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# 1 **Modelling the hygrothermal behaviour of cement-bonded wood composite** 2 **panels as permanent formwork**

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12  
13 **Keywords:** Wood-cement composite; Heat and moisture transfer; Hygrothermal behaviour;  
14 Numerical model; Moisture buffering value.

## 15 **Abstract**

16  
17 This paper reports on the hygrothermal behaviour of a new bio-based composite building  
18 material, based on recycled wood fibres used as eco-aggregate within a cementitious matrix.  
19 A coupled heat and moisture transfer was established through the material and resolved  
20 numerically with a model developed herein. Relative humidity and temperature were chosen  
21 as driving potentials. The hygric and thermal properties of the material were analysed and  
22 then used as input parameters in the model. The accuracy of the latter was verified by  
23 comparing the simulation results with experimental hygrothermal tests, from which the  
24 moisture buffering value (MBV) could be determined. The MBV showed that the wood-  
25 cement composite material might contribute to improve the indoor thermal comfort and be  
26 relevant for low-energy building design.

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29

### **Abbreviations**

30       **1)** EN197/1: European standard of Cement- Part 1: Composition, specification and  
31               conformity criteria for common cements

32       **2)** ISO12571-2000: Hygrothermal performance of building materials and products:  
33               Determination of hygroscopic sorption properties, 2000.

34       **3)** ASTM C1498-01: Standard Test Method for Hygroscopic Sorption Isotherms of  
35               Building Materials, ASTM International, West Conshohocken, PA, 2001

36

37

## Nomenclature

### 38 **Letters**

39  $A$  area,  $m^2$

40  $c_p$  specific heat,  $J.kg^{-1}.K^{-1}$

41  $D_\theta$  moisture diffusivity,  $m^2.s^{-1}$

42  $D_T$  moisture diffusivity associated to a temperature gradient,  $m^2.s^{-1}.K^{-1}$

43  $e$  thickness, m

44  $\dot{g}$  moisture diffusion flux,  $kg.m^{-2}.s^{-1}$

45  $h_{surf}$  global heat transfer coefficient,  $W.m^{-2}.K^{-1}$

46  $h_c$  convective heat transfer coefficient,  $W.m^{-2}.K^{-1}$

47  $h_r$  radiative heat transfer coefficient,  $W.m^{-2}.K^{-1}$

48  $\dot{H}$  total volumetric enthalpy,  $J.m^{-3}$

49  $L_v$  latent heat of vaporisation,  $J.kg^{-1}$

50  $m$  mass, g

51  $P_v$  partial pressure of water vapour, Pa

52  $P_{v,sat}$  saturated water vapour pressure, Pa

53  $\dot{q}$  heat flux,  $W.m^{-2}$

54  $\varphi_a$  ambient relative humidity, %

55  $t$  time, s

56  $T$  temperature, K

57  $U$  moisture content,  $\text{kg.kg}_s^{-1}$

58 ***Greek symbols***

59  $\beta_m$  convective moisture transfer coefficient,  $\text{m.s}^{-1}$

60  $\theta$  moisture volumetric content,  $\text{kg.m}^{-3}$

61  $\lambda$  thermal conductivity,  $\text{W.m}^{-1}.\text{K}^{-1}$

62  $\varphi$  relative humidity, %

63 ***Subscripts***

64  $a$  air

65  $l$  liquid

66  $ref$  reference

67  $s$  dry material

68  $surf$  upper material surface

69  $v$  vapour

70

71

## 72 **1 Introduction**

73 Wood-cement composite panels have been invented quite a long time ago, and the  
74 interest for such materials was renewed in the 1960's due to the restricted use of asbestos  
75 (Campbell and Coutts, 1980). Their main benefit is related to the availability of natural raw  
76 materials and to their reduced environmental impact, compared to many synthetic materials.  
77 Pervaiz and Sain, (2003) indeed proved that wood-based composites can behave as a 'sink' to  
78 store carbon dioxide. Another study confirmed that 1 m<sup>2</sup> of plant-based concrete wall can  
79 store 14 to 35 kg of carbon dioxide for over 100 years (Boutin et al., 2006). In addition, the  
80 presence of wood fibres has the advantage of improving the mechanical properties of the  
81 cementitious matrix (Akkaoui et al., 2017).

82 According to ADEME (French Environment & Energy Management Agency), 6.2 million  
83 tons of wood waste are produced every year in France. As any organic waste, timber  
84 biodegrading at landfill increases carbon emissions (Kim and Song, 2014), and even toxic  
85 gases can be emitted from former chemical treatments that had been used for wood  
86 preservation (Helsen and Van den Bulck, 2005). Recently, the use of wood waste as substitute  
87 to wood fibres in concrete has been highlighted by many studies as an excellent way of  
88 reducing timber disposal at landfills. Moreover, a number of works focused on recycling and  
89 reusing wood waste as aggregate in concrete or mortar, which is now becoming a sustainable  
90 and advanced solution for building materials (Lo, 2017; Sudin and Swamy, 2006; Wang et al.,  
91 2016a).

92 The hygrothermal performances of several vegetable fibres-filled cementitious matrices  
93 have already been studied, such as wood-cement composite (Akkaoui, 2014; Bouguerra et al.,  
94 1999), hemp-lime concrete (Dhakal et al., 2017; Evrard and deHerd, 2010; Lelievre et al.,  
95 2014; Tran Le et al., 2010), flax shives-cement (Page et al., 2017), rape straw-lime concrete

96 (Rahim et al., 2015), etc. These works used either experimental or numerical approaches, at  
97 different scales, to evaluate their properties. The results showed that building materials based  
98 on natural fibres offer interesting thermal and hygric properties (Cetiner and Shea, 2018),  
99 good phonic insulation, and good moisture-buffering capacity. Karade, (2010) reviewed the  
100 generation of lignocellulosic wastes (agro-forestry waste and construction demolition waste)  
101 in the world, their mechanical characteristics, as well as their advantages and limitations.  
102 Vegetable fibres added into cementitious matrices contribute to enhance fracture toughness  
103 and durability of buildings (Cheah and Ramli, 2011; Chowdhury et al., 2015; Wang et al.,  
104 2016b).

105       Herein, our interest focused on a new wood-cement composite panel, which can be used  
106 as an insulating stay-in-place or permanent formwork of buildings (Fig. 1). This permanent  
107 formwork system can be applied to modular construction, using a fast and simple assembly  
108 phase. The dimensions of formwork panels are as follows: length 2 m, height 0.5 m, and  
109 thickness 25, 35 or 50 mm. In addition to formwork, the system is composed of a  
110 prefabricated polystyrene insulation layer and a cast in situ concrete layer. Steel rods of  
111 diameter 3 mm contribute to the stability of the structure and to the connection of upper and  
112 lower formwork panels.

113       Located on both inner and outer faces of the walls, the wood-cement composite panels  
114 are exposed to many thermal and hygric stresses due to differences of temperature and  
115 humidity between opposite wall sides. The hygrothermal transfers may thus cause  
116 condensation problems, which are likely to produce mould, or at least to influence the  
117 physical properties of the walls, such as a drop of their thermally insulating character, a  
118 decrease of mechanical properties, the degradation of the interior plaster, etc., and may also  
119 induce excess energy consumption caused by ventilation needs.

120 This paper aims at characterising the hygrothermal behaviour of wood-cement composite  
121 panels through experimental and numerical approaches in order to prove their positive  
122 influence on the regulation of humidity, thus contributing to indoor comfort, and to promote  
123 their use in construction. The present work thus investigates heat and moisture transfers in  
124 such porous media based on a cementitious matrix filled with wood fibres. A numerical model  
125 consisting of two nonlinear partial differential equations was established and implemented in  
126 the Comsol Multiphysics software in order to describe and predict heat and moisture transfers  
127 through the material. In section 2, the experimental setup is presented, whereas the  
128 mathematical model is described in section 3. Then, the determination of input properties,  
129 formerly absent from the literature, is detailed in section 4. Finally, the numerical model is  
130 applied and validated in section 5, wherein the results are compared with those from the  
131 experiments and shown to be usable for predicting the hygrothermal transfers in this kind of  
132 material. The moisture buffering capacity of the composite material is also estimated, and its  
133 interest in building is discussed.

