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- 30 - The earthwork waste reuse capacity for earth construction is estimated at regional scale
- 31 - The first map of earth construction material availability at regional scale is proposed
- 32 - Five texture classes of suitability for cob soils are defined for Brittany
- 33 - Texture results call into question recommendations available in the literature

34 **Keywords:** cob; earthwork waste; earth construction; rammed earth; adobe; pedology

## 35 **1 Introduction**

36 The construction sector consumes a large volume of natural resources and is responsible for about 50 % of  
37 wastes production in the European Union [1–5]. These wastes have a negative environmental impact [2–4] and it  
38 is increasingly difficult to find suitable landfill areas [4,5]. Among these construction wastes, about 75 % are  
39 soils and stones [1,6]. Earth construction is a possible market for earthwork wastes, but no data is available about  
40 the quantification of local stocks and flows of soils suitable for earth construction. Therefore, the resources to get  
41 a low impact building must be found locally, a mission that is challenged by the local soil variability [7].

42 Overall, this situation prevents modern earth building markets to develop.

43 The aim of this paper is to propose a novel methodology to identify and quantify soil resources available for  
44 earth construction in order to assess the potential market share of the earth construction sector and waste  
45 reduction by the construction industry.

46

47 Suitability of earth for construction purposes is usually determined using a geotechnical approach, aimed at  
48 enhancing the mechanical strength of earthen specimens carried out in the laboratory [8–10]. The most cited  
49 criterion to assess earth suitability is texture, i.e. balance between clay, silt, sand and gravel content [11].

50 Consequently, grading envelopes adjusted to each earth construction technique were proposed in the literature  
51 [8,12–17]. However, textures of materials collected in vernacular earth heritage buildings do not fit inside those  
52 grading envelopes [18–23]. Thus, grading envelopes available in the literature failed to give full account of the  
53 diversity of earth employed for construction [24].

54 Another approach to identify material suitability for construction is to analyse materials traditionally used in  
55 heritage buildings [18–21]. Soils for vernacular earth construction were excavated directly on-site or at a  
56 distance less than 1 km away from the construction site [19,21,24–29]. As a consequence, the presence of earth  
57 heritage highlights the presence of soils suitable for construction [19,21]. A high proportion of earth building  
58 heritage indicates a priori (1) a large availability of earth, (2) a good quality of earth allowing easy

59 implementation, (3) a high longevity of cob buildings and (4) a favourable cultural context. Vernacular soil  
60 selection is the result of time-tested empirical experimentations and the proposed methodology aimed at  
61 rediscovering this past know-how and to consider it for modern earth building.

62

63 Several authors identified material sources through comparison between materials inside walls of heritage  
64 buildings and available local materials using geological analysis [18–20,22,27] and, more rarely, pedological  
65 analysis [19,21]. Geological maps are preferred to pedological maps for material source identification as they  
66 provide more detailed and homogeneous cartographic information [21]. However, pedology is considered as  
67 more relevant than geology for identification of earth material sources [13,19,21]. Recently, in France, the  
68 completion of regional pedological maps offers new opportunities to analyse soils next to earth heritage.  
69 Hence, the new methodology proposed in this paper is based on the cross-referencing of spatialized pedological  
70 and heritage data. Pedological particularities of areas containing earth heritage are highlighted and these  
71 particularities are used to propose criteria to assess the suitability of soils for vernacular earth construction and  
72 scale of availability of the resource to repair earth built heritage or to build new low impact buildings with  
73 integrated modern earth walls. This new methodology is exemplified in this paper in Brittany (France) but can be  
74 extended to regions having heritage and soil information. For this study, Soils of Brittany [30] and the Cultural  
75 Heritage of Brittany databases [31] were used.  
76 In Brittany the vernacular earth construction technique is cob. The cob technique employs earth elements in a  
77 plastic state, implemented wet and stacked to build a monolithic and load-bearing or freestanding wall [24]. The  
78 paper deals with cob, but the use of the methodology can be expanded to other earth construction techniques,  
79 like rammed earth or adobe masonry for example.

## 80 **2 Methodology description**

### 81 **2.1 Soil suitability determination**

82 The relative densities of earth buildings are an indicator of suitability of soils for earth construction [21].  
83 Relative densities were calculated by cross-referencing between heritage and soil databases covering the same  
84 geographical area. The spatialized heritage database must provide homogeneous information on the vernacular  
85 architecture of the studied area and must concern all vernacular materials (timber, stone, earth, solid bricks). The

86 described methodology is designed for the French soil cartographic representation called “*Référentiel Régional*  
87 *Pédologique*” (RRP), but can be adapted to other cartographic representations.

88

89 Soil cartographic representation by the RRP is a set of polygons, spatially delineated, defining Soil Map Units  
90 (SMUs) [32]. Since soils show rapid variations in three dimensions, each SMU corresponds to a soil landscape,  
91 i.e. a collection of soils, defined as a Soil Type Unit (STU), developed in a common environment. Each SMU  
92 includes 1 to 10 STUs which are not spatially delineated [30,33] (Figure 1). Each STU is divided into strata,  
93 representing the vertical variability of soil. Pedological characteristics of SMUs, STUs and strata (such as depth  
94 and thickness, texture and Cation Exchange Capacity) are gathered in a semantical database (Figure 1).

95

96 The aim of the calculation is to identify the pedological characteristics (clay, silt, sand, gravel content and Cation  
97 Exchange Capacity) of soils according to their suitability with earth building. This calculation is carried out in 3  
98 steps: (1) calculation of the frequency of earth heritage building for each Soil Type Unit, (2) exclusion of Soil  
99 Type Unit which can be regarded as outlier values, (3) calculation of minimum and maximum values of  
100 pedological characteristics of the Soil Type Units of a same frequency class. The calculation is detailed below  
101 and parameters are detailed in Table 1.

102

103 Heritage and pedological data are combined in a Geographic Information System so that the total heritage and  
104 earth heritage number of buildings, respectively  $TOT\_SMU$  and  $EARTH\_SMU$ , can be determined for each  
105 SMU. The total and earth heritage building numbers of a SMU are attributed to the STUs that compose the SMU  
106 with respect to the surface proportion of STUs in the SMU ( $SURF\_STU_{SMU_i}$ ). The total numbers of heritage and  
107 earth heritage buildings of a STU, respectively  $TOT\_STU$  and  $EARTH\_STU$ , are the sum of total or earth  
108 heritage buildings of the STU on the SMUs inside which it is present (Figure 1):

$$109 \quad TOT\_STU = \sum_i SURF\_STU_{SMU_i} \times TOT\_SMU_i \quad (1)$$

$$110 \quad EARTH\_STU = \sum_i SURF\_STU_{SMU_i} \times EARTH\_SMU_i \quad (2)$$

111 In order to discuss the relative densities of vernacular earth buildings of the studied area, the frequency of earth  
112 buildings ( $FREQ_{STU}$ ) are calculated for each STU:

113 
$$FREQ_{STU} = \frac{EARTH_{STU}}{TOT_{STU}} \quad (3)$$

114 This calculation is exemplified using a theoretical case in Figure 2.

115 Earth frequencies of STUs go from 0 to 1 and are divided into 11 frequency classes (Table 2). The frequency  
 116 describes the suitability of STUs with regard to earth construction: the higher the frequency, the higher the  
 117 suitability. Absence of earth heritage can reflect a poor suitability of available soils but this can also be explained  
 118 by historical or social reasons. Consequently, suitability of soils is assessed using frequency classes greater than  
 119 1%, but it is not possible to state that characteristics of strata with frequencies lower than 1% are not compatible  
 120 with earth construction. The frequency of a stratum ( $FREQ_{STRATA}$ ) is assumed to be equal to the frequency of its  
 121 STU ( $FREQ_{STU}$ ).

122 The standard deviation  $\sigma_{FREQ_{STU}}$  of  $FREQ_{STU}$  is calculated as below:

123 
$$\sigma_{FREQ_{STU}} = \sqrt{\frac{FREQ_{STU} \times (1 - FREQ_{STU})}{TOT_{STU}}} \quad (4)$$

124 A maximum standard deviation  $\sigma_{FREQ_{STU\_MAX}}$  is set by the researcher, in order to exclude outlier values.

125 In order to ensure that the data is representative, a minimum total heritage building per STU,  $n_{STU}$ , is calculated  
 126 for a 95% confidence interval, a margin of error  $e$  and for total heritage buildings of the STU  $N$ :

127 
$$n_{STU} = \frac{1.96^2 \times N}{1.96^2 + (2e)^2 \times (N-1)} \quad (5)$$

128 Consequently, only STUs having a standard deviation  $\sigma_{FREQ_{STU}}$  lower than  $\sigma_{FREQ_{STU\_MAX}}$  and counting  
 129 more than  $n_{STU}$  total heritage buildings are taken into consideration in the analysis.

