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Abstract

In this study, the effect of bio-chars from sugarcane bagasse pyrolysis on the thermal and mechanical properties of cement-based composites was highlighted. The sugarcane bagasse was submitted to a thermochemical conversion process (slow pyrolysis) to obtain bio-chars. Cement-based composites were elaborated using the slurry dewatering method. The results showed that the bio-chars present a rough structure, a lower content of polysaccharides and lignin than the sugarcane bagasse. Moreover, the bio-chars absorb 36% less water than the sugarcane bagasse and the use of 2% by weight of bio-chars improves the hydration of cement. Finally, the thermal and mechanical properties of cement-based composites showed that the bio-chars are promissory materials for the elaboration of insulating building materials.

Keywords

Sugarcane bagasse; bio-chars; cement-based composites; thermal properties; mechanical properties.

1. Introduction

Since the signing of Kyoto protocol in 1997, the decrease of greenhouse gases emissions has become a major issue in the world. In European Union, the building sector consumes 40% of energy produced and rejects 36% of greenhouse gases such as carbon dioxide (CO_2) in the atmosphere. Improving energy efficiency in the building sector is therefore a priority area of research in France and in the world (Zhao and Magoulès, 2012; Pérez-Lombard et al., 2008; Gonzalez et al., 2011; Julian, 2000; Murray, 1996). For this reason, in 2010, French government create two laws on the national commitment to the environment, Grenelle I and II, exposing thermal regulations for new buildings in order to reduce energy consumption and emissions of greenhouse (LOI n° 2009-967, 2009; LOI n° 2010-788, 2010).

French Caribbean islands also have an acoustic thermal and ventilation regulations adapted to the environmental context of Caribbean called RTAA DOM. These regulations provide energy autonomy by 2050 and 50% of contribution of renewable energy in primary energy consumption by 2020 (Décret n° 2009-424, 2009). In Guadeloupe, one of the French Caribbean islands, a specific regulation was adopted to improve the energy efficiency of buildings, taking into account the local specificities of the archipelago. The regulation is based primarily on improving the energy performance of buildings and on the limitation of the use of air conditioning. Knowing that in Guadeloupe 45% of greenhouse gas emissions come from the building sector, and fossil fuel plants produce 70% of the electrical energy, it is important to control this sector producer of greenhouse gases (INSEE, 2007). The main challenges for the building sector are the elaboration of materials respecting new thermal and acoustic regulations.

One way to resolve these challenges is the use of composite materials. The demand of these materials in civil construction is growing every year. Composite materials offer several benefits such as reduced weight and improvement of mechanical and thermal properties in comparison to conventional materials (Arsène et al., 2003; Da Costa et al., 2014; Lu et al., 2013).

Composites materials, used in civil construction, are a combination of an inorganic matrix (mainly cement) reinforced by other components (vegetable, carbon, glass or steel fibers), which leads to a finished material with higher properties than the starting constituents (Da Costa et al., 2014).

In Guadeloupe, the sugarcane bagasse is an industrial crop available in a huge quantity due to the sugar-alcohol industry. Every year, 700 000 tons of sugarcane are produced representing 168 000 tons of sugarcane bagasse (DAAF, 2018). The use of this feedstock as raw materials for pyrolysis could be interesting to produce bio-chars for the reinforcement of the cement matrix. Indeed, the pyrolysis, which is a thermochemical conversion process of the biomass, permits to decompose the lignin, cellulose and hemicellulose into three mainly products; bio-char, bio-oil and non-condensable gases (Imam and Capareda, 2012). Knowing that lignin and hemicellulose are prejudicial to the hydration of cement (in the case of vegetable fibers), the bio-chars will be an attractive product for an application in cement-based materials (Kochova, 2017).

The bio-chars are mainly known for applications in the remove of organic pollutants (phenol, naphthalene or methylene blue) (Zhang et al, 2013; Cao et al., 2011), inorganic pollutants (heavy metals) (Lu et al., 2014; Lima et al., 2010), toxic gases (H_2S or volatile organic compounds) (Shang et al., 2013; Xu et al., 2014), and substances from wastewater (Li et al., 2014).

For applications in building materials, Akhtar et al. (2018) studied the influence of bio-chars from rice husk or paper mill sludge on the mechanical property of concrete. The authors showed that as partial replacement of cement up to 0.1% by volume of bio-chars improve the flexural and splitting tensile strength of concrete. Gupta and al. (2018) studied the effect of the addition of bio-chars from wood saw dust on the physical and mechanical properties of mortars. The authors sowed that the addition of bio-chars up to 2% by weight modifies the cement hydration due to the filler effect of the particles. Moreover, the bio-chars decrease the density of mortar due to the porous structure and low density of the particles. However, the flexural strength did not significantly affected by the addition of bio-chars. However there is a lack of study on the use of bio-chars in cement based materials for thermal applications.

The aim of this study is to primarily characterize the bio-chars resulting of the pyrolysis of sugarcane bagasse using several techniques such as Scanning Electron Microscopy (SEM), thermogravimetric analysis (TGA), isothermal calorimetry and Fourier Transform infrared spectroscopy (FTIR). Secondly, determine the effect of the bio-chars content on the mechanical and thermal properties of cement-based composites for a potential application in building materials.

2. Materials and methods

2.1. Materials

The sugarcane bagasse, a fibrous waste left after sugarcane stalk (*Saccharum officinarum*) juice extraction, was obtained from Montebello distillery (Petit-Bourg, Guadeloupe). Dried raw sugarcane bagasse was crushed to a diameter less than 0.6 mm using a knife mill (Retsch, France), then, sieved between 0.4 and 1 mm of diameter in a horizontal sieve shaker (Retsch, France). A part of the sugarcane bagasse was submitted to a thermochemical conversion process (slow pyrolysis) and the other part was used as reference.

