out of sugar cane straw

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Abstract

The ashes of agricultural wastes from the processing of sugar cane are recognized as having pozzolanic properties. Burning of these wastes under controlled conditions, e.g. temperature and residence time results in significant improvement in reactivity. There are many reports of low-tech incinerators that have been successfully used to produce reactive rice husk ash in Asia. The paper presents the results of the evaluation of a rudimentary incinerator where sugar cane straw is burnt in order to obtain a reactive ash. The incinerator is designed and constructed according to state-of-the-art recommendations for this kind of device. Various burning trials were performed in order to obtain ash for the experiment. X-ray diffraction analysis performed on powdered ash shows significant presence of amorphous (glassy) material. Lime–pozzolana pastes were prepared. The pastes were subjected to X-ray diffraction, thermo-gravimetric analysis, chemical titration, and SEM observation, as a means to examine the pozzolanicity of the ash via the progress with time of calcium hydroxide consumption, and changes in the pore size distribution and strength. Calcium silicate hydrate phases are the main reaction product of the pozzolanic reaction. The long residence time of the ash in the burning chamber seems to be the reason for the fairly low reactivity of the ash; the reactivity of the ash was not significantly improved in comparison with that of the ash burnt in uncontrolled conditions in the open air.

Keywords: Waste management; Temperature; Thermal treatment; Pore size distribution; Hydration products; Pozzolana; Building materials; Renewable raw materials

1. Introduction

The ashes of agricultural wastes produced in the sugar industry have been shown to have pozzolanic properties [1,2,4]. This includes the ash of wastes burnt directly in the boilers at sugar factories, or the ash obtained from burning waste in the open air in sugar cane fields. It is expected that burning such materials at a specified controlled temperature for a particular residence time should bring significant improvements in reactivity. Various studies have used several different types of incinerator to burn biomass under controlled conditions, with the aim to produce active ash [3–5]. Some of them are quite complicated and costly to build and operate, thus limiting their application in non-industrialized countries. Some rudimentary incinerators have also been built with simple, low cost materials, but the rate of ash production from such incinerators is low [6–8].

The paper examines the possibility of using a rudimentary incinerator with an improved design to improve the reactivity of sugar cane straw ash (SCSA) by burning it under a controlled burning temperature and residence time. To assess the effectiveness of the process the reactivity of the resulting ash was assessed and compared with the reactivity of a SCSA burnt under uncontrolled conditions [1].

2. Experimental methods

2.1. The incinerator

The experimental incinerator (Fig. 1) was designed and built near a sugar factory in Sagua la Grande, Cuba. The design aimed to burn biomass under a controlled range of conditions

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Nomenclature

SCSA	*S*ugar *C*ane *S*traw *A*sh
CH	*C*alcium *H*ydroxide
XRD	*X*-*r*ay *d*iffraction
SEM	*S*canning *e*lectron *m*icroscopy
TG	Thermo-gravimetry
CSH	*C*alcium *S*ilicate *H*ydrate

that have previously been specified [5] — the temperature must be under 700 °C, and the residence time must be at least 2 h in order to produce a reactive ash. The target output of the incinerator is 25 kg of ash per h. The main concepts behind the design are:

1. Prior to burning, the biomass is spread within the furnace chamber in order to prevent hot spots in the heap where temperatures can rise above 700 °C. This can be accomplished by ensuring that all unburnt materials in the biomass heap are less than 40 cm from the surface of the unburnt heap.
2. Cooling of the burning chamber is done through a natural air draught, which evacuates exhaust gases. After the combustion starts, the flow of cool air controls the temperature within the burning chamber.
3. The speed of the airflow must be slow enough to avoid a significant loss of ash through the chimney.