130

131 Topsoil is rich in organic matter and was therefore inappropriate for construction purpose. Since soil excavation  
 132 was traditionally made by hand, only subsoil near the surface was used, i.e. a large surface area and a thin layer  
 133 of soil below the topsoil [24]. This is why organo-mineral (A, LA, H) and deep (appearance depth > 50 cm)  
 134 strata were not considered in the analysis.

135

136 Pedological characteristics (*CHARACTER*) were determined during the soil of Brittany campaign [30,33]. The  
 137 available pedological characteristics of the database are clay, silt, sand, gravel content and Cation Exchange  
 138 Capacity (CEC). During the soil of Brittany campaign [30,33] particle size distribution was determined by wet  
 139 sieving for fractions greater than 50  $\mu\text{m}$  and by Robinson pipette method for smaller fractions, according to

140 French Standard NF X 31-107 [34]. CEC of the database was determined using the Metson test method [35],  
 141 according to French Standard NF X 31-130 [36].

142 The pedological database contains modal, and, when available, minimum and maximum value for each  
 143 characteristic of strata. Minimum (*MIN*) and maximum (*MAX*) values illustrate the range of value that can vary  
 144 spatially due to natural variations of soils, each strata resulting from various discrete observations. When  
 145 minimum and maximum values were available, these variations were taken into account by calculation of an  
 146 estimated confidence interval. As the average and standard deviation are unknown, a half-confidence interval  
 147 ( $CONF\_INT_{STRATA}$ ) was estimated as the third of the range of the values:

$$148 \quad CONF\_INT_{STRATA} = \frac{MAX - MIN}{3} \quad (6)$$

149 Consequently, the confidence level of the estimated confidence interval is not determined.

150 For each frequency class *i* ( $CLASS_i$ ), the average value of each characteristic ( $CHARACTER_{STRATA_j\_CLASS_i}$ ),  
 151 weighted by the earth frequency of the *j*<sup>th</sup> strata ( $FREQ_{STRATA_j}$ ) is calculated:

$$152 \quad \overline{CHARACTER_{STRATA_j\_CLASS_i}} = \frac{\sum_{i,j} CHARACTER_{STRATA_j\_CLASS_j} \times FREQ_{STRATA_j}}{\sum_i FREQ_{STRATA_j}} \quad (7)$$

153 For each frequency class *i* ( $CLASS_i$ ), the average value of confidence interval of each characteristic  
 154 ( $CONF\_INT_{STRATA_j\_CLASS_i}$ ), weighted by the earth frequency of the *j*<sup>th</sup> strata ( $FREQ_{STRATA_j}$ ) is calculated:

$$155 \quad \overline{CONF\_INT_{STRATA_j\_CLASS_i}} = \frac{\sum_{i,j} CONF\_INT_{STRATA_j\_CLASS_j} \times FREQ_{STRATA_j}}{\sum_i FREQ_{STRATA_j}} \quad (8)$$

156 Finally, the minimum and maximum value of a characteristic, for a frequency class, respectively

157  $MIN_{CHARACTER\_CLASS_i}$  and  $MAX_{CHARACTER\_CLASS_i}$ , are calculated:

$$158 \quad MIN_{CHARACTER\_CLASS_i} = \overline{CHARACTER\_CLASS_i} - \overline{CONF\_INT\_CLASS_i} \quad (9)$$

$$159 \quad MAX_{CHARACTER\_CLASS_i} = \overline{CHARACTER\_CLASS_i} + \overline{CONF\_INT\_CLASS_i} \quad (10)$$

## 160 2.2 Earth resource quantification

161 In order to reflect vernacular extraction conditions, soil suitability was determined considering the horizons with  
 162 depth less than 50 cm only. Modern excavation means give access to deeper soils this is why the quantification  
 163 calculation takes into account all pedological horizons, whatever their depths are. Clay, silt, sand, gravel content  
 164 and CEC minimum and maximum values of each frequency class are used to identify strata suitable for earth



165 construction in the pedological database. The volume of earth suitable for construction for each frequency class  
 166 ( $VOL\_EARTH_{CLASS_i}$ ) is the sum of the volume of strata suitable for construction:

$$167 \quad VOL\_EARTH_{CLASS_i} = \sum THICK_{STRATA} \times SURF\_STU_{SMU} \quad (11)$$

168 The volume of earth is calculated considering several frequency classes. The classes to be considered for this  
 169 calculation are set on expertise:

$$170 \quad VOL\_EARTH = \sum_i VOL\_EARTH_{CLASS_i} \quad (12)$$

171 And the proportion of soils suitable for earth construction ( $PROP\_SOIL$ ) on the studied area is:

$$172 \quad PROP\_SOIL = \frac{VOL\_EARTH}{VOL\_SOIL} \quad (13)$$

173 Where  $VOL\_SOIL$  is the volume of all soils of the studied area.

174 To provide a cartographic representation of the resource availability, the volume of soils suitable for construction  
 175 ( $VOL\_EARTH_{SMU_i}$ ) is calculated for each SMU:

$$176 \quad VOL\_EARTH_{SMU_i} = \frac{\sum VOL\_EARTH\_STU_{SMU_i}}{n\_STU_{SMU_i}} \quad (14)$$

177 With  $VOL\_EARTH\_STU_{SMU_i}$  calculated according to equation (11) and  $n\_STU_{SMU_i}$  the number of STU in the  
 178 considered SMU.

179 Resource availability is also presented by surface. The surface of a SMU suitable for earth construction  
 180 ( $SURF\_EARTH_{SMU_i}$ ) is the sum of the surface of the STUs of this SMU suitable for earth construction  
 181 ( $SURF\_EARTH\_STU_{SMU_i}$ ):

$$182 \quad SURF\_EARTH_{SMU_i} = \sum SURF\_EARTH\_STU_{SMU_i} \quad (15)$$

### 183 **3 Application to cob in Brittany (France)**

#### 184 **3.1 Study area**

185 Brittany is part of the Armorican Massif. This Massif is the result of, at least, three orogenies. Rocks of this  
 186 geological domain are mostly old sedimentary rocks, more or less metamorphosed (sandstone, schist),  
 187 metamorphic rocks (gneiss), magmatic rocks (granite, rhyolite) and loess deposits [37–39]. Paedogenesis of the

188 massif is dominated by darkening and leaching. Locally, podsolization and a paleopedogenesis, marked by a  
189 fersiallitization, are mentioned [40].

190 Among Armorican rocks, Brioverian schists are sensitive to alteration and thus produced thick soils that  
191 favoured cob construction [18,41–44]. Soils deriving from other local parental materials (granite, sandstones,  
192 Cambrian schists) were also employed for cob construction [18]. Nevertheless, the correlation between geology  
193 and cob heritage distribution in Brittany did not provide satisfactory results [43].

### 194 **3.2 Heritage and pedological databases**

195 Since 1964, historians and architects of the *Service du Patrimoine Culturel* of Brittany have carried out a  
196 systematic field inventory of regional cultural heritage and maintained a regional database [31]. This heritage  
197 database was homogenized in order to create a unique point database, counting 113,824 entities (buildings, castle  
198 mound, archaeological sites, crosses, statues ...). To focus on vernacular building heritage, the items without  
199 information on building materials, built after 1925, of military or religious character, or built with a modern  
200 material (steel, glass, concrete, hollow brick) were removed from the database. Subsequently, a database of  
201 48,230 heritage buildings was obtained. Among these 48,230 buildings, 7,133 were identified as cob buildings,  
202 which represents 14.8% of the studied heritage (Figure 3) and 24% of the estimated total cob heritage of Brittany  
203 [44]. These buildings date back as far as the 16<sup>th</sup> century (Figure 4). Other heritage building materials were  
204 stone, timber and solid brick.

205 The heritage survey of Brittany is not yet complete. Municipalities having no data were therefore not considered  
206 in this study. The study area represents 54% of the total surface of Brittany and the proportion of study area  
207 inside and outside the vernacular cob area, determined using literature data [41,43,45,46], is well balanced  
208 (Figure 3). The geographical distribution of the study area reflects the heritage distribution of Brittany and is  
209 therefore considered as satisfactory.

210

211 Soil information at 1:250,000 map scale in Brittany was obtained in the framework of the “*Référentiel Régional*  
212 *Pédologique*” (RRP) project, started in 2005, certified in 2012 and available online [30].

### 213 **3.3 Data processing**

214 The minimum total heritage building per STU,  $n_{STU}$ , is calculated according to equation (5), considering  
215  $N = 48230$  and  $e = 0.1$ :  $n_{STU} = 96$ . The  $\sigma_{FREQ_{STU\_MAX}}$  is set to 0.03. Among 288 STUs, 68 STUs verify those  
216 two parameters and are considered for the analysis. Five of these STUs had missing information and were

217 therefore not considered for the analysis. Cob frequency ( $FREQ_{STU}$ ), frequency class ( $CLASS$ ) and standard  
218 deviation ( $\sigma_{FREQ_{STU}}$ ) of the 63 STUs employed for the analysis are presented in Table 3. Frequencies range  
219 from 0.00 to 0.49. As a consequence, 6 frequency classes were considered (Table 3).

