THERMAL PROPERTIES OF TREATED BAGASSE FIBRES REINFORCED CEMENT COMPOSITES

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ABSTRACT

In order to reduce the part of electrical consumption for air conditioning and to use environment friendly materials, composites made of vegetable fibres and cement are studied. Since 1997, the use of asbestos is forbidden in the production of thermal insulating construction materials in France. Many studies have shown that, regarding the mechanical behaviour, vegetable fibres are an interesting alternative to asbestos in fibre reinforced cement products manufactured by the Hatscheck process.

This paper deals with specific heat and thermal conductivity of cement composites reinforced with vegetable sugar cane bagasse fibres (1.5 and 3% wrtc). Moreover, thermal properties have been correlated to macroscopic density and porosity of composites. This correlation allows us to estimate thermal conductivity of fibres using a calculation inspired from Maxwell Eucken modelling.

KEYWORDS:

Cement composites; vegetable fibres; thermal conductivity; specific heat; modelling

INTRODUCTION

Composite materials incorporating vegetable natural fibres have known an increasing interest during the past decades (Tôledo-Filho et al., 2003; Savastano et al., 2000; Savastano et al., 2003a). These environment friendly materials are low-cost (Coutts, 1992) and offer advantages such as reduction of electrical consumption by air conditioning (Roma Jr et al., 2008). Moreover, the use of vegetable fibres in replacement of synthetic fibres is interesting in developing countries where the availability of tropical plants and agricultural wastes is important. Due to health reasons, since 1973, various regulations are applied to restrict and ban the use of asbestos in France and other countries (Bilba et al., 2004).

Guadeloupe, French island located in the tropical zone, has a production of about 600000 tons of sugar cane (2009). After juice extraction, the residue left is bagasse (about 190000 tons in 2009). Therefore, development of composites materials for building using this waste will be a good alternative in order to solve environment concerns and to obtain low-cost insulating materials. In this tropical area, a low thermal conductivity and a low specific heat are required to have a good thermal insulation of buildings.

Many studies have shown that, regarding the mechanical behaviour, vegetable fibres are an interesting alternative to asbestos in fibre reinforced cement products manufactured by the Hatschek process (Savastano et al., 2000; Savastano et al., 2001; Savastano et al., 2003b; Delvasto et al., 2010). But few works have demonstrated the low thermal conductivity of such vegetable fibre-Portland cement based composite materials resulting from effect of the mixture fibre/matrix (Tolêdo-Filho et al., 2003; Savastano et al., 2001) and there is no published result concerning specific heat of bagasse reinforced cement composites.

Moreover, these composites are well known for durability problem (Tolêdo-Filho et al., 2003); indeed, the alkaline cement attacks the lignin in natural fibres, hence leading to the degradation in composites strength.

This main difficulty hinders the development of these composites. To solve this problem, several approaches, such as use of pozzolans for reduction of matrix alkalinity (de Gutierrez et al., 2005), carbonatation of the matrix or immersion of fibres in slurried silica fume (Tolêdo-Filho et al., 2003) have been investigated. In this paper, in order to improve the strength to degradation of bagasse fibres in alkali environment, thermal treatment (Arsène et al., 2007) and chemical treatment have been applied to the fibres before incorporating into the cement matrix. We will present thermal properties of modified bagasse-cement composites which will allow us the estimation of thermal conductivity of fibres.

1. MATERIALS AND METHODS

The procedure of preparation of raw bagasse fibres was carried out at Université des Antilles et de la Guyane and has been described in our previous studies (Arsène et al., 2007). The sugar cane bagasse composition has already been characterized (Bilba et al., 2003) and it is summarized in Table 1.