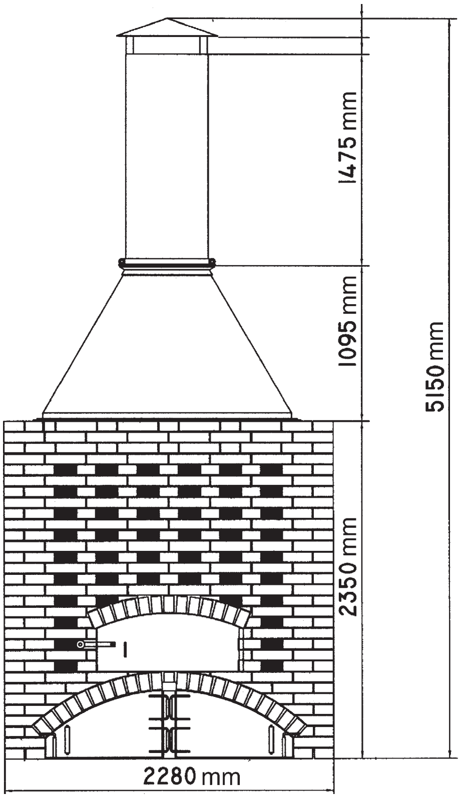

Fig. 1. Experimental incinerator, Sagua la Grande, Cuba.

Table 1
Chemical composition of the sampled ashes and calcium hydroxide (CH)

Description	(ASH 1) (%)	(ASH 2) (%)	CH (%)
CaO	10.35	11.40	72.17
MgO	3.60	3.62	0.55
SiO_2	61.73	57.36	1.40
Fe_2O_3	3.55	1.54	0.32
Al_2O_3	3.29	1.79	0.28
K_2O	2.72	4.20	0.03
BaO	0.03	0.03	0.05
SrO	0.03	0.04	0.04
Mn_2O_3	0.34	0.45	0.05
Na_2O	0.37	0.50	0.02
SO_3	1.19	1.49	0.12
CO_2	7.08	8.36	1.16
Carbon	1.17	1.55	–
Bonded H_2O	4.03	5.33	22.44
Moisture			0.88
Total	99.47	97.66	99.52

The airflow in the combustion chamber travels through meshes in the walls of the incinerator. After the start of combustion, the incoming air drags heat from the burning mass to the chimney outlet, and cools down the burning chamber. The input of cool air can be regulated in order to attain the target burning temperature and residence time. A faster airflow lowers the temperature inside the burning chamber and lowers the residence time, as the biomass burns faster. The aim is to determine the optimal draught to comply with the guidelines for biomass processing outlined in the literature [5–8].

The incinerator was designed to process raw sugar cane straw. Thermocouples were set in various places of the burning chamber in order to assess the actual temperature [3–8]. The results of testing of the prototype incinerator can be summarized as:

1. The highest temperature, measured with thermocouples in different places within the burning chamber did not exceed 600 °C. The temperature difference between upper and lower parts of the incinerator was approximately 50 °C.
2. The ash output did not exceed 12 kg/h, almost half of what was expected. Based on the ratio input/output the residence time can be estimated as 1–3 h. The low rate of output is believed to be due to (a) a deficiency in maximum exhaust flow through the chimney, and (b) an insufficient account in the design for variations in moisture content of the raw biomass with time.
3. There was a strong relationship between the intensity of the airflow and the temperature occurring in various parts of the incinerator.

2.2. Ash

The ash resulting from the burning trials was evaluated. It was burnt at temperatures under 600 °C, and were allowed to cool slowly within the incinerator for approximately 2 h. Two different ashes were sampled for the evaluation: ASH 1 was collected at the upper part of the incinerator, directly in the