To obtain a higher quantity of bio-chars, a slow pyrolysis was adopted with a residence time of 2 hours at 200 °C and a heating rate of 10°C/min under a nitrogen flow (2L/h). This thermochemical conversion process provides the best compromise between mass loss and degradation of sugars in case of sugarcane bagasse (Bilba and Ouensanga, 1996).

The cement used in this study was a commercial cement CEM II 32.5N, containing 17% by mass of natural pozzolan, supplied by Lafarge Group (Guadeloupe). The chemical composition and physical properties of the cement are shown in Table 1**.**

2.2. Composites preparation

Cement-based composites containing bio-chars, ranging from 2 to 6% by weight regarding constant amount of cement, were prepared using slurry vacuum de-watering process. This method is a reproduction, at laboratory scale, of the Hatschek process applied in the industrial production of cement-based composites (Savastano et al., 2000). Cement, bio-chars and water were mixed with an initial water/cement ratio equal to 0.8 during 5 minutes then the mix was introduced in a casting box (190 x 200 mm^2). To remove excess water, the casting box was placed under vacuum during 10 minutes. After, pads were pressed at 0.5 MPa for 5 minutes. Others authors used a compressive strength more elevated such as 3.2 MPa or 6.4 MPa (Savastano et al., 2003; Pereira et al., 2013). However, a lower compressive strength was applied to increase the porosity and consequently improve the thermal properties of the material.

After being removed from the box, the specimens were sealed in plastic bag to cure at saturated air at 23 °C for 1 day. Then, the pads were introduced in a climatic chamber at 23°C and 50% of relative humidity for 28 and 90 days of curing to study their behavior at short and medium terms. A diamond disk cooled by water was used to cut pads (120 mm

× 35 mm) for flexural tests, after curing. Thickness of samples varies between 11 to 16 mm in accordance to bio-chars content.

The designation adopted for the bio-chars/cementitious composites was:

CLA xB or xR

with CLA = CEM II 32.5 N, B = bio-chars, R = sugarcane bagasse without thermochemical conversion process and x = content of bio-char or sugarcane bagasse (wt.%) (2, 4 or 6 wt.%, with constant amount of cement) i.e. CLA 6B was a composite made with CEM II 32.5 N, and 6 wt.% of bio-chars.

2.3. Methods

2.3.1 Bio-chars characterization

Scanning electron microscopy (SEM) images of the sugarcane bagasse and bio-chars were obtained thanks to a FEI Quanta 650 microscope (10 kV, secondary electron mode) in the Centre Commun de Caractérisation de l'Université des Antilles (C3MAG, Guadeloupe).

The Fourier Transform InfraRed spectroscopy (FTIR) of the sugarcane bagasse and bio-chars were obtained using an infrared spectrometer Tensor 37 (Brucker, France). The equipment was equipped with an IR source, a separating medium infrared, a He-Ne laser, a DigiTect® DLATGS detector (deuterated triglycine sulfate doped L-alanine) and a RocksolidTM interferometer. The spectrometer was also equipped with an attenuated total reflection dispositive (ATR) device, ideal for thick or highly absorbent samples and thin films.

Thermogravimetric analysis (TGA) was conducted using a simultaneous thermal analyzer under nitrogen atmosphere at a flow rate of 20 mL/min. Thermal decomposition of the sugarcane bagasse and bio-char was carried out between 50 and 900 °C with a heating rate of 10 °C/min.

Water absorption of materials was inspired by (Gould et al., 1989) with some modifications such as the sample mass and the duration of the test. A dried sample (2 g) was mixed with distilled water and left to hydrate for 2 hours, 1, 7 and 14 days. After hydration, the excess water was removed by using a spinner salad.

The isothermal calorimetry was realized using an isothermal calorimeter C80 (SETARAM, France). Cement pastes were elaborated with cement, bio-chars or sugarcane bagasse (0, 2 and 6% by weight), water (Water/Cement fixed at 0.5) and the temperature of the calorimeter was maintained at 25°C. The heat of hydration of the mixture was monitored during 48h.

2.3.2. Bio-chars/cementitious composites characterization

After curing (28 and 90 days) under controlled conditions (25 °C and 50% relative humidity), cement-based composites were characterized by physical, thermal and mechanical tests.

- Physical properties

For all samples, the apparent porosity was determined according to (ASTM C 948, 2009).

The apparent porosity of composites was determined by the following equation:

$$\text{Apparent porosity} = [(B - C) / (B - A)] \times 100 \quad (1)$$

With A = immersed mass (g), B = saturated surface dry mass (g) and C = oven dry mass (g).

- Thermal properties

The thermal conductivity of cement-based composites was measured using a thermal conductimeter CT-mètre (Controlab, France). This method relies the determination of the temperature rise as a function of time at a given point and specified distance from a linear heat source embedded between two specimens with the same composition. Specimens dimensions was 12 cm × 14 cm and six measurements per sample was conducted respecting 1 h interval between each measurement in order to evaluate the standard deviation of the measurements.

