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Towards an easy decision tool to assess soil suitability for earth building

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Abstract

In the European Union, most of the wastes from the building sector are composed of earths. Earth construction may be an interesting outlet for the re-use of these wastes, while meeting the challenge of circular economy: in particular, it involves low-embodied energy processes and earth material can be re-used for building by end-of-life. Nonetheless, the identification of suitable earths for construction remains an issue. To overcome this problem, an option may be to analyse earth building heritage, which is at least one-century old in Europe: indeed, earth employed in these buildings can be regarded as “time-tested”, and thus suitable for construction. In this paper, more than 20 different earths collected in rammed earth heritage building in France are presented. The results are confronted both to literature and to several classifications employed in soil sciences. A classification system based on granularity and clay activity will be relevant to address the convenience of earth for building purposes.

Keywords

1. Buildings, structures & design
2. Geomaterial characterization
3. Soil classification
4. Soil suitability
5. Rammed earth
6. Cob

1 Introduction

2 The construction sector uses a large volume of natural resources and is responsible for about
3 half of the waste production in the European Union [1]. These wastes have a negative
4 environmental impact [1]–[3], and it gets increasingly difficult to find suitable landfill sites [2], [4].
5 Among these construction wastes, about 75 % consist of soils and stones [5], [6]. As already
6 highlighted for cob in Brittany, the earth building sector has a strong reuse potential for
7 earthwork wastes [7]. Planning authorities and earthwork contractors need a decision tool to be
8 able to identify the potentially reusable material among their excavated soils.

9 In Western countries, earth building gradually fell into disuse in the first half of the 20th century.
10 Most of the traditional know-how - that was mainly transmitted orally - got lost in this period,
11 including the ability to select appropriate earths for construction. It is thus necessary to
12 rediscover or reinvent the expertise regarding earth suitability.

13 Earth suitability for construction purposes is usually determined using a geotechnical approach,
14 which aims at enhancing the mechanical strength of earthen specimens carried out in the
15 laboratory or in the field [8]–[10], and at ensuring the durability of the final construction. The
16 most cited criterion to assess earth suitability is texture, i.e. balance between clay, silt, sand and
17 gravel contents [11]. Consequently, grading envelopes adjusted to each earth construction
18 technique were proposed in the literature [8], [12]–[14]. However, texture of materials collected
19 in vernacular earth heritage buildings do not systematically fit inside those grading envelopes
20 [15]–[18]. Thus, grading envelopes available in the literature failed to give full account of the
21 diversity of earth employed for construction [7], [19].

22 Therefore, another approach to identify material suitability for construction is to analyse
23 materials traditionally used in heritage buildings. This can be done thanks to the analysis of
24 samples collected inside walls of building heritage, or thanks to the cross-referencing of heritage
25 geographical distribution and geological maps [15], [20] or pedological maps [7], [20], [21]. The
26 direct analysis of samples collected in walls provides a reliable material identification but, since
27 it is highly time-consuming, only few buildings can be studied. Cross-referencing of spatial data
28 can concern a large number of heritage buildings, but material identification relies on
29 probabilities.

30 In this study, earth samples were collected in more than 20 different rammed earth heritage
31 buildings of the Auvergne-Rhone-Alpes region (France) and were analysed. The results
32 provided a renewed vision of the diversity of earth materials used in vernacular rammed-earth
33 buildings. They were also compared to the cob earth resource identification carried out by
34 Hamard et al. [7] in order to address the differences between rammed earth and cob earth.
35 Rammed earth consists in compacting earth at an optimum water content, layer by layer, inside
36 a formwork, in order to build a monolithic and load-bearing or freestanding wall (cf. Figure 1A).
37 This technique appeared near Carthage around the 9th century BC, and then travelled to Europe
38 during the 7th century, before becoming really popular during the “modern era” thanks to, for
39 example, the early work of the French architect François Cointeraux (1740-1830) [22]. It also
40 exported towards the United States and Australia during this period. Rammed earth historic and
41 vernacular constructions in some European countries are referenced in various papers such as
42 Parracha et al. [23], Ford et al.[24], or online inventories (see [25] for example). Nowadays,
43 several tens of thousands of such constructions remain in the architectural heritage of these
44 countries, and the technique is still punctually reused for new buildings. It is the main vernacular
45 earth building technique employed in the Auvergne-Rhone-Alpes region (South-East of France).
46 However, few masons still know how to implement it properly and how to choose or elaborate
47 appropriate earth compositions.



48 **Figure 1: A: A rammed earth wall in a building from the 1980's in the Auvergne-Rhone-**
49 **Alpes region (South-East of France), with clear marks of the layered structure. B:**
50 **Construction of a cob wall**

51

52 The cob technique, that will be used for comparison purposes in the classification presented in
53 section 4.2, employs earth elements in a plastic state, implemented wet and stacked to build a
54 monolithic and load-bearing or freestanding wall [19]. Cob is a very old technique and usually
55 uses more fine-grained and argillaceous soils than rammed earth. As shown in the Figure 1B, it
56 is often combined with fibers to reduce the effects of soil shrinkage during the drying process
57 and to increase the resistance and the ductility. This technique is widespread in the North-West
58 part of France and is also encountered in Europe, Africa and Asia.