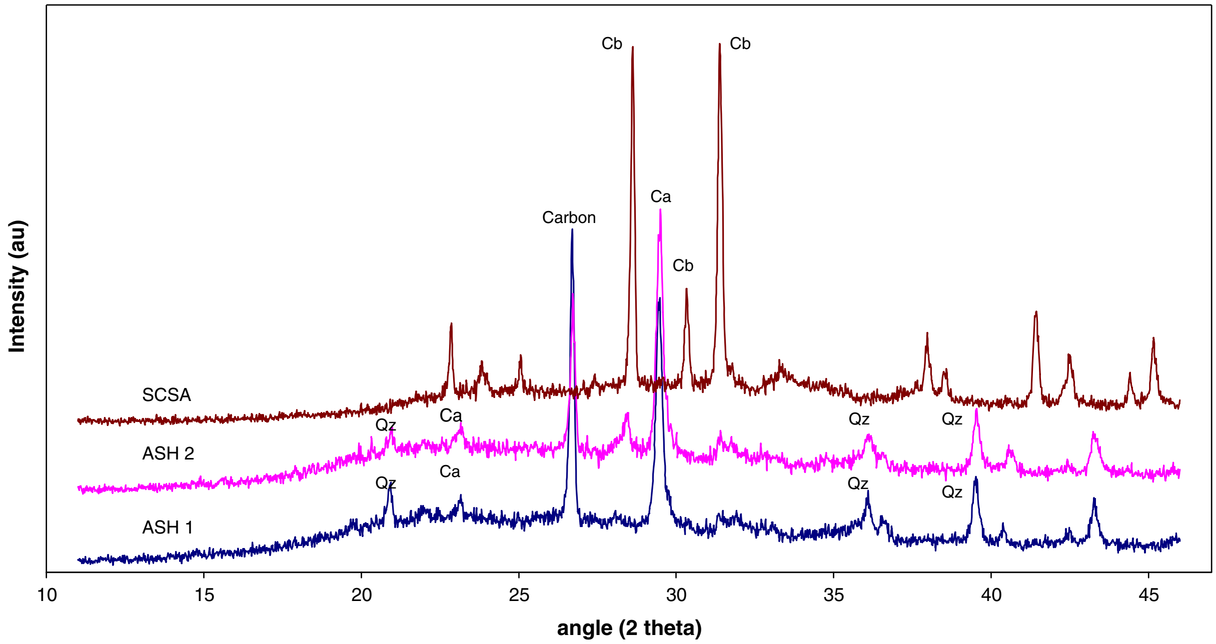

Fig. 2. XRD diagrams for controlled-firing ashes ASH 1 and ASH 2 and for an uncontrolled-firing ash (SCSA). (Qz: quartz, Cb: cristoballite, Ca: calcite).

burning chamber, and ASH 2 was collected from the bottom of the incinerator.

Table 1 shows the chemical composition of the ashes. Both have a high CaO content; and according to ASTM 618-78 can be classified as High Calcium Ashes. The differences in chemical composition between the two ashes could be related to the amount of unburnt material present, or the homogeneity of the material. The carbon content is significantly lower than that for untreated ashes referenced in previous studies [1], thus indicating that these ashes were better burnt. SCSA burnt in the open having similar finesse as ASH 1 and ASH 2 was used as reference for comparison. Its chemical composition is given in Ref. [1].

X-ray analysis was used to assess the presence of crystalline and amorphous substances in the ash. The tests were conducted in a Philips diffractometer by using Cu Kα radiation at 40 kV, 30 mA. Fig. 2 presents the X-ray traces for the two ashes, as well as for an ash burnt under uncontrolled conditions (denoted SCSA). The ashes that were fired in the incinerator (ASHES 1 and 2) show the "hump" or "halo" that corresponds to amorphous substances present in the sampled material. This "halo" appears to