- Flexural strength

The flexural strength of bio-chars/cement-based composites was determined to evaluate the potential application of the materials in building construction. Three-point bending tests was carried out using a universal testing machine model 3367 (Instron, France) with a 500 N cell, a crosshead speed of 0.5 mm/min and a span of 100 mm. Flexural strength (FS), Modulus of elasticity (MOE), Toughness (TE) and limit of proportionality (LOP) of composites was calculated according the following equations (Tonoli et al., 2009):

$$FS = (3*F_{max}*S) / (2*w*d^2) \quad (2)$$

$$MOE = (S^3*m) / (4*w*d^3) \quad (3)$$

$$TE = \text{absorbed energy} / (w*d) \quad (4)$$

$$LOP = (3*F_{LOP}*S) / (2*w*d^2) \quad (5)$$

Where F_{max} is the maximum load (N), F_{LOP} is the load at the upper point of the linear portion of the load versus displacement curve (N), S is the span (mm), w and d are the specimen width and depth respectively (mm), m is the tangent of the slope angle of the load versus displacement curve during elastic deformation, absorbed energy is the integration of the area below the load vs. deflection curve at the point corresponding to a reduction in load carrying capacity to 30% of the maximum reached.

Four samples are used to determine the average of flexural strength and standard deviation.

3. Results and discussion

3.1. Bio-chars characterization

3.1.1. Morphology

Figure 1 (a) and (b) shows pictures obtained by the scanning electron microscopy (SEM) of the sugarcane bagasse and bio-chars, respectively. Sugarcane bagasse show particles consisting of individual fibers associated in the longitudinal direction, which are parallel to each other. The thermochemical conversion process breaks the cell wall of the unitary fiber of sugarcane bagasse, which opens and gives back a rough appearance to the bio-char. This roughness is a characteristic of bio-chars that can promote the adhesion between the bio-chars and the cement matrix (Mukhopadhyay and Fangueiro, 2009).

3.1.2. Chemical structure

Figure 2 shows Fourier transformed infrared spectra (FTIR) of sugarcane bagasse and the bio-char.

The spectrum of sugarcane bagasse presents carbohydrates characteristic signals (cellulose and hemicellulose) and lignin signals located towards (Bilba and Ouensanga, 1996):

- 3359 cm^{-1}, due to vibration of elongation of the O-H bond, corresponding to the polysaccharides and lignin,
- 2921-2891 cm^{-1}, due to vibration of elongation of the aromatic C-H bond, corresponding to the polysaccharides and lignin,
- 1642-1600 cm^{-1}, due to the vibration of elongation of the aromatic C = C bonds, corresponding to the lignin,
- 1414 cm^{-1}, due to the vibration of deformation of the C-H bond, corresponding to the polysaccharides and lignin,
- 1240 cm^{-1}, due to vibration of the C-O-C ester bonds, corresponding to the polysaccharides,
- 1161 cm^{-1}, due to vibration of elongation C-O-C bonds, corresponding to the polysaccharides,
- 1035 cm^{-1}, due to vibration of elongation of the C-OH bond, corresponding to the polysaccharides and lignin,
- 830-873 cm^{-1}, due to the vibration of the aromatic C-H bond, corresponding to the polysaccharides and lignin.

These signals, characteristic of polysaccharides (cellulose and hemicellulose) and lignin observed for the sugarcane bagasse are also found in the spectrum of the bio-chars. After the thermochemical conversion process, a decrease of the intensity of all the signals is denoted except for the one located at 2921-2891 cm^{-1} corresponding to the vibration of elongation of the aromatic C-H bond. Decreases of 65 and 90% and of the intensity of the signals corresponding to lignin and polysaccharides respectively indicate that thermochemical conversion process of sugarcane bagasse affects more polysaccharides.

These observations suggest structural modifications of the sugarcane bagasse after the pyrolysis. The decrease of the intensity of specific signals such as polysaccharides or lignin, involves a decrease of their content in the component. Indeed, it has been shown that the cross-linking decreases the lignin content as it is transformed into pseudo-lignin (Bourgois et al., 1989). The polysaccharides are known to retard the hydration of the cement; the reduction of amount of polysaccharides is a good parameter for the use of bio-chars in cement-based materials.

3.1.3. Thermal decomposition

The thermogravimetric (TG) (Figure 3) and differential thermogravimetric (DTG) (Figure 4) curves can be decomposing into three zones:

- zone 1, the evaporation of moisture (29-150 °C),
- zone 2, the main decomposition of organic material (150-420 °C),
- zone 3, the continuation of this decomposition (420-900 °C).

DTG curves allow to analyze the phenomena occurring during the decomposition of bio-chars, because for each chemical phenomenon, a variation of the derivative is noted.

For sugarcane bagasse fibers, one peak is observed in zone 1, it is attributed to the loss of water present in the biomass. In the zone 2, two peaks are observed, the first between 171 and 306 °C and the second between 306 and 417 °C. These temperatures are consistent with those found by (Aboyade et al., 2011) and (Mortari et al., 2010); the authors attributed the first peak to the decomposition of hemicellulose and the second to the one of cellulose, while others authors propose the decomposition of lignin between 160 and 900 °C (Yang et al., 2007). The decomposition of lignin is slower than carbohydrates ones, because of its complex chemical structure and its thermal stability, which is better than cellulose and hemicellulose ones (Ouensanga and Picard, 1988).

For the bio-chars, the decomposition of hemicellulose is not observed on DTG curve indicating that there are no hemicelluloses in the sample. In addition, an increase of about 14% of the peak intensity related to cellulose is noted which is consistent with FTIR observations. The higher content of cellulose is due to a preferential decomposition of the hemicellulose prior to cellulose one (Arsène et al., 2007).