## 134 **2 Materials and methods**

### 135 2.1 Material formulation

136 The present wood-cement composite panel was already investigated elsewhere in terms  
137 of thermal and mechanical properties (Li et al., 2019, 2018, 2017). [Its main mechanical  
138 characteristics are presented in Table 1.](#) It is based on wood shavings from spruce, considered  
139 as a waste from the wood industry and used as aggregate, and on Portland cement type CEM  
140 II/A-L 42.5R, according to EN197/1<sup>1</sup> used as matrix. Waterglass [was also part of the  
141 composite formulation for improving the internal bonding between wood fibre and cement.](#)

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<sup>1</sup> EN-197-1 European standard of Cement- Part 1: Composition, specification and conformity criteria for common cements



142 The wood shavings were first impregnated by soaking in the sodium silicate solution for  
143 24 h before being mixed with cement CEM II. The mixture was then poured into the mould  
144 and gently pressed to accelerate the curing of the cement and improve the mechanical  
145 properties.

146 The raw bio-aggregate and the final composite material are shown in Fig. 2. Table 2  
147 indicates the proximate composition of the composite, whose dry density was evaluated at  
148  $750 \pm 20 \text{ kg/m}^3$ .

## 149 2.2 Experimental setup

150 Former works demonstrated that hygroscopic materials can regulate the indoor relative  
151 humidity and hence improve the comfort felt by the occupants (Hameury and Lundström,  
152 2004; Qin et al., 2009; Wang et al., 2016a). The material behaviour with respect to moisture is  
153 normally measured at steady-state, but studying the hygric behaviour under dynamic  
154 conditions is much more representative of the real environment. One important parameter is  
155 the moisture buffering value (MBV), which quantifies the ability of hygroscopic building  
156 materials to store and release moisture. The measurement method proposed in the  
157 NORDTEST project (Rode, 2005) was used here, and is based on a fast cycling test repeated  
158 during at least 9 days at a fixed temperature ( $23^\circ\text{C}$ ): high relative humidity (75%) during 8  
159 hours, and then low relative humidity (33 %) during 16 hours.

160 Herein, a  $10 \times 10 \times 3.5 \text{ mm}$  wood-cement composite sample was both thermally insulated  
161 and isolated from moisture on all sides except one. The top side indeed remained in contact  
162 with air, as shown in Fig. 3a. With such configuration, unidirectional transfer was allowed in  
163 the material. The sample was placed in a temperature- and humidity-controlled climatic  
164 chamber (Fig. 3), inside which a sensor was introduced to record the actual values of both  
165 relative ambient humidity and temperature. The changes of mass of the sample were

166 continuously followed with an electronic balance, also installed in the climatic chamber, and  
167 connected to a computer. Two Sensirion K-type thermocouples were placed at different  
168 depths inside the sample (8 and 24 mm) for monitoring the temporal changes of temperature  
169 (Fig. 3c).

170 Prior to the test, the sample was dried at 60°C in a ventilated oven in order to measure its  
171 dry mass. Then, the sample was reconditioned at a temperature of 23°C and relative humidity  
172 of 50% in a climatic chamber. After stabilisation, dynamic relative humidity conditions were  
173 imposed while the temperature in the chamber was maintained at 23°C.

174 The changes of both temperature and relative humidity in the climatic chamber, recorded  
175 by a sensor type “HOBO MX CO<sub>2</sub> logger”, are shown in Fig. 4. The recorded values were  
176 then used as boundary conditions for the simulation.

### 177 **3 Mathematical model**

178 The phenomenon of moisture transfer in any building envelope considered as a porous  
179 medium is driven by the diffusion of moisture in either liquid or vapour form, or both. The  
180 transfer mechanisms are not the same, depending on the phases: liquid water can be  
181 transported under the effect of a capillary pressure gradient, but the transport of water vapour  
182 is induced by a partial vapour pressure gradient. On the other hand, heat transfer occurs by  
183 one or a combination of the following mechanisms: conduction (temperature gradient),  
184 convection (air circulation), radiation (electromagnetic waves) and phase change  
185 (evaporation-condensation).

186 Generally, the combined heat, air and moisture (HAM) transfers in a porous medium can  
187 be described by a system of partial differential equations (Kunzel, 1995; Luikov, 1966; Qin et  
188 al., 2009; Rode, 2005). Many models have been presented in the literature that can solve the  
189 HAM problem by analytical methods (Qin and Zhang, 2015), or by numerical approaches

190 such as WUFI (Park et al., 2019; Yoo et al., 2019), Comsol Multiphysics (Colinart and  
 191 Glouannec, 2017; Lelievre et al., 2014; Liu et al., 2015), Matlab (Wang and Ge, 2018), etc.  
 192 Recently, Lopez et al. reviewed the codes available for HAM simulation as well as the input  
 193 parameters that are needed (López et al., 2017).

194 The model developed in the present study is based on the theory proposed by Luikov  
 195 (Luikov, 1966) and then solved with Comsol Multiphysics. In this context, the building  
 196 material is assumed to be a porous but continuous and homogeneous medium, and the system  
 197 is considered in thermodynamic equilibrium. Besides, the shrinkage, the radiation, and the  
 198 effect of gravity are neglected. The liquid phase is assumed to be incompressible ( $\rho_l =$   
 199 constant), and the solidification of water is neglected because the average temperature in  
 200 winter is usually higher than 0°C.

### 201 3.1 Leading equations

#### 202 3.1.1 Moisture transfer

203 The phenomenon of moisture transfer in a building envelope is expressed by the mass  
 204 conservation of liquid and vapour phases:

$$205 \frac{\partial \theta}{\partial t} + \vec{\nabla} \cdot (\vec{g}_l + \vec{g}_v) = 0 \text{ with:} \quad (1)$$

$$206 \vec{g}_l = -D_{l,\theta} \vec{\nabla} \theta - D_{l,T} \vec{\nabla} T = -D_{l,\theta} \xi \vec{\nabla} \varphi - D_{l,T} \vec{\nabla} T \quad \text{and} \quad (2)$$

$$207 \vec{g}_v = -D_{v,\theta} \vec{\nabla} \theta - D_{v,T} \vec{\nabla} T = -D_{v,\theta} \xi \vec{\nabla} \varphi - D_{v,T} \vec{\nabla} T \quad (3)$$

208 where  $\theta$  [kg/m<sup>3</sup>] is the volumetric moisture content, and  $\vec{g}_l$  and  $\vec{g}_v$  [kg/(m<sup>2</sup>.s)] are liquid and  
 209 vapour diffusion fluxes, respectively.  $D_{i,\theta}$  [m<sup>2</sup>/s] is the moisture diffusivity in each phase, the  
 210 index  $i$  representing the different possible states of water: ( $l$ ) for liquid and ( $v$ ) for vapour.  $D_{i,T}$   
 211 [m<sup>2</sup>/(s.K)] is the moisture diffusivity associated to temperature gradient, and since it  
 212 contributes to less than 0.05% of water and vapour transport (Liu et al., 2015), it was

213 neglected in our case, i.e., we fixed  $D_{i,T} = 0$ .  $\xi = \partial\theta / \partial\varphi = \rho_s (\partial u / \partial\varphi)$  is the sorption  
 214 capacity which can be determined experimentally,  $u$  [kg/kg<sub>s</sub>] represents the material moisture  
 215 content on dry basis,  $\varphi$  [%] is the inner relative humidity of the material, and  $\rho_s$  [kg/m<sup>3</sup>] is the  
 216 dry bulk density of the material.

