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Experimental and micromechanical analysis of the elastic properties of wood-aggregate concrete

A. Akkaoui*, S. Caré, M. Vandamme

*Laboratoire Navier, UMR 8205, École des Ponts, IFSTTAR, CNRS, UPE,
Champs-sur-Marne, France*

Abstract

In this work we aim to study the elastic behavior of wood-aggregate concrete. The objective is to determine the relevant microstructural and mechanical parameters of the constituents that influence its elastic properties. To reach this objective, we combined experiments and modeling. Experimental results show that the evolution over time of the elastic properties of wood-aggregate concrete is complex: it depends on storage conditions, content of binder and drying time. To well understand this evolution, we developed a micromechanical model based on the self-consistent scheme. This model captures well the experimental data and provides a predictive tool for the behavior of plant-based concrete.

Keywords: concrete, wood-aggregate, elastic moduli, Digital Image Correlation, modeling, self-consistent scheme

1. Introduction

Light-weight concrete composed of particles of plant origin and a mineral binder is increasingly studied. This concrete appears to be an environmentally-

Preprint Corresponding author: Abdessamad Akkaoui, Laboratoire Navier, École des Ponts, ParisTech, 6 et 8 avenue Blaise Pascal 77455 Marne-la-Vallée cedex 2 FRANCE; Email, abdessamad.akkaoui@enpc.fr

22 friendly material [1, 2]. Thermal performance of concrete is enhanced by the
23 use of plant-based particles like hemp, wood, or flax shives [3–5]. More-
24 over, plant-based concrete is characterized by sound insulation owing to its
25 permeability and its high open porosity [6]. Using this building material in
26 construction makes it possible to reduce greenhouse gas emissions [1] but
27 also to value by-products from other industries (e.g., woodwork activities or
28 agriculture). This material may be subjected to mechanical loadings. For
29 this reason, a better knowledge of its mechanical properties is required.

30 When studying experimentally the mechanical behavior of plant-based
31 concrete, the following properties are usually measured: compressive strength,
32 flexural strength and elastic properties. The stress/strain curve obtained
33 from compression or flexural test on this material is however rarely described
34 in the literature. Cérézo [6] observed that, for hemp concrete, the curve ob-
35 tained from compression testing generally presents a peak stress, before which
36 the load is carried by the binder, and after which the load is carried by the
37 aggregates. According to Nguyen et al. [7], the mechanical behavior is, at
38 the beginning of the test, elastic, with a homogeneous strain field over the
39 entire sample. Then the binder matrix is deteriorated and the stresses are
40 redirected toward the hemp particles that harden until eventual failure of the
41 specimen. These results need to be extended to other types of plant-based
42 particles.

43 The mechanical behavior of plant-based concrete depends on its mi-
44 crostructure. Several authors [8–11] reported that increasing the content of

45 binder in plant-based concrete leads to higher mechanical properties. Com-
46 pacting the concrete during its manufacturing is also a parameter that in-
47 creases its mechanical properties, as shown by Cérézo [6] and Nguyen et al.
48 [12].

49 To improve the understanding of the mechanical behavior of this con-
50 crete, homogenization models were reported in the literature. These models
51 can be classified into two categories: analytical [6, 13] and numerical models
52 [13, 14]. Analytical models use spherical (bicomposite or tricomposite) or
53 ellipsoidal inclusions and are based on the classical homogenization schemes
54 (e.g., self-consistent, Mori-Tanaka, and Hashin and Shtrikman). Numerical
55 modeling aimed principally to predict mechanical behavior of morphologi-
56 cally rich concretes (e.g., multi-phasic materials with bar shaped particles
57 and high porosity rates [14]) in the framework of linear and nonlinear elas-
58 ticity by iterative homogenization schemes. The developed model used plate
59 shape inclusions and finite element calculations. For these analytical and
60 numerical models, the simulated results are satisfactory [6, 13, 14].

61 However, in these models, two limitations can be mentioned. The first
62 one comes from the fact that the elastic properties used for the binder were
63 often measured on a free piece of this material, while the presence of the
64 plant-based particles can modify the behavior of the binder: i) the possible
65 exchange of water between the particles and the binder makes it difficult to
66 estimate the actual value of the water-to-cement mass ratio w/c ; ii) the pres-
67 ence of plant-based particles influences the hydration process and then the

68 mechanical properties of the binder; iii) the porous characteristic of plant-
69 based concrete induces an emphasized coupling of hydration and drying in the
70 material leading to a possible damage of the binder. The second limitation
71 is related to the inverse analysis to overcome the difficulties of determining
72 experimentally the elastic properties of the plant-based particles. These diffi-
73 culties come from: i) the possible effect of different treatments often applied
74 to the aggregates on their mechanical properties; ii) the variability of the
75 mechanical properties within the same species of plant-based particles; iii)
76 the evolution of these properties with the water content of the particles [15];
77 and iv) for some plant-based particles (e.g., hemp and flax shives), the dif-
78 ficulty to measure these properties in their directions of anisotropy. For all
79 these reasons, the inverse analysis is often used to back-calculate the elastic
80 properties of the plant-based particles. It is however necessary to discuss the
81 validity of these back-calculated properties.

82 The work reported here focuses especially on the study of elastic prop-
83 erties of wood-aggregate concrete using both experimental and theoretical
84 approaches. It aims at investigating a “model” material to determine the
85 effect of the properties of each constituent on the global behavior of the
86 concrete. Only non-compacted concrete is studied in our work. We first
87 measured the Young’s modulus of the material at different ages using digital
88 image correlation. Then, we developed a homogenization model based on
89 the self-consistent scheme, that we validate and discuss based on the exper-
90 imental results.

91 **2. Experimental study of the elastic properties of wood-aggregate**
92 **concrete**

93 *2.1. Materials and methods*

94 We studied mixtures of wood-aggregate concrete with identical content of
95 wood aggregates per unit volume and water-to-cement mass ratio ($w/c = 0.5$)
96 but with various proportions of cement paste. The cement used was a CPA-
97 CEM II/B-LL 32.5 supplied by Lafarge (Saint-Cloud, France). The mineral
98 composition of this cement determined by X-ray diffraction, performed at
99 École des Mines de Douai, is given in Table 1. This cement is characterized
100 by a density of 0.299, a Blaine surface area of $0.406 \text{ m}^2 \cdot \text{g}^{-1}$ and a compressive
101 strength at 28 days of 40.8 MPa. The wood shavings were supplied by Agresta
102 Technologies (Pouxieux, France) and were obtained from spruce. Their com-
103 mercial name is AGRESLITH-C and their characteristic size ranges from 4
104 to 10 mm. Those shavings underwent both thermal and physico-chemical
105 treatments to limit their absorption of water and then enhance their dimen-
106 sional stability. Their water content (defined as the water-to-dry-wood mass
107 ratio) was measured by drying a sample in an oven at 103°C for 48 hours and
108 was equal to 68.7%. Their bulk density ρ_b , defined as the mass of aggregates
109 divided by the total volume of the bunch they constitute, as provided by
110 Agresta, is $0.22\text{-}0.23 \text{ g} \cdot \text{cm}^{-3}$, while the apparent density ρ of wood, defined
111 as its mass per unit volume, is $0.69\text{-}0.70 \text{ g} \cdot \text{cm}^{-3}$.

112 In general, plant-based concrete is a cavernous material since it presents
113 a high volume of voids (porosity). This porosity is generally classified into

Table 1: Mineral composition of the cement used, obtained by X-ray diffraction.

Mineral	C ₃ S	C ₂ S beta	C ₃ A cubic	C ₄ AF	Calcite	Gypsum	Quartz
Mass fraction (%)	56.67	2.44	2.55	4.94	29.07	3.53	0.80

114 two categories: the intra-phase porosity (where the phase is the aggregate
 115 or the binder), which takes into account all voids in the binder and in the
 116 plant-based particles, and the macroscopic porosity (also called intergranu-
 117 lar porosity) representing the voids between the skeleton. This intergranu-
 118 lar porosity is created by the imperfect arrangement of particles when the
 119 amount of binder is insufficient to fill completely these voids. In this work,
 120 the quantity of wood aggregates, considered as a granular medium, was such
 121 that shavings were at their maximum random close packing (i.e., the ratio of
 122 their bulk density ρ_b to the density ρ of wood was considered equal to 33%
 123 [2]), while the content of cement was added in such amounts that the concrete
 124 kept a cavernous structure. We chose four cement-to-wood mass ratios c/a :
 125 $c/a = 1.25, 1.75, 2.25,$ and 2.75 . These proportions are not the ones used in
 126 commercialized concretes, they were chosen to evaluate the influence of the
 127 quantity of binder on the mechanical properties. Figure 1 shows pictures of
 128 the four mixtures.