When comparing bio-char and sugarcane bagasse TG curves:

- In zone 1, between 29 and 150 °C, mass losses of 8% and 4.8% for the sugarcane bagasse and bio-chars, respectively, are calculated. Theses mass losses are associated to the evaporation of moisture in the fibers (Aboyade et al., 2011; Mortari et al., 2010). This result indicates that the bio-chars contain less water than the sugarcane bagasse. This observation is consistent with the decrease in the intensity of the O-H band (3359 cm^{-1}) in the infrared spectrum of bio-chars compared to sugarcane bagasse (Figure 2). The presence of moisture in the sample after the pyrolysis can be due to the high relative humidity of the laboratory. Indeed, the fibers may absorb water until the test.
- In zone 2, between 150 and 420 °C, mass losses are the highest, they are equal to 64.5% and 61.8% for sugarcane bagasse and bio-chars, respectively. The lignocellulosic biomass, composed primarily of hemicellulose, cellulose and lignin, is decomposed in this temperature range (Pasangulapati et al., 2012). The mass loss of the sugarcane bagasse is higher than the one of bio-chars, which suggests a higher amount of lignocellulosic compounds in the sugarcane bagasse than the bio-chars. The decrease of intensity of the signals related to polysaccharides and lignin

on the infrared spectrum of the bio-chars (Figure 2) is consistent with these observations.

- In zone 3, between 420 and 900 °C, the decomposition of cellulose continues, the degradation of heavier volatiles, the cracking of C-C bonds and the formation of char occurs. Lignin is also degraded into this region (Roque-Diaz et al., 1985; Kumar et al., 2008).

3.1.4. Water absorption

The curves of water absorbed by the sugarcane bagasse and bio-chars are presented in Figure 5.

Both curves present the same trend but some differences, when considering the quantity of water absorbed, can be noted. The sugarcane bagasse absorbs between 25 and 75% more water than the bio-chars at any time. From 20 hours, the curves reach a saturation mass, which is equal to 4.2 g of water/g of material for the sugarcane bagasse and 2.7 g of water/g of material for the bio-chars, that is to say 1.6 times less water in case of bio-chars.

The hydrophilicity of the bio-chars comes from the formation of hydrogen bonds between water molecules and molecules having -OH groups at the surface of fibers (Shafizadeh, 1982). The decrease of the intensity of the characteristic band of the group -OH observed for bio-chars (Figure 2) confirms the decrease of the mass of water absorbed by the bio-chars.

3.1.4. Isothermal calorimetry

The Figure 6 shows the heat of hydration of cement pastes containing 0, 2 and 6% by weight of bio-chars or sugarcane bagasse.

The hydration of cement is an exothermic reaction that can be described in 5 stages:

- the initial period, up to 30 min, attributed to the dissolution of cement resulting in a release of heat;
- the induction period, between 30 min and 1hour, this period is characterized by a low heat release;
- the acceleration period, between 1h and up to 12h, during this period the setting of cement begins, the calcium silicate hydrates and the calcium hydroxide are formed resulting in a important release of heat. The higher quantity of heat is released during this period;
- the deceleration period, between 12h and 40 hours, during this period the heat decrease and the layer of hydrates around the particle of cement increases;
- the steady stage, between 24h and can continue for years, during this period the hydration reactions continue slowly.

It can be observed that the bio-chars as well as the sugarcane bagasse modify the cement hydration. The total heat released by the specimens after 48 hours is shown in Table 2. For 2% by weight, an increase of 9%, in comparison to control, is observed for cement pastes containing bio-chars. While for the sugarcane bagasse a decrease of 9%, in comparison to Control, is observed. The difference of behavior between both materials can be due to the higher content of cellulose in the bio-chars (observed section 3.1.3), which bring additional nucleation sites for the formation of hydration products (Thomas et al., 2009). Moreover, both materials present a retarding effect on the cement hydration. This phenomenon is due to the remaining polysaccharides and lignin presents in the sugar cane bagasse and bio-chars, which decrease the concentration of calcium ions and retard the formation of the hydration products (acceleration period).

For 6% by weight, a huge drop of the heat of hydration is observed for cement pastes containing bio-chars and sugarcane bagasse. This behavior is mainly due to the high quantity of polysaccharide released by both components.

3.2. Composites

3.2.1 Apparent porosity

The apparent porosity of the sugarcane bagasse and bio-chars is present in Table 3.

An increase of the apparent porosity of cement-based composites are noted when the amount of bio-chars increases. The same behavior is observed for cement-based composites with the sugarcane bagasse. The increase of the porosity with the bio-chars content is due to the water absorbed by the bio-chars during mixing, which leads to a higher quantity of water in the vicinity of the bio-chars. At the end of the elaboration process, the water/cement (W/C) ratio of cement-based composites is equal to 0.47, 0.50 and 0.55 for 2, 4 and 6% by weight of bio-chars, respectively. It is known that a high water/cement ratio provides a high porosity in the cement-based composites (Vu et al., 2009).

To reduce the porosity of cement-based composites, the compressive strength generally applied to remove the excess of water during the elaboration of the cement-based composites varies between 3.2 and 6.4 MPa (Savastano et al., 2003; Pereira et al., 2013). However, in this study the thermal properties of the material were prevailed. Indeed, a material with a high porosity will present better thermal properties than the one with lower porosity.

3.2.2 Thermal properties

3.2.2.1. Thermal conductivity

The thermal conductivity is the ability of a material to conduct heat, that is to say the transport of heat through the material as the result of a temperature gradient.

Table 4 shows the thermal conductivity of cement-based composites containing sugarcane bagasse and bio-chars at 28 and 90 days.

A decrease of the thermal conductivity of cement-based composites with the bio-chars content is observed. The lowest value is obtained by cement-based composites containing 6% by weight; the decreases are around 45 and 30% at 28 and 90 days, respectively. This phenomenon is explained by the increase of the porosity of the material observed section 3.2.1.

