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1 *Auto-coherent homogenization applied to the assessment of thermal conductivity: case of sugar cane*
2 *bagasse fibers and moisture content effect*

3
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15
16 Abstract

17 **The purpose of this study is** to evaluate the thermal conductivity of sugar cane bagasse
18 fibers **when they reinforce** vegetable fibers/cement composites using auto-coherent
19 homogenization. The moisture content effect on the thermal conductivity of composites
20 is also studied. When the fiber content increases, porosity increases **according to a linear**
21 **rule** and bulk density and thermal conductivity of composites decrease. When the
22 moisture content grows, the thermal conductivity of composites increases. **When**
23 **applying auto-coherent homogenization**, in dry state, **results show** a gap of less than
24 10% between experimental and modeled values **of composites thermal conductivity and**
25 **a mean sugar cane bagasse fibers thermal conductivity of 0.110 W/m.K.** In wet state
26 (56% RH), there is an **approximate** agreement of 1,4% between estimated and
27 experimental values of thermal conductivity of composites up to 4 wt% of fibers
28 content.

29
30 Keywords : Natural fibers ; Thermal properties ; Cement composites ; Auto – coherent
31 homogenization; Moisture content.

32
33 1. Introduction

34
35 Guadeloupe (French West Indies) is a Caribbean island with a tropical climate [1, 2]
36 were various vegetable fibers, including agro – industrial wastes, are low-cost and/or
37 abundantly available [3-4]. This **archipelago** has a high seismicity and is prone to violent
38 hurricanes [5]. Therefore, the main construction material used **in the building sector** is
39 conventional cement and its derivatives (concrete blocks, bricks, ...) [6-7].

40 French thermal and acoustic regulations advocate the use of 50% renewable power in
41 energy consumption by 2020 [7]. One way to reduce the energy consumption, as
42 consequence to increase the renewable energy ratio, is to use less air-conditioning in
43 infrastructures [7]. To achieve this goal, the partial replacement of cement by vegetable
44 fibers as reinforcement of cementitious matrix **is considered** [1, 3, 6, 7]. Indeed,
45 vegetable fibers **are known to** have insulating properties that is to say a low thermal
46 conductivity and appear to be a good alternative to synthetic fibers such as glass fibers
47 or asbestos fibers, commonly used for building insulation [8-10]. As observed by
48 Onésippe et al. in 2010 [3] and even now, few works have demonstrated the low thermal
49 conductivity of vegetable fibers cement-based composites as well as the thermal

50 conductivity of vegetable fibers (when they are incorporated in the composites) and the
51 influence of moisture on thermal conductivity of these composites. The presence of
52 wood fibers reduces the density of the material [11] and decreases its thermal
53 conductivity [3, 6, 10].

54 Vegetable fibers are vulnerable to alkalinity of matrix thus causing debonding of the
55 fiber / matrix interface and thus a decrease in the mechanical performance of the
56 composites [3, 9]. To limit vulnerability of vegetable fibers in the matrix, various
57 treatments of fibers have been considered such as chemical (acid or alkaline), physical-
58 chemical, thermal and mechanical treatments [9, 11]. These various treatments lead to a
59 strengthening of fiber/matrix interface [12] because they induce, on the one hand, the
60 modification of the morphology of the fibers and, on the other hand, the reduction of the
61 contents of hemicellulose and extractible materials which are inhibitors of the hydration
62 of the binder [12].

63 Moreover, vegetable fibers are hydrophilic and their high affinity for water may thwart
64 the hydration of matrix [13]. To overcome this competition, some authors propose the
65 pyrolysis [12, 14] or the pre-wetting [15-18] of vegetable particles to retain their
66 original volume (porosity) and so, play a role of water tank during the setting phase of
67 the binder. Collet [13] recommends a pre-wetting of the binder with water prior to its
68 addition to vegetable particles in order to ensure a good hydration of binder and to
69 avoid competition between cement and fibers hydration [19].

70
71 The purposes of this study are to (1) estimate the modeled value of thermal conductivity
72 of vegetable fibers when they reinforce cement matrix and (2) measure the effect of
73 moisture content on vegetable fibers/cement composites thermal properties. To reach
74 these goals, cement composites reinforced by various amounts of sugar cane bagasse
75 fibers ranging from 2 to 8 wt % were considered. Sugar cane bagasse fibers are widely
76 available in Guadeloupe : according to Food Directorate of Agriculture and Forestry
77 from Guadeloupe, the island produces 680000 tons/year of sugar cane mainly used for
78 the sugar and rum industries [20]. Bagasse is the solid lignocellulosic leftover after
79 extraction of juice from the sugar cane stalk and is cheap compared to synthetic fibers
80 [21].

81 In order to achieve the modeling of thermal conductivity of fibers, the first part is
82 dedicated to the study of bagasse fibers / cement composites : measurements of thermal
83 conductivity and physical-chemical characteristics (density, apparent volume and
84 porosity). The thermal conductivity is studied at three different moisture contents. In
85 the second part, a model of thermal conductivity of fibers and composites, in dry and
86 wet states, is applied. The purposes of this work is (1) to propose a way to assess the
87 thermal conductivity of bagasse fibers incorporated in this kind of composites, as very
88 few data's of thermal conductivity of vegetable fibers are available and (2) to compare
89 the (experimental and numerical) behaviors of composites when they are placed in
90 different relative humidity (RH) to establish, if possible, a relation between thermal
91 conductivity of composites and RH. Generally, in the literature, many models make it
92 possible to estimate the thermal conductivity of dry concrete and dry composite
93 materials on the basis of knowing the conductivity of each component and its
94 concentration [22-27]. Several of them are based on the auto-coherent homogenization
95 (HAC) model [25-28]. This model uses the statements of self-consistent field concept
96 and of spherical geometry of inclusions in composites; for examples:

97 - autoclaved aerated concrete for Boutin [29],

- 98 - synthetic foams in continuous medium for Felske [30],
- 99 - wood shaving and concrete for Bederina et al. [25],
- 100 - cement composites containing rubber waste particles by Benazzouk et al.
- 101 [26],
- 102 - hemp concretes by Collet and Pretot [28] ,
- 103 - insulating building materials made from date palm fibers mesh by
- 104 Boukhattem et al. [26].