Table 1 – Botanical analysis of studied fibres

Fibres	Extractives (weight %)	Cellulose (weight %)	Hemicellulose (weight %)	Lignin (weight %)	Sum (weight %) except humidity	Humidity (weight %)
Raw bagasse	3.90	48.38	25.30	21.80	99.38	7.50
BAGP	1.80	47.30	24.54	22.15	95.79	12.21
BAGB	2.35	50.35	15.75	16.86	85.31	5.17

Legend: BAGP is for pyrolyzed (retified) bagasse; BAGB is for alkali treated bagasse

Raw fibres with diameters between 0.4 mm and 1 mm have been selected and two types of treatments were applied to them in order to prevent degradation of fibres by alkaline cement matrix:

- Heat–treatment : pyrolysis (retification) under controlled atmosphere (N_2 flow, 2l/h) during 2 h and at 200°C which is the optimal temperature to obtain retified fibre without formation of char (Bilba et al., 2004). The pyrolyzed (retified) fibres will be named "BAGP".
- Chemical treatment: attack by a 5% by mass alkaline solution of $Ca(OH)_2$. The alkali treated fibres will be named "BAGB".

A Portland cement marketed as ASTM type I, a graded natural river sand (standardized specification), calcium carbonate and water were used to prepare the matrix. Tables 2 and 3 report the physical and chemical properties of the cement. 93.5% by weight of the limestone filler is $CaCO_3$.

Table 2 – Physical and mechanical properties of cement

Blaine	Size greater than 45 µm	Normal consistency	Initial setting	Final setting	Compressive strength		Density
m^2/g	%	%	min	min	1 day (MPa)	3 days (MPa)	kg/m^3
423	3.08	27.70	159	312	7.30	19.80	3.03

Table 3 – Chemical properties of cement (X-rays diffraction)

CaO %	C2S %	C3S %	SiO_2 %	L.O.I. %	I.R. %	Al_2O_3 %	Fe_2O_3 %	SO_3 %	MgO %	K_2O %	Na_2O %
57.81	43.24	27.67	22.05	7.96	5.94	4.23	4.23	1.98	1.52	0.18	0.17

Composites elaboration

Composites were elaborated at Universidad del Valle (Cali, Colombia).

The content of sand and calcium carbonate were kept constant at 50% and 30% by weight of cement respectively. The proportions of the matrix compounds were by weight percent with respect to Portland cement (wrtc): sand 50%, limestone powder 30%, bentonite 1.5 and 3%, cellulose pulp 4%, silica fume 5%, an aqueous copolymer dispersion of butyl acrylate and styrene from BASF (Acronal® 296 D) 7.5%. The amount of fibres was changed from 0 to 3% wrtc. Slurry of each mix contains a water/cement ratio of 0.9 (weight by weight) being prepared before its pouring on a casting bed that was subjected to vacuum to obtain a flat sheet. After the slurry dewatering process, pads (160 x 50 x 8 mm^3) cut from the fresh laminate were cured for 21 days at 100% of relative humidity and left to air dry in the laboratory for 7 days at room temperature.

Five mixes were elaborated: two formulations for the two types of fibres treatment (for each fibre contents) and one as the control (reference without any fibre). Proportions of mixes are shown in Table 4. The composites will be noted "CBAGP" and "CBAGB" for composites reinforced with retified bagasse fibres and composites reinforced with alkaline bagasse fibres, respectively.

Table 4 – Proportions of the mixes elaborated.

Composites	Fibres and treatment	Bentonite (% wrtc)	Fibres (% wrtc)	Acrylic polymer (% wrtc)	Silica fume (% wrtc)	Cellulose pulp (% wrtc)
Control	-	3	0	7.5	5	4
CBAGB1.5	BAGB	3	1.5	7.5	5	4
CBAGP1.5	BAGP	3	1.5	7.5	5	4
CBAGB3	BAGB	3	3	7.5	5	4
CBAGP3	BAGP	3	3	7.5	5	4

Thermal conductivity

Thermal tests were conducted under controlled laboratory conditions (temperature ~ (298±1) K and relative humidity of 70–80%) on 112 days old specimen. The apparatus used was a thermal conductivimeter "CT–mètre" with a thermal probe commercialized by Controlab (Saint–Ouen, France). Six measurements were conducted for each composite with one-hour interval between each measurement in order to evaluate the standard deviation of the results.