At 28 days, the addition of 4% by weight of bio-chars decreases the thermal conductivity of cement-based composites by 25% in comparison to cement-based composites with the sugarcane bagasse. At 90 days, the greater decrease is obtained for cement-based composites containing 2% by weight of bio-chars, with a decrease equal to 6%. The decrease of the thermal conductivity of cement-based composites containing bio-chars (up to 4% by weight) in comparison to the one containing the sugarcane bagasse can be due to the difference between the chemical compositions of both materials. This result is consistent with the observation made in section 3.1.2. From 6% by weight of bio-chars, the thermal conductivity of bio-chars composites is higher than the one of sugarcane bagasse. This behavior can be explained by the existence of a critical level of addition where the chemical composition of the bio-chars doesn’t have anymore influence on the thermal conductivity and other parameters such as fibers agglomeration and/or dispersion can have more impact.

The bio-chars/cement based composites present lower thermal conductivity than conventional fibers/cement composites observed in the literature (Tonoli et. al., 2011). The more the thermal conductivity is low, the less the material conducts heat and the more the material is insulating (Hegger et al., 2010). According to the results, the bio-chars present a huge potential for the elaboration of insulating materials.

3.2.3. Mechanical properties

Table 5 shows the mechanical properties of cement-based composites at 28 and 90 days.

As expected the flexural strength of all cement-based composites present a lower flexural strength than the one observed in the literature (Ballesteros et al., 2018; Pereira et al., 2013). This result can be explained by the compressive strength used during the elaboration of the composites. Indeed, the compressive strength used for the elaboration of the composites was 0.5 MPa, a value lower of the ones observed in the literature. Using this value of compressive strength, the composites present a high water content, which leads to a higher porosity after curing. Knowing that the porosity and the mechanical properties are inversely related, cement-based composites with high porosity present low flexural strength.

The statistical analysis of the data was performed using Statistica software. The comparison of the average values by Tukey test at 5% of significance level showed that the thermochemical conversion does not have influence on the flexural strength of the composites.

The standard specification ASTM C1325 gives the mechanical properties requirements for Flat Fiber-Cement Sheets. According to the standard specification, the lower limit value of flexural strength is 4 MPa (with an acceptable quality limit of 4%). However, neither composite meet the requirement. An increase of the compressive strength during the elaboration of the composites should allow to reach the minimal value.

It can be observed that the modulus of elasticity of cement-based composites decreases with bio-chars content. Generally, the decrease of modulus of elasticity is associated to the increase of reinforcing material content as observed by others authors (Savastano et al., 2000). The specific modulus of elasticity is a very important parameter reflecting the ability of composites to deform elastically; the more flexible a material is, the lower modulus of elasticity is (Thakur, 2013). This property of bio-chars/cementitious composites can be interesting for building materials in earthquake areas such as Guadeloupe.

Toughness is ability of material to resist to crack propagation. The high toughness of cement-based composites is due to the ability of the bio-chars to inhibit crack propagation and fracture; the load stress is transferred from the matrix to the bio-char (Thakur, 2013). At 28 and 90 days, the toughness of cement-based composites increases due to the increase of bio-chars content.

The limit of proportionality is the stress at first crack, the load at which the load-strain curve ceases to be linear. The statistical analysis of the data showed that the limit of proportionality of composites with bio-char is not influenced by fibers content.

The thermochemical conversion process does not improve the mechanical behavior of cement-based composites; this behavior can be due to the length of bio-chars compared with the sugarcane bagasse. Indeed, the toughness is associated to the length of reinforcing material (Savastano et al., 2003), this results is consistent with the decrease of toughness for cement-based composites with bio-chars in comparison to cement-based composites with sugarcane bagasse (Table 5).

4. Conclusion

Based on the experimental results obtained in this study, the following conclusions can be drawn:

1. The scanning electron microscopy showed that the bio-char presents a rough surface that could increase it adhesion to the cement matrix.
2. The Fourier transformed infrared spectra of bio-chars showed that the thermochemical conversion of sugarcane bagasse modifies the structure forming bio-chars with lower polysaccharide and lignin content.
3. The thermogravimetric analysis showed that the thermochemical process conversion of sugarcane bagasse forms bio-char without hemicellulose. The absence of hemicellulose in the bio-char is very interesting for a use in cement matrix.
4. The water absorption tests showed that bio-chars absorb lower quantity of water than sugarcane bagasse.
5. The isothermal calorimetry test showed that the use of 2% by weight of bio-chars improves the hydration of cement pastes.
6. The thermal conductivity tests showed the addition of 4% by weight of bio-chars decreases the thermal conductivity of cement-based composites by 25% in comparison to cement-based composites with sugarcane bagasse.
7. The flexural strength tests showed that cement-based composites containing bio-chars and sugarcane bagasse present similar mechanical performances.

According to the results of the study, the bio-chars present a huge potential for the elaboration of insulating building materials to reduce the energy consumption of building construction.