105 Among them, Felske [30], established equations allowing the estimation of the thermal
106 conductivity of regular hollow spheres particles (synthetic foam), while the other
107 previous authors [25-29] focused on a distribution of spherical particles with different
108 diameter. Although the geometries involved are the same as in our materials, it appears
109 that Felske's special case and critical values are not suitable in this study because Felske
110 assumed that the particles are uniform. Bagasse fibers, being vegetable matter, are not
111 uniform [31] and more, there is no perfect thermal contact between the vegetable
112 matter and the cementitious matrix. Finally, the auto-coherent homogenization
113 equations, as described by [25-29], were chosen because they are well suited to
114 materials with very different pores sizes (such as concrete) [29] and they are currently
115 employed when studying thermal conductivity of concrete.
116 Thus, in this work on vegetable fibers/cement composite materials,

- 117 - a focus has been made on the model already confirmed and largely used in the
- 118 field of cementitious materials containing vegetable matter that is to say the
- 119 HAC model,
- 120 - this HAC model as described by [22-29] has been applied to assess the
- 121 numerical value of thermal conductivity of bagasse fibers/cement composites
- 122 in wet and dry states and it was possible for us to deduce the thermal
- 123 conductivity of sugar cane bagasse fibers in the cement composites.

124 To our knowledge, very few models of thermal conductivity of vegetable fibers / cement
125 composites and even less models of the thermal conductivity of vegetable fibers alone
126 are proposed in the literature [3, 8].

127

128 2. Materials

129 2.1 Sugar cane bagasse fibers

130 Sugar cane bagasse fibers are named NBF and were collected from Montebello distillery
131 (Petit-Bourg, Guadeloupe, FWI). Fibers were crushed with a knife mill (Restch, France)
132 and sieved in the laboratory to obtain final length varying from 1 to 10 mm and width
133 between 0.4 and 1 mm. The sugar cane bagasse fibers chemical composition has already
134 been determined [32] and is summarized in Table 1.

135

136 2.2 Binder

137 The binder was a white Portland cement CEM I 52.5 N manufactured by Axton society.
138 This Portland cement CEM I 52.5N complies with European standard EN 197-1 [33]. Its
139 chemical composition and some of its physical characteristics are presented in Table 2.

140

141 2.3 Composites formulations and preparation

142 A reference sample (i.e. without any fibers) has been prepared. It is named L.
143 Composites were made by mixing each type of binder with various amounts of sugar
144 cane bagasse fibers. Formulations of composites, named LFN, are presented in Table 3.
145 All composites were prepared according to the mixing sequence indicated in Table 4 and
146 tap water was used.
147 The obtained pastes were casted in normalized molds of dimensions 40*40*160 mm³.
148 According to EN 196-1 standard [34], a compaction (10 strokes by step – 2 steps) with a
149 shaking table was applied to each sample. Then the isotropic samples, with a random
150 repartition of fibers in the binder, were removed from the mold and left for curing
151 during 28 days in a climatic chamber (25°C, RH = 70%).

152 153 3. Methods

154 155 3.1 Bulk dry density, apparent volume and porosity measurements of composites

156 The bulk dry density ρ_A was deduced from the dry mass and apparent volume of
157 samples. To determine the dry mass, samples were placed in an oven at 105°C (+/- 1°C).
158 The dry state was reached once the mass of each sample was stabilized.
159 The apparent volume of each sample was measured by using a sliding caliper (accuracy
160 of +/- 0.01 mm). Each mean dimension is calculated from an average of three
161 measurements.

162 Composites true density ρ_V has been measured using helium gas intrusion under helium
163 gas flow with a “Pycnomatic” Thermo Electron Corporation equipment (France)
164 pycnometer. Five measurements were conducted for each composite at 298 K, relative
165 humidity of 70–80%. The open porosity η is deduced from bulk dry and true densities
166 using equation (1):

$$167 \quad \eta = 1 - \frac{\rho_A}{\rho_V} \quad \text{equation 1}$$

168 where ρ_A is bulk dry density, ρ_V is true density of samples and η is open porosity.

169 170 3.2 Thermal conductivity testing

171 The tests were performed with a C-therm TCi unit (Setaram, France). The C-Therm TCi
172 employs the Modified Transient Plane Source (MTPS) technique. The one-sided,
173 interfacial heat reflectance sensor applies a momentary constant heat source to the
174 sample. A known current is applied to the sensor’s spiral heating element, providing a
175 small amount of heat. The sensor’s guard ring is fired simultaneously supporting a one-
176 dimensional heat exchange between the primary sensor coil and the sample. The
177 current applied to the coil results in a rise in temperature at the interface between the
178 sensor and sample, which induces a change in the voltage drop of the sensor element.
179 The increase in temperature is monitored with the sensor’s voltage and is used to
180 determine the thermo-physical properties of the sample. The thermal conductivity is
181 inversely proportional to the rate of increase in the sensor voltage (or temperature
182 increase). Thermal conductivity is measured directly [35].

183 For precise measurement of thermal conductivity, samples are first polished using a
184 rotate polishing machine with sandpaper (Dremel, USA). Three levels of moisture are
185 evaluated: 0%, 56% and saturated state 100% of relative humidity. We choose 56% RH
186 as an intermediate value in relative humidity because, in real conditions, cement
187 composites do not reach dry-oven or saturated conditions. The dry state (0% RH) is
188 obtained by drying the material in an oven at 105°C (+/- 1°C) and then placing it in a

189 desiccator until the time of testing. To measure the thermal conductivity at 56 % RH,
190 samples are placed in a desiccator whose humidity is controlled using saturated saline
191 solutions of sodium bicarbonate. Local measurements are made on the lateral and
192 transverse sides of samples and an average value is calculated. To ensure that the
193 moisture content has not changed, samples are weighed before and after measurement.