129 As the cement paste fills the inter-particle porosity, the volume fractions
 130 of the two phases (i.e., wood aggregates and cement paste) are defined by
 131 the ratio of the volume of the phase to the apparent volume of wood aggre-
 132 gates required to prepare the samples. Assuming that the cement paste fills
 133 the inter-particle porosity without modifying the apparent volume (since the

134 layer of cement paste coating the aggregates is only a fraction of their diam-
 135 eter, as seen in the X-ray microtomography image presented in Figure 2 of a
 136 sample of wood-aggregate concrete studied in [2]), the latter was considered
 137 as the total volume of the samples. Table 2 summarizes the quantities of
 138 used materials and the resulting volume fractions. It should be noted that
 139 the volume fractions of cement paste presented in Table 2 were calculated
 140 assuming that the aggregates do not exchange water with the cement paste
 141 during the mixing process. We assume that this exchange of water can be
 142 neglected in our case given the treatments that the aggregates underwent
 143 and the used mixing process (i.e., we first mixed water and cement and then
 144 we added gradually the aggregates). In the case of a potential exchange of
 145 water during mixing, the volume fraction of cement paste should be modified
 146 accordingly since it is the sum of the volume of the cement powder and of
 147 the water available for hydration.

Table 2: Quantities of materials used and calculated volume fractions of studied mixtures. c/a is the cement-to-wood mass ratio.

	c/a	1.25	1.75	2.25	2.75
Mass of materials (g)	aggregate	1407.1	1407.1	1407.1	1407.1
	cement	1758.9	2462.5	3166.1	3869.6
	water	879.5	1231.2	1583.0	1934.8
Volume fractions (%)	aggregate	33	33	33	33
	cement paste	22.3	31.2	40.1	49.0
	air	44.7	35.8	26.9	18.0

148 We used a standard mixing machine to mix the constituents of concrete.
 149 We first mixed cement and water. Then, we gradually introduced the wood

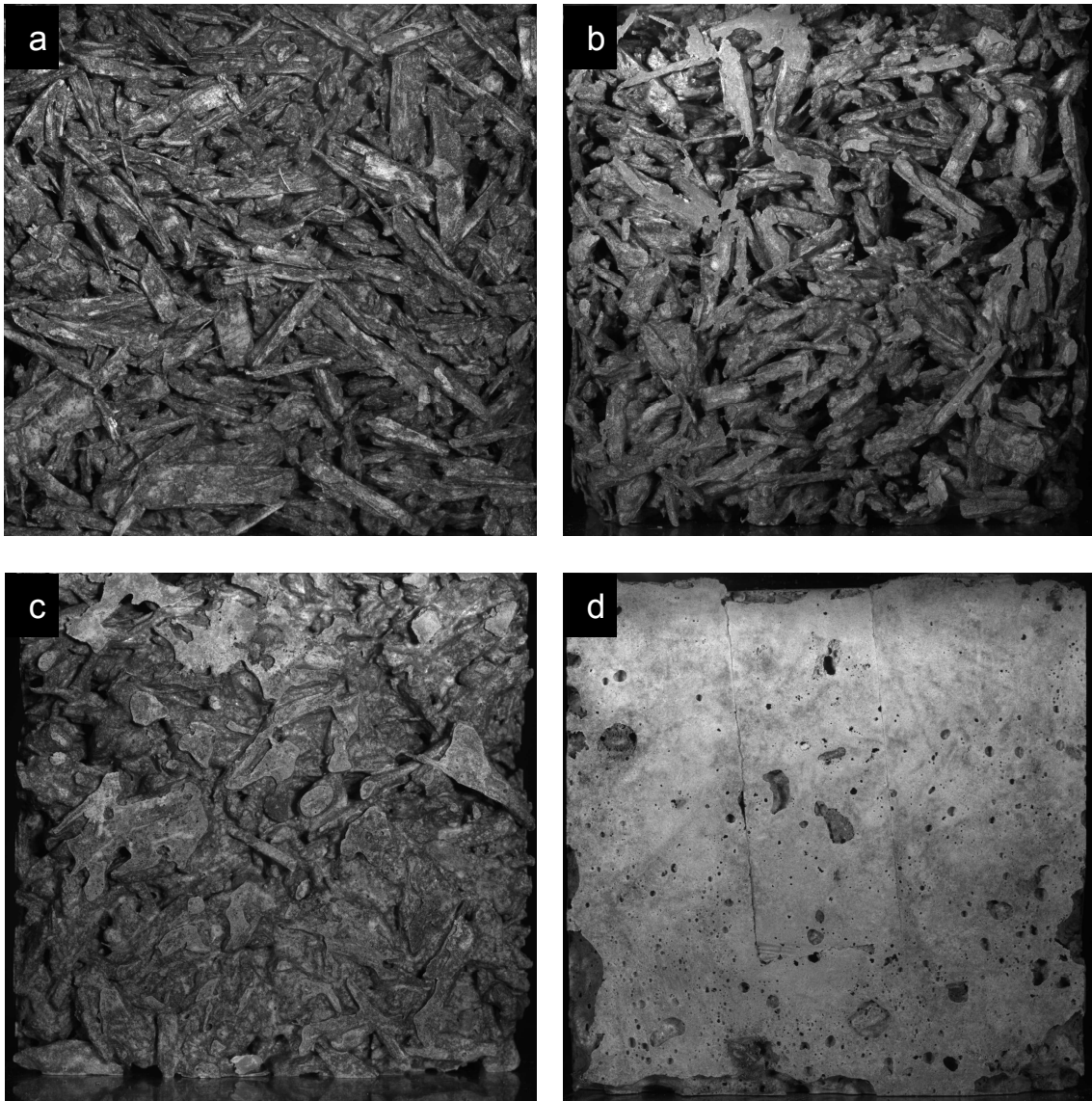


Figure 1: Pictures of the studied wood-aggregate concrete with various cement-to-wood mass ratios: a) $c/a = 1.25$, b) $c/a = 1.75$, c) $c/a = 2.25$, and d) $c/a = 2.75$.

150 aggregates. The total mixing time was 7 minutes. For each mixture, we pre-
151 pared several cubic specimens with dimensions of about $7 \times 7 \times 7 \text{ cm}^3$. These
152 dimensions are sufficient taking into account the size of the aggregates (which

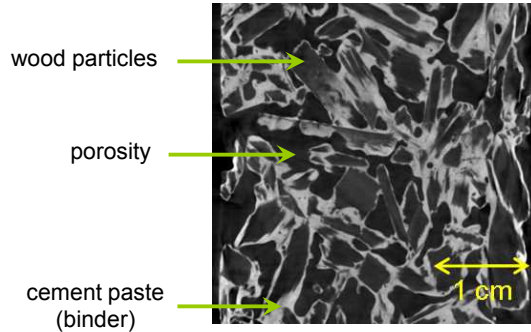


Figure 2: X-ray microtomography image of a sample of wood-aggregate concrete with $c/a = 2$ studied in [2].

153 ranges from 4 to 10 mm). The samples were kept in sealed conditions and
 154 demolded two days after casting. Then they were subjected to various stages
 155 of storage conditions. Two series of samples were subjected to two differ-
 156 ent conditions: a first series was kept in sealed conditions (by wrapping the
 157 samples into plastic films) until the day of testing; while a second series of
 158 samples was in humid conditions (i.e., relative humidity $h_r \geq 90\%$, tem-
 159 perature $T = 20^\circ\text{C}$) for 8 days and then at room conditions ($h_r \simeq 60\%$,
 160 $T = 20^\circ\text{C}$), which is closer to the conditions of use of the material.

161 We also prepared cubic samples, with dimensions of about $7 \times 7 \times 7 \text{ cm}^3$,
 162 of cement paste with a water-to-cement mass ratio $w/c = 0.5$ and we kept
 163 them, as for the second series of samples, in humid conditions (i.e., relative
 164 humidity $h_r \geq 90\%$, temperature $T = 20^\circ\text{C}$) for 8 days and then under room
 165 conditions ($h_r \simeq 60\%$, $T = 20^\circ\text{C}$) until the day of testing.

166 We used a MTS compression machine with a maximum capacity of 100
 167 kN to perform uniaxial compression tests on our cubic samples, at different
 168 ages up to 104 days. For each test, four loading/unloading cycles with an

169 increasing maximum load were performed followed by a last loading up to
170 failure. The loading rate was 10 mm/min. The compressing machine was
171 equipped with a force sensor to assess the stress applied to the material. For
172 the strains, because of the difficulty in using strain gauges or displacement
173 sensors due to the porous nature of the material, they were determined using
174 2D digital image correlation. The principle of this technique is to acquire
175 during the test images of the tested sample, i.e., to follow a face of the
176 specimen while subjected to compression. Figure 3 presents the experimental
177 device used in this study. This device is composed of: the press, a lighting
178 system and a mounting base on which is fixed an acquisition camera. This
179 camera is a Pike F-421B/C with a resolution of 2048×2048 pixels. The image
180 acquisition rate was set at 2 Hz.

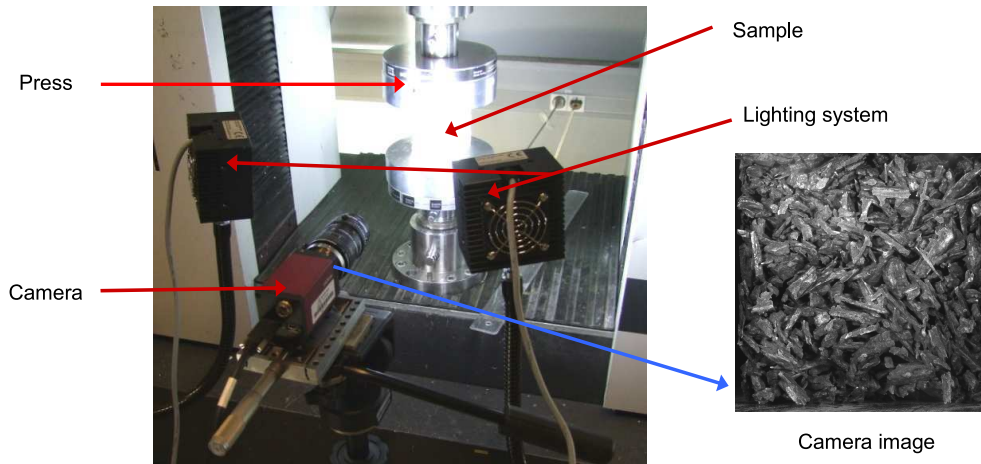


Figure 3: Experimental device used to perform compression tests.