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Figures

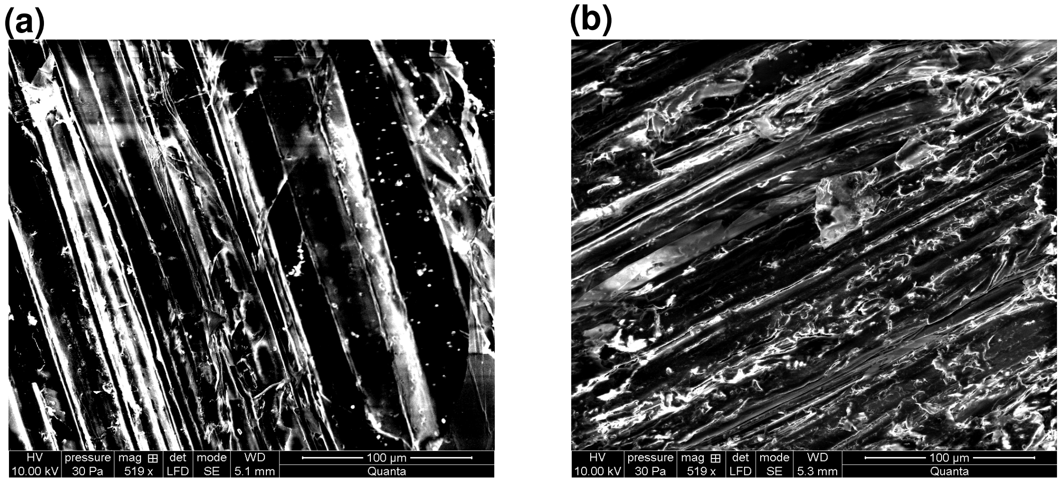

Figure 1. Scanning electron micrographs of the (a) sugarcane bagasse and (b) bio-chars