Isothermal calorimetry

Isothermal calorimetry has been carried out on a C80 calorimeter (Setaram, France) at Université des Antilles et de la Guyane. This apparatus is usually used to determine specific heat of cement composites under air atmosphere. All samples have been measured at least twice.

Macroscopic density

Composites porosity has been measured using helium gas intrusion under helium gas flow with a "Pycnomatic" Thermo Electron Corporation equipment (Les Ulis, France) pycnometer. Five measurements on different small pieces of samples were conducted for each composite at 298 K, relative humidity of 70–80%.

Mercury intrusion porosimetry measurements

Porosity of the composites has been studied by mercury intrusion porosimetry from 0.1 to 200 MPa with mercury porosimeters Thermofinnigan (France) Pascal 140 and Pascal 240. This range of pressure corresponds to pore radius from 58 µm to 3.7 nm. At least, two measurements were carried out.

RESULTS AND DISCUSSION

Thermal properties of composites

Figure 4 presents the evolution of thermal conductivity according to fibre content and fibre treatment for 112 days old composites.

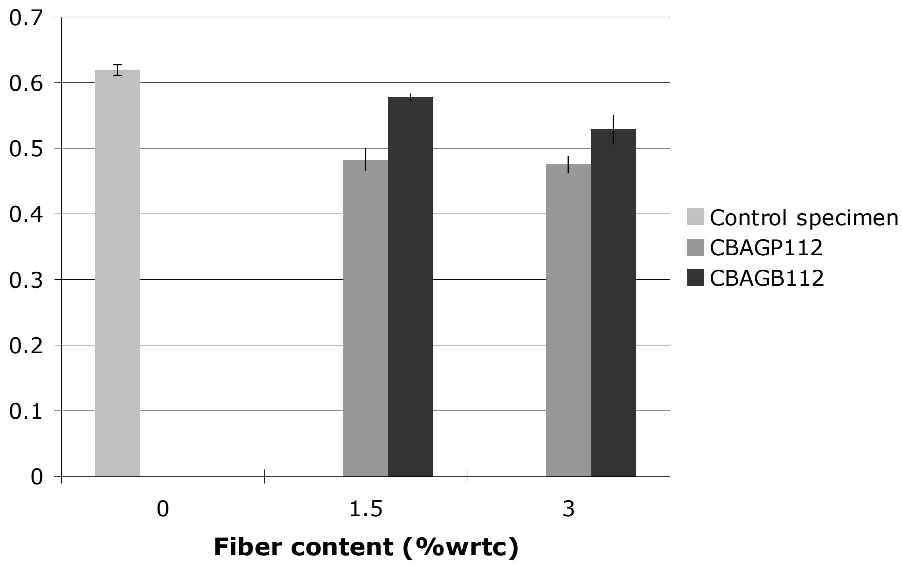


Figure 1 – Evolution of thermal conductivity of 112 days old composites according to fibre content and fibre treatment.

The thermal conductivity of composites decreases from 0.56 W/m.K for CBAGB1.5 to 0.45 W/m.K for CBAGP3. As previously described (Khedari et al., 2001; Asasutjarit et al., 2007), in case of synthetic or vegetable fibres, by increasing fibre content, there is a progressive decrease of thermal conductivity of cement composites.

This indicates a promising potential for development because it is reported (Asasutjarit et al., 2007) that thermal conductivity of cellulose commercial board is around 0.68 W/m K.

The effect of fibres on thermal conductivity is much stronger for retified bagasse fibres than for alkaline bagasse fibres; lowest thermal conductivity λ is noted for highest amount of added BAGP fibres.

The thermal conductivity is inversely proportional to the voids in the composites. The packing of fibres generates the voids (Khedari et al., 2001). As shown by Table 5, the highest the fibre content, the lowest is the density. However, we observe that the density values of composites reinforced with 1.5% wrtc of fibres are slightly higher (around 10%) than that presented by the control sample (reference) and that the composites reinforced with 3% wrtc of fibres are only 3-10 % higher than reference density value. This behaviour may be related to the nature of density measured (true density). It is assumed that the matrix density is lower than the fibres density based on the possible existence of non-connected pores or pores that are not reachable by helium gas.