194

195 3.3 Modeling of thermal conductivity of composites by auto-coherent homogenization

196 The auto-coherent homogenization is used in order to model the thermal conductivity of
197 bagasse fibers / cement composites. This method was initially developed for the
198 mechanical characterization of composites materials [25-26] and was then extended to
199 electrostatic, magnetostatic, electric conduction and thermal properties, which are
200 mathematically analogous [18, 28]. The principle of the method is that the
201 heterogeneous material is assimilated to an equivalent homogeneous material, which
202 must be characterized (knowledge of the conductivity of each component and its
203 concentration). Thus, a transition of micro-scale (components) to macroscopic scale
204 (material) allows to express overall thermal conductivity in terms of characteristics of
205 each component (conductivity, volume concentration).

206

207 3.3.1 Dry state

208 The auto-coherent homogenization is well described by Collet and Pretot [28]. Briefly,
209 the dried material is considered as an assembly of spherical inclusions of various sizes.
210 In the case of material with two-components, it is meant to be a sphere of radius R_a and
211 thermal conductivity λ_a (component "a" is the air contained within the vegetable fibers)
212 surrounded by a concentric shell of component "s" (s is the fiber block) of thermal
213 conductivity λ_s and radius R_s . λ_d is the thermal conductivity of the equivalent
214 homogeneous material also called effective conductivity (Figure 1).

215 The expression of effective conductivity λ_d (equation 2) is obtained by assuming that the
216 energy contained in the heterogeneous medium is equivalent to that of the
217 homogeneous medium under the same boundary conditions [26, 28].

218

$$219 \quad \lambda_d = \lambda_s = \left[1 + \frac{\varepsilon}{\frac{1-\varepsilon}{3} + \frac{1}{\lambda_a/\lambda_s - 1}} \right]; \quad \varepsilon = \left(\frac{R_a}{R_s} \right)^3 \quad \text{equation 2}$$

220

221 where ε is the volume concentration of air phase: it is assumed that the concentration of

unconnected phase is equal to the ratio of external and internal pores [29].

222 According to Boutin [29], this assumption is only satisfied if the material consists of an
223 assembly of composites spheres of variable sizes. Collet and Pretot [28] made this same
224 assumption in case of hemp concrete composites, which are close to bagasse
225 cementitious composites of this study.

226

227 We assume that the fibers / dry binder composite is a three components material. In
 228 that case, the tri-composite inclusion method is used for the modeling of thermal
 229 conductivity assuming that a spherical air bubble “a” is surrounded by a concentric
 230 vegetable particles shell “f” itself surrounded by a binder shell “s” (Figure 2).

231 This type of wildcard inclusion is based on three assumptions:

- 232 - the binder consists of cement and microscopic air bubbles trapped in closed-
 233 pores;
- 234 - the vegetable particles consist of plant part and intra-particle air;
- 235 - the air bubble is the microscopic and macroscopic air contained in open pores of
 236 material.

237 The expression of thermal conductivity of vegetable fibers / cement composites is
 238 therefore given by equation 3.

239

$$\lambda = \lambda_s \left[1 + \frac{\theta}{\frac{1-\theta}{3} + \frac{1 + \frac{\delta}{3} \left(\frac{\lambda_a - 1}{\lambda_f} \right)}{\frac{\lambda_a - 1}{\lambda_s} - \frac{\delta}{3} \left(\frac{\lambda_a - 1}{\lambda_f} \right) \left(\frac{2\lambda_f}{\lambda_s} + 1 \right)}} \right]$$

equation 3

240

241 where $\theta = 1 - \frac{1}{k+1} \left(\frac{\rho}{\rho_s} \right)$, $\delta = \frac{\rho}{\rho_f} \frac{k}{k+1} \frac{1}{1 - \frac{\rho}{\rho_s} \frac{1}{k+1}}$ and $k = m_f / m_s$

242 θ and δ are concentrations directly calculated from the mass m of each component (of
 243 known density ρ). This definition of k is based on the assumption that the change of
 244 properties between powdered cement and dry hydrated cement (i.e. hydrated cement at
 245 0%RH) does not cause a significant variation in the thermal conductivity of composite
 246 [15]. For each formulation, the characteristic parameter k is calculated as the ratio
 247 between the mass of bagasse fibers and the mass of powdered cement [25].
 248

249 3.3.2 Wet state

250 The modeling process of wet composite involves two steps:

- 251 - the first step allows creating homogeneous medium “sf” of vegetable particles “f”
 252 and hydrated binder “s” at 0% RH,
- 253 - in the second step, the homogeneous medium “sf” is included in a tri-composite
 254 (air, water, “sf”) model to obtain the final homogenized wet composite. The
 255 vegetable fibers “f” and dry binder “s” are therefore considered as a
 256 homogeneous medium “sf” and not as two separated phases (Figure 3).

257 Equation 4 gives the expression of equivalent conductivity of “sf” composite as a
 258 function of conductivity of each component (fibers and hydrated binder at 0% RH). The
 259 parameter ε' is used to evaluate the volume concentration of fibers in the binder.

$$\lambda_{sf} = \lambda_s \left[1 + \frac{\varepsilon'}{\frac{1-\varepsilon'}{3} + \frac{1}{\lambda_f/\lambda_s - 1}} \right] ; \quad \varepsilon' = \left(R_f / R_s \right)^3 = \frac{1}{1 + k \frac{\rho_f}{\rho_s}} \quad \text{equation 4}$$

261 where λ is for the thermal conductivity, k is the ratio of mass (as defined in equation 3)
 262 and ρ is the density.