181 The digital image correlation (DIC) method [16] provides access to the
182 2D displacement field and hence to the strains of the sample during the

183 test. In this study, we used the in-house CMV code [17] for processing the
184 acquired images. The size of the correlation window was 40×40 pixels. The
185 combination of the strains provided by this code with the stresses determined
186 with the compression machine allowed us to study the mechanical behavior
187 of the tested material. Only one test was performed at each age, but the
188 repeatability was checked on three samples with $c/a = 1.25$ at 42 days: the
189 coefficient of variation (i.e., the standard deviation divided by the absolute
190 value of the arithmetic mean) of the measured Young's modulus was 10%.

191 2.2. Young's moduli of cement paste and spruce wood

192 On the samples of cement paste described in section 2.1, we performed
193 compression tests at 21 and 28 days. The resulting Young's moduli are
194 6695 ± 86 MPa at 21 days and 9536 ± 543 MPa at 28 days. Le Roy [18]
195 proposed the following formula to estimate the Young's modulus E_p of cement
196 paste at 28 days:

$$E_p = k_{pe} \frac{K R_c}{\left(1 + 3.15 \frac{w/c}{(1+0.15(1-\exp(-11s/c)))}\right)^{2.4}} \quad (1)$$

197 where $k_{pe} = 220$, R_c is the standard compressive strength (i.e., strength
198 measured on cement mortars by the test procedures in the European standard
199 EN 197) of cement paste at 28 days ($R_c = 41$ MPa for the CEM II type
200 cement used in this work according to the specifications provided by the
201 manufacturer), w/c is the water-to-cement mass ratio (0.5 in our case), s/c is

202 the silica fume-to-cement mass ratio (0 in our case) and K is a proportionality
203 coefficient ($K = 8$ for the experiments of Marchand et al. quoted by [18]).
204 Using this formula, the Young's modulus estimated for our cement paste
205 was 7455 MPa. Taking into account the uncertainties of the parameters of
206 the proposed formula, the value we measured for our cement paste, even if
207 it is slightly higher than the estimated one, remains in the right order of
208 magnitude.

209 For spruce wood, which is an anisotropic material, we performed com-
210 pression tests in the three main directions of this material: the longitudinal
211 direction (that of the fibers), the radial direction (the direction of growth in
212 diameter), and the tangential direction. The tests were carried out on pieces
213 of solid wood that had not undergone any treatment. Pieces were stored
214 in an ambient environment such that their water content (defined as the
215 water-to-dry-wood mass ratio) was around 7%. The size of the samples was
216 about $30 \times 30 \times 100 \text{ mm}^3$ for longitudinal tests, and about $30 \times 30 \times 30 \text{ mm}^3$
217 for radial and tangential tests. The measured Young's moduli were 13700
218 MPa, 1090 MPa and 800 MPa in the longitudinal, radial and tangential di-
219 rections, respectively. These measurements are slightly higher compared to
220 bibliographic data summarized in Table 3, which were obtained at water con-
221 tent of 12%. Note that Sitka and Engelmann in this table are two types of
222 spruce wood. However, according to Gerhards [15], the Young's moduli of
223 wood depend on its water content. We can estimate the stiffness that the
224 spruce we tested should exhibit at water content of 12% using the following

225 corrections [19]:

$$E_t^h = E_t^{12} (1 - 0.015(h - 12)) \quad (2a)$$

$$E_v^h = E_v^{12} (1 - 0.030(h - 12)), \quad (2b)$$

226 where E_t^h and E_t^{12} are the longitudinal Young's moduli at a water content of
 227 h and 12 (in percent), respectively; E_v^h and E_v^{12} are the Young's moduli in
 228 the direction v ($v = r$ for radial and $v = t$ for tangential) at a water content
 229 of h and 12 (in percent), respectively. The resulting values are presented in
 230 Table 3. These values of Young's moduli extrapolated to a water content of
 231 12% are consistent with literature data [20, 21] obtained at the same water
 232 content.

Table 3: Elastic properties of spruce wood in its three principal directions: longitudinal E_l , radial E_r , and tangential E_t Young's modulus; and Poisson's ratios ν_{rl} , ν_{tr} and ν_{lt} at water content of 12%.

Reference	E_l (MPa)	E_r (MPa)	E_t (MPa)	ν_{rl}	ν_{tr}	ν_{lt}
[20]	10700	649	348	0.02	0.3	0.4
[21] Sitka	10890	849	468	0.04	0.248	0.467
[21] Engelmann	9790	1253	578	0.083	0.255	0.462
Our data	12760	950	700	-	-	-

233 2.3. Mechanical behavior of wood-aggregate concrete

234 2.3.1. Stress/strain curves

235 Figure 4 shows typical stress/strain curves obtained by compression of
 236 wood-aggregate concrete. The analysis of these curves shows that the me-
 237 chanical behavior of this material is complex and depends on its content of

238 cement: at the beginning of the compression test, the behavior is linear elas-
 239 tic whatever the content of cement paste. The limit of the elastic domain
 240 depends, however, on the amount of binder (cement paste) in the material.
 241 The higher the amount of binder, the wider the elastic domain. This result
 242 can be explained by the fact that the load is carried mostly by the binder at
 243 the beginning of the compression test [7], particularly for concretes with a
 244 high content of binder.

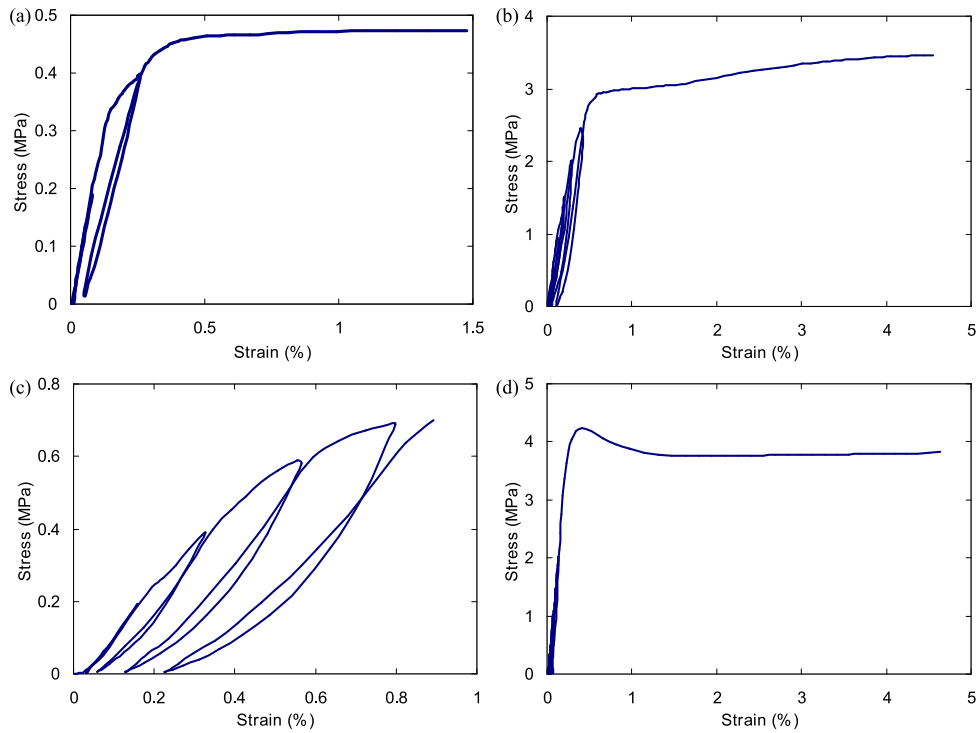


Figure 4: Typical behavior of wood-aggregate concrete: (a) with a low content of cement, (b) with an intermediate content of cement, (c) zoom in cyclic loading, and (d) with a high content of cement.

245 After the elastic phase of the behavior, residual strains appear, as we
 246 observe in Figure 4(c). These residual strains, which indicate an elastoplastic

247 behavior, might be due to the damage of the binder (i.e., progressive cracks
248 in the cement matrix and/or in the aggregate/binder interfaces). This phase
249 ends by a possible failure of the binder.