## 220 **4 Results and discussion**

### 221 **4.1 Resource identification**

#### 222 **4.1.1 Texture**

223 Textures (clay, silt, sand and gravel contents) of pedological strata for 5 frequency classes are presented in Table  
224 4, and the 20-50% cob frequency textures are presented in Figure 5. The coloured surfaces of the radar graphical  
225 representation of Figure 5 allow an easy comparison between recommended textures, but only the extremum  
226 clay, silt, sand and gravel contents are to be considered. They do not present any minimum gravel content, only a  
227 maximum value, ranging from 2% for 40-50% frequency class to 30% for the 1-10% frequency class (Table 4),  
228 indicating that vernacular cob earth in Brittany had no or low gravel content.

229 Gravels are sometimes observed in vernacular cob walls. These gravels might have been added on purpose but  
230 most of the time it might have been already present in the excavated soil. As highlighted by [24] gravels can play  
231 the role of shrinkage crack barrier and therefore temper the drying shrinkage effect. However, most of the time,  
232 natural fibres were added in order to play this role [24]. Past builders prepared the cob mixture by trampling the  
233 material bare foot of wearing wooden clog. Large gravels have made the cob mixing difficult. Moreover, cob  
234 walls were often cut to rectify their surface and gravels disturbed this action [24,47]. This is why, most of the  
235 time, large gravels were removed from earth. Consequently, past builders developed specific cob techniques  
236 adapted to earth with high gravel content, but, when possible, little or zero gravel content earth were preferred.  
237 From our field observations in Brittany cob heritage walls with large gravels are an exception. Results are  
238 consistent with the constraints of the vernacular cob process.

239

240 Clay, silt and sand content of strata having an affinity with cob have a minimum and a maximum value (Figure  
241 5, Table 4). These three granular fractions were therefore required for cob construction. The balance between  
242 these three fractions is clearly in favour of silts, since they represent 37% to 57% of the material (Figure 5, Table  
243 4). Among the large variety of soils available in Brittany, cob heritage preferentially set up on silty soils (Figure  
244 5).

245 Fine earth fraction ( $< 2$  mm) represents the clay, silt and sand content of earth without coarse elements (Clay +  
246 Silt + Sand = 100%). The texture of fine earth are depicted by points in the GEPPA texture triangle [48],  
247 conventionally used for French soil identification (Figure 6). In this representation, whatever the gravel content,  
248 sum of clay, silt and sand content is 100%.

249 Among soils of Brittany, textures of fine earth with a 1-50% cob frequency are the siltiest (Figure 6). The texture  
250 of fine earth of 40-50% cob frequency is mostly silty, and with lower cob frequencies, the silt fraction decreases  
251 in favour of the sand fraction and maximum clay content slightly increases (Figure 6, Table 5).

#### 252 **4.1.2 Comparison of texture results with existing recommendations**

253 Different grading envelopes are proposed in the literature [13–15,17]. These recommendations were adapted and  
254 are presented in Figure 7 and Figure 8(a).

255 The comparison between texture of strata, identified as having an affinity with cob heritage in Brittany, with  
256 recommended textures for cob available in the literature (Figure 7) indicates that: (1) clay content of cob with a  
257 20-50% cob frequency is inside the literature recommendations [13–15,17]; (2) recommendations from the  
258 literature propose a minimum gravel content [13–15,17], supporting the hypothesis that gravels are necessary in  
259 cob material, which contradicts the results of this study; (3) the balance between sand and silt is in favour of sand  
260 in the literature [13–15,17] and in favour of silt in this study.

261 As for texture of earth with coarse elements, the texture of fine earth within the cob area of Brittany widely  
262 differs from recommended texture of fine earth available in literature (Figure 8(a)). The same difference has  
263 been highlighted by several authors for vernacular cob materials [18–21], vernacular adobe [22] and vernacular  
264 rammed earth materials [23,29]. In fact, earth suitability recommendations are based on a theoretical laboratory  
265 approach, whereas vernacular soil selection is the result of time-tested empirical experimentations. Textures  
266 identified in this study enlarge the volume of possible earth material suitable for cob construction and call into  
267 question recommendations available in the literature.

#### 268 **4.1.3 Comparison of texture results with existing data**

269 Data on textures of heritage cob buildings are available for Germany [47] and the United Kingdom [20]. These  
270 data have been adapted and are presented in Figure 8(b). Fine earth material of cob heritage in Germany, more  
271 precisely in Saxony, Saxony-Anhalt and Thuringia [47], have a sand/silt balance quite similar to high frequency  
272 fine earth texture determined for cob in Brittany, but their clay content (2-6%) is smaller (Figure 8(b)).

273 In Devon (United Kingdom), it is demonstrated that traditional cob walls built with soils derived from Permo-  
274 Triassic rocks had higher propensity to structural failure than those derived from the “Culm measure” rocks [20].  
275 Textures of fine earth, from what the authors called a “high risk zone”, labelled by red circles on Figure 8(b), are  
276 outside the texture of fine earth identified for cob in this study. Results are therefore in accordance with those of  
277 Keefe et al. [20]. Nonetheless, even if considered as “high risk” materials, historical builders in Devon managed  
278 to build cob houses with these earth. Thus, textures of earth identified as suitable for traditional cob in Brittany  
279 do not cover the entire textures of earth employed in Devon’s vernacular cob. Since no information was provided  
280 on texture of earth of undamaged cob walls, it was not possible to state if earth suitable for cob in Devon are  
281 inside or outside the cob area defined in the present study (Figure 8(b)).  
282 Hence, the results of this study are relevant only for Brittany. Nevertheless, silty textures of fine earth seem to  
283 have been preferred by past builders, at least in Brittany and Germany.

#### 284 4.1.4 Cation Exchange Capacity and clay

285 Cation Exchange Capacity (CEC) of a soil is intimately linked to the specific surface area of clay and organic  
286 matter content [49–52]. CEC of strata with a 10-50% cob frequency range from 2.8 to 6.2  $\text{cmol}^+ \cdot \text{kg}^{-1}$  (Table 4),  
287 whereas CEC of all strata of Brittany range from 0.5 to 106.0  $\text{cmol}^+ \cdot \text{kg}^{-1}$ . Strata with a 10-50% cob frequency  
288 (Figure 9(a)) of Brittany exhibit CEC which corresponds to no or little organic matter content and low activity  
289 clay soils [53].

290 The organo-mineral strata were not taken into account for the data analysis (section 2.1), thus organic matter  
291 content of strata considered in the analysis is very low, and its contribution to CEC is limited. Assuming that  
292 CEC can be attributed to clay only, the CEC of the clay fraction was calculated (CL\_CEC, Table 4). According  
293 to their CEC, the clay fraction of strata with a cob affinity is mainly composed of Illite and Kaolinite clay types,  
294 i.e. clay with low or medium sensitivity to water (Table 4, Figure 9(b)). This is in agreement with the literature:  
295 cob mixture is implemented at plastic state and drying shrinkage could generate wide cracks that might affect  
296 mechanical resistance.

297 In earth with a 20-50% cob frequency, when CEC of clay (CL\_CEC) increases, the clay content decreases  
298 (Figure 9(b)): the more the specific surface of the clay, the less the required clay content. A linear relationship is  
299 proposed between Clay content (CLAY) and Cation Exchange Capacity of Clay (CL\_CEC) for cob in Brittany  
300 with a correlation coefficient of 0.78 and a standard error of 2.3. This relationship, together with its standard  
301 deviation, is presented in Figure 9(b), the upper standard error line is the value above which the specific surface

302 developed by clays might generate harmful shrinkage, and the lower standard error line is the value below which  
303 the specific surface developed by clays might not be enough to provide sufficient cohesion to the material. There  
304 is an optimum clay content [24,54–56] and this optimum clay content decreases when CEC of clays increases  
305 (Figure 9(b)).

306 Past masons added elements to the cob mixture to play the role of shrinkage crack barriers, such as fibres, in  
307 order to employ earth that would have shrunk too much [24]. As the fibre content and the cob variation  
308 technique employed for heritage cob buildings studied here are unknown, this might have affected the  
309 correlation coefficient of the clay content and clay CEC relationship (Figure 9(b)).

#### 310 **4.1.5 Earth and cob process**

311 There are many variations of the vernacular cob construction process resulting from the adaptation of the  
312 technique to local environments [24]. The earth could have been adapted to the cob process. For example the  
313 addition of fibres was often used to limit shrinkage cracks and made it possible the use of too clayey earth  
314 [13,24,57]. The process could have also been adapted to the earth. The rectification of the surface of cob walls  
315 containing large gravels could be done by beating the surface of the wall [24,26,44]. Thus, a strong link occurs  
316 between the available earth and the process employed. The frequencies calculated in this study are valid for  
317 vernacular techniques traditionally employed in Brittany, under this local climate and social context. The most  
318 widespread vernacular cob technique of Brittany consisted in treading earth and straw into a plastic consistency,  
319 stacking clods of cob into the wall, compacted by treading action and rectifying the faces of the walls by a  
320 trimming action (case (a), [24]). However, other cob techniques are encountered in Brittany. As no information  
321 is available about the technique employed for cob building construction in the heritage database, it is not  
322 possible to discuss the suitability of earth with any specific cob variation technique.

