

Thermal and mechanical properties of hardened cement paste reinforced with Posidonia-Oceanica natural fibers

Ons Hamdaoui, Oualid Limam, Laurent Ibos, Atef Mazioud

▶ To cite this version:

Ons Hamdaoui, Oualid Limam, Laurent Ibos, Atef Mazioud. Thermal and mechanical properties of hardened cement paste reinforced with Posidonia-Oceanica natural fibers. Construction and Building Materials, 2021, 269, pp.121339 -. 10.1016/j.conbuildmat.2020.121339 . hal-03492950

HAL Id: hal-03492950 https://hal.science/hal-03492950

Submitted on 2 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Thermal and mechanical properties of hardened cement paste reinforced with *Posidonia-Oceanica* natural fibers

3

4

5 Ons HAMDAOUI¹, Oualid LIMAM², Laurent IBOS¹, Atef MAZIOUD¹

6

7 ¹ University of Paris Est Créteil, CERTES, OSU Efluve, 61 av. du Général de Gaulle,
8 94010 Créteil Cedex, France

9 ² University of Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis, Laboratoire de Génie
10 Civil, BP 37, 1002 Tunis, Tunisia

11

12 Abstract

13 This paper focuses on thermal and mechanical properties of a hardened cement paste 14 reinforced with Posidonia-Oceanica fibers. Fibers volume fractions are varied from 0% to 20%. Thermophysical and mechanical properties are measured. Simplified models are 15 16 developed to predict thermal conductivity, tensile and compressive stresses and fracture 17 toughness variation as a function of fibers volume fraction and geometrical characteristics of 18 samples. Results showed that the addition of Posidonia-Oceanica fibers improved the material insulating properties. In fact, a decrease of about 22% (from 0.0718 W.m⁻¹.K⁻¹ to 19 0.559 W.m⁻¹.K⁻¹) of thermal conductivity was found with adding 20% of fibers compared to 20 21 control cement paste.

22 Concerning mechanical properties, flexural and compressive strengths increased for fiber 23 volume fractions in the range of 5 to 10% and then decreased for higher fiber volume 24 fractions. It was shown through a simplified model and MEB observations that agglomeration 25 of fibers for high volume fraction is behind this phenomenon. Moreover, a noticeable increase 26 of toughness was observed with increasing fibers amount: for instance, an increase of about

27	65% (from 0.245 MPa.m ^{$1/2$} to 0.404 MPa.m ^{$1/2$}) was observed with the introduction of 20% of							
28	fibers in the composite. Simplified analytical models are also developed to predict thermal							
29	conductivity, tensile and compressive strengths and fracture toughness. These models are							
30	validated with experimental data.							
31								
32	Key words: natural fibers, composite, experimental measurement, models, thermal							
33	properties, mechanical properties.							
34								
35	Nomenclature							
36	- <i>b</i> : width of the mechanical test sample, mm							
37	- w: depth of the mechanical test sample, mm							
38	- L: span of the mechanical test sample, mm							
39	- A: compressive test sample are, mm^2							
40	- <i>a</i> : notch length, mm							
41	- $\boldsymbol{\beta}$: ratio between <i>a</i> and <i>w</i>							
42	- F_f : load required for failure in flexural test, kN							
43	- F_c : load required for failure in compressive test, kN							
44	- P_f : load required for failure in flexural test for pre-notched sample, kN							
45	k: thermal conductivity, W.m ⁻¹ .K ⁻¹							
46	- k_H : homogenized composite thermal conductivity, W.m ⁻¹ .K ⁻¹							
47	k_m : matrix thermal conductivity, W.m ⁻¹ .K ⁻¹							

48	-	k_{f} fibers thermal conductivity, W.m ⁻¹ .K ⁻¹
49	-	k_{hl} : thermal conductivity in the volume V_2 , W.m ⁻¹ .K ⁻¹
50	-	k_{h2} : thermal conductivity in the volume V_3 , en W.m ⁻¹ .K ⁻¹
51	-	<i>k</i> _{inf} : lower thermal conductivity of the first order model, W.m ⁻¹ .K ⁻¹
52	-	k_{sup} : upper thermal conductivity of the first order model, en W.m ⁻¹ .K ⁻¹
53	-	α : thermal diffusivity, m ² .s ⁻¹
54	-	ρ : density, en kg.m ⁻³
55	-	ρ_{H} : homogenized composite density, kg.m ⁻³
56	-	ρ_{f} : fibers density, kg.m ⁻³
57	-	ρ_m : matrix density, en kg.m ⁻³
58	-	φ : fibers volume fraction, %
59	-	φ_m : matrix volume fraction, %
60	-	φ_{pl} : 'parallel' fibers volume fraction relatively to heat flux in the volume V_l , %
61	-	φ'_{pl} : 'parallel' fibers volume fraction relatively to heat flux in the volume V_2 , %
62	-	φ_{sl} : 'series' fibers volume fraction relatively to heat flux in the volume V_2 , %
63	-	<i>d</i> : fibers effective diameter, mm
64	-	d_0 : fibers mean diameter, mm
65	-	d_0 : fibers equivalent diameter, mm
66	-	<i>l</i> : mean length of fibers, mm

67	-	D_1 : Horizontal distance between fibers, mm
68	-	D_2 : Vertical distance between fibers, mm
69	-	S: RVE area of dimensions $(d + D_2)^2$, mm ²
70	-	ε : ratio between D_l and l
71	-	γ : ratio between D_1 and D_2
72	-	δ : ratio between 1 and d ₀
73	-	$\sigma_{traction}$: tensile strength obtained by flexural test, MPa
74	-	$\sigma_{traction, c}$: composite tensile strength obtained by flexural test, MPa
75	-	$\sigma_{traction, T}$: direct composite tensile strength, MPa
76	-	$\sigma_{compression, c}$: compressive strength, MPa
77	-	$\sigma_{compression, c}$: composite compressive strength, MPa
78	-	$\sigma_{traction, m}$: matrix tensile strength obtained by flexural test, MPa
79	-	τ : interface shear strength, MPa
80	-	K_c : fracture toughness, MPa.m ^{1/2}
81	-	<i>G_c</i> : composite fracture energy, MPa.m
82	-	<i>G_m</i> : matrix fracture energy, MPa.m
83	-	G': fracture energy of the volume containing the fiber and the matrix, MPa.m
84	-	<i>E_c</i> : composite Young's modulus, MPa
85	-	<i>E_m</i> : matrix Young's modulus, MPa

- *E_f*: fibers Young's modulus, MPa

87

88 **1. Introduction**

The use of natural fibers in construction materials is not recent. Over the decades and with countries industrialization, industrial materials have been developed and replaced traditional materials. However, with incentives to integrate sustainable development projects, there is a return to old materials and practices based on scientific researches.