250 After the failure of the binder, we observed two main types of behav-
251 ior depending on the content of binder. In the case where this content of
252 binder is high, we observed a peak in the stress/strain curve (see, e.g., Fig-
253 ure 4(d)). This peak could be due to the fact that (1) the behavior of the
254 binder is brittle and (2) the stiffness of the aggregates is lower than that of
255 the binder [6], thus explaining the decrease in the stress supported by the
256 material. The peak is followed by a plateau corresponding to the compaction
257 of the granular skeleton, making the material denser (closing intergranular
258 and possibly intragranular porosities). In contrast, stress/strain curves of
259 wood-aggregate concrete with low content of binder show no peak (see, e.g.,
260 Figure 4(a)). The plateau corresponding to the compaction of the aggregates
261 is usually the maximum stress. The absence of a peak may be explained by
262 the fact that, at low content of binder, only a thin layer of cement paste is
263 surrounding the aggregate, so that the fraction of the loading supported by
264 the aggregates is significant.

265 These results are, in general, consistent with those of the hemp concrete
266 studies [6, 7, 12]. It therefore seems that this behavior characterizes the
267 concrete made of plant-based aggregates.

268 We used the stress/strain curves of the compression tests to determine the
269 Young's modulus of the studied concrete. This Young's modulus is calculated

270 from the linear portion of the curves. As we performed load/unload cycles
 271 on each tested specimen, the Young's modulus is the average of the moduli
 272 on these cycles, as illustrated in Figure 5.

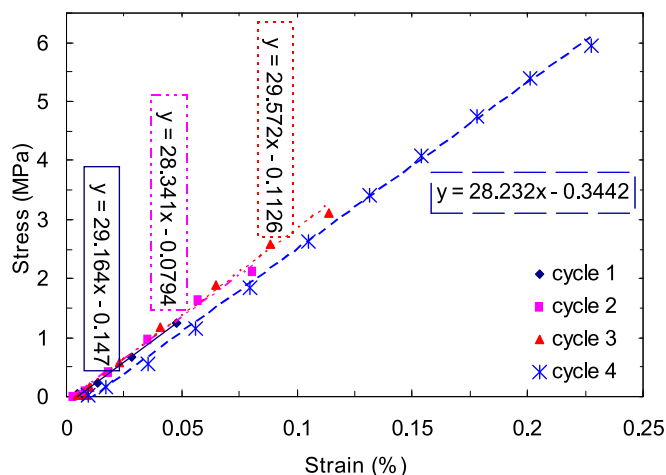


Figure 5: Typical case of determining the Young's modulus of wood-aggregate concrete from the stress/strain curve.

273 2.3.2. Young's modulus

274 We performed compression tests on the first series of samples (i.e., the
 275 one kept in sealed conditions), as described in section 2.1, at the age of 28, 62
 276 and 104 days. Table 4 presents the mass losses of the tested samples. This
 277 table shows that the mass of the samples decreased slightly (less than 4%)
 278 under the studied conditions. The reason can be that the films we used did
 279 not completely prevent exchange of humidity between our samples and the
 280 external environment. Table 5 summarizes the measured Young's moduli.
 281 For all studied mixtures, the Young's modulus increased between 28 and
 282 62 days. This increase might be attributed to the fact that, in absence of

283 exchange of humidity with the external environment, the hydration process
 284 continues to progress after 28 days. The water consumed by the hydration
 285 may be balanced by the transfer of humidity from wood aggregate to cement
 286 paste, which makes the hydration continue and enhances accordingly the
 287 elastic properties of the concrete. However, between 62 and 104 days, we
 288 observed an opposite trend for samples with low content of cement paste
 289 (i.e., samples with $c/a = 1.25$ and $c/a = 1.75$). For concrete with $c/a = 2.25$,
 290 the measured Young's modulus at 104 days was very high (nearly twice)
 291 compared to that at 62 days. These two trends after 62 days may be ascribed
 292 to the fact that some samples underwent a significant damage while others
 293 did not. Note that the Young's modulus of the concrete with $c/a = 2.75$ at
 294 104 days could not be measured because of a problem during the test.

Table 4: Mass loss (%) of samples of wood-aggregate concrete in sealed conditions.

Composition	Age (days)		
	28	62	104
$c/a = 1.25$	1.3	2.2	3.4
$c/a = 1.75$	0.5	2.1	3.7
$c/a = 2.25$	0.8	1.6	2.6
$c/a = 2.75$	0.4	1.1	3.1

Table 5: Young's modulus (MPa) of the wood-aggregate concrete in sealed conditions.

Composition	Age (days)		
	28	62	104
$c/a = 1.25$	170.6	228.9	150.6
$c/a = 1.75$	281.8	482.4	409.7
$c/a = 2.25$	650.1	857.8	1680.7
$c/a = 2.75$	1102.6	1643.6	-

295 As described in section 2.1, the second series of samples was kept in
296 conditions of use (i.e., humid conditions with relative humidity $h_r \geq 90\%$
297 for 8 days then at room conditions with $h_r \simeq 60\%$). Figure 6a displays
298 the decrease in mass of the samples under these conditions. The difference
299 of storage conditions resulted in two rates of mass loss: lower up to 8 days
300 (mass decreased by less than 3.5%) and higher after 8 days, as long as humid-
301 ity balance between samples and the outside environment was not achieved
302 (which occurred at around 30 days). Figure 6b presents the evolutions with
303 time of Young's moduli of wood-aggregate concrete until the age of 28 days
304 in conditions of use. With identical wood content, the Young's modulus in-
305 creased when the content of cement increased. This result is consistent with
306 the fact that the cement paste fills the intergranular porosity. The higher
307 the content of cement, the less porous the wood-aggregate concrete, and the
308 higher its Young's modulus. Figure 6b shows also that the Young's modu-
309 lus of wood-aggregate concrete increased with its age up to 28 days. This
310 increase in Young's moduli is a result of the evolution of two processes: hy-
311 dration and drying. The hydration of cement paste may enhance its elastic
312 properties, and drying of wood-aggregate concrete may induce an increase in
313 elastic properties of both cement paste and wood aggregates. It is however
314 difficult to identify the contribution of each of the processes on the raise of
315 Young's modulus of the concrete.

316 After the age of 28 days, two trends can be distinguished, as seen in
317 Figure 6b: for the concrete with low content of cement paste (i.e., mixtures

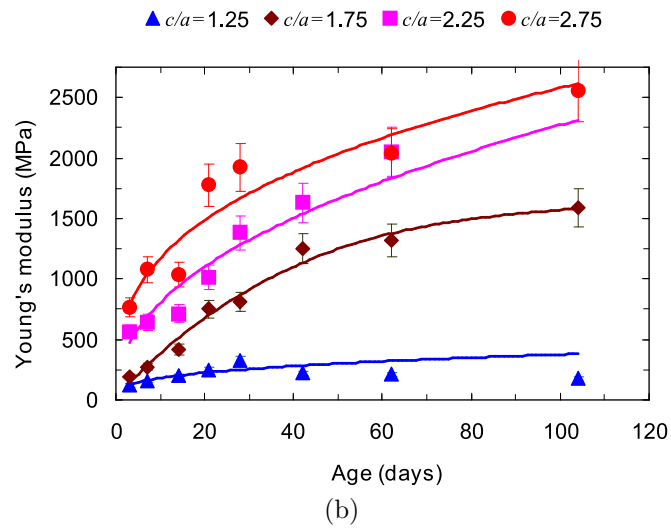
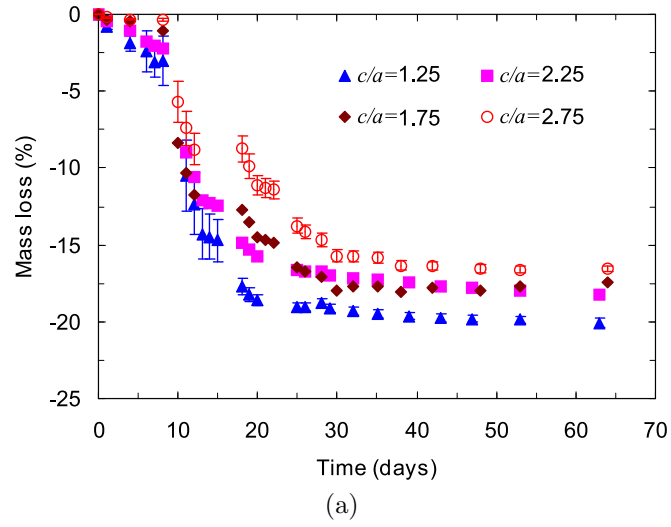


Figure 6: (a) evolution of the mass loss and (b) Young's modulus of wood-aggregate concrete kept in humid conditions for 8 days then at room conditions.

318 with $c/a = 1.25$ and $c/a = 1.75$), The Young's modulus was stabilized or
 319 even decreased (for mixture with $c/a = 1.25$ which contains the lowest con-
 320 tent of cement paste); while for the concrete with high content of cement

321 paste (i.e., mixtures with $c/a = 2.25$ and $c/a = 2.75$), it increased contin-
322 uously. The mass loss (Figure 6a) indicates that the mass of the samples
323 was stabilized at around 30 days. Drying is then no longer involved in the
324 evolution of the Young's modulus of wood-aggregate concrete after 30 days.
325 The hydration-induced modification of the microstructure of the material or
326 a possible damage of the binder are consequently the main factors driving
327 the change in its Young's modulus in that period. The low content of ce-
328 ment paste in concretes with $c/a = 1.25$ and $c/a = 1.75$ might then explain
329 their behavior after 28 days, since only a thin layer of binder surrounds the
330 aggregates. Any decline in its quality in time, for example due to damage
331 which seems to be more significant for concrete with low content of cement
332 paste, induces a decrease in Young's modulus of wood-aggregate concrete.