323 In the area of a given SMU, a high proportion of cob heritage indicates a favourable context. It is assumed that  
324 the highest frequency class depicts the most suitable soils of Brittany for vernacular cob construction.

325 Because these results need to be compared to those of other vernacular cob regions, they should be used only as  
326 a decision support tool for modern cob applications and not for standardisation purposes.

#### 327 **4.2 Resource quantification**

328 The cob resource quantification was carried out according to section 2.2, considering a 10-50% cob frequency  
329 class. This large frequency class is thought to better reflect the earth availability in a modern context for cob.

330 A geographical representation, by percentage of surface and by percentage of volume, calculated for each SMU,  
331 of soils suitable for cob in Brittany, is presented in Figure 10. Geographical distribution of cob heritage, drawn  
332 according to several literature sources [41,43,45,46] is also presented in Figure 10. Thanks to the percentage of  
333 available earth calculated, a quantitative estimation of the availability of the resource at regional scale is  
334 proposed in Table 6.

335 The availability of cob soils, expressed in surface, is greater in the East part of Brittany and well correlated with  
336 the geographical distribution of cob heritage, whereas there is no correlation between the geographical  
337 distribution of cob soils by volume and cob heritage (Figure 10). This result suggests that the geographical  
338 continuity of the resource is more important than the volume of the resource in order to allow the development of  
339 a local earth construction culture. Nowadays, modern excavation provides access to resources that were not  
340 accessible by manual excavation means. The representation of the resource by surface should be regarded as a  
341 representation of the availability of cob soil in a historical context, and the representation by volume should be  
342 regarded as a representation of the availability of cob soil in a modern context.

343

344 Macro scale orders of magnitude of the volume of available soil resource for cob were calculated (Table 6). The  
345 volume of soil available for vernacular cob technique in Brittany was estimated at 6.8 billion m<sup>3</sup>, i.e. 8.8 billion  
346 tonnes, and represents 23% of total soils of Brittany. The estimated proportion of the regional cob resource  
347 already consumed by past builders is 0.03%. The hypothetical consumption of the entire resource would enable  
348 the construction of 88 million homes and if all housing of Brittany were made of cob, 2.1% of the cob resource  
349 would have been consumed (Table 6). These figures illustrate the huge availability of earth material. These  
350 calculations are based on 10-50% cob frequency soils and considering vernacular cob technique only.

351 Considering that it is possible to use other types of earth with mechanized cob, that skilled craftsmen are able to  
352 use earth outside the 10-50% cob frequency area and that other earth construction techniques could be employed,  
353 these orders of magnitude should therefore be regarded as minimum values in a modern earth construction  
354 context.

355 Nonetheless, soil is a non-renewable material on the human time scale and it provides various ecosystem  
356 services concerning provisioning, regulating, cultural and supporting services [58]. Extraction of earth for  
357 construction might impact multifunctional roles of soil. Management of the consumption of this resource should  
358 therefore be carefully considered.

359 Currently, earthworks excavations generate large amounts of landfilled soils. In Brittany, 2.8 million tons of  
360 soils are landfilled every year. Considering that 23% of these landfilled soils are suitable for cob, in 2012, 0.6  
361 million tons of earth were available in Brittany and would have enabled the construction of 52% of individual  
362 housing of Brittany that year (Table 6). The resource of earth suitable for cob in Brittany is huge and earthwork  
363 extractions already provide large amounts of these earth every year. This high-quality construction material  
364 could be valued in the building sector, instead of ending up as waste in landfills.

## 365 **5 Conclusion**

366 A novel methodology, based on the cross-referencing of pedological and heritage data, was proposed to identify  
367 the pedological/geotechnical characteristics (clay, silt, sand, gravel content and Cation Exchange Capacity) of  
368 soils employed in vernacular earth buildings.

369 The methodology applied at the regional scale in France (for a given area of 27,200 km<sup>2</sup> in Brittany) enabled to  
370 specify five new texture and Cation Exchange Capacity classes of suitability for cob soils. Texture results of this  
371 first application call into question recommendations available in the literature and further investigations are  
372 needed to highlight the reasons for these differences.

373 Using those characteristics, the first map of availability of cob earth material at regional scale has been drawn  
374 and it was estimated that 23 % of earthworks wastes, in Brittany, could be upcycled for earth construction. This  
375 quantification is a minimum value, since other soils could be used with mechanized cob techniques or by skilled  
376 craftsmen and other earth construction techniques could be employed. The results highlight the large availability  
377 of materials for earth construction in Brittany. However, earth remains a non-renewable material and this  
378 resource has to be properly managed, requiring an appropriate building design and maintenance in order to  
379 increase longevity and to avoid the use of admixture, preventing earth reversibility at end of life.

380  
381 This novel methodology is very promising since it provides valuable data for economic and environmental  
382 assessment and significant results for the discussion on soil suitability to repair earth built heritage or to build  
383 new low impact buildings with integrated modern earth walls. To further the discussion on the identification and  
384 quantification of soils for construction, the same methodology should be applied to other regions with different  
385 earth construction techniques.



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392

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530

531 **Captions for figures**

532 *Figure 1. Pedological database: Soil Map Units (SMUs) are a spatialized depiction of soil landscapes at a scale of*  
533 *1:125,000, SMUs are composed of a proportion, expressed in surface, of various Soil Type Units (STUs) and STU consist of*  
534 *several strata. Only SMUs are delineated.*

535 *Figure 2. Exemplification of earth frequency calculation for two hypothetical Soil Type Units among 3 Soil Map Units*

536 *Figure 3. Maps of available information in Brittany concerning Heritage database [31], and vernacular cob area of*  
537 *Brittany (a) [41,43,45,46]; 1:250,000 soil map figuring complex Soil Map Units (SMU) (b) [30]; map of municipalities*  
538 *possessing heritage data, defining the study area, together with vernacular cob area of Brittany (c) [41,43,45,46].*

539 *Figure 4. Temporal distribution of cob buildings of the studied area.*

540 *Figure 5. Texture of soils of 40-50 %; 30-40 % and 20-30 % cob frequency classes (a) and comparison of these textures (20-*  
541 *50 % cob frequency) with all soils of Brittany (b).*

542 *Figure 6. Texture of fine earth of strata of Brittany according to their cob frequency (a) (diamond are mode values and error*  
543 *bars are estimated confidence interval) and cob frequency classes (b).*

544 *Figure 7. Comparison between texture of soils with a 20-50 % cob frequency identified in Brittany and recommended texture*  
545 *available in literature, proposed by Morris [17] (a), Harries et al. [14] (b), Keefe [13] (c) and Jaquin and Augarde [15] (d).*

546 *Figure 8. Confrontation of texture of fine earth identified as suitable for vernacular cob construction in Brittany with cob*  
547 *recommended texture available in literature (a) [13–15,17] and texture of fine earth of German cob soils [47] and damaged*  
548 *cob walls built with soils derived from Permo-Triassic rocks in the United-Kingdom (b) [20].*

549 *Figure 9. Cation Exchange Capacity (CEC) of strata of Brittany plotted against cob frequency (a) and clay content of strata*  
550 *with a 20-50 % cob frequency plotted against the CEC of clay fraction (b).*

551 *Figure 10. Map of SMU resource availability for vernacular cob in Brittany, considering strata with a 10-50 % cob*  
552 *frequency by surface (a), by volume (b) and comparison with vernacular cob area [41,43,45,46].*

553

554 **Captions for tables**

555 *Table 1. Definition of parameters used for soil suitability determination*

556 *Table 2. Frequency classes of earth buildings within STU.*

557 *Table 3. Frequency, frequency class and standard deviation ( $\sigma_{FREQSTU}$ ) of Soil Type Unit (STU), calculated according to*  
558 *section 2.1. Description of STUs can be found online: <http://www.sols-de-bretagne.fr/> [30].*

559 *Table 4. Texture (in percentage by mass), Cation Exchange Capacity (CEC) of soils and Cation Exchange Capacity of clay*  
560 *fraction (CL\_CEC), according to cob frequency classes.*

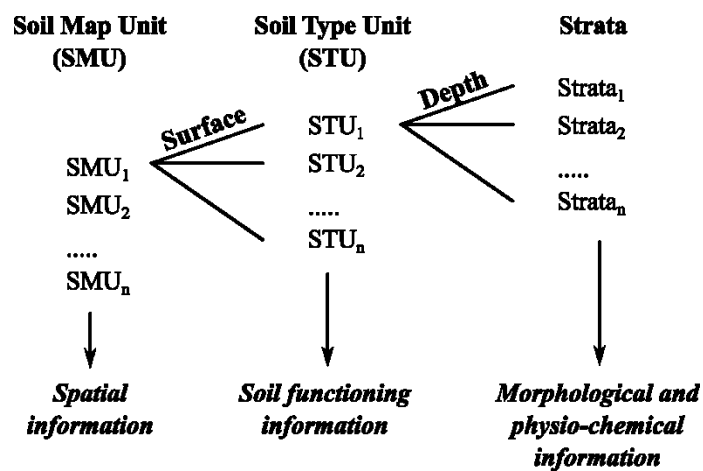
561 *Table 5. Texture of fine earth (clay + silt + sand = 100%, in percentage by mass), of soils according to cob frequency*  
562 *classes.*