In this context, the use of natural fibers in cement-based building materials has been a subject
of interest of several studies such as [1-9].

A bibliographic synthesis of the formulation of cementitious composites with natural fibers ofthese articles is conducted and presented in table 1.

97 It is well known that the incorporation of natural fibers in a cement matrix influences the 98 density and thermal conductivity. Usually, there is a decrease of thermal conductivity and 99 density values with the increase of fibers fraction [10-15]. However, Wongsa *et al.* [9] 100 showed that there is no significant impact of fibers amount on studied composites thermal 101 conductivity. In fact, fibers volume fraction in this work did not exceed 1%.

102 Cementitious composites have relatively good compressive strength and weak tensile 103 strength. The reinforcement of cementitious matrices with fibers allows the improvement of 104 tensile strength, fracture toughness, material ductility and bridge the developed cracks 105 [13,16,17,18]. Typically, the presence of fibers in composites does not improve the resistance 106 to crack apparition, it influences the post-cracking behavior [19,20]. The strength increase is 107 usually a few percent, but the toughness is highly increased.

108 The present research is focused on studying the effect the reinforcement of a cement paste 109 with *Posidonia Oceanica* natural fibers. *Posidonia-Oceanica* is an aquatic Mediterranean

110 plant from the *Posidoniaceae* family. In autumn, leaves and balls of *Posidonia-Oceanica* are

111 accumulated in beaches with various fragmentations. These debris are frequently eliminated 112 from beaches. Therefore, the valorization of this "waste product" in construction materials 113 seems interesting.

The use of fibers extracted from *Posidonia Oceanica* balls as an insulation material have been studied in our previous work [21]. Results showed that these fibers could be used as a thermal insulation material. Indeed, fibers thermal conductivity is close to the most commonly used thermal insulation materials: thermal conductivity values are lying between 0.04 and 0.07 W.m⁻¹.K⁻¹. However, their heat capacity is significantly higher (about 2500 J.kg⁻¹.K⁻¹) [21].

In this work, the effect of the reinforcement of cement paste with *Posidonia Oceanica* fibersis investigated. Table 1 was used to choose the studied composites formulation.

Allegue *et al.* [5] have studied the effect of the reinforcement of a cement paste with *Posidonia-Oceanica* natural fibers on mechanical compressive and flexural strengths. This reference is used to compare results found in this work concerning mechanical properties. The originality of our paper consists in the study of thermal properties and the proposition of analytical models to predict thermal and mechanical properties.

Thus, the present article is structured in the following way. Section 2 describes samples preparation and characterization methods employed. Section 3 presents and discusses experimental results. Analytical models to predict thermal and mechanical properties and a comparison with experimental data are proposed and discussed in section 4. Section 5 summarizes our major conclusions.

Matrix	Fibers	Water/Cement	Volume	Fibers	Chemical	References
			fraction	length	treatment	
			(%)	(mm)		
Concrete	Sisal	0.57	1% à 5% (mass fraction)	50	None	[1]
Mortar	Sisal	0.4	3%	375	NaOH	[2]
	Coconut			25	CaOH	
Cement paste	Hemp	0.5	0 à 20%	20	None	[3]
Cement paste	Sisal	N/A	1% à 5%	1.66	None	[4]
	Eucalyptus		(mass	0.66		
			fraction)			
Cement paste	Posidonia-	0.5 à 1	0 à 20%	N/A	None	[5]
Cement paste	Flax	1	2%	25	- Rhéomac	[6]
					treated fibers	
					- boiled fibers	
					- Cement	
					coated fibers	
Mortar	Flax	0.5	1% to 3%	16	Plasma	[7]
	Hemp		(mass			
			fraction)			
Mortar	Hemp	0.5	0 to 3%	6 - 12 - 18	None	[8]

			(mass			
			fraction)			
Geopolymer	Sisal	N/A	0%, 0.5%,	3.5 - 4	N/A	[9]
mortar	Coconut		0.75%, and			
			1.0%			

133 **2. Experimental program**

134 **2.1.** Samples preparation and microstructure

The studied composites were made of Portland cement paste CEM I 42.5 R and natural fibers of 1cm of length. Fibers were mechanically extracted from the marine Mediterranean plant *Posidonia-Oceanica* previously washed and dried. The water cement ratio is 0.5. Fibers volume fraction considered are 0, 5%, 10%, 15% and 20%.

Samples of $44 \times 44 \times 10 \text{ mm}^3$ were prepared for thermal tests and samples of $40 \times 40 \times 160 \text{ mm}^3$ for mechanical tests. Pre-notched samples with 8 mm tip width were prepared for fracture test. Three specimens were prepared for each group. All the specimens were demolded after 24h and conserved 28 days in the laboratory with recording of temperature and humidity. The temperature was about $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and the relative humidity was about $50\% \pm 5\%$.

Experimental results are obtained after hydration and results considered are obtained from the average of 3 samples. Thermophysical properties (density, thermal conductivity, thermal diffusivity and heat capacity) and mechanical properties (compressive strength, flexural strength and toughness) are evaluated and discussed.

SEM images of composites observed with JEOL 6301F scanning electron microscope are presented in Figure 1. As it can be seen, fibers of diameter of about 100 µm with a hollow structure are randomly dispersed in the cement paste. Additionally, as shown in Figure 2, some agglomerations of fibers are observed and lead to an additional porosity.



153 Figure 1. SEM images for Posidonia-Oceanica fibers reinforced hardened cement paste ($\varphi = 5\%$)

- 154
- 155

fibers agglomeration



157 Figure 2: SEM images of fibers agglomeration in Posidonia-Oceanica reinforced cement hardened

158

paste ($\varphi = 20\%$)

160 2.2. Methods

161 **2.2.1. Thermal tests**

Thermal properties (thermal conductivity and thermal diffusivity) are measured with the Hot-Disk Transient Plane Source (TPS) method. This method consists in applying a controlled heat flux with a plane probe placed between two samples of the material to be tested. This probe is connected to the TPS device and acts as a heating source and a temperature sensor: the increase of the probe electrical resistance corresponding to the increase of its temperature is recorded.

168 More details concerning this method are available in a previous work [21] and in references 169 [22-25].

In this work a TPS 2500 device is used. A probe (Reference 5465) with a radius of 3.189 mm
is used. A heating power of 80 mW is applied during 20 s.