217 Thus, the moisture balance equation (1) can be transformed in terms of relative humidity  
 218 into:

$$219 \quad \xi \frac{\partial\varphi}{\partial t} + \vec{\nabla} \cdot \left( -\xi (D_{i,\theta} + D_{v,\theta}) \vec{\nabla}\varphi \right) = 0 \quad (4)$$

### 220 3.1.2 Heat transfer

221 The energy conservation equation is given by:

$$222 \quad \frac{\partial\hat{H}}{\partial t} + \vec{\nabla} \cdot \vec{q} = 0 \quad (5)$$

223 where  $\hat{H}$  [J/m<sup>3</sup>] is the total volumetric enthalpy and  $\vec{q}$  [W/m<sup>2</sup>] is the heat flux which is  
 224 transferred by thermal conduction, convection and phase change:

$$225 \quad \hat{H} = \rho_s c_{p,s} (T - T_{ref}) + \rho_l c_{p,l} (T - T_{ref}) + \rho_v (L_v + c_{p,v} (T - T_{ref})) \quad (6)$$

$$226 \quad \vec{q} = -\lambda \vec{\nabla}T + \vec{g}_l c_{p,l} (T - T_{ref}) + \vec{g}_v c_{p,v} (T - T_{ref}) + \vec{g}_v L_v \quad (7)$$

227 where  $\lambda$  [W/(m.K)] is the thermal conductivity of the material, and  $c_{p,s}$ ,  $c_{p,l}$  and  $c_{p,v}$  [J/(kg.K)]  
 228 are the specific heats of dry material, liquid water and water vapour, respectively.  $T_{ref} =$   
 229 273.15 K is the reference temperature, and  $L_v = 2.5 \times 10^6$  J/kg is the latent heat of vaporisation  
 230 of water at the reference temperature  $T_{ref}$ .

231 Substituting Eq. (6-7) into Eq. (5), the energy conservation leads to an equation [that](#)  
 232 depends on both temperature and moisture:

$$\begin{aligned}
233 \quad & \rho_s c_{p,m} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\lambda \vec{\nabla} T) + \vec{\nabla} \cdot \left( \xi \left( D_{l,\theta} c_{p,l} (T - T_{ref}) + D_{v,\theta} (c_{p,v} (T - T_{ref}) + L_v) \right) \vec{\nabla} \varphi \right) \\
& - \left( c_{p,l} (T - T_{ref}) \frac{\partial \rho_l}{\partial t} + (c_{p,v} (T - T_{ref}) + L_v) \frac{\partial \rho_v}{\partial t} \right) = 0 \quad (8)
\end{aligned}$$

234 where  $c_{p,m}$  [J/(kg.K)] is the heat capacity of the material, such that  $c_{p,m} = c_{p,s} + \frac{\rho_v}{\rho_s} c_{p,v} + \frac{\rho_l}{\rho_s} c_{p,l}$ .

### 235 3.2 Boundary conditions

236 Heat and mass transfers are applied to the upper surface, assuming that no transfer is  
237 possible at the sides and at the bottom of the sample (see again Fig. 3). The moisture flow  
238 through the surface  $\dot{g}$  [kg/(m<sup>2</sup>.s)] reads:

$$239 \quad \dot{g}_{surf} = -\beta_m (P_v - P_{v,a}) \quad (9)$$

240 where  $\beta_m$  [kg/(Pa.m<sup>2</sup>.s)] is the convective moisture transfer coefficient which can be  
241 calculated using the convective heat transfer coefficient  $h_c$  [W/(m<sup>2</sup>.K)] (Liu et al., 2015):  
242  $\beta_m = 7.7 \times 10^{-9} h_c$ . In Eq. (9),  $P_v$  [Pa] represents the partial pressure of water vapour, which is  
243 moisture-dependent so that  $P_v = \varphi P_{v,sat}$ , and  $P_{v,surf}$  [Pa] is the ambient pressure above the  
244 material surface.

245 The heat flow  $\dot{q}$  [W/m<sup>2</sup>] across the upper material surface involves convection and  
246 radiation fluxes, and is given by:

$$247 \quad \dot{q}_{surf} = -h_{surf} (T - T_a) + (L_v + c_{p,v} (T - T_{ref})) \dot{g}_{surf} \quad (10)$$

248 where  $h_{surf}$  [W/(m<sup>2</sup>.K)] is the global heat transfer coefficient which combines convection  $h_c$   
249 and radiation  $h_r$  such that  $h_{surf} = h_c + h_r$ .  $T_a$  [K] is the ambient temperature in the climatic  
250 chamber.

## 251 **4 Input properties**

252 In order to feed the numerical model, several quantities need to be measured, such as  
253 sorption capacity and thermal conductivity. The other quantities that need to be known were  
254 found in the literature.

### 255 4.1 Isothermal sorption

256 A gravimetric method was applied for the measurement of the isothermal sorption curve  
257 according to ISO12571-2000<sup>2</sup>, which consists in following the changes of mass of the  
258 material as a function of relative humidity. For that purpose, 6 cubic samples of side 35 mm  
259 were first dried at 60°C in a ventilated oven according to ASTM C1498-01<sup>3</sup>. Then, the dried  
260 samples were placed in the same climatic chamber as before at controlled relative humidity  
261 and fixed temperature of 23°C. The samples were weighed at regular intervals until the mass  
262 stabilised within less than 0.1%, so that the material was assumed to be at equilibrium. The  
263 tests were repeated and averaged for seven levels of relative humidity: 20, 30, 40, 50, 60, 70  
264 and 80% RH, from which the sorption curve could be obtained. Because of the low water  
265 permeability of the sample, the whole experiment lasted for several weeks, depending on the  
266 considered RH. Reaching the equilibrium indeed takes much longer at high ambient relative  
267 humidity.

### 268 4.2 Thermal conductivity

269 The Hot Disk TPS 2500 S analyser (Fig. 5) was used to measure the thermal conductivity  
270 of the wood-cement material. The method is based on a transiently heated plane sensor that  
271 acts as both heat source and dynamic temperature probe. This sensor consists of an  
272 electrically conducting pattern in the shape of a double spiral, which has been etched out of a

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<sup>2</sup> Hygrothermal performance of building materials and products: Determination of hygroscopic sorption properties, 2000

<sup>3</sup> Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials, ASTM International, West Conshohocken, PA, 2001

273 thin nickel foil and sandwiched between two thin sheets of Kapton®. During the experiment,  
274 the hot disk sensor was fitted between two identical pieces of samples to be investigated,  
275 having relevant sizes (i.e., same as before: cubes of side 35 mm) for considering them as  
276 semi-infinite media with respect to sensor size. The thermal conductivity was calculated with  
277 the Hot Disk 6.1 software, based on tests carried out at equilibrium for different levels of  
278 relative humidity at fixed temperature of 23°C.