563 *Table 6. Estimation of soil availability for cob construction in Brittany, by volume, mass and proportion, estimation of*  
564 *consumption of the resource by heritage and orders of magnitude of potential cob resource provided by earthworks.*

565

566 Figures with captions

567



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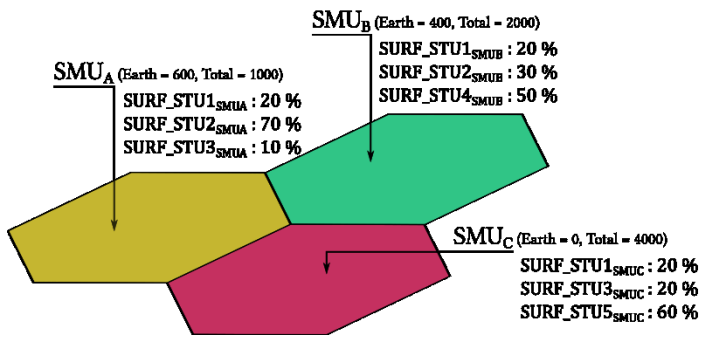
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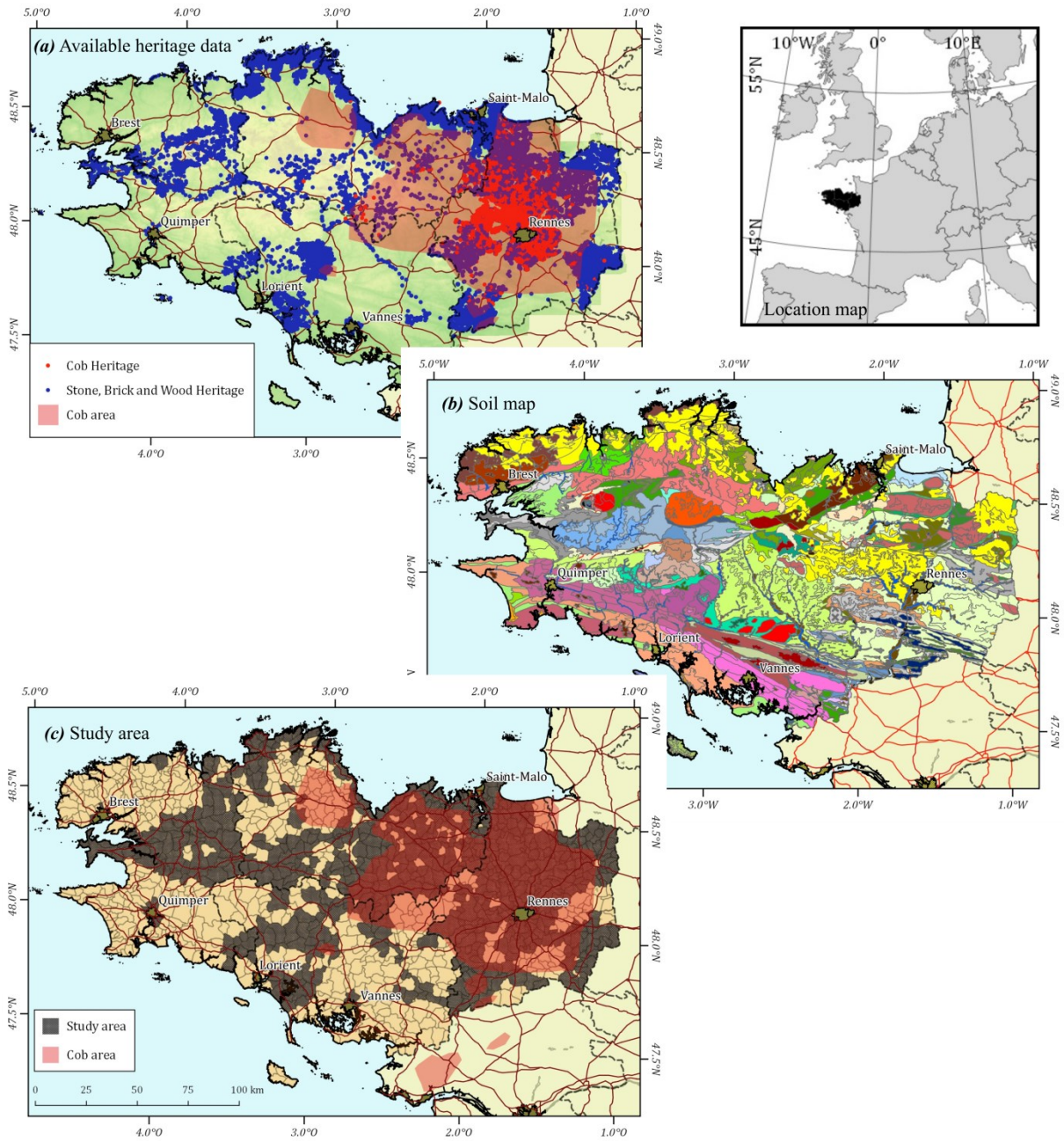
	STU <sub>1</sub>		STU <sub>2</sub>	
	TOT_STU	EARTH_STU	TOT_STU	EARTH_STU
SMU <sub>A</sub>	200	120	700	420
SMU <sub>B</sub>	400	80	600	120
SMU <sub>C</sub>	800	0	0	0
Total	1400	200	1300	540
FREQ <sub>STU</sub>	0.14		0.42	

574

575 *Figure 2. Exemplification of earth frequency calculation for two hypothetical Soil Type Units among 3 Soil Map Units*

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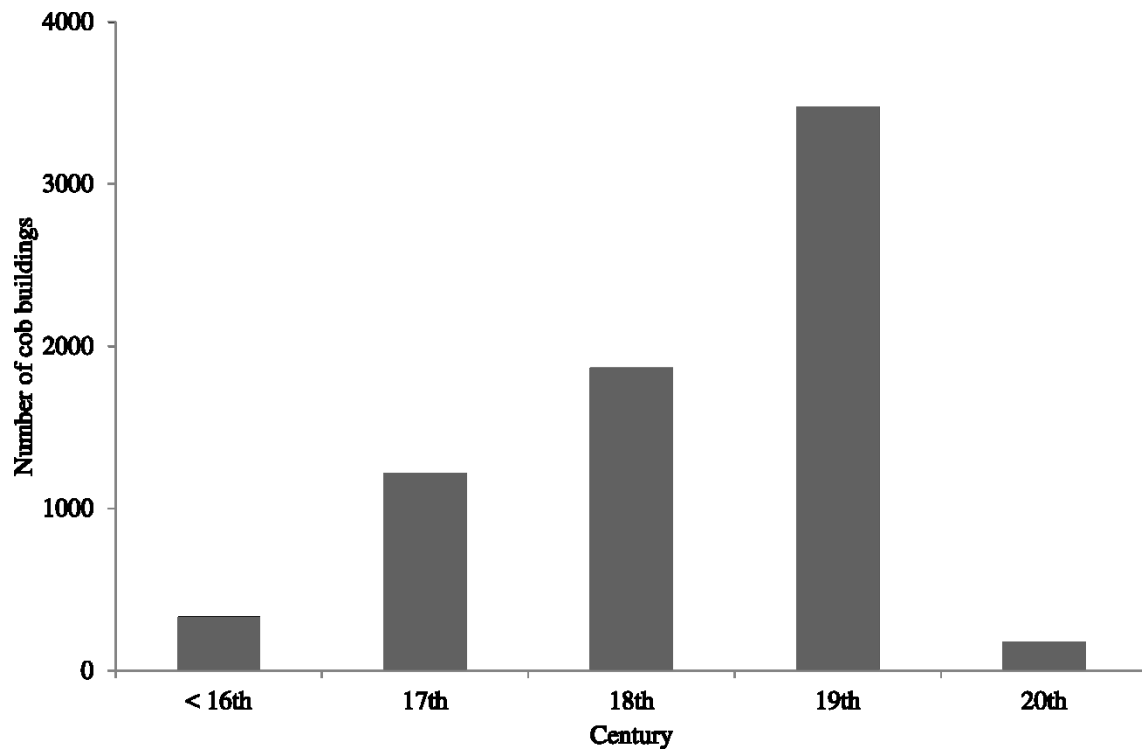
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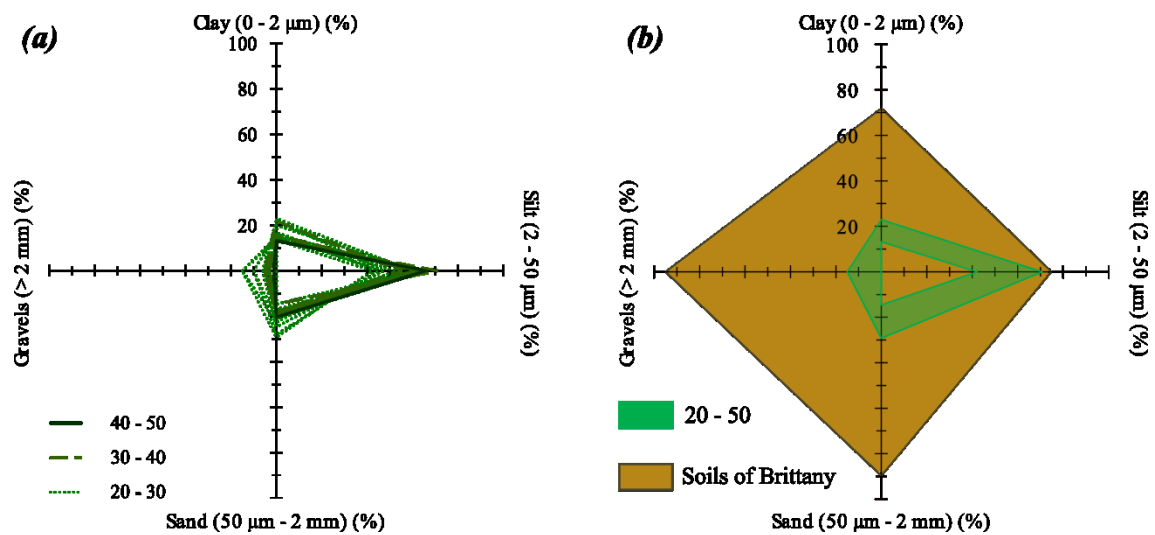
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585 *Figure 4. Temporal distribution of cob buildings of the studied area.*