172 Repeatability measurements of thermal conductivity and thermal diffusivity with the Hot-173 Disk method have been carried out and showed that the standard deviation is about 4% for 174 thermal conductivity measurements and 9% for thermal diffusivity [21]. These values are 175 considered in the results of this study.

176

177 **2.2.2. Mechanical tests**

Mechanical tests are performed according to NF EN 12390 standard [26] and using an Universal Testing Machine FORM+TEST apparatus equipped with a 50 kN load cell. Samples of $40\times40\times160$ mm³ are horizontally placed upon two parallel supporting rollers spaced with 100 mm. A vertical load is applied in the middle of the sample with a constant speed of 50 N.s⁻¹. The load required to break the specimen *F_f* is recorded and the tensile strength obtained by flexural test is calculated as follows:

184
$$\sigma_{traction} = \frac{1.5 \times F_f \times L}{bw^2}$$
(1)

185 b, w are samples width and depth (b = 40 mm, w = 40 mm) and L is the span (L=120 mm). After failure prismatic beams used in flexural test are placed between two $40 \times 40 \text{ mm}^2$ plates 186 until rupture. The compressive strength is calculated from the failure load F_c and the sample 187 188 area A ($A = 40 \text{ x} 40 \text{ mm}^2$). 189 The fracture toughness is determined according to ISO 12135 standard [27]. Pre-notched samples of size $40 \times 40 \times 16$ mm³ are placed in the flexural machine as shown in Figure 3. 190 191 Fracture toughness *Kc* is calculated as follows: 192 $Kc = \frac{LP_f}{hw^{3/2}} f(\beta)$ 193 (2)

194

195 Where: b = 40 mm, w = 40 mm and L = 120 mm.

196 *a* is the notch length and P_f is the load required for rupture.

197
$$\beta = \frac{a}{w}$$
(3)

198 and

199
$$f(\beta) = \frac{3}{2}\sqrt{\beta} \frac{1,99 - \beta(1-\beta)(2,15-3,93\beta+2,7\beta^2)}{(1+2\beta)(1-\beta)^{3/2}}$$
(4)



201

Figure 3. Notched beam specimen under flexural test

202

203 The average and the standard deviation of three samples are considered for mechanical204 properties.

205

206 **3. Experimental results**

207 **3.1. Density**

Samples density has been calculated from the average of the measurement of weight andvolume of three samples.

Density variation as function of fiber volume fraction is presented in Figure 4. Results indicate that the material becomes slightly less dense with the increase of fibers volume fraction. Indeed, the density varies from 1761 kg.m⁻³ to 1613 kg.m⁻³: a reduction of 8 % compared to the control cement paste is noted. This result is expected because of the hollow structure of fibers shown in SEM images of Figure 1 that generate voids and pores in the matrix. There is also an additional porosity coming from the fiber matrix interface and the fibers agglomeration (see Figure 2).

217 Composites density ρ_H as a function of fibers volume fraction φ could be written as follows:

218

$$\rho_{H} = \varphi \rho_{f} + (1 - \varphi) \rho_{m} \tag{5}$$

219 Where ρ_f and ρ_m are respectively fibers and matrix densities.

Equation 5 allows the identification of ρ_m and ρ_f . Estimated densities are 1713 for ρ_m and 1214 kg.m⁻³ for ρ_f . A bibliographic synthesis was carried out by Pickering *et al.* [28] and showed that densities of natural fibers (Coir, Sisal, Hemp, Jute,) are situated between 1200 kg.m⁻³ and 1600 kg.m⁻³.

This relashionship is available for samples including fibers. However, density founded for $\varphi=0$ is slightly lower than experimental measured density. This could be explained by fibers incorporation that tends increase matrix porosity.



227

228

Figure 4. Samples density as function of fibers volume fraction

229

3.2. Thermal conductivity

Thermal conductivity values as a function of fibers volume fraction are presented in Figure 5. Cement composites containing *Posidonia-Oceanica* fibers thermal conductivity is varying from 0.718 W.m⁻¹.K⁻¹ to 0.559 W.m⁻¹.K⁻¹ for composites including 20% fibers volume fraction, thus showing a decrease of about 22%. This decrease could be explained by the density decrease and porosity increase that leads to reduce the heat transfer and the huge difference between fibers and matrix thermal conductivities: fibers thermal conductivity (k_f =

0.047 to 0.070 W.m⁻¹.K⁻¹) [21] is at least 10 times lower than that of the matrix ($k_m = 0.718$ 237 W.m⁻¹.K⁻¹). In addition, the fibers incorporation in the matrix creates many interfaces that 238 239 act as thermal contact resistances and leads to a decrease in thermal conductivity. This 240 result has been also reported by many researches. Benmansour et al. [12] in their study of 241 the development of an insulation material made of mortar including date palm fibers. 242 Authors have noted a decrease of 92.5% in thermal conductivity values. This important drop 243 compared to our results is due to the fibers content tested that reaches 30% weight fraction. Belhaj et al. [13] have noted a decrease from 1.4 W.m⁻¹K⁻¹ to 1.32 W.m⁻¹K⁻¹ on thermal 244 245 conductivity values of barley straw reinforced cement. Onésippe et al. [14] have reported that thermal conductivity decreases from 0.62 $W.m^{-1}K^{-1}$ to 0.46 $m^{-1}K^{-1}$ with the introduction 246 of Bagasse fibers in a cement-based matrix. Same ascertainments have been noticed by 247 248 Akinyemi et al. [15] in their work concerning the incorporation of banana fibers and wood 249 bottom ash in a cement matrix.

In addition, samples thermal conductivity relative variation as a function of the density relative variation presented in Figure 6 shows that there is a correlation between these two properties. This result confirms those already observed by Ibos [29] for other natural fibers used in the reinforcement of organic or mineral matrices.





As shown in Figure 7, samples thermal diffusivity is ranging between $0.362 \times 10^{-6} \text{ m}^2 \text{.s}^{-1}$ and 262 $0.298 \times 10^{-6} \text{ m}^2 \text{.s}^{-1}$. Thermal diffusivity decreases very slightly with the incorporation of 263 fibers in the cement matrix. A decrease of 12% is observed from the introduction of 5% of 264 265 fibers. However, non-significant variation is noted for higher fibers volume fractions, 266 regarding measurement uncertainties. Therefore, it could be reported that *Posidonia-Oceanica* 267 fibers introducing in cement matrix plays a minor influence on thermal diffusivity. Onésippe 268 et al. [14] have calculated thermal diffusivities of their Bagasse fibers reinforced cement 269 composites from their thermal conductivity, density and heat capacity measurements. Thermal 270 diffusivities found in their study do not show important variation and are lying between 1.18× $10^{-6} \text{ m}^2.\text{s}^{-1}$ and $1.58 \times 10^{-6} \text{ m}^2.\text{s}^{-1}$. 271





273

Figure 7. Samples thermal diffusivity as function of fibers volume fraction

274

275 **3.4. Flexural strength**

Flexural strength is the tensile strength obtained by flexural test and estimated by Equation 1.