### 279 4.3 Moisture diffusivity

280 The moisture diffusivity  $D_\theta$  characterises the moisture transfer ability through a material  
281 under a gradient of vapour pressure, and is such that  $D_\theta = D_{l,\theta} + D_{v,\theta}$ . The latter terms are the  
282 moisture diffusivities in liquid phase,  $D_{l,\theta}$ , and in vapour phase,  $D_{v,\theta}$ . Their values were taken  
283 from the literature (Bouguerra et al., 1999; Houngan et al., 2015) for a wood-cement  
284 composite and are presented in Fig. 6 as a function of moisture content. We indeed assumed  
285 that the behaviour of our material is similar to that reported in the literature, due to its very  
286 close composition, and this assumption was validated below by our parametric numerical  
287 study. As clearly seen in Fig. 6, the vapour diffusivity of wood-cement composite decreases  
288 when the water content increases, due to capillary condensation. On the contrary, the liquid  
289 diffusivity dramatically increases [because of the high relative humidity at which the liquid](#)  
290 [water tends to saturation in the pores, which allows the water to be free and thus to diffuse](#)  
291 [more easily.](#)

### 292 4.4 Other parameters and initial conditions

293 Other properties of wood-cement material, as well input parameters for the model, are  
294 listed in [Table 3](#).

## 295 5 Results and discussion

### 296 5.1 Moisture sorption and related changes of thermal conductivity

297 Fig. 7 shows the water sorption curve of the wood-cement composite material between  
298 20 % and 80 % RH, obtained from the procedure described in section 4.1, i.e., averaged on 6  
299 different samples. The experimental data were correctly fitted by the Guggenheim – Anderson  
300 – de Boer (GAB) model, which has been widely used for fitting the moisture adsorption-  
301 desorption curve of bio-based building materials. It reads (Anderson, 1946; De Boer, 1953;  
302 Guggenheim, 1966):

$$303 \quad u = \frac{X_G C_G K \varphi}{(1 - K \varphi)(1 + (C_G - 1)K \varphi)} \quad (11)$$

304 where  $X_G$ ,  $C_G$  and  $K$  are adjustable parameters. For the material studied,  $X_G = 0.0359$ ,  $C_G =$   
305  $29.689$  and  $K = 0.839$  were found from the fit presented in Fig. 7.

306 The thermal conductivity  $\lambda$  measured at each hygrothermal equilibrium as described in  
307 section 4.2 is illustrated in Fig. 8, and was linearly fitted as a function of relative humidity:  
308  $\lambda = a \varphi + b$ , where  $a$  and  $b$  are adjustable parameters. As expected,  $\lambda$  increases with relative  
309 humidity. All experimental results thus show the clear dependency of relative humidity on  
310 both hygric and thermal properties of wood-cement composite material, in complete  
311 agreement with the literature (Lelievre et al., 2014; Palumbo et al., 2016).

### 312 5.2 Model validation

313 The previous equations (4) and (8) describing the coupled heat and moisture transfers  
314 have been solved with the commercial software Comsol Multiphysics using the finite-element  
315 method. The model was first validated by the benchmark case in HAMSTAD project  
316 (Hagentoft et al., 2004), which is a platform for evaluating the numerical model of heat and  
317 moisture transfers for building walls. For the simulation of hygrothermal tests, 8820 triangle  
318 meshes were set. The mesh size, time step and tolerance were 2 mm, 30 s and  $10^{-8}$ ,



319 respectively. The running time was less than 10 min. Experimental and simulation results of  
320 the fast cycling test described in section 2.2 are compared in Fig. 9.

321 Experimental evolutions show cyclic variations of mass and temperature. The mass  
322 variation shows increases then decreases. The increase in mass is due to the sudden increase  
323 in the ambient relative humidity, and therefore the vapour pressure becomes greater than the  
324 vapour pressure at the surface of the material, which has the effect of vapour flow to the  
325 material and thereby increases its water content. Conversely, the decrease in mass is due to  
326 the decrease in the relative humidity, which passes below its equilibrium value at the surface.

327 With regard to the temperature, during the mass gain, there is a rapid increase thereof,  
328 then a slower decrease tending towards the equilibrium temperature. Conversely, these two  
329 steps are also observable during the loss of mass. The first step (sudden increase in  
330 temperature) is due to the condensation of the steam during the mass gain. This phenomenon  
331 could be explained by the increase of the temperature of the chamber recorded by the sensor,  
332 but a complementary simulation showed that this phenomenon also existed when the  
333 temperature was fixed.

334 The second step observed, corresponding to a slow decrease in temperature, is explained  
335 by a compensation of the mass flow towards the interior of the material. As the water content  
336 increases at the surface, a water content gradient is created from the outside to the inside,  
337 which imposes a flow of steam inwards. When this vapour leaves the volume concerned, there  
338 is then a transfer of energy that compensates for the increase in temperature relative to the  
339 superficial condensation. During the evaporation steps, these phenomena appear in the  
340 opposite direction.

341 The measured and calculated amplitudes of both temperature and moisture are almost  
342 identical, although some differences are observed. Indeed, it can be seen on the temperature  
343 profile at 8 mm deep (Fig. 9a) that the difference between experiment and simulation is about

344 0.3°C for both adsorption and desorption phases. Besides, the results of temperature  
345 simulation at 24 mm deep upon desorption are very close to the measurements, whereas a  
346 deviation of 0.5°C can be observed upon adsorption (Fig. 9b). The temperature values at  
347 different depths (8 and 24 mm) are very close to each other when simulated, but this is not the  
348 same as for the experimental ones. It is possible that such differences originate from physical  
349 phenomena not taken into account in the model. For instance, vapour diffusion associated to  
350 temperature gradient was neglected in this study, and this may impact the changes of  
351 temperature. Similar shifts between experimental and simulated temperature profiles can be  
352 found in (Lelievre et al., 2014) for bio-based building materials.

353 On the mass profile (Fig. 9c) the difference between experiment and simulation is less  
354 than 2%. The amplitude represents the amount of moisture adsorbed and desorbed by the  
355 sample during the whole cycle. The simulation suggests that the cyclic changes are rather  
356 constant, whereas the experimental recordings show a slight global increase with time, better  
357 seen at day #9.

### 358 5.3 Model sensitivity analysis

359 The numerical model developed herein allows predicting the hygrothermal transfers in  
360 the porous medium. Nevertheless, several factors may have an impact on the simulation  
361 results, so that parametric studies are required, focusing on boundary conditions (air  
362 temperature and relative humidity) and moisture diffusion coefficients.

#### 363 5.3.1 *Boundary conditions*

364 In order to check the effect of the boundary conditions on the temperature profiles, the air  
365 temperature in the climatic chamber was varied, and its impact on the simulation results is  
366 illustrated in Fig. 10a and 10b. The results were only shown up to 4 days for clarity. At fixed  
367 relative humidity, no influence was found on both position and amplitude of each peak when

368 the air temperature varied by  $\pm 0.5$  °C. The variation of air temperature caused a deviation of  
369  $\pm 3$  % of the temperatures inside the material, but no change of mass.

370 In contrast, the variation of relative humidity of air by  $\pm 5\%$  at fixed temperature had a  
371 significant impact on the mass, as evidenced in Fig. 10c. In this figure, the temperature was  
372 not shown since it did not change. The position and amplitude of mass at each peak also  
373 remained almost constant, but the increase or decrease of RH in air tended to increase or  
374 reduce the mass, respectively. Therefore, the change of RH has a significant effect on the  
375 moisture transfer in the material. This finding demonstrates that monitoring very accurately  
376 the environment in the climatic chamber is necessary for obtaining reliable results.

### 377 5.3.2 Moisture diffusivity

378 The impact of moisture diffusivity in vapour and liquid phase on the prediction of  
379 hygrothermal transfer was evaluated by varying the values of  $D_{v,\theta}$  and  $D_{l,\theta}$ , respectively, by  $\pm$   
380 25 %. As shown in Fig. 11, increasing the two moisture diffusion coefficients (referred to as  
381  $D_\theta \times 1.25$  in the plots) led to the increase of both the inner relative humidity and the mass of  
382 the sample. The difference of mass change was about 0.3%. Reciprocally, the reduction of  
383 moisture diffusion coefficients (referred to as  $D_\theta \times 0.75$ ) caused a decrease of both the inner  
384 relative humidity and the mass of the sample. However, the three temperature profiles were  
385 very close to each other. The simulation thus proves that the moisture diffusion coefficients  
386 have a low influence on the results obtained.