586

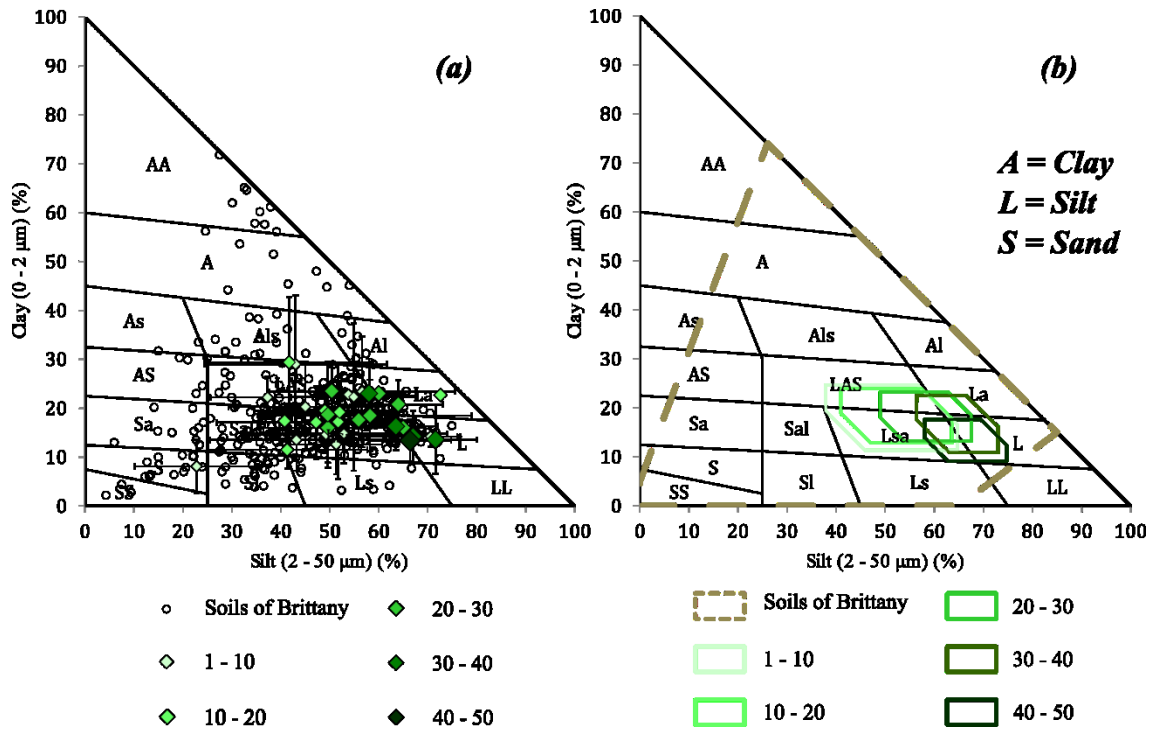


587

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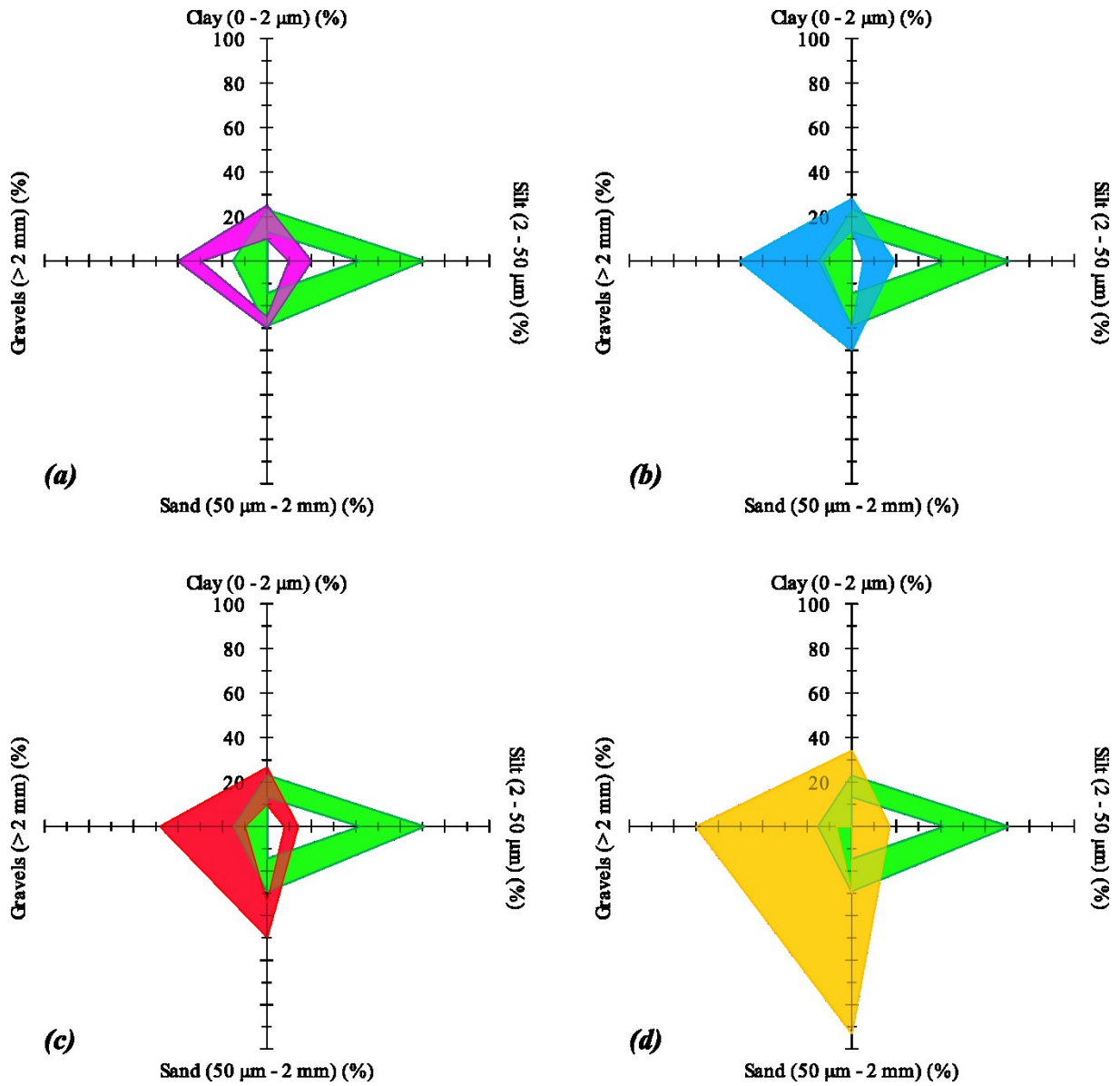
592

593 *Figure 6. Texture of fine earth of strata of Brittany according to their cob frequency (a) (diamond are mode values and error*