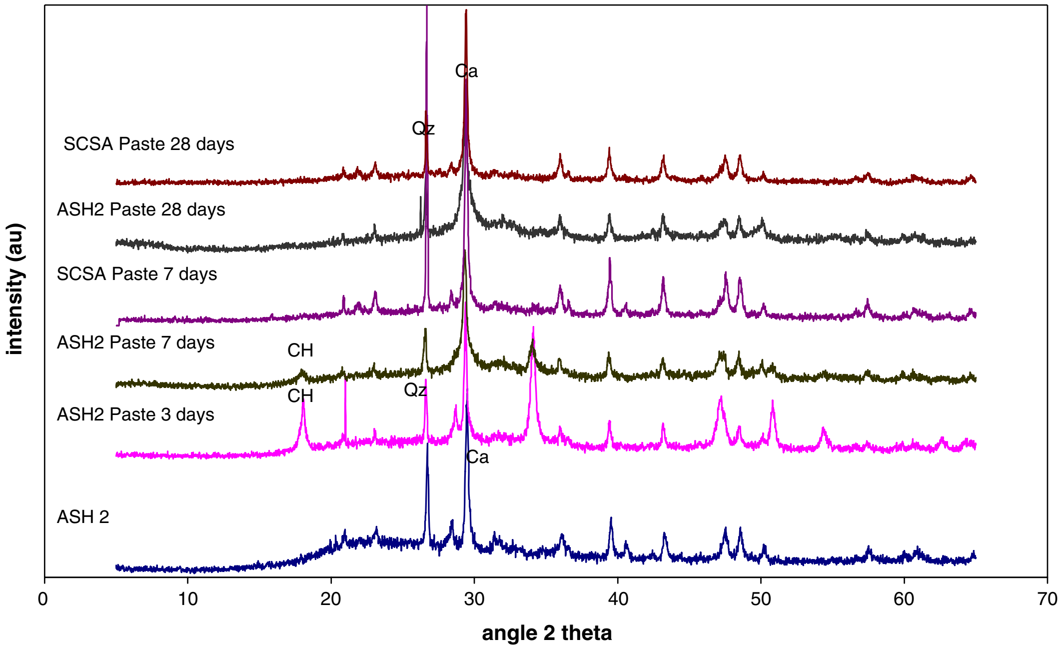

Fig. 3. XRD diagrams for lime–pozzolana pastes made with ASH 2 at 3, 7, 28, 45 and 90 days (CH: portlandite, Qz: quartz, Ca: calcite).

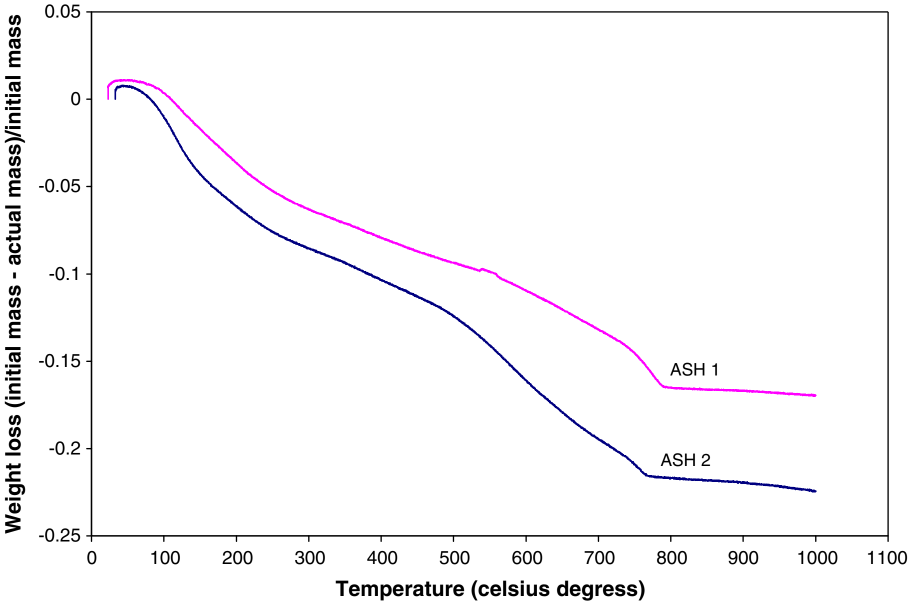

Fig. 4. TG diagrams for powder from ash 28 days lime–ash pastes.

be wider and larger than that of the SCSA ash. In uncontrolled-firing calcite and cristobalite were the predominant minerals identified. In controlled firing there are fewer crystalline compounds — cristobalite has disappeared and quartz is evident. This tends to confirm that combustion of ASHES 1 and 2 occurred at a lower temperature than that of SCSA.