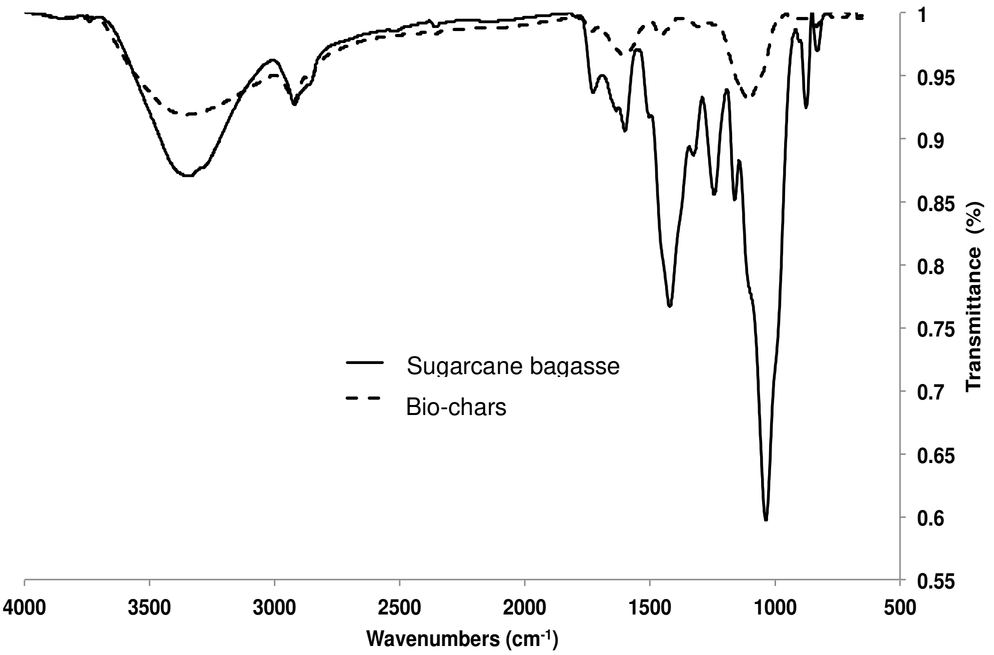

Figure 2. FTIR spectra of the sugarcane bagasse and bio-chars

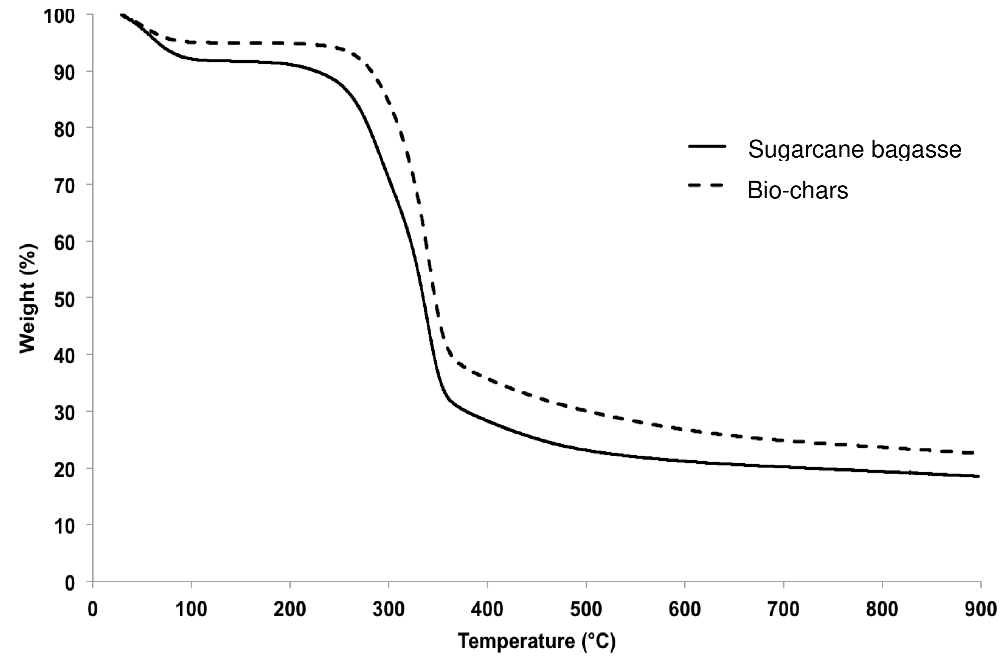

Figure 3. ATG curves of the sugarcane bagasse and bio-chars

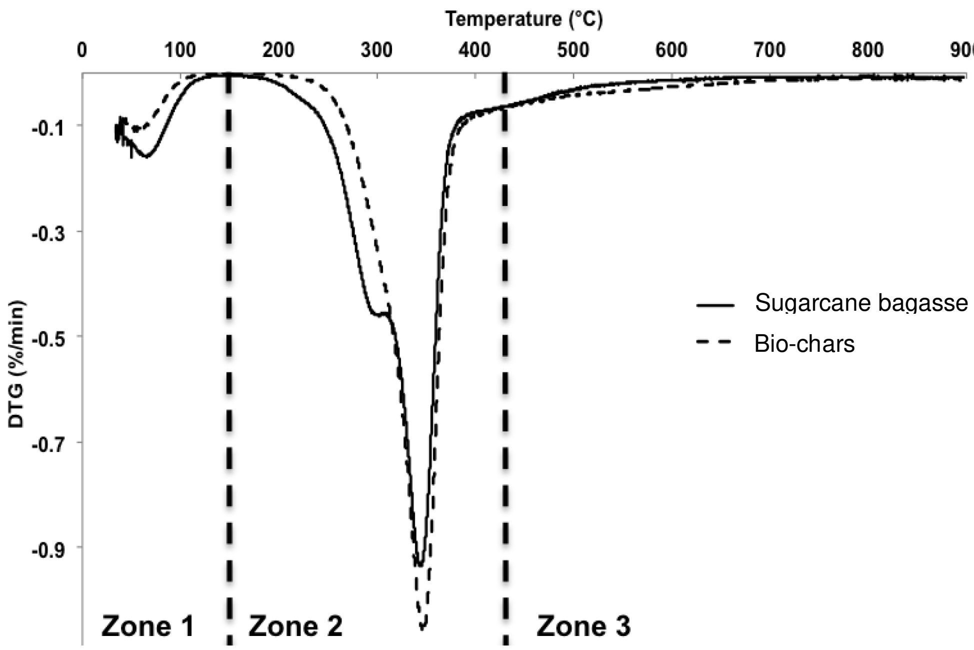

Figure 4. DTG curves of the sugarcane bagasse and bio-chars

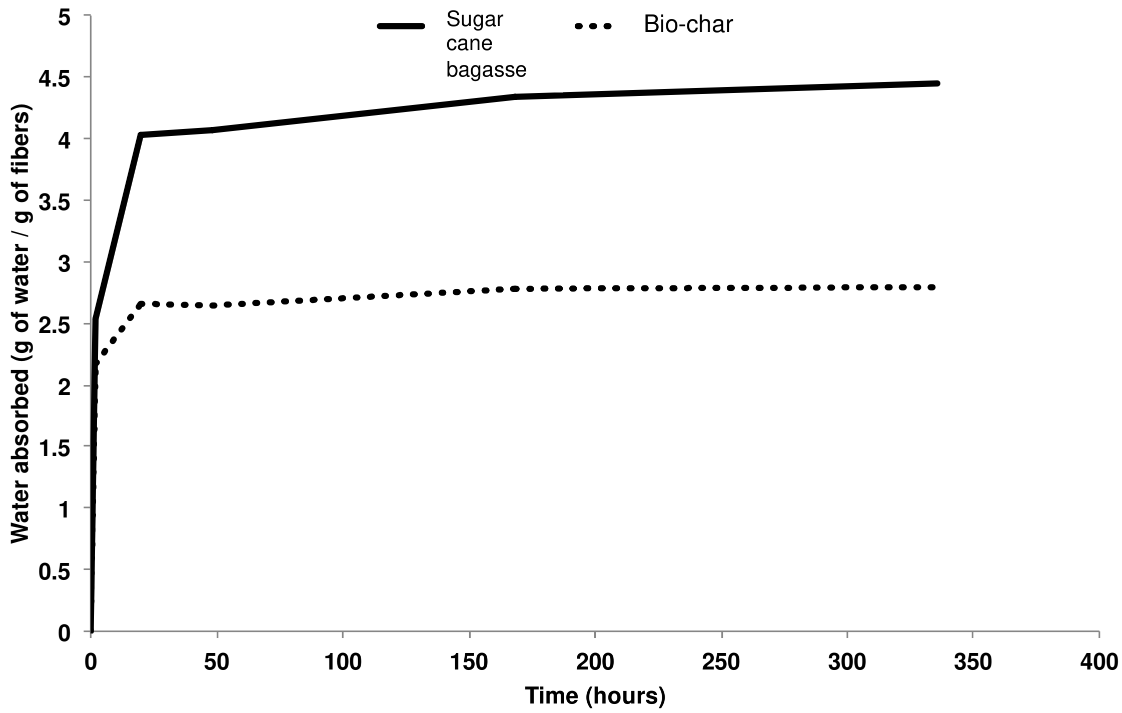

Figure 5. Evolution of water absorbed by the sugarcane bagasse and bio-chars with time