263 In the second step, the tri-composite inclusions model allows expressing the
 264 conductivity of composite in wet states (equation 5).

$$\lambda_H = \lambda_{sf} \left[1 + \frac{\theta}{\frac{1-\theta}{3} + \frac{1 + \frac{\delta}{3} \left(\frac{\lambda_a}{\lambda_w} - 1 \right)}{\frac{\lambda_a}{\lambda_w} - 1 - \frac{\delta}{3} \left(\frac{\lambda_a}{\lambda_w} - 1 \right) \left(2 \frac{\lambda_w}{\lambda_{sf}} + 1 \right)}} \right] \quad \text{equation 5}$$

$$k_1 = \frac{m_w}{m_s + m_f}, \quad \theta = \left(\frac{R_w}{R_{sf}} \right)^3 = 1 - \frac{1}{1 + k_1} \frac{\rho_h}{\rho_{sf}} \quad \text{and} \quad \delta = k_1 \frac{\rho_{sf}}{\rho_w} \left(\frac{1}{1 - \frac{\rho_H}{\rho_{sf}} \frac{1}{k_1 + 1}} - 1 \right)$$

267 λ is for the thermal conductivity, k is the ratio of mass of water (w) related mass of
 268 cement (s) + mass of fibers (f).

269 θ and δ are concentrations directly calculated from the mass m of each component (of
 270 known density ρ)

271

272 4. Results and discussion

273 In order to estimate thermal conductivity of vegetable fibers, some properties of
 274 composites are required: physical properties (bulk dry density, open porosity) and
 275 thermal conductivity.

276

277 4.1 Bulk density and open porosity of composites at 0% RH

278 Figure 4 reports the variation of bulk density as a function of the fiber contents for LFN
 279 composites in the dry state. As expected, the more the fiber content, the lower the bulk
 280 density is [36]. The first significant decrease is obvious: it corresponds to the addition of
 281 2% by weight of bagasse fibers, which are a lightweight material. Between 2 and 4% by
 282 weight of fibers, there is a light decrease. After 4 wt%, bulk density decreased at a
 283 relatively constant rate with increased fiber content as observed by [37].

284 Figure 5 presents the evolution of LFN composites porosity according to their fiber
 285 content in the dry state.

286 Porosity of material is gradually increasing with the amount of bagasse fibers. This
 287 increase with addition of fibers is explained by the formation of air voids in the
 288 microstructure of paste (due to the presence of fibers which are porous) and the voids
 289 content becomes high as fiber volume fraction increases [36]. Moreover, short fibers, as
 290 used in this study, are considered to be more difficult to align and pack densely. The

291 packing of short fibers in cement paste leads to increase the amount of voids [10] and
292 therefore porosity.

293

294 4.2 Thermal conductivity of composites

295 4.2.1 Experimental thermal conductivity

296 4.2.1.1 Dry state

297 Figure 6 illustrates the evolution of thermal conductivity of LFN composites according to
298 fiber content at 0% of relative humidity. According to Demirboga [38], thermal
299 conductivity of Portland cement type I is (1.230 +/- 0.050) W/m.K.

300 The purpose of including vegetable fibers in cement is to develop a more insulating
301 material than cement in order to use it as an interior partition or an interior insulating
302 coating in the housing, for examples. It would help to prohibit the leaking of heat on
303 both sides of the partitions [36]. First, as expected, the thermal conductivity of Portland
304 cement is strongly decreased (by a factor of around 2) by introducing 2 wt % of
305 vegetable fibers. Then, thermal conductivity of cement samples decreases slightly when
306 increasing fiber content [10, 27, 36]. This decrease follows a logarithmic evolution.
307 According to [3], thermal conductivity of treated bagasse fibers is lower than that of
308 cement paste, so we assume it's the same for raw bagasse fibers: its thermal
309 conductivity is lower than that of cement. Consequently, this decrease is expected with
310 law of mixture. Moreover, thermal conductivity is inversely proportional to the voids in
311 composites [10, 39] and as shown by Figure 5, porosity of samples increases with the
312 fiber content. Based on these results, the linear relation between the thermal
313 conductivity k of bagasse composites and bulk density ρ is:

$$314 \quad k = 0.0005\rho - 0.0924 \quad (R^2 = 0.78267) \quad \text{equation 6}$$

315 where k is thermal conductivity and ρ bulk density.

316 Equation 6 is consistent with classical equations applied to evaluate thermal
317 conductivity of insulating materials used in the field of construction [39].

318

319 4.2.1.2 Sensitivity of thermal conductivity to moisture content

320 Thermal conductivity was also studied for the same composites at 56% and 100% of
321 relative humidity (saturated state).

322 Fibrous media are known to often have a geometric anisotropy linked (1) to the
323 anisotropy of the fibers themselves and (2) to their orientation within the material. In
324 the case of vegetable fibers, an anisotropy of the thermal properties appears locally, as
325 the tensor of conductivity of fibers is generally orthotropic [38]. We assume that the
326 thermal conductivity of studied composites is isotropic because fibers are randomly
327 oriented and properties of short fibers (in this study, length varying from 1 to 10 mm
328 and width between 0.4 and 1 mm) composites are isotropic [41].

329 Figure 7 presents the thermal conductivity of samples according to their bulk density for
330 different moisture contents.

331 The more the percentage of pores, the lighter the specimen are and the lower their
332 thermal conductivities are as observed by others [10]. That is to say that the lighter a
333 material is and the better is its insulating power. The thermal conductivity of the
334 composites in saturated conditions is greater than in the dry state [27]. This fact is
335 explained by the thermal conductivity of water, which is 25 times higher than air [42];

336 the presence of air will alter the overall thermal conductivity of the material by
337 decreasing it. The composite subjected to a relative humidity of 56% exhibited a mass
338 gain of 4 to 8% (in comparison with dry state), which involves the increase from 15 to
339 50% of the thermal conductivity of materials. For moisture contents close to saturation,
340 the thermal conductivity of the composite increases by around 100 % of its value in the
341 dry state. These results are in accordance with those exhibited by Asadi et al. [39].

342

343 4.2.2 Numerical thermal conductivity

344 4.2.2.1 Dry state

345 Firstly, by knowing the thermal conductivity of pure hardened cement paste, λ_d and its
346 porosity measured with helium pycnometer, we can calculate the conductivity of solid
347 particles λ_s using equation 2. The value of λ_s is 1.125 W/m.K.

348 To estimate thermal conductivity of fibers, the auto-coherent method applied to three
349 phases medium (equation 3) is used in combination with least squares method of
350 minimization. The mean square deviation between experimental and numerical thermal
351 conductivities of dry composites is minimized and bagasse fibers thermal conductivity is
352 estimated. Its average value is about 0.110 W/m.K. This value is consistent with the
353 values estimated by Onésippe et al. [3] for treated bagasse fibers.