277 Flexural strength as a function of fibers volume fraction is presented in Figure 8.

278 Results revealed that flexural strength increases by 27% for the composites including 5% of 279 fibers compared to the cement paste. For higher fibers volume fraction, flexural strength 280 decreases but still remains higher than the control cement paste strength. Fibers presence in a 281 cementitious matrix improves the composite tensile and allows crack bridging. For higher 282 fiber content, mixing becomes difficult and composites homogeneity is affected by fibers 283 agglomeration. Allegue *et al.* [5] have reported the same behavior of their composites made of 284 a cement matrix with *Posidonia-Oceanica* fibers. Flexural strengths for composites with 0.5 285 W/C ratio were found between 4.3 MPa and 5.6 MPa. The slight difference compared to our 286 results could be associated to the difference between the type of cement used. Sedan et al. [3] 287 have revealed the same trend in their study of a cement matrix reinforced with hemp fibers. 288 For fiber contents varying from 0 to 20% and a W/C ratio of 0.5, authors noted flexural 289 strength values between 4 MPa and 6.8 MPa. Belhaj et al. [13] have noticed an increase of 6% and a decrease of 6% compared to the control samples when adding respectively 5 kg.m⁻³ 290 291 and 15 kg.m⁻³ of barley straws.





Figure 8. Samples flexural strength as function of fibers volume fraction

3.5. Compressive strength

296 Samples compressive strength as a function of fibers content is presented in Figure 9. Results 297 revealed that compressive strength has the same behavior than tensile strength obtained by 298 flexural test: it increases with the addition of fibers then it decreases then but still higher than 299 the control cement strength. The peak corresponding to a 27% of strength increase is obtained 300 at 10% of fibers volume fraction. This decrease could be associated to the rise of composite 301 porosity. However, the optimal compression strength is obtained for 10% of fibers volume 302 fraction. A similar behavior was also reported by Allegue et al. [5]. Zaroudi et al. [30] also 303 reported such a variation in a study concerning the use of polyolefin fiber on an eco-friendly 304 concrete. Authors indicated that there is a slight rise of compressive strength values with the introduction of 0.5 kg.m⁻³ of fibers, and a decrease is observed for higher fibers content. 305 306 However, Benmansour et al. [12] have observed a substantial decrease of compressive 307 strength when increasing date palm fibers fraction in mortar.





Figure 9. Samples compressive strength as function of fibers volume fraction

311 **3.6. Toughness**

Fracture toughness variation as a function of fibers volume fraction is presented in Figure 10.A linear and significant increase of toughness is observed with the increase of fibers content.

314 An increase of 65% is observed for composites including 20% of fibers. Thus, it could be 315 deduced that the addition of fibers significantly improves the material toughness and therefore 316 its resistance to cracks propagation. This leads to the decrease of the material brittleness and 317 of its ductility due to the role of fibers in the bridging of cracks. Fibrous composites crack 318 bridging is owing to the presence of frictional shear resistance along the interface between 319 fibers and matrix [31]. Similar results have been reported for cement-based composites with 320 natural or synthetic fibers by Banthia et al. [17,18], Fu et al. [19], Mohr et al. [32] Juarez et 321 al. [33], Akhavan et al. [34], Bekhiti et al. [35] and Wang et al. [36].

322



323



Figure 10. Samples toughness as function of fibers volume fraction

325

326 4. Analytical models

327 **4.1. Hypothesis, microstructure and geometrical model**

328 Several approaches and models to predict the mechanical and thermal properties of short fiber 329 composites are available in the literature. It is well known that composites properties are 330 dependent to fibers shape, length, orientation and the fiber-matrix interface [37,38].

Based on the experimental data and assuming some simplifying hypothesis chosen from
 composites microstructure, simplified models were developed to predict thermal conductivity,
 tensile and compressive strengths and fracture toughness as a function of fibers volume

334 fraction.

In order to predict composites properties, the following simplifying hypotheses areconsidered:

337 - fibers are cylindrical with an average diameter of 100 μm (see SEM images of Figure
338 1);

- fibers are of average 10 mm length (measured with a caliper);

- fibers are considered uniformly distributed in the matrix;

- fibers are horizontally oriented in the matrix;

for thermal model, heat flux is considered perpendicular relatively to fibers arrangement
and for mechanical model load direction is in the same direction of fibers. These two
configurations are chosen because they correspond to the expected application of these
materials as a construction material. Measurements were performed accordingly to these
hypotheses.

It was observed from SEM images of composites (see Figure 2) that fibers tend to
agglomerate. This phenomenon depends on fibers volume fraction. Thus, an effective
diameter *d* of the fibers as a function of the volume fraction could be defined. *d* is the
diameter of inclusion which represents an agglomeration of fibers or a distributed single

351 fibers for low volume fractions of fibers. The effective diameter *d* is considered linearly352 increasing as a function of fibers volume fraction:

$$d = d_0 + 20\varphi d_0 \tag{6}$$

354 Where d_0 is the fiber diameter (100 μm) and φ is the ratio of fibers fraction.

355 This is an empirical relationship chosen from SEM images. In fact, for a composite with 20% 356 of fibers it could be observed that a bundle of five fibers is formed. The effective diameter d357 is then 500 μm in this case.

Assuming the simplified hypotheses presented above, the geometric model considered for theanalytical predictions is presented in Figure 11.

360 Inclusion distribution in the matrix considered for analytical model and the simplified 361 representative volume element (RVE) corresponding to a half-cylindrical fiber included in a

362 cement parallelepiped are presented in Figures 11 and 12.







Figure 11. Simplified repartition of inclusions in the matrix



367

Figure 12. Elementary representative volume of composite V_0

368

369 Three variables ε , γ , and δ are defined such as:

$$\varepsilon = \frac{D_1}{l} \tag{7}$$

$$\gamma = \frac{D_1}{D_2} \tag{8}$$

$$\delta = \frac{l}{d_0} \tag{9}$$

373 γ is assumed equal to 50 (the same ratio between fibers mi-length 5 mm and diameter 100 374 μ m).