Table 5 – Average macroscopic density of 365 days old composites according to fibre content.

Sample	Control	CBAGP		CBAGB	
% wrtc fiber	0	1.5	3	1.5	3
Macroscopic density (g/cm^3)	2.4891 [±0.0094]	2.8109 [±0.0229]	2.7264 [±0.0256]	2.7500 [±0.0131]	2.5646 [±0.0010]

Measurements of specific heat have also been taken between 303 K and 353 K. Values of specific heat of reinforcement and composites according to fibre content and fibre treatment are reported in Table 6.

Whatever the type of treatment, specific heat of fibres is of the same order of magnitude; however presence of treated fibres affects the specific heat.

Specific heat of control specimen is (0.2673 ± 0.0068) J/g.K. When the fibre content increases, there is a progressive decrease of specific heat for both types of fibres. The lowest value is obtained for CBAGP. Literature reports that with increasing synthetic fibre content, there is an increase of specific heat (Chung, 2000). There is no published result concerning the specific heat of vegetable fibres reinforced cement composites in order to compare our results. We can check if these experimental data are supported by a classical mixture law.

We consider the total specific heat of composite as a contribution on one hand of fibres one and on the other hand of matrix one according to the theoretical expression:

$$Cp_{composite} = \left(Cp_{fibers} x\, v_{fibers}\right) + \left(Cp_{matrix} x\, v_{matrix}\right) \tag{1}$$

where Cp_{fibers} and v_{fibers} are respectively specific heat and volume fraction of the fibres and Cp_{matrix} and v_{matrix} are respectively specific heat and volume fraction of the matrix.

We assume that:

$$v_{fibers} + v_{matrix} = 1 \tag{2}$$

Table 6 summarizes specific heat experimental and theoretical results for composites. Alkaline fibres composites exhibit higher specific values than pyrolyzed fibres composites but both of them have the same magnitude. We notice that with increasing fibre content, there is a decrease of specific heat of composites.

Table 6 – Specific heat of bagasse fibres and composites

	Raw bagasse	BAGP	BAGB	CBAGP		CBAGB	
% wrtc of fiber	-	-	-	1.5	3	1.5	3
Experimental specific heat (J/g.K)	0.6281 [±0.0416]	0.5816 [±0.0060]	0.6430 [±0.0529]	0.2301 [±0.0145]	0.1996 [±0.0221]	0.2519 [±0.0064]	0.2244 [±0.0023]
Theoretical specific heat (J/g.K)	-	-	-	0.2746	0.2815	0.2757	0.2835

We observe that the low values of specific heat are explained by the specific heat of reinforcement. Figure 2 is the representation of Cp prediction from composites composition according to experimental data. Dash line represents the area where there is a perfect agreement between prediction and experimental (ideal model).