333 *2.3.3. Partial conclusion*

334 The experimental results presented above show that the evolution of
335 Young's modulus of wood-aggregate concrete changed its trend after 28
336 days whatever the storage conditions. This evolution of Young's modulus
337 of wood-aggregate concrete depends in fact on the content of cement paste:
338 mixtures with low content of cement paste ($c/a = 1.25$ and $c/a = 1.75$) on
339 the one hand, and those with high content of cement paste ($c/a = 2.25$ and
340 $c/a = 2.75$) on the other hand, have similar behaviors. A possible significant
341 damage of some samples after 28 days (see [22]), especially those with low
342 content of cement paste, may explain this difference. In the next section,

343 we present a predictive tool for the elastic behavior of wood-aggregate con-
344 crete. Modeling the damage is not the subject of this work, and therefore
345 only results up to 28 days are taken into account.

346 **3. Micromechanical modeling**

347 The experimental study presented in the previous section is completed
348 by a modeling work. The purpose of this modeling work is to provide a
349 predictive tool of the elastic behavior of wood-aggregate concrete, in order
350 to enable us to identify relevant parameters influencing this behavior. This
351 predictive tool is based on the technique of micromechanical homogenization.
352 This homogenization aims, in the framework of elasticity, to determine the
353 stiffness tensor of the macroscopic medium, based on the microstructure and
354 the mechanical properties of its different constituents. This exercise gener-
355 ally follows four basic steps [23]: firstly the definition of the representative
356 elementary volume (REV), secondly the choice of an appropriate mechanical
357 loading on this REV, thirdly the determination of localization fields, and
358 finally homogenization per se.

359 The definition of an REV involves representing an elementary volume of
360 heterogeneous material, by describing its geometry and its constitution, on
361 which the micromechanical analysis will be performed.

362 The purpose of the localization is to identify the local strain and stress
363 fields resulting from a macroscopically imposed mechanical loading.

364 The homogenization step consists in determining the stiffness tensor of

365 the equivalent medium from the identified mechanical response (strain and
366 stress fields) of the REV to the imposed loading. This determination can be
367 done using only the average of these fields upon each phase (constituent).

368 We adopt this approach in the next section to derive our micromechanical
369 model.

370 *3.1. Derivation of the model*

371 The concrete that we studied is characterized by randomly oriented ag-
372 gregates, since in the absence of compaction, these aggregates have no pref-
373 erential orientation. According to the work of Mom et al. [14], taking into
374 account the anisotropy and the shape of the wood aggregate is not necessary
375 to model the elastic properties of concrete incorporating randomly oriented
376 particles. Therefore, we chose spherical shapes to represent wood aggregates
377 in this work.

378 Figure 7(a) schematically shows the microstructure of wood-aggregate
379 concrete based on the observations of section 2.1 (see Figure 1). The mi-
380 crostructure shows that the wood aggregate is surrounded by a layer of
381 binder (with a variable thickness) while air occupies the porosity between
382 these aggregates (intergranular porosity). For this reason, we opted for the
383 microstructural cell shown in Figure 7(b). This microstructural cell con-
384 sists of two types of inclusions: a 2-layer spherical inclusion representing
385 wood aggregate surrounded by the binder; and a simple spherical inclusion
386 representing intergranular porosity. These inclusions are immersed into the

387 homogenized medium whose properties are to be determined.

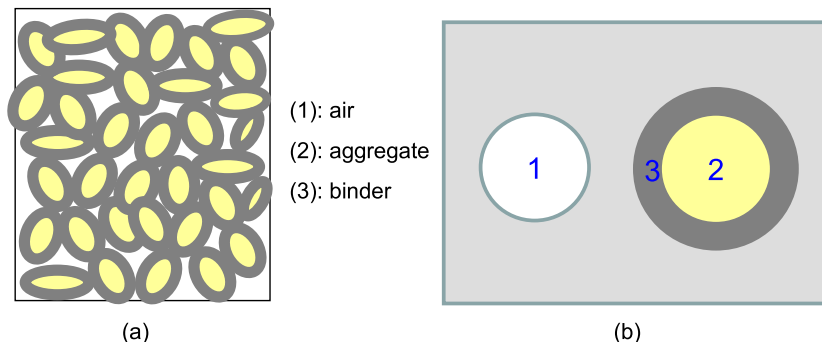


Figure 7: (a) Simplified microstructure of wood-aggregate concrete and (b) unit cell used to model the elastic properties of that concrete.

388 Due to the microstructure of the studied material, we chose to use the
389 self-consistent scheme. This scheme is indeed very well suited to the modeling
390 of granular materials for which no phase can be regarded as the matrix [23].
391 Since the objective is to determine the elastic properties of the studied con-
392 crete, we can consider only the linear elastic range of the constituents: the
393 mechanical behavior of cement paste, which is the binder, is isotropic; while
394 that of wood aggregate, being modeled by a spherical inclusion, can also
395 be considered isotropic. Thus, the behavior of the homogenized equivalent
396 medium is also isotropic linear elastic.

397 To make the approach easier, we transform the problem with two inclu-
398 sions (i.e., a simple sphere and a 2-layer composite sphere) into two basic
399 problems: the first with one spherical inclusion and the second with one 2-
400 layer composite sphere; both are subjected to a uniform strain tensor $\underline{\underline{\mathbf{E}}}^\infty$
401 at infinity, as we can see in Figure 8. The problem with a unique spherical

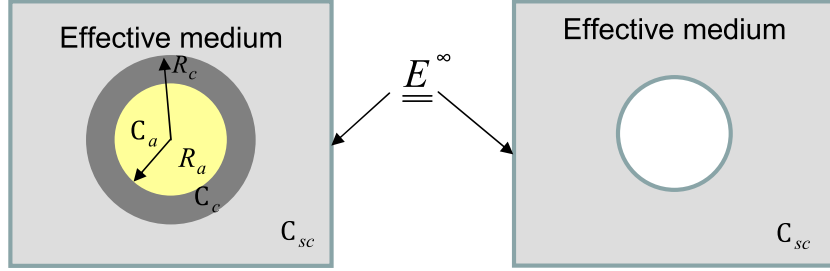


Figure 8: Basic problems with two-layer composites sphere (left) and simple composite sphere (right).

402 inclusion is the classic problem of the inclusion of Eshelby. The second prob-
 403 lem with 2-layer spherical inclusion was developed by Christensen and Lo
 404 [24]. Its solution was generalized to the case of n -layer spherical inclusions
 405 by Hervé and Zaoui [25] and applied by Caré and Hervé [26], Hervé et al.
 406 [27]. The method of resolution used in the case of our material is explained
 407 in Appendix A.

408 By combining the solutions of these two problems, we get the bulk mod-
 409 ulus k_h of the homogenized medium:

$$k_h = \frac{f_a \frac{3\mathcal{X}_a}{\mathcal{X}_h} k_a + f_c \frac{3\mathcal{X}_c}{\mathcal{X}_h} k_c}{f_p \frac{1}{1 - \alpha_h} + f_a \frac{3\mathcal{X}_a}{\mathcal{X}_h} + f_c \frac{3\mathcal{X}_c}{\mathcal{X}_h}}, \quad (3)$$

410 and its the shear modulus μ_h :

$$\mu_h = \frac{f_a \frac{1}{\mathcal{S}_h} \left(\mathcal{S}_a - \frac{21}{5} \frac{R_a^2}{(1 - 2\nu_a)} \mathcal{T}_a \right) \mu_a + f_c \frac{1}{\mathcal{S}_h} \left(\mathcal{S}_c - \frac{21}{5} \frac{R_c^5 - R_a^5}{(1 - 2\nu_c)(R_c^3 - R_a^3)} \mathcal{T}_c \right) \mu_c}{f_p \frac{1}{1 - \beta_h} + f_a \frac{1}{\mathcal{S}_h} \left(\mathcal{S}_a - \frac{21}{5} \frac{R_a^2}{(1 - 2\nu_a)} \mathcal{T}_a \right) + f_c \frac{1}{\mathcal{S}_h} \left(\mathcal{S}_c - \frac{21}{5} \frac{R_c^5 - R_a^5}{(1 - 2\nu_c)(R_c^3 - R_a^3)} \mathcal{T}_c \right)}, \quad (4)$$

411 where: \mathcal{X}_i , \mathcal{S}_i and \mathcal{T}_i are constants determined using the boundary conditions
 412 (see Appendix A), R_i is the radius of the i phase (see Figure 8), ν is the
 413 Poisson’s ratio, and α_h and β_h two parameters depending on k_h and μ_h [23].

414 The system of two implicit equations (3) and (4) with two unknowns k_h
 415 and μ_h can be solved analytically using an algebraic computing tool.