354 Figure 8 shows that the theoretical values calculated using equation 3 are consistent
355 with the experimental measurements in the case of dry composites, whatever the bulk
356 density. A gap of less than 10% is obtained.

357

358 4.2.2.2. Wet state (100% RH)

359 As with the previous model, a comparison of the results is made in the case of wet
360 composites (56% RH, Figure 9 and 100% RH, Figure 10). For 56% RH, there is a good
361 agreement between numerical and experimental values in low fibers contents (approx.
362 less than 4 wt%), which correspond to bulk densities greater than 1360 kg/m³. Below
363 this value, it seems that the model underestimates thermal conductivity of composites
364 by about 10 to 20%. This underestimation reaches nearly 30% at saturated state (100%
365 RH), whatever the bulk density, as shown by Figure 10. The model used for numerical
366 calculation considered the shape of the aggregates to be spherical. This underestimation
367 may be due to the geometrical distribution of void phase that is to say distribution of
368 pore structure. This difference can also be explained by conduction phenomenon due to
369 free water or entrapped water that implies the use of a more complex modeling to
370 explain the behavior. Moreover, the experimental conductivity is the average of local
371 measurements that depend on surface conditions, orientation of fibers and compacting
372 direction. In addition, polishing of samples with high fiber content is difficult and can
373 cause local differences in thickness.

374 The thermal conductivity calculated by the model seems to be little sensitive to changes
375 induced by the generic water cell. This little sensitivity is explained by low volume of
376 water adsorbed in this range of humidity.

377

378 5. Perspectives

379 Generally, in Guadeloupe, the relative humidity of the air varies between 70% and 80%
380 [42], that is to say that the thermal conductivity of composites would be greater than in
381 the dry state. The composites of this study cannot be considered as insulating materials
382 for our climatic conditions. In order to decrease their thermal conductivity, we

383 considered treatment of bagasse fibers before incorporating them into Portland cement.
384 We choose to analyze the effect of pyrolysis treatment on sorption/desorption
385 behaviors of the bagasse fibers. The sorption isotherm of natural bagasse fibers NBF is
386 compared to that of pyrolyzed fibers, TBF which are prepared under controlled inert
387 atmosphere (N₂ flow, 2 L/h) during 2 h at 240°C [43]. It is obtained experimentally by
388 assessing the moisture content of the product in equilibrium with different air relative
389 humidity at an average temperature of (22±3) °C. Relative humidity is controlled by
390 saturated saline solutions according to ISO-12571 norm [44]. The moisture content w is
391 deduced using the equation 7:

392
$$w = \frac{m - m_0}{m_0} \quad \text{equation 7}$$

393 Where m and m_0 are the mass of the sample in respectively steady state conditions and
394 initial dry state.

395 In Figure 11, the isotherms present a S-shape corresponding to the type IV of the Rogers
396 classification. This behavior is frequently observed in cellulose-based materials [45]. We
397 can see that pyrolyzed bagasse fibers are less hygroscopic than natural bagasse fibers,
398 particularly at high relative humidity (decrease of 30% of its sorption capacity). Indeed,
399 hemicellulose degradation during pyrolysis (between 160 and 260°C) [32] makes the
400 TBF less sensitive to moisture; generally, they become more hydrophobic [3]. This last
401 point encourages us to develop pyrolyzed bagasse fiber / cement composites. As
402 mentioned by Collet and Pretot [28], thermal conductivity of hygroscopic materials
403 increases with moisture content. The pyrolyzed fibers being more hydrophobic [3] than
404 the raw fibers, they would generate less moisture in the composites that is to say that
405 the ratio air/water will be increased. As thermal conductivity of air is lower than that of
406 water [35], the resulting composites would have lower thermal conductivities (if we
407 consider a simple law of mixture) than the LFN and would allow our materials to be
408 considered as insulating materials in the field of construction.

409

410 6. Conclusions

411 A theoretical modeling based on auto-coherent homogenization is proposed to estimate
412 the thermal conductivity of bagasse fibers, that is a novelty. The model is also used to
413 estimate the conductivity of fibers and cement and then the conductivity of composites
414 under both dry (good fitting with the model) and wet conditions.

415 The bagasse fibers / cement composites materials present low thermal conductivity.
416 The study shows that the thermal conductivity of such composites depends both on
417 fibers / cement ratio (bulk density) and moisture content. The best insulating properties
418 are obtained with an untreated bagasse fiber content around 8 % wt.

419 Further investigations on pores size and distribution are required in order to improve
420 the accuracy of the model in wet conditions.

421 We explore the isotherm sorption of pyrolyzed bagasse fibers. These data confirm that
422 the pyrolysis allows obtaining more hydrophobic fibers, which once included in cement,
423 would provide more insulating materials for building applications.

424

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430 l'habitation et la construction" (n° ANR-12-IS09-0002-01).

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432
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580

581 **Figures caption**

582

583 Figure 1: Auto-coherent method applied to two-phase medium - geometry of an
584 elementary inclusion composite

585 Where R_a and thermal conductivity λ_a (component “a” is the air contained within the
586 vegetable fibers) surrounded by a concentric shell of component “s” (s is the fiber block)
587 of thermal conductivity λ_s and radius R_s , λ_a is the thermal conductivity of the equivalent
588 homogeneous material also called effective conductivity

589

590 Figure 2: Auto-coherent method applied to three-phase medium - geometry of an
591 elementary inclusion composite

592 Where a spherical air bubble “a” is surrounded by a concentric vegetable particles shell
593 “f” itself surrounded by a binder shell “s”

594

595 Figure 3 : Double homogenization of auto-coherent model (binder+ vegetable particles)
596 Where a is for air, w is for water and H for hydrated composite

597

598 Figure 4 : Bulk density of composites according to their fiber content in the dry state
599 (RH = 0%)

600

601 Figure 5 : Porosity of composites according to their fiber content in the dry state (RH =
602 0%)

603

604 Figure 6 : Experimental thermal conductivity of LFN composites according to their fiber
605 content in the dry state (RH = 0%)

606

607 Figure 7 : Experimental thermal conductivity of LFN composites according to their bulk
608 density at different moisture contents

609

610 Figure 8 : Comparison between numerical calculations and experimental results of
611 composites thermal conductivity in the dry state according to bulk density

612

613 Figure 9 : Thermal conductivity varying with bulk density: comparison between
614 numerical calculations and experimental results in the wet state (RH=56%)

615

616 Figure 10: Thermal conductivity varying with bulk density: comparison between
617 numerical calculations and experimental results in the wet state (RH=100%)

618

619 Figure 11 : Isotherm sorption of natural (NBF) and pyrolyzed bagasse fibers (TBF) at
620 (22±3)°C. In red: sorption; in green: desorption.