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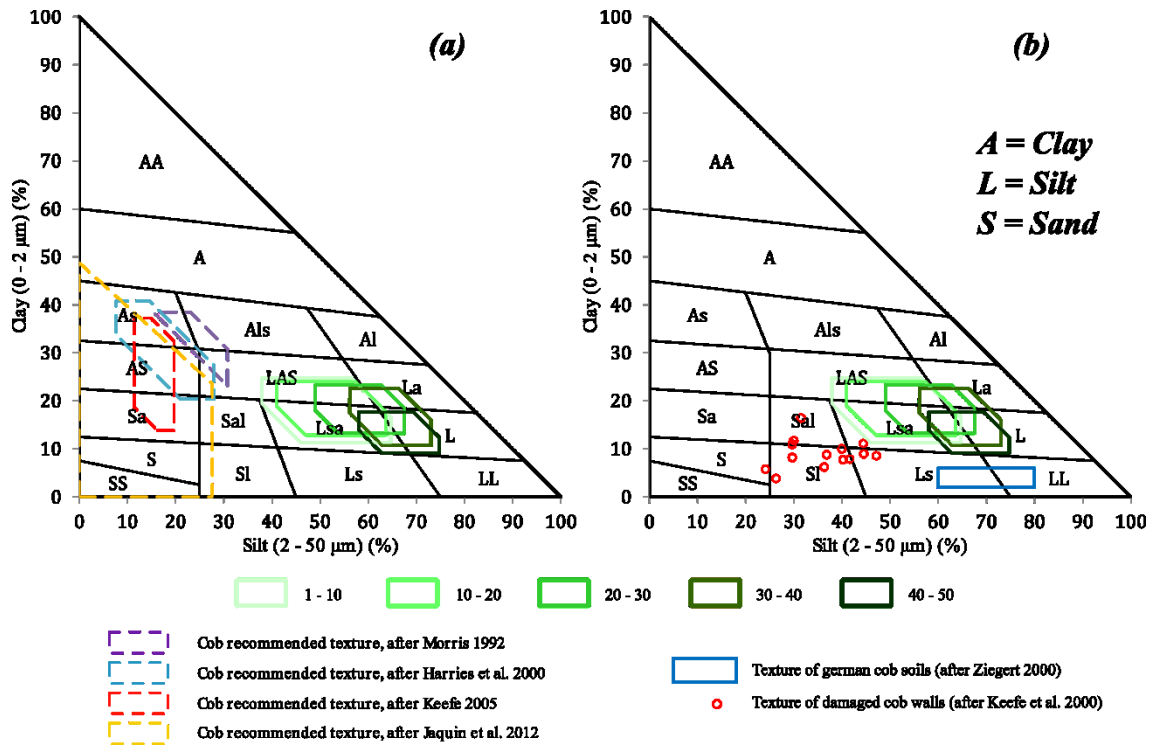


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598 *Figure 7. Comparison between texture of soils with a 20-50 % cob frequency identified in Brittany and recommended texture*  
599 *available in literature, proposed by Morris [17] (a), Harries et al. [14] (b), Keefe [13] (c) and Jaquin and Augarde [15] (d).*

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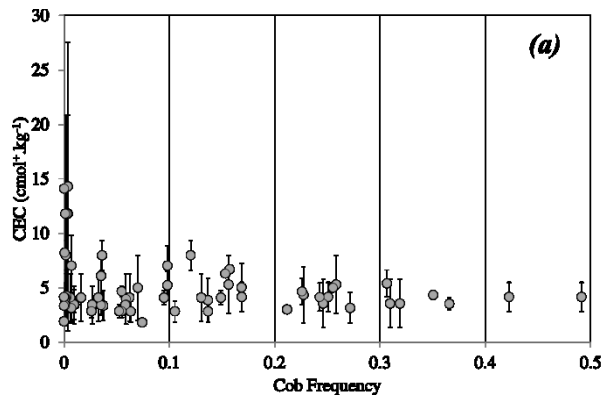
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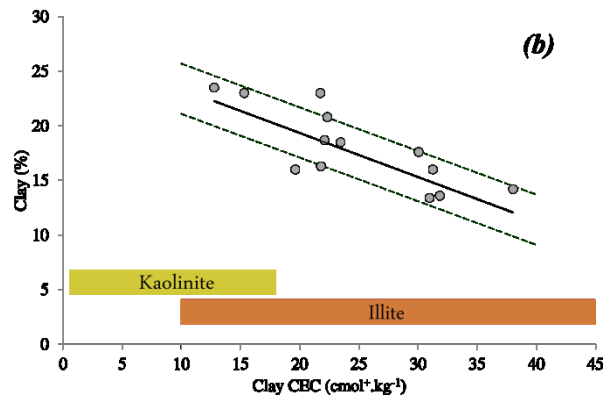
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Figure 8. Confrontation of texture of fine earth identified as suitable for vernacular cob construction in Brittany with cob recommended texture available in literature (a) [13–15,17] and texture of fine earth of German cob soils [47] and damaged cob walls built with soils derived from Permo-Triassic rocks in the United-Kingdom (b) [20].

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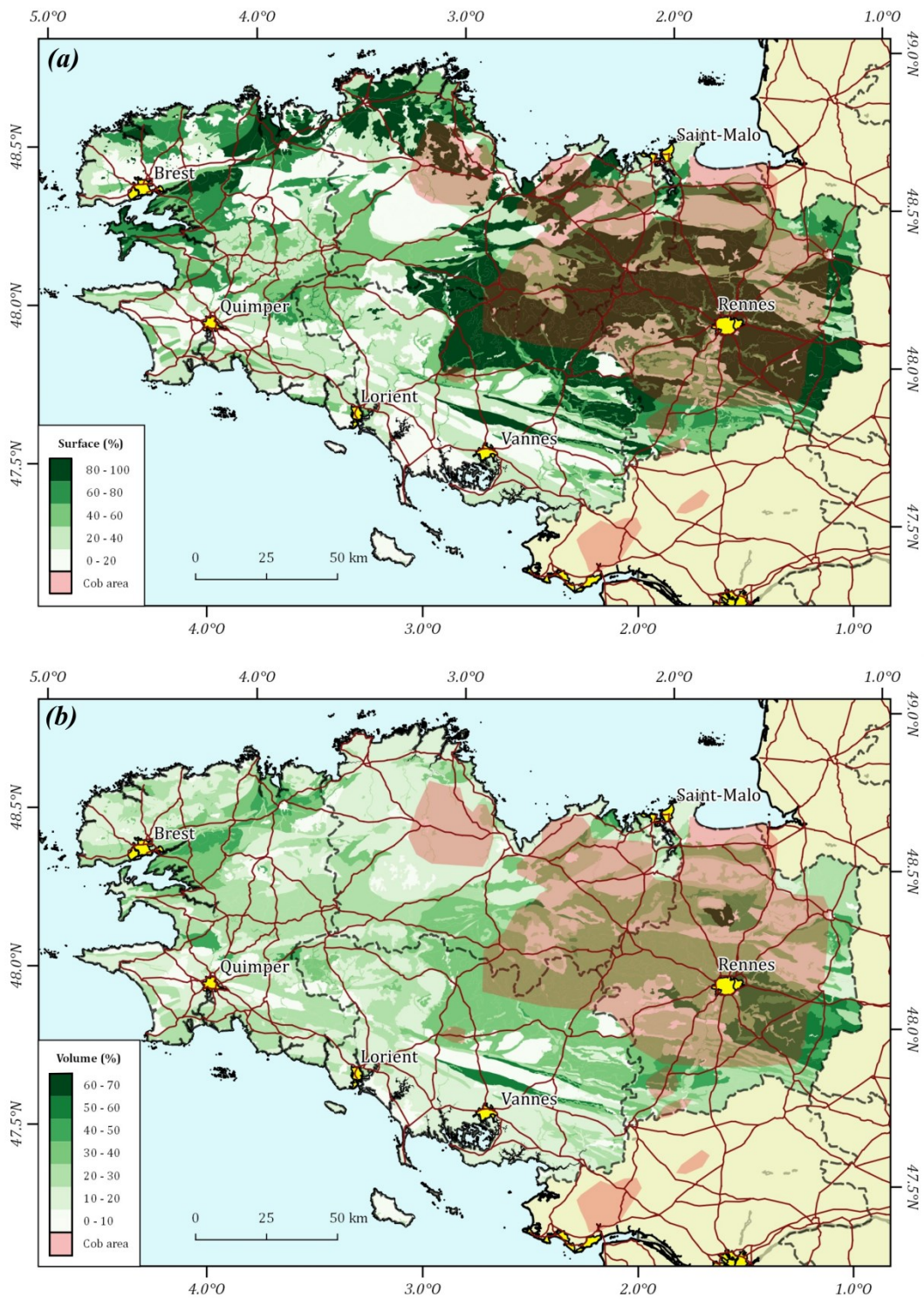
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609 *Figure 9. Cation Exchange Capacity (CEC) of strata of Brittany plotted against cob frequency (a) and clay content of strata*  
610 *with a 20-50 % cob frequency plotted against the CEC of clay fraction (b).*

611





612

613 *Figure 10. Map of SMU resource availability for vernacular cob in Brittany, considering strata with a 10-50 % cob*

614 *frequency by surface (a), by volume (b) and comparison with vernacular cob area [41,43,45,46].*