416 3.2. Calibration of the model with experimental results

417 The system of equations (3) and (4) involves several parameters. The
 418 first parameters are the volume fractions. These volume fractions were the-
 419 oretically calculated and presented in Table 2. The second parameters are
 420 the radii R_a and R_c which appear explicitly in both equations (3) and (4)
 421 but also implicitly in the constants \mathcal{X}_i , \mathcal{S}_i and \mathcal{T}_i . However, these radii are
 422 eliminated since the R_a/R_c ratio is linked to the volume fractions f_a and f_c
 423 via the following equation:

$$\frac{(R_a)^3}{(R_c)^3} = \frac{V_a}{V_c + V_a} = \frac{f_a}{f_c + f_a} \quad (5)$$

424 The last parameters involved in the system to be solved are the elastic prop-
 425 erties of the constituents (i.e., aggregates and cement paste). Bulk and shear
 426 moduli are replaced by their expressions in terms of the pair “Young’s mod-
 427 ulus E and Poisson’s ratio ν ”. We consider in hereinafter that the Poisson’s
 428 ratio of each phase is constant. For the cement paste, the Poisson’s ratio
 429 is 0.2, while for wood aggregates (whose behavior was considered isotropic
 430 since they are randomly oriented), its value is chosen equal to 0.1 by analogy

431 with what was done for hemp particles [6, 14]. This value will be discussed
432 further.

433 The missing parameters are the Young's moduli of the constituents over
434 time. These moduli are difficult to measure because of the various reasons
435 previously cited in section 1. For these reasons, we decided to determine these
436 quantities by inverse analysis based on the experimental results presented
437 in section 2.3.2 and check that their orders of magnitude are correct. To
438 do so, we used the following assumptions: (1) the Young's modulus of the
439 cement paste is considered identical for the four c/a ratios at all times; (2)
440 we neglect the evolution over time of the Young's modulus of wood aggregate
441 and we consider it identical for all studied c/a ratios. These assumptions will
442 be discussed later. Moreover, as mentioned in section 2.3.2, we limited the
443 study to the period up to 28 days. We therefore have to calibrate five Young's
444 moduli of cement paste (at 3, 7, 14, 21 and 28 days) and one Young's modulus
445 of wood aggregates, from all measurements. This calibration was performed
446 using a data adjustment function ("NonlinearFit" of Maple Software), which
447 minimizes differences between the model function and the data according to
448 the least squares method.

449 Figure 9 presents the values of the calibrated Young's moduli for the
450 cement paste and wood aggregates. The values of estimated Young's mod-
451 uli for the cement paste are generally lower than those we measured on a
452 pure cement paste at 21 and 28 days (see section 2.2). The difference may
453 confirm the modification of the process of hydration of the cement in the

454 presence of wood aggregates, a phenomenon observed by Govin et al. [28].
 455 A second explanation for the difference between the measurements and the
 456 calibrated values could be the hydration/drying coupling. This coupling is
 457 more pronounced for the wood-aggregate concrete than for the bulk cement
 458 paste, due to the higher intergranular porosity of the former. The presence
 459 of drying can slow down cement hydration when the relative humidity drops
 460 below 80% [29] thus explaining the lower elastic moduli calibrated for the
 461 cement paste in our concrete. A possible damage at some interfaces between
 462 aggregate and binder would be another reason to justify the low calibrated
 463 values: cracks at the interface result in additional porosity and a different
 464 transmission of stresses between the aggregate and the cement paste. This
 465 damage could be taken into account to enhance the model.

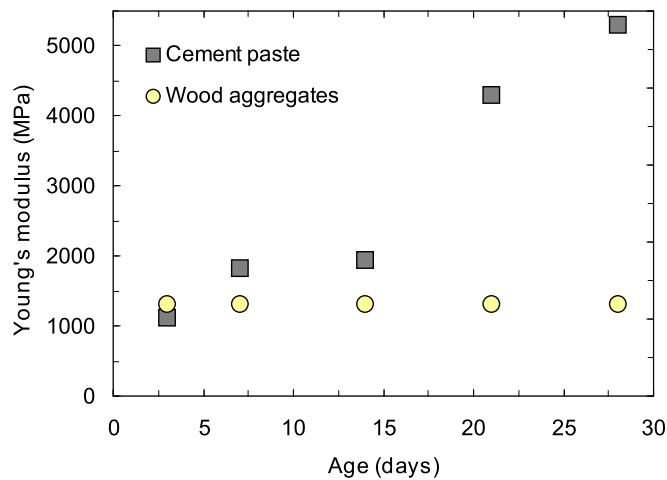


Figure 9: Young's moduli of wood aggregates and of cement paste, calibrated on experimental Young's moduli of wood-aggregate concrete.

466 The estimated Young's modulus for wood aggregates is compared to an

467 equivalent isotropic Young's modulus calculated from the Young moduli and
468 Poisson's ratios of spruce wood in its three anisotropy directions (given in
469 Table 3). Although wood is a heterogeneous material, we can determine its
470 bulk modulus k based on the data of Table 3 (see Appendix B) and, by
471 assuming a Poisson's ratio of 0.1, deduce an equivalent Young's modulus.
472 Table 6 shows the results. The average value of the Young's moduli obtained
473 from the literature is 1232 MPa. This value is consistent with the value
474 which we calibrated, which is 1192 MPa. The effect of the variation of the
475 mechanical properties of wood, in particular due to the change in its water
476 content, will be discussed in the next section.

Table 6: Bulk modulus k and estimated equivalent isotropic Young's modulus for the spruce wood.

Reference	Bulk modulus k (MPa)	Equivalent isotropic Young's modulus (MPa)
[20]	377.7	906.6
[21] Sitka	662.6	1200.3
[21] Engelmann	500.1	1590.2
Mean (MPa)	513.5	1232.3

477 3.3. Discussion

478 In the previous section, we calibrated the model we developed on the
479 experimental measurements. Realistic values were obtained for the calibrated
480 Young's moduli of the constituents of wood-aggregate concrete. We can
481 thus use the model to predict the Young's modulus of the studied concrete,
482 but also to discuss the effect of the properties of the constituents on the
483 elastic behavior of this material. Figure 10 compares the estimated and

484 measured evolutions of this Young's modulus for different c/a mass ratios.
 485 This figure shows that the developed model captures well the experimental
 486 measurements over time for all studied c/a mass ratios. The model can then
 487 be used as a predictive tool to optimize elastic properties of wood-aggregate
 488 concrete.

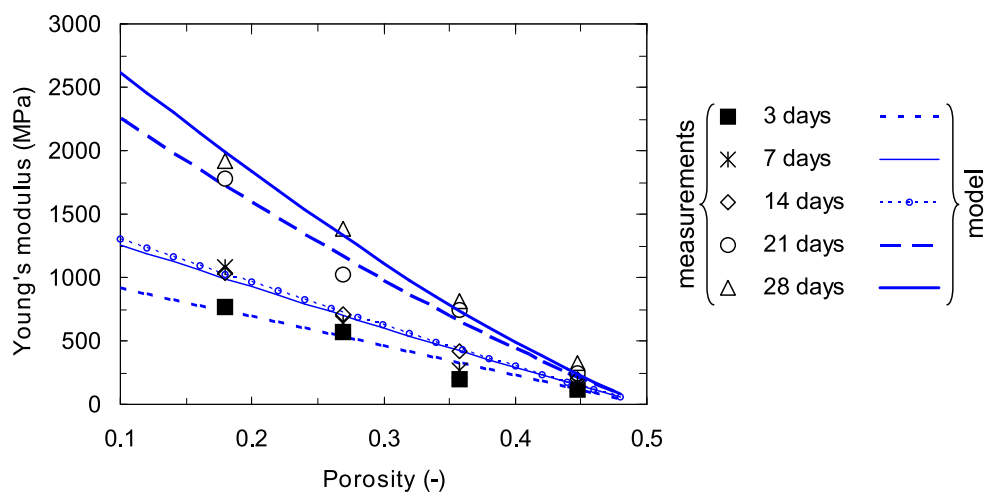


Figure 10: Young's moduli of wood-aggregate concrete as a function of its intergranular porosity: comparison between the experimental measurements and estimates of the derived model.

489 However, we made some assumptions that should be discussed. The first
 490 assumption is the choice of the Poisson's ratio ν_a of wood aggregates. The
 491 value of 0.1 was used for modeling elastic properties of hemp concretes [6],
 492 [14] but was not discussed. Here, by varying its value, we study the effect of
 493 this choice on the Young's modulus estimated with our model. Figure 11a
 494 illustrates the results obtained at 28 days for three values of the Poisson's
 495 ratio, i.e., $\nu_a = 0.1, 0.2$ and 0.3 . We can clearly see that the three curves are
 496 identical, indicating that the Poisson's ratio of the aggregates does not affect

497 the Young's modulus of the concrete predicted with our model. However, a
 498 comparison of the back-calculated Young's modulus $E_a^{\text{calibrated}}$ of the wood
 499 with the one $E_a^{\text{estimated}}$ derived from bibliographic data (Table 7) shows that
 500 the best agreement between the two moduli is obtained for $\nu_a = 0.1$. For $\nu_a =$
 501 0.2 and $\nu_a = 0.3$, back-calculation gives values of $E_a^{\text{calibrated}}$ equal to 1237 MPa
 502 and 1247 MPa, respectively; while the values of $E_a^{\text{estimated}}$ calculated based on
 503 the literature data were 924 MPa and 616 MPa, respectively. Therefore, the
 504 most appropriate value of the Poisson's ratio for an isotropic representation
 505 of the wood particle is $\nu_a = 0.1$.

Table 7: Calibrated equivalent Young's modulus $E_a^{\text{calibrated}}$ of wood aggregates based on micromechanical model compared to the modulus $E_a^{\text{estimated}}$ estimated from the elastic properties of wood in its directions of anisotropy (literature data), for different values of Poisson's ratio.