375 Cylindrical fiber (of length *l* and diameter d_0) is then replaced as shown in Figure 13 by an 376 equivalent parallelepiped of same length and volume. The square section of this "equivalent" 377 fiber is $d_0'^2$. Thus, we obtain:

$$\frac{\pi d_0^2}{4} \times \frac{l}{2} = d_0^{2} \times \frac{l}{2} \Leftrightarrow d_0^{2} = d_0 \frac{\sqrt{\pi}}{2}$$
(10)



The modified representative volume element V_I is presented in Figure 14. The heat flow direction considered is also presented. The surface projection of the RVE for thermal and mechanical models are respectively shown in Figures 15 and 16. This RVE is then divided into sub-volumes. Equivalent volume fractions (φ_{p1} , φ_{s1} and φ_{p1} ') for each volume are defined. The volume V_I is composed of a cement parallelepiped in parallel with a volume V_2 relatively to the heat flow direction. V_2 is composed of a fiber parallelepiped in a cement parallelepiped as shown in Figure 17. Therefore, a 'parallel' volume fraction φ_{p1} could be defined as follows:

$$\varphi_{p1} = \frac{l}{l+D_1} = \frac{1}{1+\frac{D_1}{l}} = \frac{1}{1+\varepsilon}$$
(11)

389

391 Where l is the average length of fibers, D_l is the horizontal distance between fibers.

392



393



Figure 14. Modified representative volume element V₁



Figure 15. Geometrical thermal model projection



Figure 16. Geometrical mechanical model projection



Figure 17. Representative volume element V₂

403 The RVE V_2 is then subdivided into two volumes: a volume corresponding to the matrix in 404 series with a volume V_3 where V_3 is a parallelepiped of fiber embedded in a cement

405 parallelepiped as shown in Figure 18. A 'series' fibers volume fraction φ_{s1} is determined 406 considering the volume V_2 and defined as follows:

407
$$\varphi_{s1} = \frac{d'_0}{d'_0 + D_2} = \frac{\sqrt{\pi}d_0}{\sqrt{\pi}d'_0 + 2D_2} = \frac{1}{1 + \frac{2}{\sqrt{\pi}} \times \frac{\varepsilon\delta}{\gamma}}$$
(12)

408 'Parallel' fibers volume fraction φ_{p1} ' could be defined with considering the volume V_3 (see 409 Figure 18) as follows:

410
$$\varphi'_{p1} = \frac{d'_0}{d'_0 + D_2} = \frac{\sqrt{\pi}d_0}{\sqrt{\pi}d'_0 + 2D_2} = \frac{1}{1 + \frac{2}{\sqrt{\pi}} \times \frac{\varepsilon\delta}{\gamma}} = \varphi_{s1}$$
(13)

411



412

415

413 *Figure 18. Elementary representative volume V₃ for thermal model*

414 Finally, total fibers volume fraction φ is:

$$\varphi = \varphi_{p1} \times \varphi_{s1} \times \varphi_{p1}' \tag{14}$$

416 To determine distances D_1 and D_2 , Equation 14 is considered. φ_{p1} , φ_{s1} and φ_{p1}' are 417 respectively replaced by their formulas of Equations (11), (12) and (13). Variables ε , γ , and δ 418 are then used to find D_1 and D_2 .

419 It amounts to solve for each fibers volume fraction φ the following degree 3 Equation:

420
$$\varphi \delta^2 \varepsilon^3 + \varphi \delta (\delta + 2) \varepsilon^2 + (2\delta + 1) \varphi \varepsilon + 1 - \varphi = 0$$
(15)

421 We recall that for a given volume fraction, parameters δ and γ are known (see Equations 8 422 and 9). Thus, solving Equation 15 allows the determination of ε . RVE dimensions D_l ($D_1 =$ 423 $\varepsilon \times l$) and D_2 ($D_2 = \frac{D_1}{\gamma}$) are then calculated.

424 The variation of effective fibers diameter *d* calculated with Equation 6 and results of the 425 estimated horizontal and vertical distances between fibers D_1 and D_2 are presented in Figure 426 19 as a function of fibers volume fraction φ .





429

428

Figure 19. Distances d, D_1 and D_2 as a function of fibers volume fraction

430

431 **4.2. Thermal model**

432 The equivalent thermal conductivity k_H of the composite could be written by considering the 433 RVE V_I as a function of the volume fraction φ_{p1} given by Equation 11, the matrix thermal 434 conductivity k_m and the thermal conductivity of the volume V₂ k_{h1}:

435
$$k_{H} = \varphi_{p1}k_{h1} + (1 - \varphi_{p1})k_{m}$$
(16)

436 k_{h1} is calculated on the basis of Equation 17 using the volume fraction φ_{s1} , the matrix 437 thermal conductivity k_m and k_{h2} the thermal conductivity of the volume V_3 .

438
$$\frac{1}{k_{h1}} = \frac{\varphi_{s1}}{k_{h2}} + \frac{(1 - \varphi_{s1})}{k_m}$$
(17)

439 k_{h2} is calculated on the basis of Equation 18 using the volume fraction φ_{p1} , the matrix 440 thermal conductivity k_m and fibers thermal conductivity k_m .

441
$$k_{h2} = \varphi_{p1}' k_f + (1 - \varphi_{p1}') k_m$$
(18)

442

443 **4.3.** Comparison between thermal conductivity model and experimental results

The experimental measurements of thermal conductivity are compared to the upper and the lower bounds given by the first order thermal models. These models allow to define for a composite material the lower bound k_{inf} and the upper bound k_{sup} of thermal conductivity k. Assuming that the composite is a multi-layers material, the lower bound is giving by considering a series assembly of the material layers relatively to the heat flow direction. The upper bound is given by considering a parallel assembly of fibers and matrix relatively to the heat flow.

For a two homogenous layers material, k_{inf} and k_{sup} thermal conductivity limits are written as a function of the fibers volume fractions φ and fibers and matrix thermal conductivities k_f and k_m as follows [37]:

454
$$\frac{1}{k_{\inf}} = \frac{(1-\varphi)}{k_m} + \frac{\varphi}{k_f}$$
(19)

455
$$k_{\sup} = (1 - \varphi)k_m + \varphi k_f$$
(20)

456 k_m is the hardened cement paste without fibers thermal conductivity ($k_m = 0.718 \text{ W.m}^{-1}.\text{K}^{-1}$)

457 and k_f is *Posidonia-Oceanica* fibers thermal ($k_f = 0.070 \text{ W.m}^{-1}$.K⁻¹) corresponding to fibers

458 maximal thermal conductivity measured in a previous work [21].