621

622

623 Table 1: Botanical composition of raw sugar cane bagasse fibers (NBF) [29].

624

Cellulose	Hemicellulose	Lignin	Extractives	Humidity	Sum (except humidity)
wt %	wt %	wt %	wt %	wt %	wt %
48.68	25.46	21.94	3.92	7.50	100

625

626

627 Table 2: Chemical composition and some physical characteristics of CEM I 52,5 N [5].

628

Content wt %						
SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO
21.45	0.22	4.08	65.05	0.06	0.20	0.49
Loss on ignition (wt %)						
1.45						
Bulk density (g/cm³)						
3.08						
Median particle size (µm)						
15.70						
Specific area (cm²/g)						
4200						

629

630

631 Table 3 : Formulations of LFN composites.

632

Composites	Binder	NBF/binder ratio (by mass)	Water/binder ratio (by mass)	Mass (g) relative to 1000 g of cement paste		
				NBF	CEM I	Water
L (without fibers)	1	0	0.4	0	704	296
LFN1	1	0.02	0.60	12.3	617.3	370.4
LFN2	1	0.03	0.60	18.4	613.5	368.1
LFN3	1	0.04	0.60	24.4	609.8	365.8
LFN4	1	0.05	0.60	30.3	606.1	363.6
LFN5	1	0.08	0.60	47.6	595.2	357.2

633

634

635 Table 4 : Mixing sequence of elaboration of composites.

636

Mixing sequence	Time
Adding the pre-wetted binder in the mixing container	0
Mixing the binder at slow speed (140 rpm)	30 s
Adding the rest of the water	30 s
Mixing at high speed (285 rpm)	2 min
Progressive addition of vegetable fibers	2 min
Mixing at high speed (285 rpm)	5 min

637

Figure 1 : Auto-coherent method applied to two-phase medium - geometry of an elementary inclusion composite

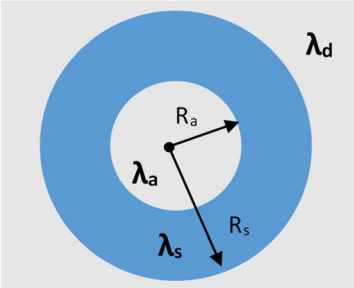


Figure 2 : Auto-coherent method applied to three-phase medium - geometry of an elementary inclusion composite

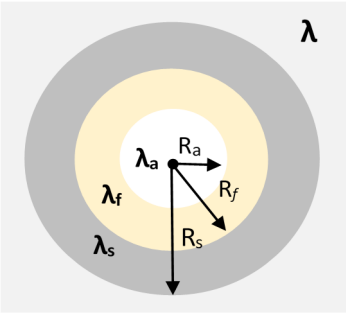


Figure 3 : Double homogenization of auto-coherent model (binder+ vegetable particles)

where a is for air, w is for water and H for hydrated composite

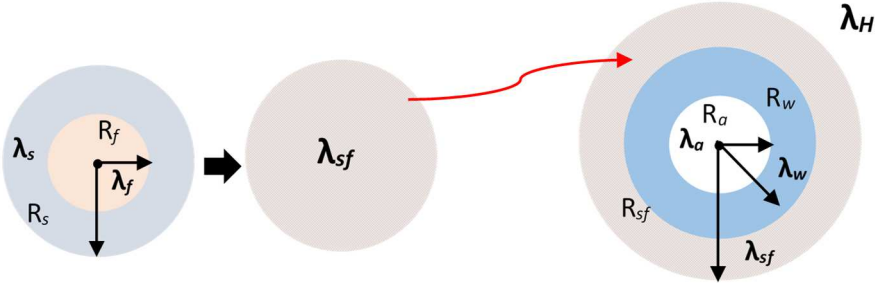


Figure 4 : Bulk density of composites according fiber content in the dry state (RH = 0%)

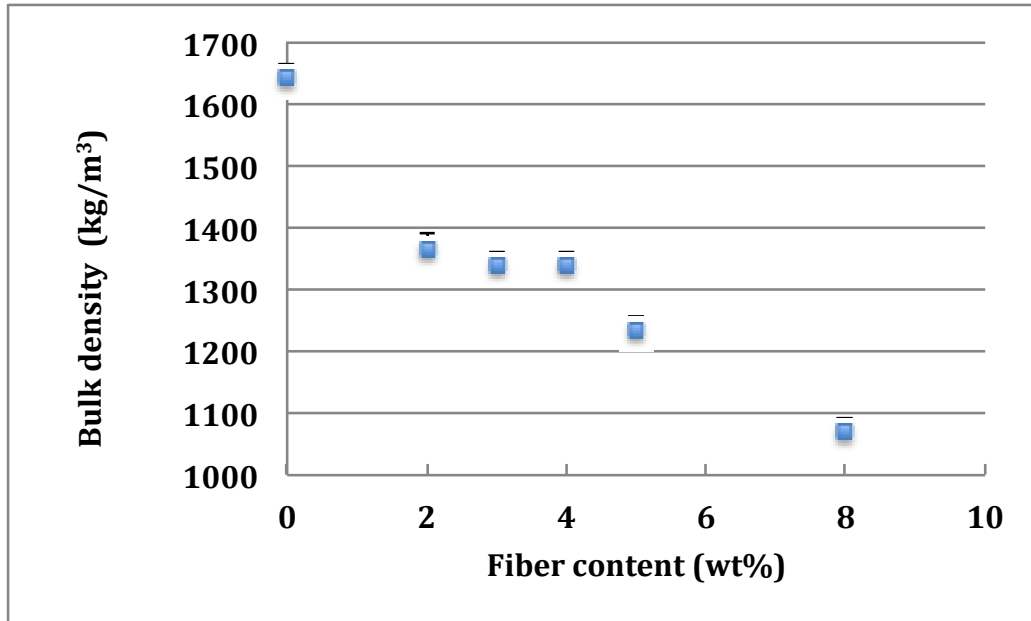


Figure 5 : Porosity of composites according to their fiber content in the dry state (RH = 0%)