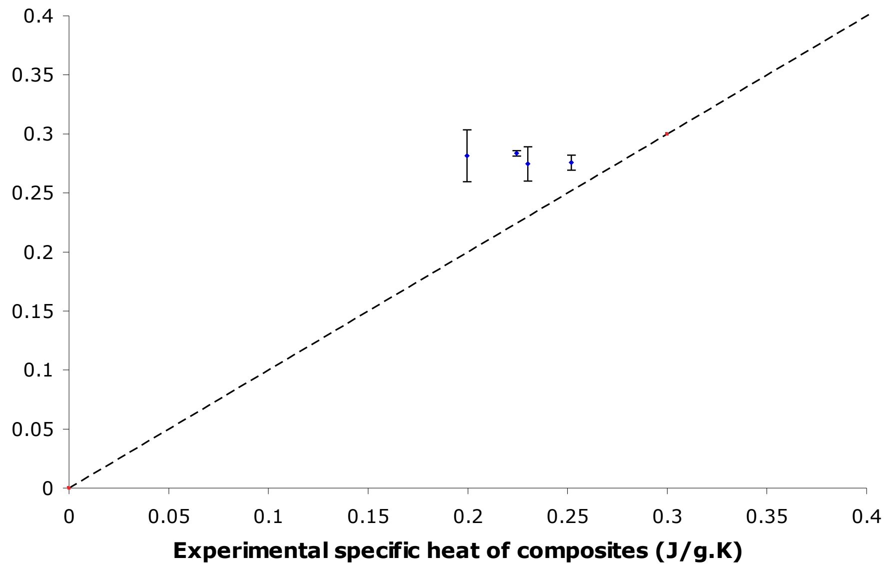
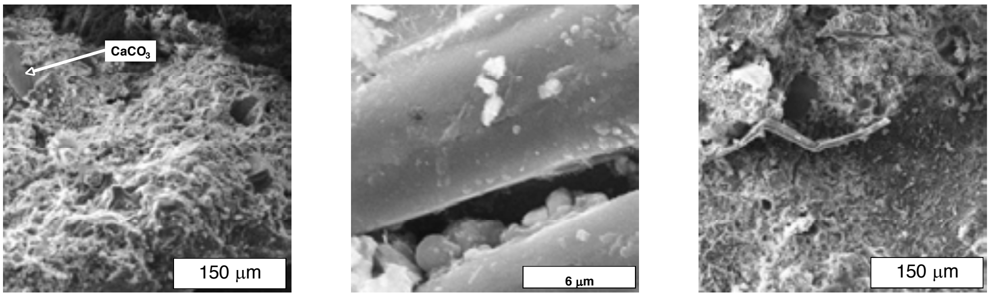


Figure 2 – Specific heat prediction versus experimental specific heat of composites.

From the theoretical point, specific heat increases with fibre content that seems obvious because fibre specific heat is higher than matrix specific heat. Our experimental values are not on the dash line of the slope unity: the prediction of mixture law is not in very good agreement with experimental results. This difference could be due to defects in composites such as void content, lack of adhesion at fibre/matrix interface and fibres defects (Chung, 2000). There is a possible lack of adhesion at fibre/matrix interface due to method of elaboration. Figure 3 presents SEM pictures of CBAGB and CBAGP with fibre content of 3% wrtc.



(a) x 200 (a) x5000 (b) x200

Figure 3 – SEM pictures of CBAGP (a) and CBAGB (b) with fiber content of 3%wrtc.

We can see that there are some fragments of $CaCO_3$ packed onto fibre surface. This packing is thought to be partly responsible of a smaller interface area with matrix and the loss of specific heat. Indeed, slippage at the interface contributes to the specific heat and the interface acts as a thermal barrier. Moreover, we suppose that the fact experimental specific heat decrease with fibre content whereas theoretical values increase with fibre content can be explained by the presence of porosity (about 45%) in samples.

Estimation of thermal properties of bagasse fibres

According to Wang et al. (2006) thermal conductivity of cement/fibre composite can be determined using the Maxwell-Eucken equation:

$$K = \frac{k_m v_m + k_f v_f \frac{3k_m}{2k_m + k_f}}{v_m + v_f \frac{3k_m}{2k_m + k_f}} \qquad (3)$$

where K is the effective thermal conductivity of the composite,

k_m and v_m are respectively the thermal conductivity and volume fraction of the continuous phase i.e. the matrix,

k_f and v_f are respectively the thermal conductivity and volume fraction of the dispersed phase i.e. the fibres.

We assume that $v_m + v_f = 1$.

This expression can be formulated as:

$$\frac{K - k_m}{k_m} = \frac{3(k_f - k_m)v_f}{(k_m - k_f)v_f + 2k_m + k_f} \qquad (4)$$

If we suppose v_f very small, we can write:

$$\frac{K-k_m}{k_m} \cong \frac{3(k_f-k_m)}{2k_m+k_f} v_f \left[1-\frac{(k_m-k_f)}{2k_m+k_f} v_f\right]$$
(5)

First, we will neglect the right term, in order to find an expression of $\frac{K-k_m}{k_m}$ according to v_f.