459 Figure 20 illustrates a comparison between the experimental values of thermal conductivity 460 and the model developed in part 4.2. The experimental and proposed model values are 461 ranging between lower and upper limits of series and parallel models. The model developed462 to estimate thermal conductivity has the same variation of experimental measurements.



Figure 20. Comparison between experimental and analytical thermal conductivities

466 **4.4. Mechanical model**

467 Fibrous composites failure is depending on fiber matrix interface. Matthews *et al.* have468 reported that two modes of failure are possible [39]: fibers rupture or fibers sliding.

- 469 Figure 19 presents a part of composite after flexural test. It could be observed by examining
- 470 the rupture surface of composites that fibers are undamaged. Therefore, it could be assumed

471 that

- 472 rupture occurs rather by fibers sliding at fiber-matrix interface.
- 473 The corresponding geometric model is shown in Figure 16.
- 474 The composite tensile strain $\sigma_{traction,c}$ is defined as a function of the interface shear strength τ ,
- 475 the matrix tensile strain $\sigma_{traction,m}$, the geometric properties of the fiber l and d and the fiber
- 476 volume fractions φ .
- According to Matthews *et al.* [39] and Van Hattum *et al.* [40], the tensile strain is given by
 Equation 21 where *d* is the agglomerated fibers diameter supposed variable as a function of
 fibers volume fraction.

$$\sigma_{traction,c} = \varphi \times \frac{\tau \times l}{2d} + (1 - \varphi) \times \sigma_{traction,m}$$
(21)



481

482 *Figure 21. Composite specimen fractured surface observed after flexural test (rupture by fibers*

485 4.5. Tensile and compressive strengths models and comparison with experimental results

486 Equation 15 is considered in order to determine the tensile strength variation as a function of
487 fibers volume fraction. The effective diameter *d* is replaced by Equation 6, Equation 21
488 becomes:

489
$$\sigma_{traction,c} = \varphi \times \frac{\tau \times l}{2(d_0 + 20\varphi d_0)} + (1 - \varphi) \times \sigma_{traction,m}$$
(22)

490 The value of the interface shear strength is estimated by model identification with 491 experimental data. A value of τ of 0.328 MPa is identified. Figure 22 presents a comparison of 492 experimental tensile strengths with the analytical model previously presented. The tensile 493 strength is increasing until a maximal strength corresponding to optimal amount fibers 494 fraction in the cement matrix. Above this value, strength decreases.

495 In order to determine the direct tensile strength $\sigma_{\text{traction},T}$ from tensile strength obtained by 496 flexion $\sigma_{\text{traction,c}}$, the CERIB (Centre d'Etudes et de Recherches de l'Industrie du Béton) 497 proposed the following formula [41]:

498 $\sigma_{traction,T} = 0.6\sigma_{traction,c}$ (23)

499 Compressive strength and tensile strength are correlated by the following relationship [42,43]:

500 $\sigma_{compression,c} = f \sigma^{g}_{traction,T}$ (24)

501 Where f and g are two constants to be determined by model identification with experimental 502 measurements.

503 $\sigma_{traction,T}$ of the Equation 24 is replaced by Equation 23. $\sigma_{traction,c}$ is then replaced by Equation 504 22, $\sigma_{compression,c}$ becomes:

505
$$\sigma_{compression,c} = 0.6f(\varphi \times \frac{\tau \times l}{2(d_0 + 20\varphi d_0)} + (1 - \varphi) \times \sigma_{traction,m})^g$$
(25)

506 Coefficients f and g are estimated by model fitting with experimental results. Values found 507 are 8.46 for f and 1.1 for g. The interface shear strength τ taken is 0.328 MPa (value found in 508 section 4.5). The model of compressive strength is then plotted in Figure 23 and compared to 509 measured compressive strengths. It can be easily seen that both model and experimental data 510 have the same trend: there is an increase of composite compressive strength with fiber 511 incorporating until a maximum value. Then, for higher fiber volume fractions, the 512 compressive strength decreases. Classical models did not predict this variation of strength. It 513 has been demonstrated through this simplified model that this behavior is due to fibers 514 agglomeration for high fibers content.





516

Figure 22. Comparison between experimental and analytical tensile strengths



Figure 23. Comparison between experimental and analytical compressive strength

519

518

520 4.6. Toughness model and comparison with experimental results

521 In this section rupture energy of an homogenized RVE is considered. Fracture toughness 522 could be written as a function of the fracture energy Gc and Young's modulus Ec by in the 523 following way [39]:

524

$$K_c = \sqrt{E_c G_c} \tag{26}$$

525 The homogenized composite fracture energy Gc can be expressed as a function of the rupture 526 energy in the volume part containing the matrix G_m and the fracture energy of the part 527 containing a part of fiber and matrix G'.

528
$$G_{c}.S = G_{m}.S + G'.2\pi d \frac{l}{2}$$
(27)

- 529 Where S is the area of dimensions $(d + D_2)^2$ (see Figure 16).
- 530 The fracture energy *Gc* becomes:

531
$$G_{c} = G_{m} + G' \frac{\pi dl}{(d + D_{2})^{2}}$$
(28)

532 Furthermore, Young's modulus can be written according to the law of mixing as follows:

533
$$E_c = \varphi . E_f + (1 - \varphi) . E_m$$
 (29)

534 *Gc* is replaced by Equation 28, *Ec* by Equation 29 and *d* by Equation 6.

535 It follows that equation 27 becomes:

536
$$K_{c} = \sqrt{(\varphi . E_{f} + (1 - \varphi) . E_{m}) . (G_{m} + G' \frac{\pi (d_{0} + 20\varphi d_{0})l}{(d_{0} + 20\varphi d_{0} + D_{2})^{2}})}$$
(30)

537

538 According to Haecker et al. [44], Young's modulus of Portland cement paste with 0.5 539 water/cement ratio is 20 GPa. The fracture energy of the matrix G_m is estimated from the 540 matrix experimentally determined fracture toughness and cement paste young modulus. 541 *Posidonia-Oceanica* fibers Young's modulus E_{f} , fracture energy in the volume containing the 542 fiber and the matrix G' are estimated by reducing the gap of uncertainties between the model 543 and the experimental data. D_2 is considered variable as a function of fibers volume fraction φ 544 and calculated as shown in section 4.1. G' identified is about 90 N.m⁻¹. E_f is about 100 GPa, E_f could be accepted because according to literature natural fibers Young's modulus is 545 546 varying from 6 to 130 GPa [45] and [46].