Lime–pozzolana pastes were prepared with ASH 1 and ASH 2 using calcium hydroxide with the composition shown in Table 1. The ash and lime were intimately mixed and ground in a ball mill to a fineness similar to that of Portland cement. For chemical and porosity testing, fresh pastes were cast into 35 mm cylindrical film containers and tightly capped until testing to prevent carbonation. For mechanical testing 40 × 40 × 160 mm paste prisms were cast. The prisms were covered with a plastic sheet to prevent carbonation of the un-reacted lime due to contact with air, and cured at room temperature. Specimens were demoulded just prior to testing. The lime/ash mix proportions were: 30/70% (wt.). The water demand was established in accordance with Cuban standard NC 54-207:80 — this standard is similar to ISO/R 679:68 and embodies similar methods found in ASTM C191, C451 and C109.

Reactivity of the pozzolan was assessed in a number of ways:

1. Measurement of the reduction of calcium hydroxide (CH) with time. This was qualitatively assessed by reduction in the

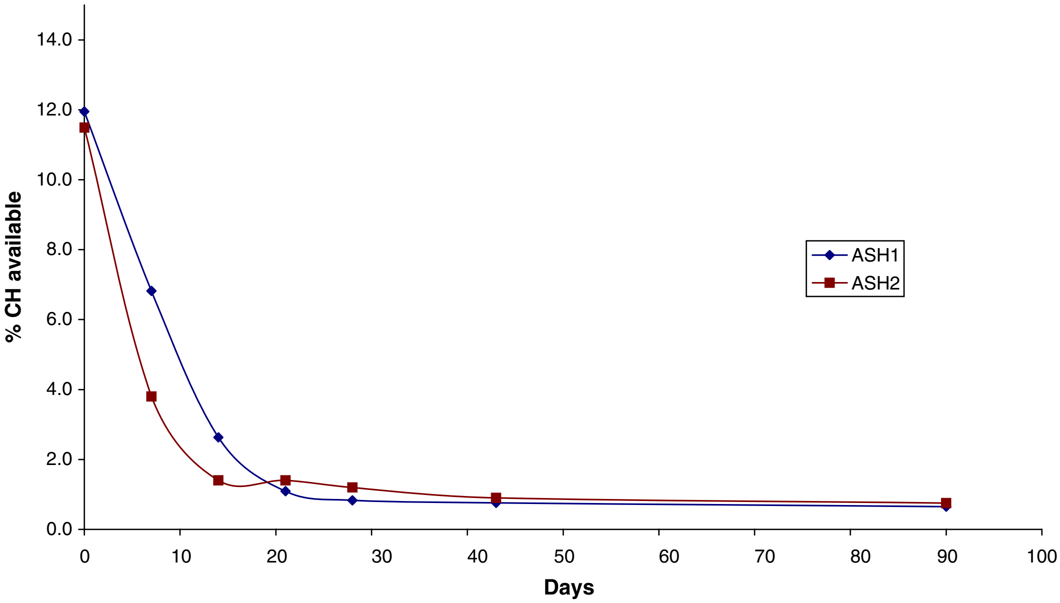

Fig. 5. CH titration for lime–pozzolana pastes made with ASH 1 and ASH 2.

Table 2
Results of XRD measurements in lime–pozzolana pastes

No.	Sample	Age	Detected phases
1	Original ash	–	Quartz, calcite
2	Hydrated pastes	3 days	Quartz, calcite, portlandite
3	Hydrated pastes	7 days	Quartz, calcite, portlandite
4	Hydrated pastes	28 days	Quartz, calcite, C–S–H
5	Hydrated pastes	45 days	Quartz, calcite, C–S–H
6	Hydrated pastes	90 days	Quartz, calcite, C–S–H

portlandite ($Ca(OH)_2$) X-ray peaks with time due to its consumption in the pozzolanic reaction, and quantitatively assessed by (a) the weight loss associated with CH dehydroxylation in the range around 500 °C during thermo-gravimetry, and (b) CH titration in lime–pozzolana pastes over time.