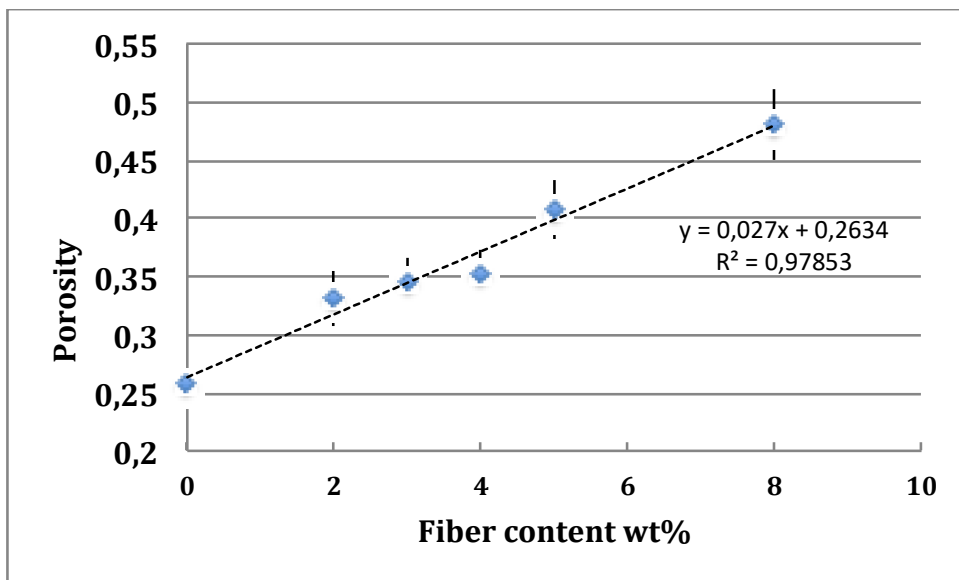


Figure 6 : Thermal conductivity of LFN composites according to fiber content

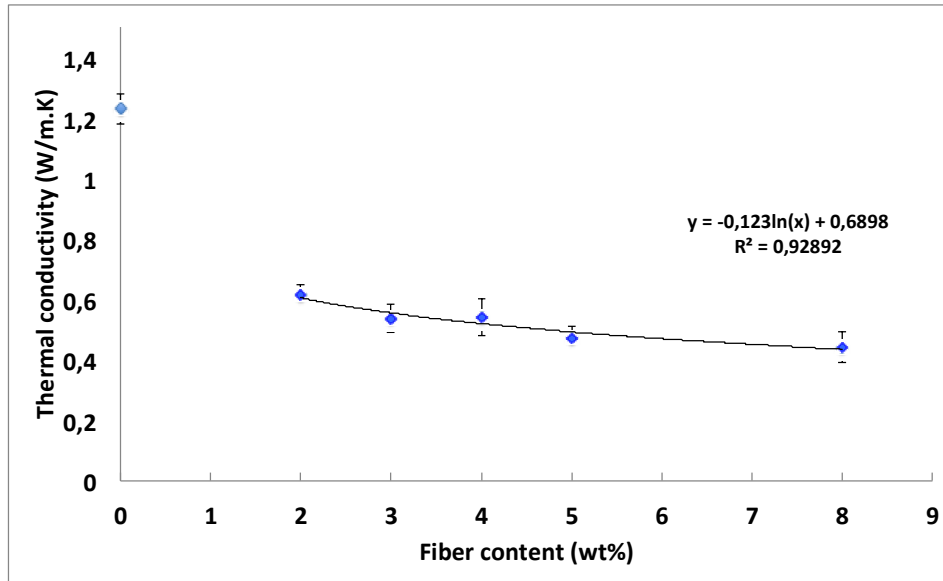


Figure 7: Thermal conductivity of LFN composites according to their bulk density at different moisture contents

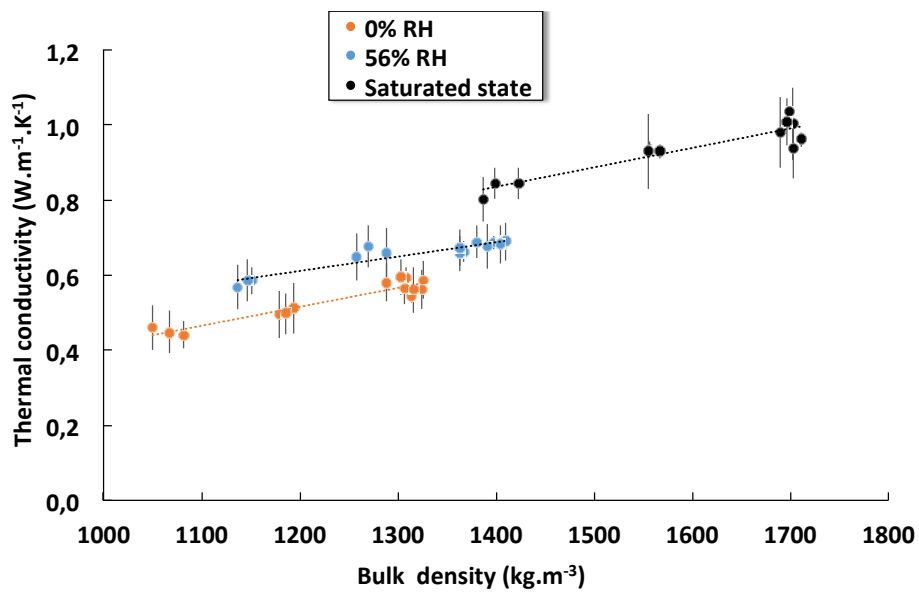


Figure 8: Comparison between theoretical calculations and experimental results of thermal conductivity of dry composites according to bulk density