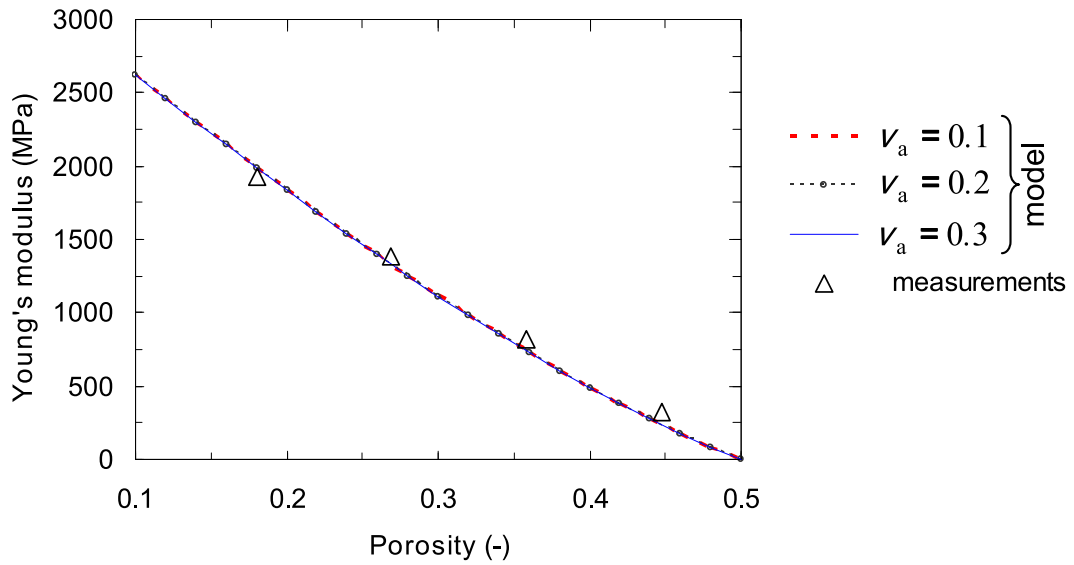
Poisson's ratio ν_a (-)	0.1	0.2	0.3
$E_a^{\text{calibrated}}$ (MPa)	1192	1237	1247
$E_a^{\text{estimated}}$ (MPa)	1232	924	616

506 The second assumption to be discussed is the temporal constancy of the
 507 Young's modulus E_a of the wood aggregates. This assumption is not always
 508 valid, especially in the presence of drying, since the mechanical properties of
 509 wood depend on its water content. If the water content of wood is modified
 510 from 25 to 12% (corresponding to a change of relative humidity from 100%
 511 to 60%), its elastic properties will increase by 15 to around 25% [15]. For the
 512 spruce wood, in addition to the measurements presented in section 2.2, we
 513 measured the Young's moduli at a water content of 25%. The longitudinal
 514 Young's modulus decreased from 12760 MPa (value estimated by using Eq.

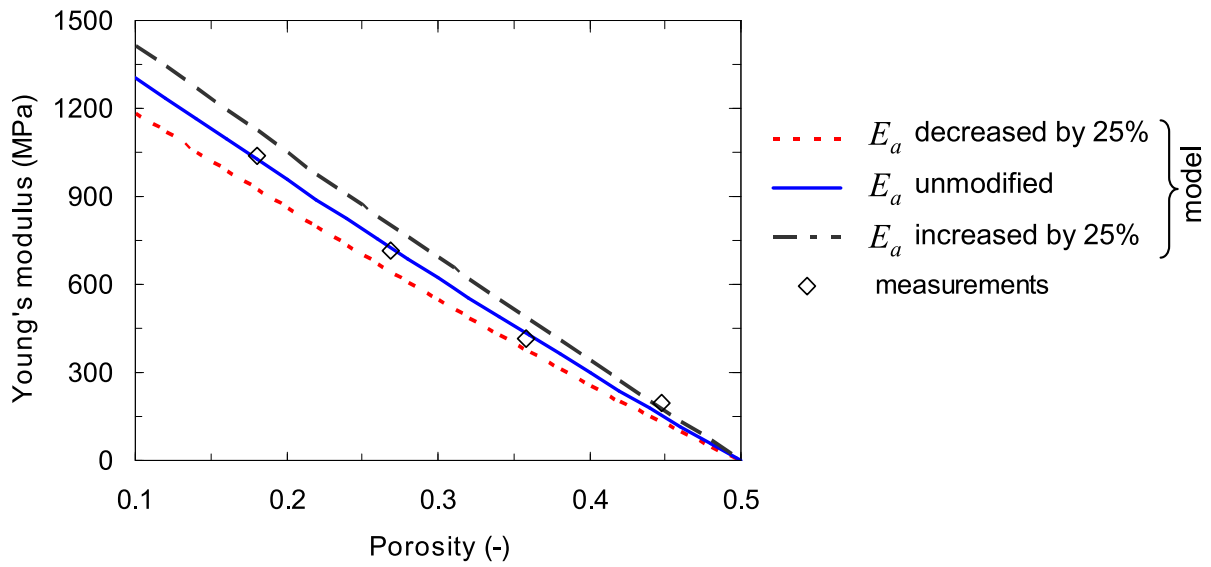
515 (2)) for a wood with a water content of 12% to 10300 MPa for a wood
516 with water content of 25%. It may therefore be important to take into
517 account this variation in the modeling. To quantify the effect of a change
518 in the Young's modulus of wood aggregates on the predicted stiffness of the
519 concrete, we compared the results obtained with the back-calculated value
520 to those obtained with an increase and a decrease of this back-calculated
521 value. Figure 11b illustrates this comparison for the concrete at 14 days. In
522 this figure, we can see that modifying the Young's modulus of the aggregates
523 by $\pm 25\%$ induces a variation of the Young's moduli of the concrete ranging
524 from $\pm 8\%$ for a porosity of 0.1 to $\pm 17\%$ for a porosity of 0.48. The order of
525 magnitude remains however correct.

526 The third assumption is the fact that we considered identical elastic prop-
527 erties of cement paste for the four studied mixtures of wood-aggregate con-
528 crete. This assumption seems to be strong, since the cement paste may
529 present different microstructures due to the difference of c/a ratios. Satis-
530 factory results are, however, produced by the model using this assumption,
531 indicating that it remains reasonable in the conditions of the present study.
532 The amount of wood aggregates is probably so high that it influences in
533 identical way the cement pastes in the range of this work.

534 In conclusion of this discussion, we can confirm the validity of the de-
535 veloped model. This model remains limited to the case of a concrete with
536 an intergranular porosity of less than 50%, which is the percolation limit of
537 the self-consistent scheme. This threshold porosity, defined as the porosity



(a)



(b)

Figure 11: Effect of elastic properties of wood aggregates on the Young's moduli of wood-aggregate concrete, as predicted with the derived model:: (a) effect of Poisson's ratio (at 28 days) and (b) effect of Young's modulus (at 14 days).

538 above which the homogenized Young's modulus vanishes, is obtained in our
539 case for a cement-to-wood mass ratio of 0.95-0.96. For concretes presenting
540 an intergranular porosity higher than 50%, an adaptation of the model to
541 the case of ellipsoidal inclusions could be a promising solution. Indeed, for
542 the self-consistent scheme, the percolation threshold depends on the aspect
543 ratio of the inclusions [30].

544 **4. Conclusion**

545 In this work, we studied experimentally and theoretically the elastic prop-
546 erties of wood-aggregate concrete, which is a very complex material that re-
547 quires original characterization methods. This study showed the potential of
548 digital image correlation technique to overcome some difficulties related to
549 the characterization of the elastic behavior of this material. However, further
550 work is required to deal with other difficulties in particular regarding how to
551 assess some properties of each constituent (i.e., of the cement paste and of
552 the aggregates) after the mixing of the concrete, in particular: water content,
553 elastic properties, and so on.

554 This study showed also that micromechanical models yield predictive
555 tools for the behavior of such heterogeneous materials. It is however nec-
556 essary to take into account the interactions (i.e., exchange of water, mod-
557 ification of hydration and so on) between the various constituents. These
558 interactions prevent the use of the properties measured on each individual
559 component as input parameters of the models. This result highlights the

560 importance of combining modeling and experiment to better understand the
561 phenomena involved in complex materials such as wood-aggregate concrete.

562 The work reported here supports some results in the literature. The
563 comparison between the Young's modulus measured on a free piece of cement
564 paste and the one back-calculated from the fit of the micromechanical model
565 confirms the effect of the presence of plant-based particles on the hydration of
566 cement. Moreover, the model here developed captures well experimental data
567 despite not taking into account the form and anisotropy of wood aggregates.
568 Therefore, for a heterogeneous material containing elongated particles whose
569 behavior is anisotropic, the use of spherical inclusions is sufficient to predict
570 the macroscopic behavior, when these particles are randomly oriented.

571 The parametric study in this work showed that some input parameters
572 (e.g., elastic properties of wood aggregates) of the micromechanical model
573 have less influence on the homogenized properties than others (e.g., elastic
574 properties of cement paste, volume fractions of phases). This finding might
575 be used to determine priorities in terms of needs of characterization of the
576 constituents of wood-aggregate concrete after mixing, but also for other con-
577 cretes whose microstructure is similar to that of wood-aggregate concrete,
578 like hemp concrete, concrete with flax shives and other bio-based materials.