2. Observation of the reaction products using scanning electron microscopy (SEM) and X-ray diffraction.
3. Measurement of the compressive strength of pastes at 28 days.

The XRD measurements and CH titration testing of powdered lime–pozzolana pastes were carried out at 3, 7, 28, 45, and 90 days. MIP and SEM examination were conducted at 90 days. Compressive strength was determined at 28 days.

3. Results and discussion

3.1. CH consumption with time

XRD diagrams of pastes made with ASH 2, presented in Fig. 3, show that most of the CH present in the fresh paste at 3 days has disappeared at 28 days, apparently consumed in the pozzolanic reaction. This indicates that the major part of this reaction is completed before 28 days. The diagrams for the pastes made with ashes ASH 1 and ASH 2 are nearly identical. The same behavior is observed in SCSA pastes tested at 3 and 28 days.

Fig. 4 shows typical weight-loss vs. temperature curves obtained from ASH 1 and ASH 2 pastes during TG analysis. The shape of the curves are similar for both ashes. Pastes containing significant quantities of CH typically show a relatively abrupt weight loss due to CH dehydroxylation in the region around 500 °C. This loss is not observed in Fig. 4. Although a small amount of carbonation of the pastes has occurred (weight loss at 760 °C), the TG analysis supports the idea that most, if not all, of the CH has been consumed by the pozzolanic reaction.

The CH consumption was also assessed by titration at various ages. Fig. 5 presents the results of the experiment. Most of the CH is consumed in the first two weeks after the hydration of the pastes.

As measured by CH consumption, pastes made with ASH 1 and ASH 2 show almost the same reactivity when compared to SCSA burnt in the open air (as reported in Ref. [1]).

3.2. Reaction products

Table 2 shows the main crystalline phases measured by XRD in the lime–pozzolana pastes at different ages. C–S–H is visible at 28 days, and increases in size with time, although some confusion at early stages is created by interference with the calcite peak. The quartz phases found in the ash remain unchanged in the pastes, indicating that the crystalline silica did not react.

Finally, SEM observations of the hydrated pastes at age 28 days confirm the presence of C–S–H needle-like phases in lime–pozzolana pastes made with the thermally treated ash (see Fig. 6). These phases appear to be similar to the ones reported in the literature [9,10]. No major differences were found in comparison with C–S–H phases observed in lime–pozzolana pastes made with untreated SCSA ashes presented in Fig. 7.

3.3. Mechanical properties

Fig. 8 presents the results of compressive strength tests performed in pastes made with ASH 2 and ASH 1 and with untreated SCSA ash [1]. The 7 days' strength is slightly higher in pastes made with treated ash; however the difference at 28 day between both results is not significant.

3.4. Effect of the thermal treatment

The different tests performed on the ashes resulting from the incinerator show that there is no significant increase in the

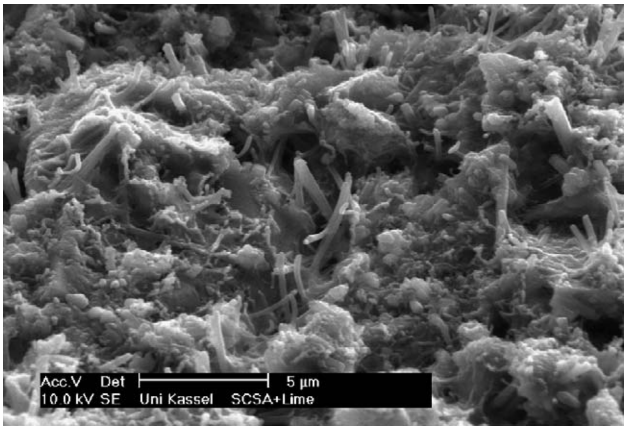

Fig. 6. SEM pictures for pastes made with ASH 1.