Figure 24 illustrates the developed model of fracture toughness *Kc* variation as a function of fibers volume fraction compared to experimental results. It can be easily observed that the proposed model has the same variation with experimental data for fiber content ranging between 0% and 20% and that fracture toughness is increasing with fibers volume fraction increase. It confirms that fibers incorporating in a cement brittle matrix improves its ductility.



553 Figure 24. Experimental and analytical fracture toughness of composites as function of fibers volume

fraction

554

552

555

556 **5. Conclusion**

This study investigated the reinforcement of cement paste with Posidonia-Oceanica natural 557 558 fibers. The effect of fibers volume fraction variation on composites thermal and mechanical 559 preparties had been studied. Posidonia-Oceanica fibers volume fraction considered have 560 been varied from 0 to 20%. It was found that fibers volume fraction increase allows the 561 improvement of the material insulation properties: thermal conductivity values have 562 decreased of about 22% with the use of about 20% of fibers volume fraction. An analytical 563 model de predict the thermal conductivity as a function of volume fraction has been also 564 developed. This model was compared to experimental data between 0 and 20% fibers volume 565 fraction.

566 Composites mechanical properties have been measured and analytical models were defined to 567 predict composites compressive, tensile strengths and fracture toughness as a function of 568 fibers volume fractions. It was observed that compressive and flexural strengths increased of 569 about 27% between 5% and 10% then decreased but still higher than specimens without 570 fibers. However, it appears that fracture toughness was significantly increased with the 571 increase of fibers fraction. Analytical models for variation of compressive and tensile 572 strengths and fracture toughness have been also developed and compared to experimental 573 data. It was shown that the pic observed in compressive and tensile strengths is due to fibers 574 agglomeration for high volume fraction. It was also shown that fibers incorporating in this 575 cementitious matrix increases significantly the material ductility and his ability to bridge 576 cracks.

As a result of this research, the use of natural fibers of *Posidonia-Oceanica* in the reinforcement of a cement matrix seems an interesting application for their valorization in the construction domain. Material thermal and mechanical properties could be improved. This improvement depends on fibers quantity which depends on the intended application. If a maximal strength is needed fibers volume fraction should preferably not exceed 10% and if the priority is having maximal ductility and/or good insulation properties, fibers volume fraction could be higher.

584 Moreover, models developed in this work could give an estimation of thermal conductivity, 585 fracture toughness and compressive and tensile strengths as a function of any *Posidonia*-586 *Oceanica* fibers volume fraction.

587 **References**

- 588
- [1] Swift, D. G., & Smith, R. B. L. (1978, August). Sisal fibre reinforcement of cement paste
 and concrete. In *Proc. Int. Conf. on Materials of Construction for Developing Countries. Asian Inst. of Tech., Bangkok* (pp. 193-198).
- 592 [2] Tolêdo Filho, R. D., Scrivener, K., England, G. L., & Ghavami, K. (2000). Durability of
 593 alkali-sensitive sisal and coconut fibres in cement mortar composites. *Cement and*594 *concrete composites*, 22(2), 127-143.
- 595 [3] Sedan, D., Pagnoux, C., Smith, A., & Chotard, T. (2007, August). Propriétés mécaniques
 596 de matériaux enchevêtrés à base de fibre de chanvre et matrice cimentaire. In *Congrès*597 *français de mécanique*. AFM, Maison de la Mécanique, 39/41 rue Louis Blanc-92400
 598 Courbevoie.
- [4] Roma Jr, L. C., Martello, L. S., & Savastano Jr, H. (2008). Evaluation of mechanical,
 physical and thermal performance of cement-based tiles reinforced with vegetable
 fibers. *Construction and Building Materials*, 22(4), 668-674.
- [5] Allegue, L., Zidi, M., & Sghaier, S. (2015). Mechanical properties of Posidonia oceanica
 fibers reinforced cement. *Journal of Composite Materials*, 49(5), 509-517.
- 604 [6] Sawsen, C., Fouzia, K., Mohamed, B., & Moussa, G. (2015). Effect of flax fibers
 605 treatments on the rheological and the mechanical behavior of a cement
 606 composite. *Construction and Building Materials*, 79, 229-235.
- 607 [7] Fantilli, A. P., Chiaia, B., & Gorino, A. (2016). Fiber volume fraction and ductility index
 608 of concrete beams. *Cement and Concrete Composites*, 65, 139-149.
- [8] Çomak, B., Bideci, A., & Bideci, Ö. S. (2018). Effects of hemp fibers on characteristics of
 cement based mortar. *Construction and Building Materials*, *169*, 794-799.
- [9] Wongsa, A., Kunthawatwong, R., Naenudon, S., Sata, V., & Chindaprasirt, P. (2020).
 Natural fiber reinforced high calcium fly ash geopolymer mortar. *Construction and Building Materials*, 241, 118143.
- [10] Khedari, J., Watsanasathaporn, P., & Hirunlabh, J. (2005). Development of fibre-based
 soil-cement block with low thermal conductivity. *Cement and concrete composites*, 27(1), 111-116.
- [11] Bentchikou, M., Guidoum, A., Scrivener, K., Silhadi, K., & Hanini, S. (2012). Effect of
 recycled cellulose fibres on the properties of lightweight cement composite
 matrix. *Construction and Building Materials*, *34*, 451-456.