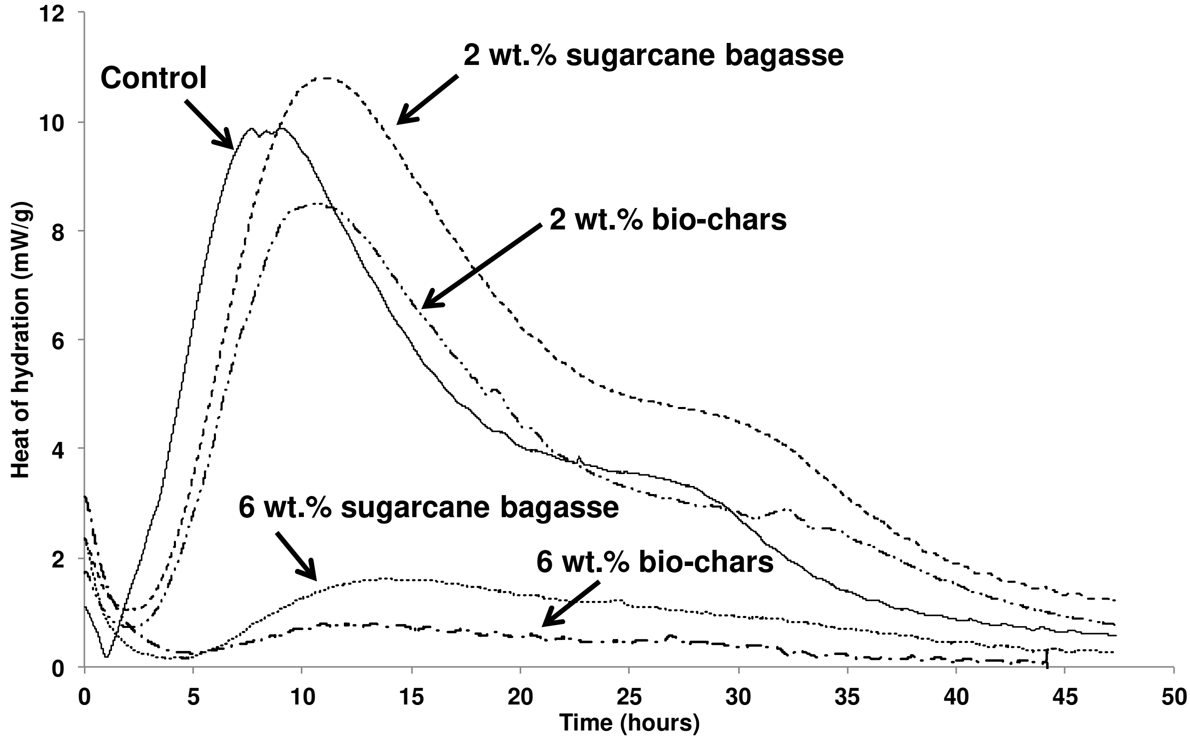

Figure 6. Heat of hydration of cement pastes containing 0, 2 and 6% by weight of bio-chars or sugarcane bagasse

Tables

Table 1. Chemical composition and physical properties of the cement

Chemical composition (wt.%)	CEM II 32.5 N
SiO_2	24.66
Fe_2O_3	5.04
Al_2O_3	7.06
CaO	55.70
Na_2O	0.28
K_2O	0.38
MgO	1.60
Cl	-
True density (g/cm^3)	3.07
Particles size, (μm)	15.70
Blaine finenesse (cm^2/g)	3190

Table 2. Total heat released by the cement pastes

Total heat released (J/g of cement)	
Control	256
2 wt.% sugarcane bagasse	278
2 wt.% bio-chars	232
6 wt.% sugarcane bagasse	59
6 wt.% bio-chars	47

Table 3. Physical properties of cement-based composites at 28 and 90 days

Apparent porosity (%)		
	28 days	90 days
CLA 2R	46.09±0.34	44.73±2.23
CLA 4R	51.27±0.97	55.13±2.76
CLA 6R	76.16±2.94	65.29±3.87
CLA 2B	43.54±3.06	43.65±2.18
CLA 4B	54.40±0.52	52.83±2.64
CLA 6B	60.61±0.52	65.88±3.93

Table 4. Thermal properties of cement-based composites at 28 and 90 days

Thermal conductivity (W/m.K)		
	28 days	90 days
CLA 2R	0.328	0.342
CLA 4R	0.300	0.314
CLA 6R	0.214	0.274

CLA 2B	0.314	0.314
CLA 4B	0.228	0.285
CLA 6B	0.228	0.287

Table 5. Mechanical properties of cement-based composites at 28 and 90 days

Composites	**Flexural strength (MPa)**		**Modulus of elasticity (GPa)**		**Toughness (J/m^2)**		**Limit of proportionality (MPa)**	
	28 days	**90 days**	**28 days**	**90 days**	**28 days**	**90 days**	**28 days**	**90 days**
CLA 2R	2.44±0.44	2.31±0.5	1.78±0.37	1.75±0.72	3.75±0.24	3.71±0.51	1.35±0.24	0.52±0.15
CLA 4R	2.53±0.72	2.69±0.53	1.80±0.27	1.51±0.21	12.10±1.74	11.80±1.53	1.42±0.61	1.28±0.31
CLA 6R	1.85±0.31	2.08±0.17	0.71±0.13	0.89±0.13	17.72±2.78	21.38±0.79	0.95±0.22	0.91±0.12
CLA 2B	2.77±0.29	3.09±0.81	1.97±0.29	2.43±0.43	4.03±0.52	3.70±0.50	1.18±0.37	1.25±0.14
CLA 4B	1.39±0.17	1.76±0.30	0.63±0.18	0.77±0.20	5.93±0.69	7.18±0.96	1.48±0.22	0.88±0.14
CLA 6B	2.02±0.28	1.92±0.06	0.70±0.27	0.58±0.06	7.98±1.38	9.34±1.21	1.28±0.14	1.13±0.09