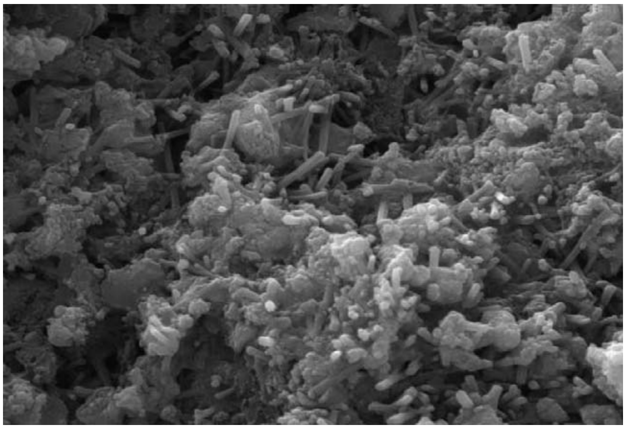

Fig. 7. SEM micrograph for pastes made with SCSA ash burnt in the open air.

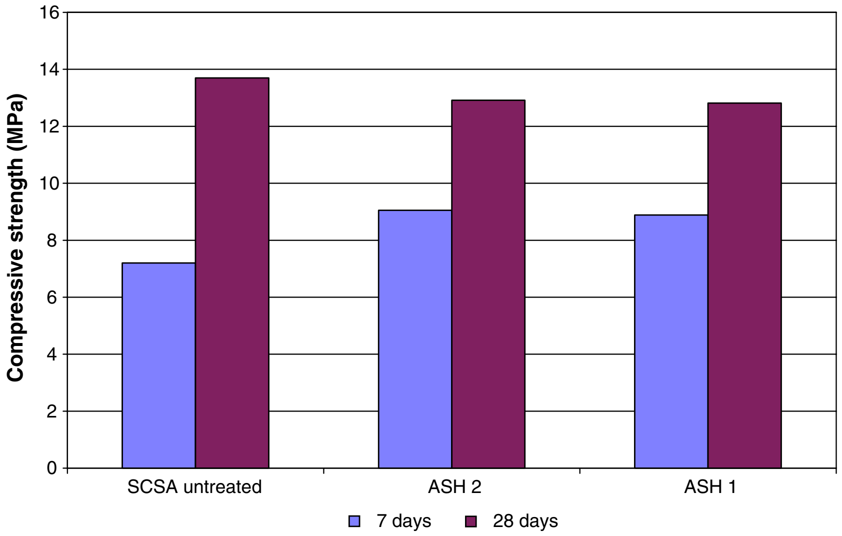

Fig. 8. Twenty-eight days compressive strength of pastes.

reactivity of the ashes through the thermal treatment in the incinerator tested in this work. Although the mineralogical study shows that the ashes resulting from it have less crystalline phases, the pastes do not reflect a significant improvement in their mechanical properties, which could imply that the reactivity has not been improved in comparison with burning the ash in the open air.

The reason for this could be the relatively long residence time of the ash in the burning chamber, and the slow cooling process afterward, which could not eventually enable the formation of a more amorphous and thus more reactive structure. This, combined with the low output shown by the incinerators in their use, practically confirms that before using these kinds of rudimentary incinerators for the production of reactive pozzolan out of agricultural wastes these problems have to be addressed.

4. Conclusions

1. The ashes resulting from burning sugar cane straw in a rudimentary incinerator as presented in this paper yield a relatively reactive pozzolan, basically given by the fact that the burning temperature is kept under 600 °C and little carbon is present in the ash.
2. Although the resulting ashes proved to have less crystalline phases and more amorphous substance in their composition, no significant improvements in their reactivity were observed, in comparison with sugar cane straw ash burnt in the open air. The reason for this could be the relatively long residence time of the ash in the burning chamber, and the slow cooling process afterward, which could deter the formation of a more amorphous and thus more reactive structure.
3. The tested incinerator needs to be further improved in order to address the two main problems revealed from this study: (a) low output of ash, and (b) long residence time and cooling rate of the ash.

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