### 387 5.4 Moisture buffering value

388 The moisture buffering value, MBV [ $\text{g}/(\text{m}^2 \cdot \% \text{RH})$ ], quantifies the ability of a given  
389 building material to adsorb and release moisture. This is an important parameter with respect  
390 to interior comfort. It is calculated by (Rode, 2005):

$$391 \quad MBV = \frac{\Delta m}{A \cdot (RH_{high} - RH_{low})} \quad (12)$$

392 where  $\Delta m$  [g] is the variation of mass during moisture adsorption and release,  $A$  [m<sup>2</sup>] is the  
393 contact area of the sample with air, and  $RH_{high}$  and  $RH_{low}$  [%] represent high and low relative  
394 humidity (75% and 33%, respectively). The mass change experimentally measured during 24h  
395 is presented in Fig. 12.

396 The MBV are classified according to Fig. 13. The highest values correspond to building  
397 materials that best allow regulating the indoor relative humidity, and which are thus referred  
398 to as “excellent” from this point of view. The MBV of the present wood-cement composite  
399 material was found to be 1.16 g/(m<sup>2</sup>.%RH), and hence can be considered as "good" (i.e.,  $1 <$   
400  $MBV < 2$ ). This finding confirms that this building material can contribute to the  
401 improvement of the indoor hygrothermal comfort.

## 402 **6 Conclusion**

403 A wood-cement composite material based on recycled wood waste was investigated in  
404 terms of hygrothermal transfers, with an expected impact on the indoor comfort.

405 Heat and moisture transfers in such porous medium were described by mass and energy  
406 balance equations, and hygrothermal properties were also determined experimentally with  
407 relative humidity dependence and then used as input parameters for the numerical model.

408 The simulations results were found to be in good agreement with the experiments,  
409 thereby confirming the relevance of the used material properties. However, slight differences  
410 between experiments and simulations were observed, which might originate from physical  
411 phenomena not considered in the model (such as vapour diffusion associated with temperature  
412 gradient).

413 Sensitivity analysis on the boundary conditions such as temperature or relative humidity  
414 of air had a non-negligible impact on the results. Moreover, the moisture diffusion  
415 coefficients had a slight impact on the moisture transfer. A good moisture buffering capacity

416 was found that confirms the potential of the present wood-cement composite for regulating  
417 the indoor humidity.

418 The present paper is a first step towards in-depth studies of the hygrothermal behaviour  
419 of wood-cement composites from material scale to building scale. The properties measured  
420 herein and the model that was developed can indeed be applied for studying heat and moisture  
421 transfers in buildings incorporating this type of formwork, so that its benefit can be firmly  
422 established. Moreover, [the study of thickness impact could be interesting for future](#)  
423 [development.](#)

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- 554
- 555

556 Table 1. Mechanical properties of wood-cement panel (Li et al., 2018).

557

Wood-cement panel	Value (MPa)
Elastic modulus	1820
Elastic limit	1.6
Flexural strength	2.5
Compressive strength	5.3

558

559



560

Table 2. Composition of wood-cement composite material.

Ingredients	Wt. %	Vol. %
Wood	43.2	67.3
Cement	35.1	22.9
Silica	12.6	3.0
Water	9.1	6.8

561

562

Table 3. Input parameters and initial conditions

Parameter	Unit	Value	Ref
Specific heat of dry material $c_{p,s}$	J/(kg.K)	870	(Incropera et al., 2006)
Specific heat of liquid water $c_{p,l}$	J/(kg.K)	4180	(Incropera et al., 2006)
Specific heat of water vapour $c_{p,v}$	J/(kg.K)	1580	(Incropera et al., 2006)
Saturated water vapour pressure $P_{v,sat}$	Pa	$101325 \times 10^{\left(\frac{17.443 - \frac{2795}{T}}{T} - 3.868 \times \log_{10} T\right)}$	(Incropera et al., 2006)
Latent heat of vaporization $L_v$	J/kg	$2.5 \times 10^6$	(Incropera et al., 2006)
Global heat transfer coefficient $h_{surf}$	W/(m <sup>2</sup> .K)	15	
Initial temperature $T_0$	°C	23.3	
Initial relative humidity $\varphi_0$	%	53	

**Fig. 1.** Description of stay-in-place wood-cement formwork system: (a) photo of a construction site using wood-cement formwork; and (b) scheme of formwork system.

**Fig. 2.** (a) Raw bio-aggregate (spruce shavings); and (b) final wood-cement composite material.

**Fig. 3.** Experimental device for measuring temperature and mass changes: (a) scheme of sample cross-section with insulation and protection from moisture, and position of temperature probes; (b) and (c) sample with thermocouples, installed on an electronic balance in the climatic chamber, and connected to a computer.

**Fig. 4.** Dynamic conditions of ambiance temperature ( $T_a$ ) and relative humidity ( $\varphi_a$ ) measured in the climatic chamber during the test.

**Fig. 5.** Hot Disk device: (a) analyser; and (b) sensor with one sample.

**Fig. 6.** Moisture diffusivity in liquid phase,  $D_{l,\theta}$ , and in vapour phase,  $D_{v,\theta}$ , of wood-concrete material.

**Fig. 7.** Moisture sorption isotherm (red points) and its fit by the GAB equation (Eq. 11, black curve) such that 
$$u = \frac{0.894\varphi}{(1-0.839\varphi)(1+24.07\varphi)}$$

**Fig. 8.** Measured thermal conductivity at 23°C as a function of relative humidity (black points), and its linear fit (red line) such that 
$$\lambda = 0.0189 \varphi + 0.1987$$

**Fig. 9.** Comparison between experimental (black dotted lines) and simulation (red continuous line) results during the fast cycling test: changes of temperature with time at (a) 8mm-deep; and (b) 24mm-deep; and (c) temporal changes of moisture.

**Fig. 10.** Experimental (black solid line) and simulated (dotted line) temperature evolutions with a variation of  $\pm 0.5^\circ\text{C}$  (reference in green,  $+0.5^\circ\text{C}$  in blue, and  $-0.5^\circ\text{C}$  in red): (a) at 8 mm deep, and (b) at 24 mm deep; (c) Simulated mass sample evolution with a variation of  $\pm 5\%$  on  $\varphi_a$  (with the reference in solid black line,  $+5\%$  in dotted blue line, and  $-5\%$  in dashed red line).

**Fig. 11.** Impact of moisture diffusivity on: (a) the inner relative humidity of the sample at 8 mm and 24 mm deep; and (b) the sample mass (red line: reference diffusion coefficients; blue

line: diffusion coefficients decreased by 25%; green line: diffusion coefficients increased by 25%).

**Fig. 12.** Change of mass of wood-cement composite during a fast cycling test repeated during at least 9 days at a fixed temperature (23°C) and high RH (75%) during 8 hours followed by low RH (33 %) during 16 hours.

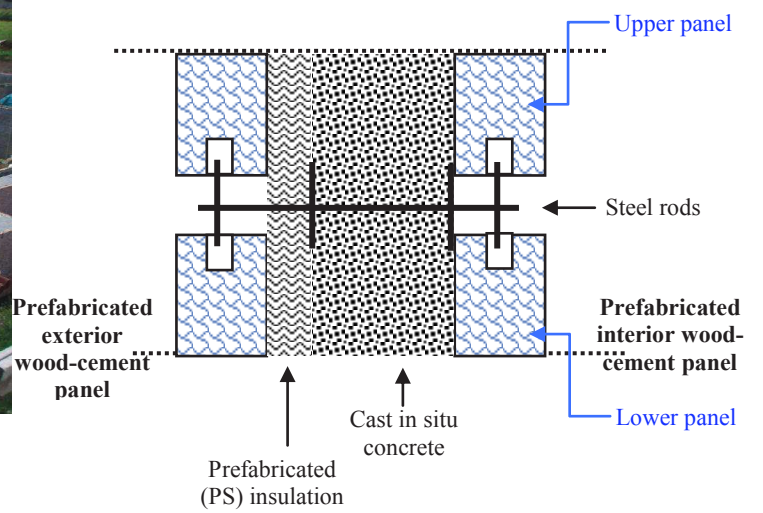
**Fig. 13.** Practical MBV classification.

# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 1**



(a)



(b)

## Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

Figure 2



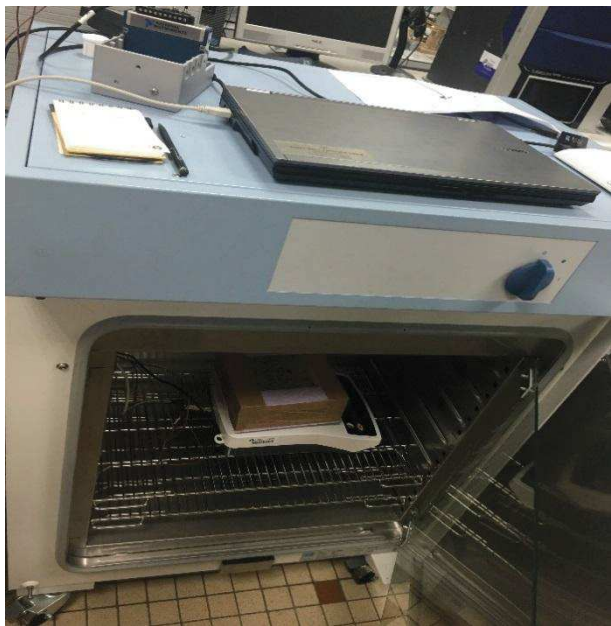
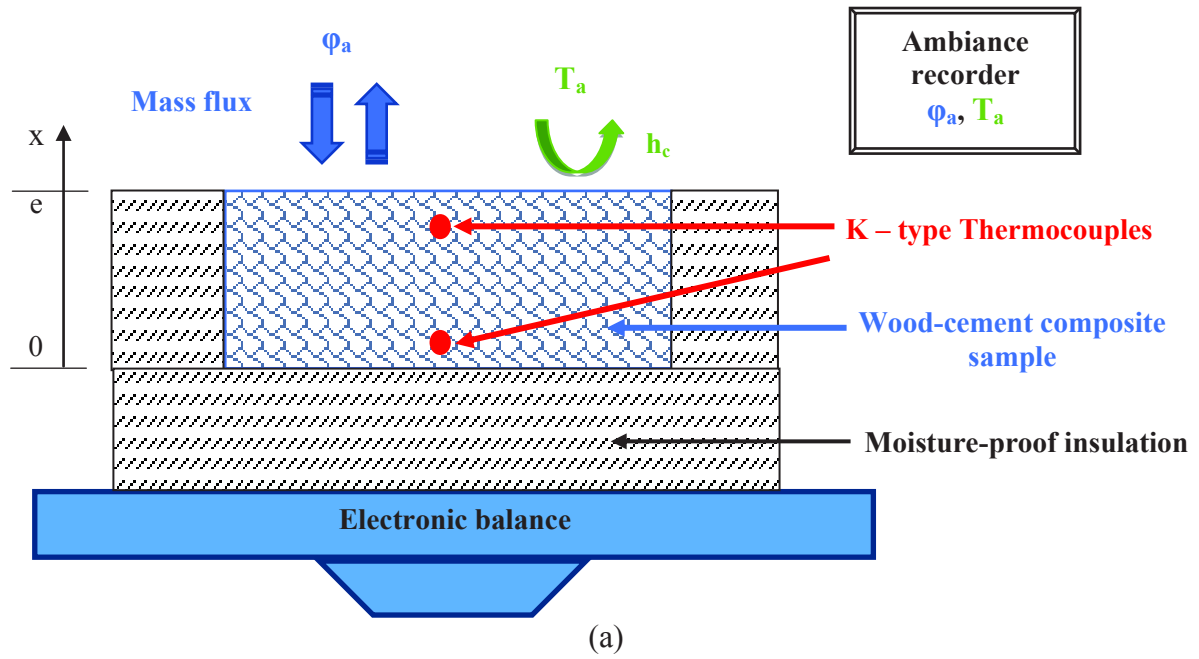
(a)



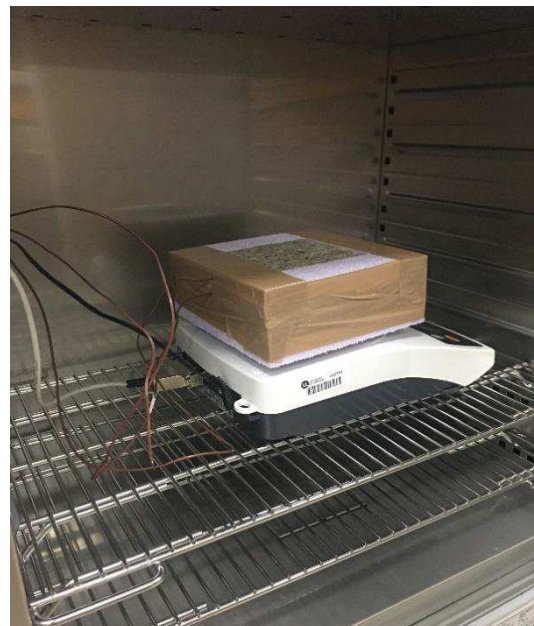
(b)

# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 3**



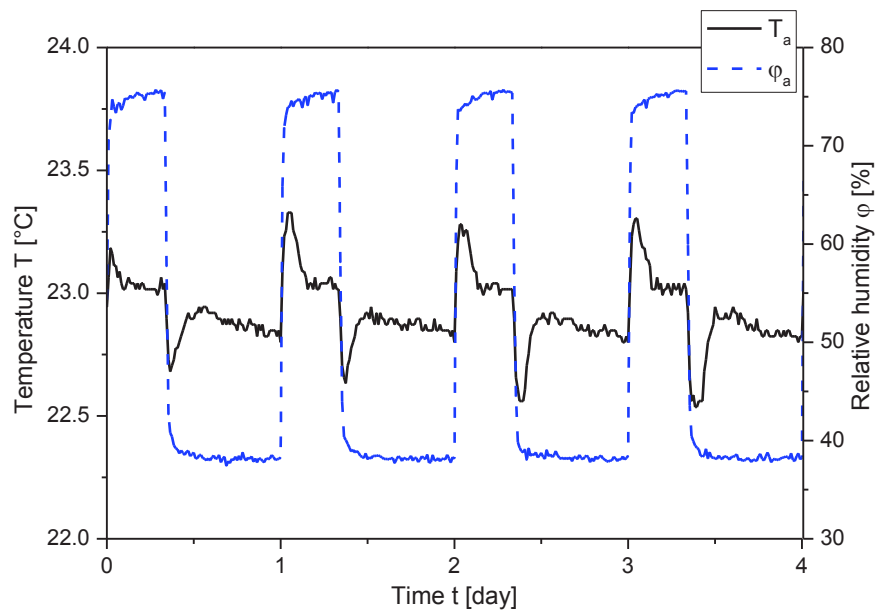
(b)



(c)

# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 4**



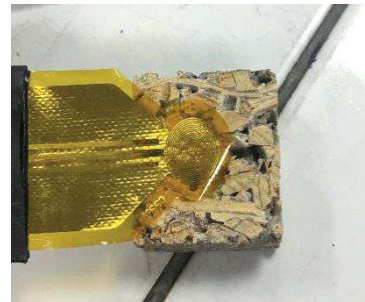


# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 5**



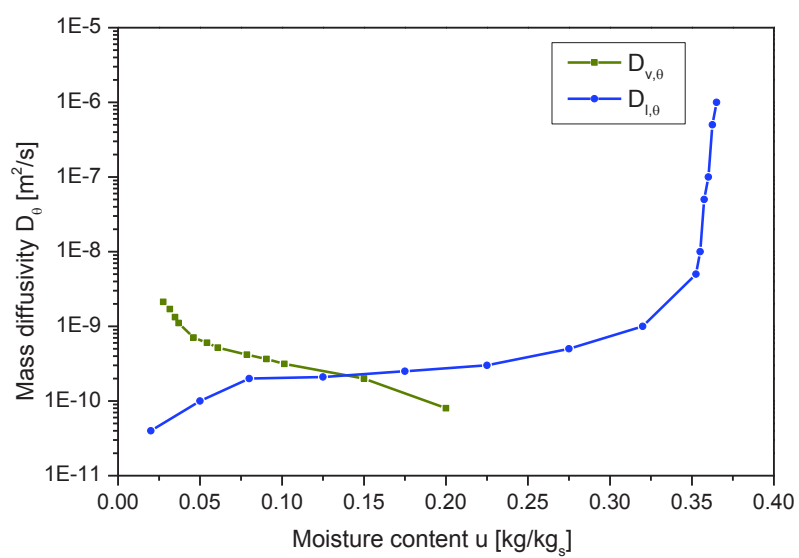
(a)



(b)

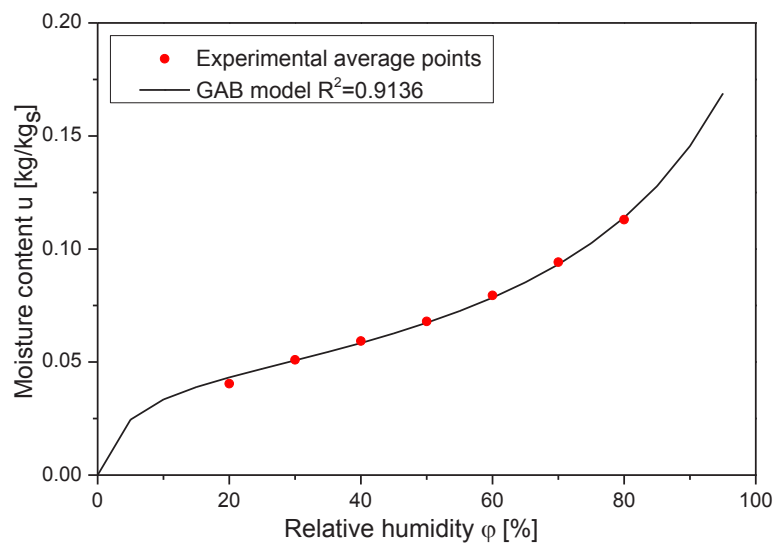
# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 6**



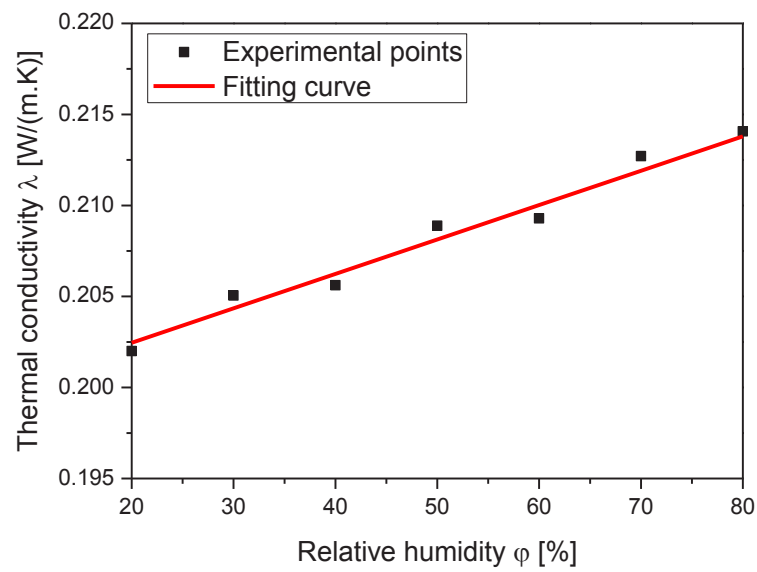
# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 7**



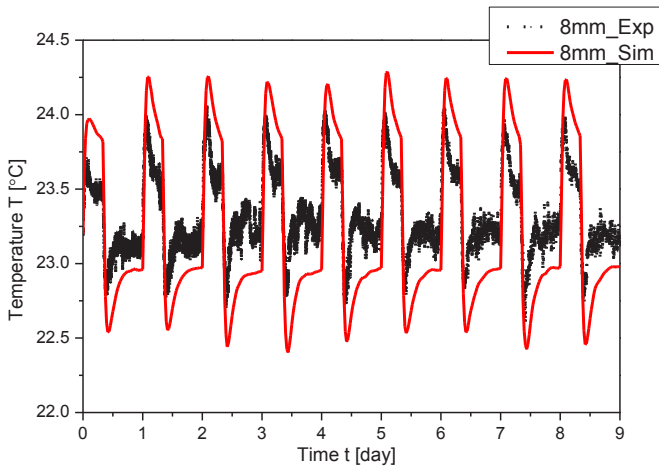
## Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 8**

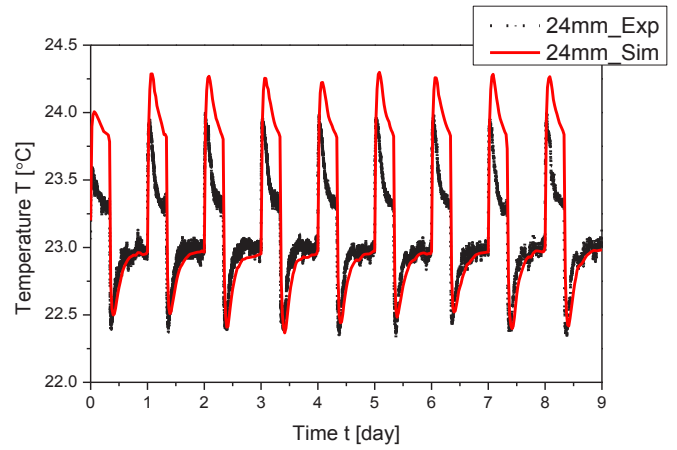


# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

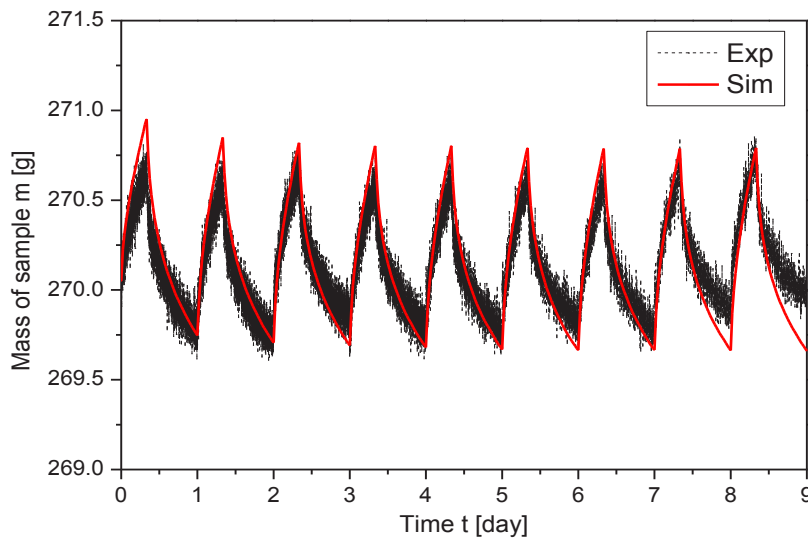
**Figure 9**



(a)