615 **Tables with captions**

616

617 *Table 1. Definition of parameters used for the determination of soil suitability*

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<b><i>SMU</i></b>	Soil Map Unit: spatially delineated polygon corresponding to a soil landscape, i.e. a collection of Soil Type Units
<b><i>STU</i></b>	Soil Type Unit: portion of the soil cover which has identical pedogenesis and, at any point in space, the same sequence of diagnostic horizons
<b><i>SURF_STU<sub>SMU</sub></i></b>	Surface proportion of a STU in a SMU
<b><i>TOT_SMU</i></b>	Total number of heritage building of a SMU
<b><i>TOT_STU</i></b>	Total number of heritage building of a STU
<b><i>EARTH_SMU</i></b>	Total number of earth heritage building of a SMU
<b><i>EARTH_STU</i></b>	Total number of earth heritage building of a STU
<b><i>SURF_STU<sub>SMU<sub>i</sub></sub></i></b>	Proportion of surface of a STU in a SMU
<b><i>FREQ<sub>STU</sub></i></b>	Frequency of earth building heritage among the building heritage of a STU. This parameter describes the suitability of STUs with earth building
<b><i>FREQ<sub>STRATA</sub></i></b>	Frequency of earth building heritage among the building heritage of a Strata
<b><i>σ<sub>FREQ<sub>STU</sub></sub></i></b>	Standard deviation of the earth building frequency of a STU. A maximum standard deviation is set by the researcher to exclude outlier values
<b><i>n<sub>STU</sub></i></b>	Minimum total heritage building per STU. Only STUs with a number of total heritage building higher than $n_{STU}$ are considered for the calculation
<b><i>CHARACTER</i></b>	Pedological characteristic (clay, silt, sand, gravel content and Cation Exchange Capacity)
<b><i>CLASS</i></b>	Class of frequency of earth building heritage (see Table 2)
<b><i>CONF_INT<sub>STRATA</sub></i></b>	Estimation of the half-confidence interval of a pedological characteristic of a strata
<b><i>CHARACTER<sub>STRATA<sub>j</sub></sub>_CLASS<sub>i</sub></i></b>	Average value of a pedological characteristic of a earth building frequency class
<b><i>CONF_INT<sub>STRATA<sub>j</sub></sub>_CLASS<sub>i</sub></i></b>	Average value of the confidence interval of each pedological characteristic of a earth building frequency class
<b><i>MIN<sub>CHARACTER</sub>_CLASS<sub>i</sub></i></b>	Minimum value of a pedological characteristic of a earth building frequency class
<b><i>MAX<sub>CHARACTER</sub>_CLASS<sub>i</sub></i></b>	Maximum value of a pedological characteristic of a earth building frequency class

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621 *Table 2. Frequency classes of earth buildings within STU.*

Frequency ( <i>FREQ</i> )	Frequency classes ( <i>CLASS</i> ) (%)
0.9 - 1.0	90 - 100
0.8 - 0.9	80 - 90
0.7 - 0.8	70 - 80
0.6 - 0.7	60 - 70
0.5 - 0.6	50 - 60
0.4 - 0.5	40 - 50
0.3 - 0.4	30 - 40
0.2 - 0.3	20 - 30
0.1 - 0.2	10 - 20
0.01 - 0.1	1 - 10
0.0 - 0.01	0 - 1

622

623 Table 3. Frequency, frequency class and standard deviation ( $\sigma_{FREQ_{STU}}$ ) of Soil Type Unit (STU), calculated according to  
 624 section 2.1. Description of STUs can be found online: <http://www.sols-de-bretagne.fr/> [30].

STU	Cob frequency ( $FREQ_{STU}$ )	Frequency class (CLASS) (%)	Standard deviation ( $\sigma_{FREQ_{STU}}$ )
247	0.49	40-50	0.018
289	0.42	40-50	0.022
183	0.37	30-40	0.016
346	0.35	30-40	0.029
286	0.32	30-40	0.018
248	0.31	30-40	0.011
85	0.31	30-40	0.018
61	0.27	20-30	0.015
51	0.26	20-30	0.009
336	0.26	20-30	0.020
246	0.25	20-30	0.019
251	0.25	20-30	0.016
92	0.24	20-30	0.027
86	0.23	20-30	0.012
442	0.23	20-30	0.017
184	0.21	20-30	0.021
257	0.17	10-20	0.014
431	0.17	10-20	0.006
188	0.16	10-20	0.026
66	0.16	10-20	0.024
512	0.15	10-20	0.022
63	0.15	10-20	0.024
282	0.14	10-20	0.021
112	0.13	10-20	0.022
182	0.12	10-20	0.026
255	0.11	10-20	0.018
340	0.10	1-10	0.014
56	0.09	1-10	0.015
21	0.07	1-10	0.017
441	0.07	1-10	0.012
254	0.06	1-10	0.025
65	0.06	1-10	0.013
62	0.06	1-10	0.024
13	0.06	1-10	0.013
243	0.05	1-10	0.018
281	0.05	1-10	0.011
82	0.04	1-10	0.005
180	0.04	1-10	0.008
331	0.04	1-10	0.017
53	0.03	1-10	0.015
26	0.03	1-10	0.012
245	0.03	1-10	0.010
54	0.02	1-10	0.003
14	0.01	0-1	0.004
57	0.01	0-1	0.005
68	0.01	0-1	0.005
113	0.01	0-1	0.004
59	0.00	0-1	0.003
89	0.00	0-1	0.003
64	0.00	0-1	0.003
80	0.00	0-1	0.003
181	0.00	0-1	0.004
111	0.00	0-1	0.003
150	0.00	0-1	0.003
100	0.00	0-1	0.002
97	0.00	0-1	0.003
67	0.00	0-1	0.002
72	0.00	0-1	0.001
262	0.00	0-1	0.001
102	0.00	0-1	0.001
101	0.00	0-1	0.000
250	0.00	0-1	0.000
290	0.00	0-1	0.000

625

626 Table 4. Texture (in percentage by mass), Cation Exchange Capacity (CEC) of soils and Cation Exchange Capacity of clay  
 627 fraction (CL\_CEC), according to cob frequency classes.

Frequency class (%)	Clay (0 - 2 $\mu$ m) (%)		Silt (2 - 50 $\mu$ m) (%)		Sand (50 $\mu$ m - 2mm) (%)		Gravel (>2mm) (%)		CEC (cmol <sup>+</sup> .kg <sup>-1</sup> )		CL_CEC (cmol <sup>+</sup> .kg <sup>-1</sup> )
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Average
40-50	9	17	57	74	13	28	0	2	2.8	5.5	31
30-40	11	22	54	70	10	25	0	9	2.8	5.3	26
20-30	12	22	46	63	13	31	0	20	3.0	5.5	24
10-20	12	22	37	58	17	37	0	21	3.6	6.2	28
1-10	10	21	32	55	16	36	2	30	3.0	5.4	25

628

629 Table 5. Texture of fine earth (clay + silt + sand = 100%, in percentage by mass), of soils according to cob frequency  
 630 classes.

Frequency class (%)	Clay (0 - 2 $\mu$ m) (%)		Silt (2 - 50 $\mu$ m) (%)		Sand (50 $\mu$ m - 2mm) (%)	
	Min	Max	Min	Max	Min	Max
40-50	9	18	58	75	13	28
30-40	11	23	56	73	11	26
20-30	13	23	49	68	14	33
10-20	13	24	41	64	19	40
1-10	11	25	38	65	19	43

631

632 Table 6. Estimation of soil availability for cob construction in Brittany, by volume, mass and proportion, estimation of  
 633 consummation of the resource by heritage and orders of magnitude of potential cob resource provided by earthworks.

Volume of soil identified as suitable for cob in Brittany (m <sup>3</sup> )	6.8E+09
Mass of soil identified as suitable for cob in Brittany (t) <sup>(1)</sup>	8.8E+09
Proportion of soils of Brittany identified as suitable for cob (%)	23
Estimation of cob earth resource already consumed by cob heritage (%) <sup>(2)</sup>	0.03
Number of housing feasible, consuming the entire cob resource <sup>(3)</sup>	8.8E+07
Number of total housing in Brittany in 2013 <sup>(4)</sup>	1.8E+06
Resource consummation if all housing of Brittany were made of cob (%)	2.1
Landfilled soils suitable for cob in Brittany in 2012 (t) <sup>(5)</sup>	6.49E+05
Number of housing feasible, consuming suitable landfilled soils <sup>(3)</sup>	6490
Number of housing built in Brittany in 2013 <sup>(4)</sup>	12544
Cob potential market share in Brittany (%)	52

<sup>(1)</sup> considering a soil density of 1.3 t.m<sup>-3</sup>

<sup>(2)</sup> considering 30,000 buildings and 100 t per building

<sup>(3)</sup> considering 100 t per building as suggested by [13]

<sup>(4)</sup> source: INSEE

<sup>(5)</sup> considering 23 % of excavated soils, source: Cellule Économique de Bretagne

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