If %f is the weight percentage,

$$v_f = 1-\frac{\rho}{\rho_m}\left(1-\frac{\%f}{100}\right)$$
(6)

where ρ is the composite bulk density and ρ_m, matrix bulk density. These values are obtained via mercury porosity measurements.

Modelling results.

If $A=\frac{3(k_f-k_m)}{2k_m+k_f}$, it follows $k_f = k_m \frac{3+2A}{3-A}$ (A is the coefficient director of the curves).

The main results, with a good correlation (R = 0.99) are in Table 7.

Table 7 – Thermal conductivity modelling results.

	Retified bagasse fibres		Alkaline bagasse fibres	
% f	1.5	3	1.5	3
v_f	0.1909	0.2818	0.2115	0.2096
$\rho_{composite}$ (g/cm^3)	1.6155	1.4561	1.5744	1.6024
k_f (W/m.K)	0.1781		0.1092	

We notice that our v_f values are quite high. Indeed, true density of light wood, as balsa, is approximately 0.1 g.cm^{-3} (density of balsa ranges from 0.04 to 0.38 g.cm^{-3} (Vural & Ravichandran, 2003). Considering this theoretical value, we would find corrected v_f values around 0.06 and 0.12 (6% and 12%, respectively). This suggests two hypotheses, either density of vegetable fibre is lower than the density 0.1 g.cm^{-3} of light wood or either the model is not fully adapted to study this composite material.

As there is no information about thermal conductivity of vegetable fibre, the Maxwell-Eucken equation allows the estimation of the thermal conductivity of retified and alkali-treated bagasse fibres with a good correlation. Others measurements have to been carried out.

k_f, thermal conductivity of fibres, is calculated without any approximation and by using our experimental values.

Figure 4 presents the trend of the calculated curve for BAGP composites. The linear trend of the curve of thermal conductivity K of the composite versus volume fraction v_f of the fibre shows that the model is convenient for BAGP composites.

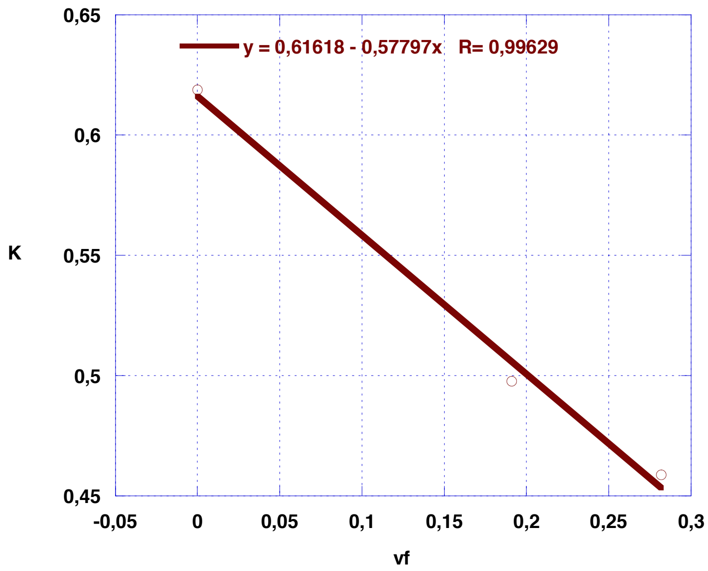


Figure 4 – Thermal modelling of BAGP composites.

CONCLUSION

Thermal conductivity and specific heat of vegetable fibres/cement composites are important parameters in the use of such materials in construction for saving energy. In this study, particular attention is given to the influence of weight fraction of fibres, fibres treatment on thermal properties. Composites elaborated with retified bagasse fibres are lower heat conductor materials than those elaborated with alkaline bagasse fibres. They also store less heat than the matrix; regarding specific heat, lowest values are obtained with CBAGP but both types of composites show lower specific heat than the plain matrix. Thermal behaviour of these cement composites reinforced by bagasse fibres show a quite good correlation with Maxwell-Eucken modeling if we assume that the density of bagasse fibres is lower than light wood (balsa) one. Further experiments are planned in order to study the influence of void on thermal behaviour of composites.

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