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684 New York, 1944.

685 **Appendix A. Two-layered composite sphere problem in elasticity**

686 We consider a representative elementary volume of wood-aggregate con-
 687 crete, subjected in its boundary to a uniform strain tensor $\underline{\underline{\mathbf{E}}}$. We aim to
 688 determine the microscopic strain tensor at each phase (cement paste and
 689 wood aggregates). To do so, we use the microstructural cell presented in
 690 Figure 8. This microstructural cell is embedded in an infinite elastic homo-
 691 geneous medium having the stiffness tensor \mathbb{C}_h , and subjected to an auxiliary
 692 uniform strain tensor $\underline{\underline{\mathbf{E}}}^\infty$ at infinity.

693 To solve the problem easily, we first consider a spherical macroscopic
 694 strain $\underline{\underline{\mathbf{E}}}^\infty = \mathbf{E}^\infty \underline{\underline{\mathbf{I}}}$ at infinity. The displacement field solution of the problem
 695 in each phase i ($i = c, a, h$) is looked for in the form (Love [31]):

$$\boldsymbol{\xi}_r^i = \mathcal{X}_i r + \frac{\mathcal{Y}_i}{r^2}, \quad \boldsymbol{\xi}_\theta^i = \boldsymbol{\xi}_\phi^i = 0, \quad (\text{A.1})$$

696 where we used the spherical coordinates (r, θ, ϕ) , and \mathcal{X}_i and \mathcal{Y}_i are scalar
 697 constants to be determined. The stress tensor in each phase i is given by:

$$\boldsymbol{\sigma}_{rr}^i = 3k_i \mathcal{X}_i - 4\mu_i \frac{\mathcal{Y}_i}{r^3}, \quad \boldsymbol{\sigma}_{\theta\theta}^i = \boldsymbol{\sigma}_{\phi\phi}^i = 3k_i \mathcal{X}_i + 2\mu_i \frac{\mathcal{Y}_i}{r^3}, \quad \boldsymbol{\sigma}_{r\theta} = \boldsymbol{\sigma}_{r\phi} = \boldsymbol{\sigma}_{\theta\phi} = 0, \quad (\text{A.2})$$

698 where k_i and μ_i are the bulk and the shear moduli of the phase i . The
 699 constant \mathcal{X}_a vanishes to avoid a singularity at the center of the composite
 700 sphere; and from the boundary condition at infinity, we get: $\mathcal{X}_h = \mathbf{E}^\infty$. The
 701 other constants are determined by the condition of the continuity of stress

702 and displacement fields at the interfaces $r = R_a$ and $r = R_c$.

703 We now examine the case of a purely deviatoric macroscopic strain $\underline{\underline{\mathbf{E}}}^\infty =$
 704 $\underline{\underline{\mathbf{E}}}^\infty (\underline{\mathbf{e}}_1 \otimes \underline{\mathbf{e}}_2 + \underline{\mathbf{e}}_2 \otimes \underline{\mathbf{e}}_1)$ at infinity. The displacement field solution of the
 705 problem in each phase is looked for in the form (Love [31]):

$$\begin{cases} \xi_r^i = \Gamma_r^i(r) \sin^2 \theta \cos 2\phi \\ \xi_\theta^i = \Gamma_\theta^i(r) \sin \theta \cos \theta \cos 2\phi \\ \xi_\phi^i = \Gamma_\phi^i(r) \sin \theta \sin 2\phi \end{cases} \quad (\text{A.3})$$

706 with Γ_r^i , Γ_θ^i and Γ_ϕ^i scalar functions that depend only on r , and whose ex-
 707 pressions are given by the following equations:

$$\begin{cases} \Gamma_r^i = \mathcal{S}_i r - 6 \frac{\nu_i}{1 - 2\nu_i} \mathcal{T}_i r^3 + 3 \frac{\mathcal{U}_i}{r^4} + \frac{5 - 4\nu_i}{1 - 2\nu_i} \frac{\mathcal{V}_i}{r^2} \\ \Gamma_\theta^i = \mathcal{S}_i r - \frac{7 - 4\nu_i}{1 - 2\nu_i} \mathcal{T}_i r^3 - 2 \frac{\mathcal{U}_i}{r^4} + 2 \frac{\mathcal{V}_i}{r^2} \\ \Gamma_\phi^i = -\Gamma_\theta^i \end{cases} \quad (\text{A.4})$$

708 where: ν_i is the Poisson's ratio of the phase i ; and \mathcal{S}_i , \mathcal{T}_i , \mathcal{U}_i and \mathcal{V}_i are scalar
 709 constants to be determined. The stress tensor resulting from the loading can
 710 be determined in each phase from its constitutive law as follows:

$$\underline{\underline{\boldsymbol{\sigma}}}^i = \mathbb{C}_i : \nabla \underline{\underline{\boldsymbol{\xi}}}^i \quad (\text{A.5})$$

711 Here we give the expressions of $\boldsymbol{\sigma}_{rr}$ and $\boldsymbol{\sigma}_{r\theta}$ that we need to determine the

712 constants:

$$\begin{cases} \sigma_{rr}^i = \left(2\mu_i \mathcal{S}_i + (3k_i - 2\mu_i) \mathcal{T}_i r^2 - \frac{24\mu_i}{r^5} \mathcal{U}_i - \frac{18k_i + 8\mu_i}{r^3} \mathcal{V}_i \right) \sin^2 \theta \cos 2\phi \\ \sigma_{r\theta}^i = \left(2\mu_i \mathcal{S}_i - \frac{2}{3} (24k_i + 5\mu_i) \mathcal{T}_i r^2 + \frac{16\mu_i}{r^5} \mathcal{U}_i + \frac{6k_i}{r^3} \mathcal{V}_i \right) \sin \theta \cos \theta \cos 2\phi \end{cases} \quad (\text{A.6})$$

713 where we replaced the Poisson's ratio by its expression as a function of the
714 bulk and the shear moduli.

715 The constants \mathcal{U}_g , \mathcal{V}_g and \mathcal{T}_h vanish because of the boundary conditions
716 at $r = 0$ and $r \rightarrow \infty$; and from the boundary condition at infinity, we
717 get: $\mathcal{S}_h = \mathbf{E}^\infty$. The other constants are determined by the condition of the
718 continuity of stress (σ_{rr} and $\sigma_{r\theta}$) and displacement (ξ_r and ξ_θ) fields at the
719 interfaces $r = R_a$ and $r = R_c$.

720 Appendix B. Determination of the bulk modulus of wood aggregates

721

722 This section aims to determine the bulk modulus of wood aggregates
723 basing on the Young's moduli and Poisson's ratios of wood in its directions
724 of anisotropy. The bulk modulus k of a material measures the material's
725 resistance to uniform compression. It links the stress to the strain of the
726 material. More precisely, k is the proportionality coefficient between the
727 isostatic stress s and the isostatic strain rate e . We can then write:

$$s = ke, \quad (\text{B.1})$$

728 with:

$$s = \sigma_{11} = \sigma_{22} = \sigma_{33} \quad \text{and} \quad e = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}. \quad (\text{B.2})$$

729 Wood is an orthotropic material. Its constitutive law can be written in
730 Voigt notation as follows:

$$\begin{bmatrix} \varepsilon_l \\ \varepsilon_r \\ \varepsilon_t \\ \gamma_{rt} \\ \gamma_{lt} \\ \gamma_{lr} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_l} & \frac{-\nu_{rl}}{E_r} & \frac{-\nu_{tl}}{E_t} & 0 & 0 & 0 \\ \frac{-\nu_{lr}}{E_l} & \frac{1}{E_r} & \frac{-\nu_{tr}}{E_t} & 0 & 0 & 0 \\ \frac{-\nu_{lt}}{E_l} & \frac{-\nu_{rt}}{E_r} & \frac{1}{E_t} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\mu_{rt}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\mu_{lt}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\mu_{lr}} \end{bmatrix} \begin{bmatrix} \sigma_l \\ \sigma_r \\ \sigma_t \\ \tau_{rt} \\ \tau_{lt} \\ \tau_{lr} \end{bmatrix}, \quad (\text{B.3})$$

731 with:

$$\frac{-\nu_{lr}}{E_l} = \frac{-\nu_{rl}}{E_r}, \quad \frac{-\nu_{lt}}{E_l} = \frac{-\nu_{tl}}{E_t}, \quad \frac{-\nu_{rt}}{E_r} = \frac{-\nu_{tr}}{E_t}. \quad (\text{B.4})$$

732 Using this constitutive law, we can express $e^a = \varepsilon_l + \varepsilon_r + \varepsilon_t$ as a function
733 of $s^a = \frac{1}{3}(\sigma_l + \sigma_r + \sigma_t)$ taking into account the fact that $\sigma_l = \sigma_r = \sigma_t$. And
734 using this expression together with equation (B.1), the following equation
735 yields:

$$\frac{1}{k^a} = \frac{1 - \nu_{lr} - \nu_{lt}}{E_l} + \frac{1 - \nu_{rl} - \nu_{rt}}{E_r} + \frac{1 - \nu_{tr} - \nu_{tl}}{E_t}. \quad (\text{B.5})$$