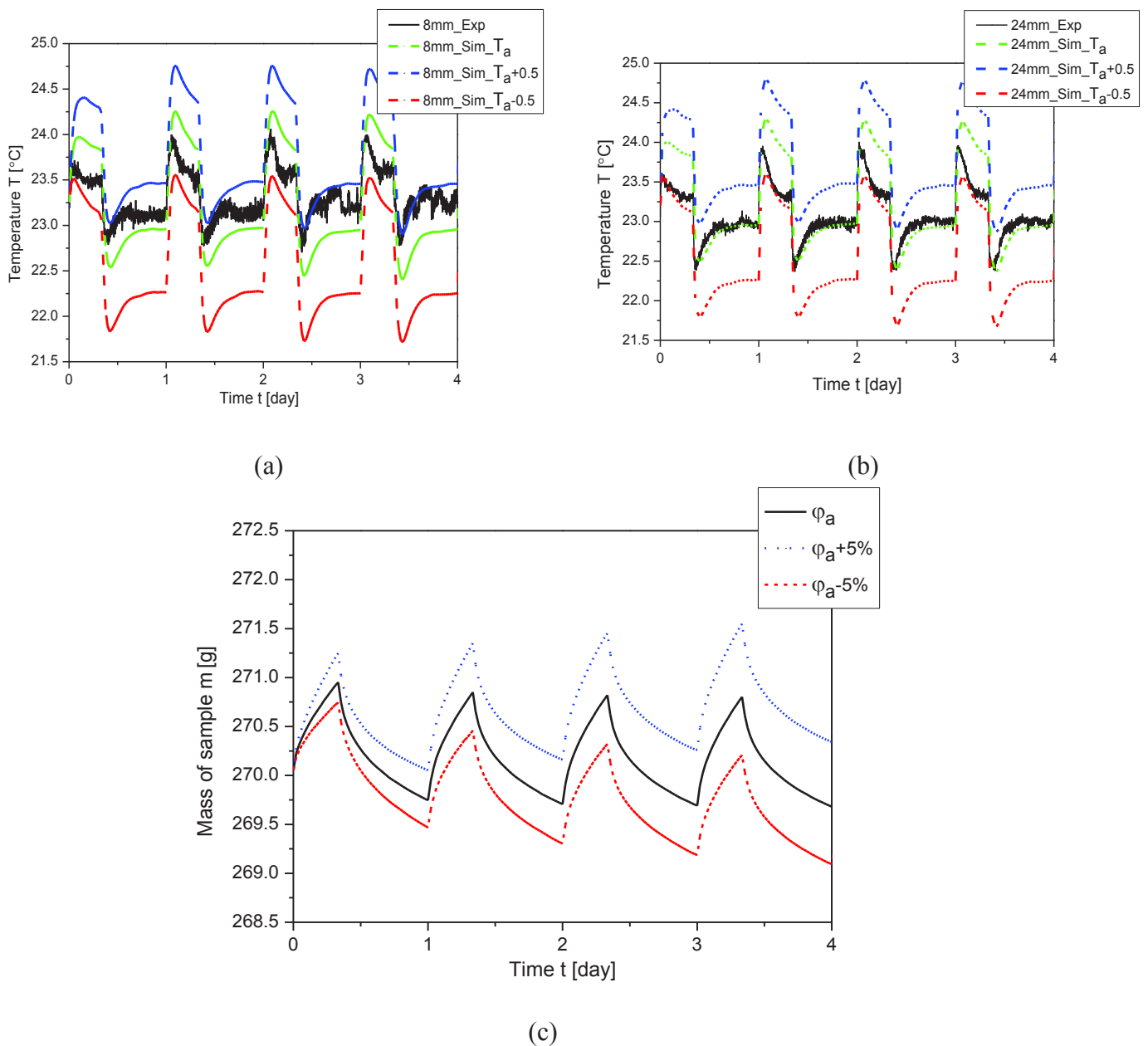


(b)



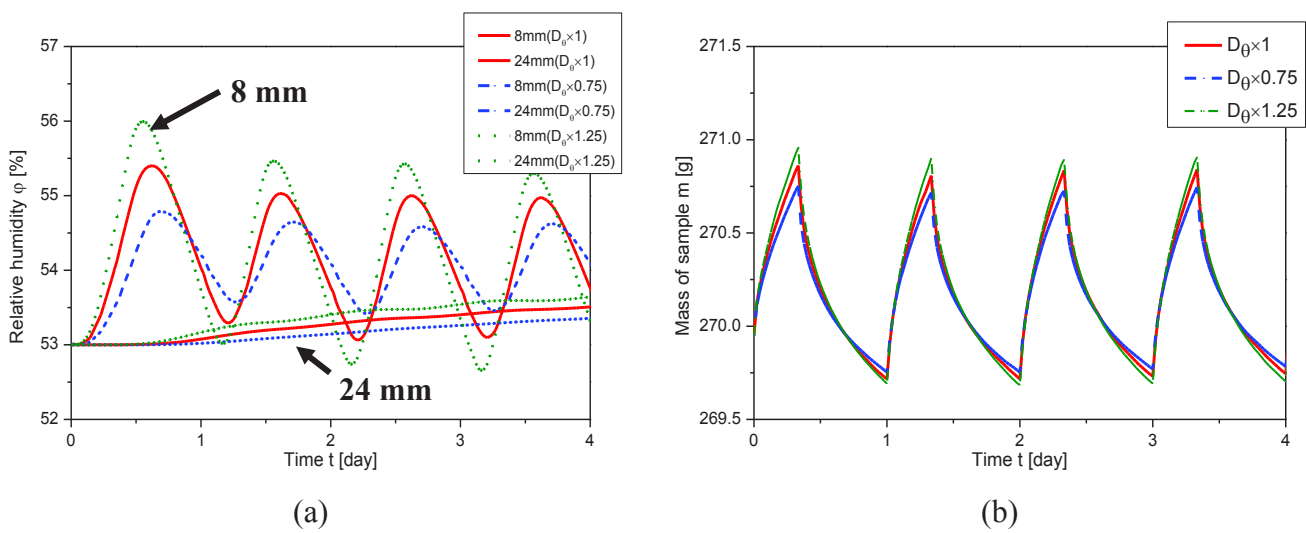
(c)

# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 10**

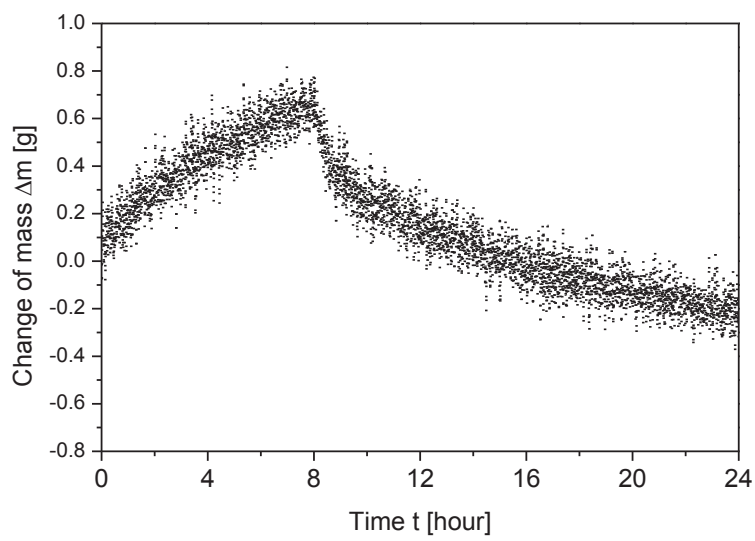
# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 11**



# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 12**





# Modelling the hygrothermal behaviour of cement-bonded wood composite panels as permanent formwork

**Figure 13**