- [12] Benmansour, N., Agoudjil, B., Gherabli, A., Kareche, A., & Boudenne, A. (2014).
 Thermal and mechanical performance of natural mortar reinforced with date palm
 fibers for use as insulating materials in building. *Energy and Buildings*, *81*, 98-104.
- [13] Belhadj, B., Bederina, M., Makhloufi, Z., Dheilly, R. M., Montrelay, N., & Quéneudéc,
 M. (2016). Contribution to the development of a sand concrete lightened by the
 addition of barley straws. *Construction and Building Materials*, *113*, 513-522.
- 626 [14] Onésippe, C., Passe-Coutrin, N., Toro, F., Delvasto, S., Bilba, K., & Arsène, M. A.
 627 (2010). Sugar cane bagasse fibres reinforced cement composites: thermal
 628 considerations. *Composites Part A: Applied Science and Manufacturing*, 41(4), 549629 556.
- [15] Akinyemi, B. A., & Dai, C. (2020). Development of banana fibers and wood bottom ash
 modified cement mortars. *Construction and Building Materials*, 241, 118041.
- [16] Swift, D. G., & Smith, R. B. L. (1979). The flexural strength of cement-based composites
 using low modulus (sisal) fibres. *Composites*, *10*(3), 145-148.
- [17] Banthia, N., Moncef, A., Chokri, K., & Sheng, J. (1995). Uniaxial tensile response of
 microfibre reinforced cement composites. *Materials and Structures*, 28(9), 507-517.
- [18] Banthia, N., & Sheng, J. (1996). Fracture toughness of micro-fiber reinforced cement
 concrete. *Cement and concrete composites*, *18*(4), 251-269.
- [19] Mihashi, H., & Kohno, Y. (2007). Toughening mechanism of hybrid fiber reinforced
 cement composites. In *6th International conference on fracture mechanics of concrete and concrete structures*.
- [20] Fu, C. Q., Ma, Q. Y., Jin, X. Y., Shah, A. A., & Tian, Y. (2014). Fracture property of
 steel fiber reinforced concrete at early age. *Computers and Concrete*, *13*(1), 31-47.
- [21] Hamdaoui, O., Ibos, L., Mazioud, A., Safi, M., & Limam, O. (2018). Thermophysical
 characterization of *Posidonia Oceanica* marine fibers intended to be used as an
 insulation material in Mediterranean buildings. *Construction and Building Materials*, 180, 68-76.
- 647 [22] Gustafsson, S. E. (1991). Transient plane source techniques for thermal conductivity and
 648 thermal diffusivity measurements of solid materials. *Review of scientific*649 *instruments*, 62(3), 797-804.
- [23] Gustavsson, M., Karawacki, E., & Gustafsson, S. E. (1994). Thermal conductivity,
 thermal diffusivity, and specific heat of thin samples from transient measurements
 with hot disk sensors. *Review of Scientific Instruments*, 65(12), 3856-3859.

- [24] Log, T., & Gustafsson, S. E. (1995). Transient plane source (TPS) technique for
 measuring thermal transport properties of building materials. *Fire and materials*, 19(1), 43-49.
- 656 [25] Krapez, J. C. (2007). Mesure de l'effusivité thermique-Méthodes photothermiques.
- 657 [26] EN, N. 12390-3, 2012. Norme. Essais pour béton durci-Partie, 3.
- [27] ISO 12135, 2016. Matériaux métalliques Méthode unifiée d'essai pour la détermination
 de la ténacité quasi statique.
- [28] Pickering, K. L., Efendy, M. A., & Le, T. M. (2016). A review of recent developments in
 natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing*, 83, 98-112.
- [29] Ibos, L (2012). Métrologie thermique appliquée à la caractérisation thermophysique des
 composites et au contrôle de structures par thermographie, HDR Université Paris-Est.
- [30] Zaroudi, M., Madandoust, R., & Aghaee, K. (2020). Fresh and hardened properties of an
 eco-friendly fiber reinforced self-consolidated concrete composed of polyolefin fiber
 and natural zeolite. *Construction and Building Materials*, 241, 118064.
- [31] Nair, S. V. (1990). Crack-wake debonding and toughness in fiber-or whisker-reinforced
 brittle-matrix composites. *Journal of the American Ceramic Society*, *73*(10), 28392847.
- [32] Mohr, B. J., Nanko, H., & Kurtis, K. E. (2005). Durability of kraft pulp fiber–cement
 composites to wet/dry cycling. *Cement and Concrete Composites*, 27(4), 435-448.

673 [33] Juarez, C. A., Fajardo, G., Monroy, S., Duran-Herrera, A., Valdez, P., & Magniont, C.

- 674 (2015). Comparative study between natural and PVA fibers to reduce plastic shrinkage
 675 cracking in cement-based composite. *Construction and Building Materials*, *91*, 164676 170.
- [34] Akhavan, A., Catchmark, J., & Rajabipour, F. (2017). Ductility enhancement of
 autoclaved cellulose fiber reinforced cement boards manufactured using a laboratory
 method simulating the Hatschek process. *Construction and Building Materials*, 135,
 251-259.
- [35] Bekhiti, M., Trouzine, H., & Rabehi, M. (2019). Influence of waste tire rubber fibers on
 swelling behavior, unconfined compressive strength and ductility of cement stabilized
 bentonite clay soil. *Construction and Building Materials*, 208, 304-313.
- [36] Wang, D., Wang, H., Larsson, S., Benzerzour, M., Maherzi, W., & Amar, M. (2020).
 Effect of basalt fiber inclusion on the mechanical properties and microstructure of
 cement-solidified kaolinite. *Construction and Building Materials*, 241, 118085.

- [37] Bigg, D. M. (1995). Thermal conductivity of heterophase polymer compositions. In
 Thermal and electrical conductivity of polymer materials (pp.1-30). Springer, Berlin,
 Heidelberg.
- [38] Zhandarov, S., & Mäder, E. (2005). Characterization of fiber/matrix interface strength:
 applicability of different tests, approaches and parameters. *Composites Science and Technology*, 65(1), 149-160.
- [39] Matthews, F. L., & Rawlings, R. D. (1999). Composite materials: engineering and
 science. CRC press.
- [40] Van Hattum, F. W. J., & Bernardo, C. A. (1999). A model to predict the strength of short
 fiber composites. *Polymer composites*, 20(4), 524-533.
- 697 [41] Beinish, H. Éprouvettes en béton : leurs essais. CERIB, 2000
- 698 [42] Neville, A. M. (1995). *Properties of concrete* (Vol. 4). London: Longman.
- [43] Yao, W., Jiang, S., Fei, W., & Cai, T. (2017). Correlation between the compressive,
 tensile strength of old concrete under marine environment and prediction of long-term
 strength. *Advances in Materials Science and Engineering*, 2017, 12.
- [44] Haecker, C. J., Garboczi, E. J., Bullard, J. W., Bohn, R. B., Sun, Z., Shah, S. P., & Voigt,
 T. (2005). Modeling the linear elastic properties of Portland cement paste. *Cement and Concrete Research*, *35*(10), 1948-1960.
- [45] Wambua, P., Ivens, J., & Verpoest, I. (2003). Natural fibres: can they replace glass in
 fibre reinforced plastics ?. *Composites science and technology*, *63*(9), 1259-1264.
- [46] Baley, C. (2014). Fibres naturelles de renfort pour matériaux composites. sl: Techniques
 de l'ingénieur. *Ref. AM*, *5*, 130.