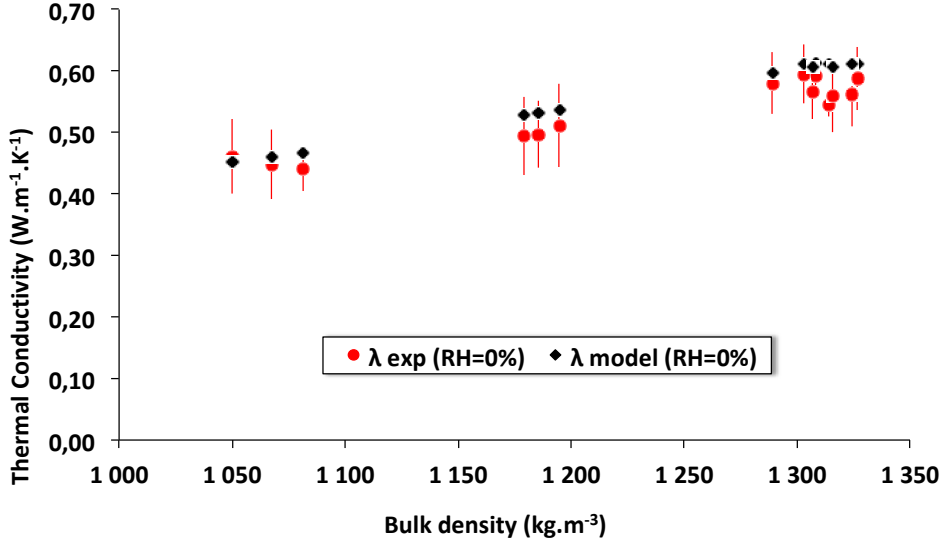


Figure 9: Thermal conductivity varying with bulk density: comparison between theoretical calculations and experimental results (RH=56%)

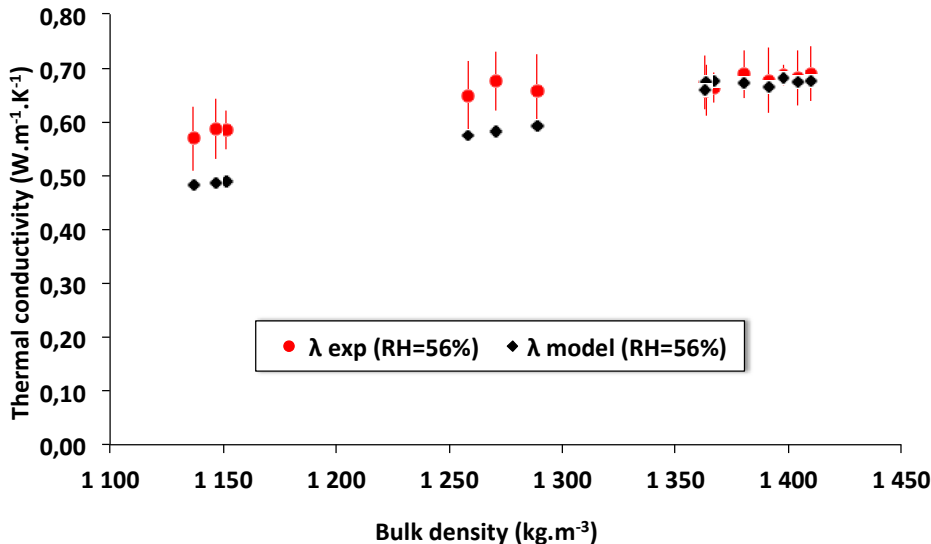


Figure 10: Thermal conductivity varying with bulk density: comparison between theoretical calculations and experimental results (RH=100%)

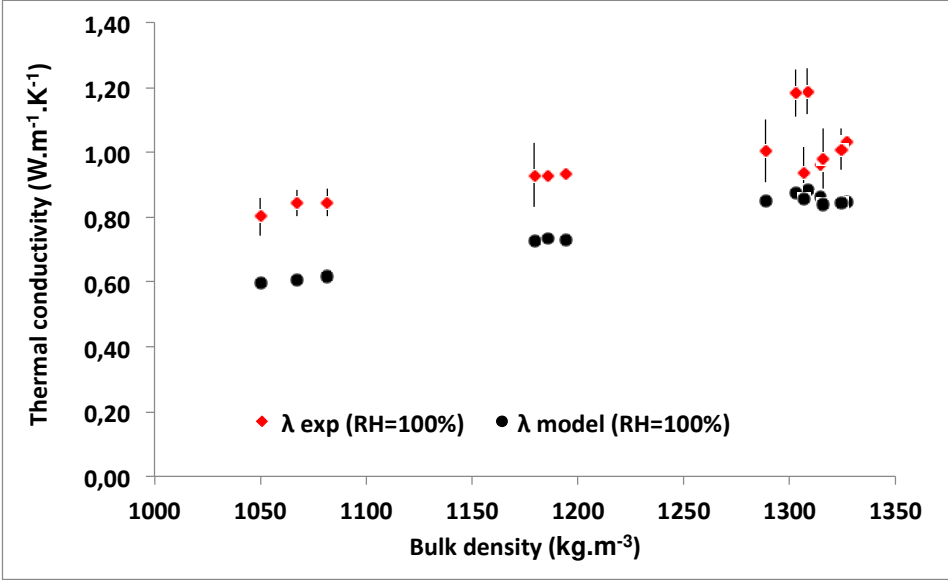


Figure 11 : Sorption isotherms of natural (NBF) and pyrolyzed (TBF) bagasse fibers at (22±3)°C. In red: sorption; in green: desorption.