59 In both techniques (rammed earth and cob) the soil material used in the building process was
60 usually extracted at a very short distance from the construction site, typically by digging a pond
61 in the garden adjoining the house or by selecting an appropriate soil in a nearby field. As a
62 consequence, historically, the development of a given technique in a given area has been
63 closely linked to the local geographical, geological and pedological contexts, but also to the
64 local transfers of knowledge. Indeed, most soils can potentially be implemented through
65 different techniques. Conversely, a given technique may be applied to a certain variety of soils.
66 Eventually, some preparation (like sieving or stabilization) may be needed. This historical
67 approach helps understanding why earth suitability may be analysed through direct analysis of
68 samples as well as cross-referencing of spatial data.

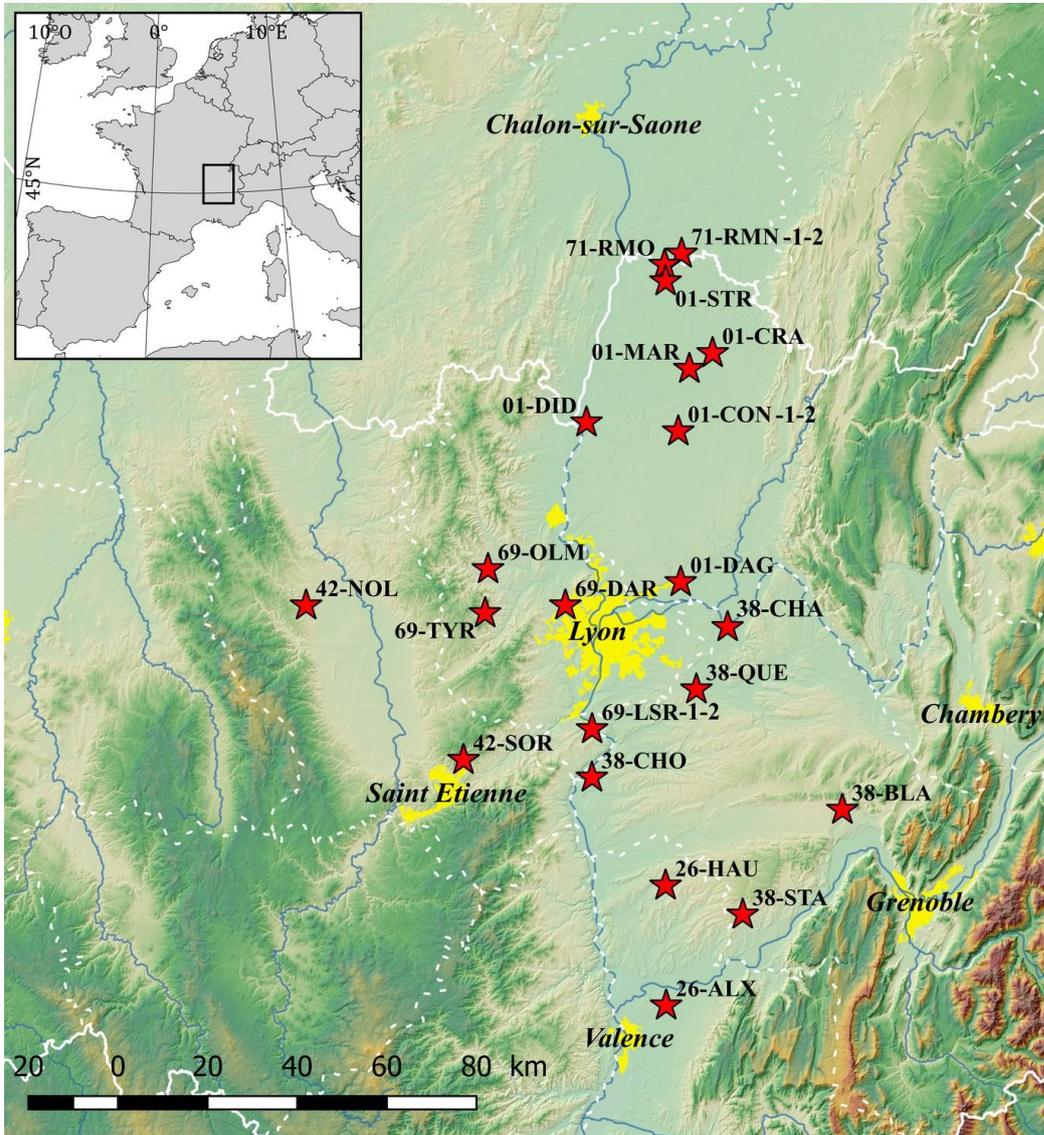
69

70 **2. Materials and methods**

71 *2.1 Surveying method and study area*

72 The experimental research program presented in this paper is mainly focused on the direct
73 analysis of rammed earth buildings. It was conducted through a sampling campaign on various
74 constructions of the Rhône-Alpes region, France. The location of the different sampling sites is
75 shown on Figure 2. They were selected under various criteria. First, the buildings had to be
76 constituted essentially of natural rammed earth, without any additional binders such as lime or
77 cement (which is usually the case for heritage buildings in France). Moreover, the samples had
78 to be collected during a renovation or a demolition program, because the minimum sample size
79 for geotechnical identification (defined in standards for soil testing such as NF P 94-056 [26]),
80 considering the particle sizes of the material, was frequently around 50 kg. Therefore, the

81 sampling process could lead to significant openings in the walls, which was not acceptable for a
82 building in service. Finally, the sampling sites had to be well distributed across the Auvergne-
83 Rhone-Alpes region, in order to cover a large diversity of geological and pedological contexts
84 and building types.



85
86 **Figure 2: An overview of the surveying area and the sampling sites in the Auvergne-**
87 **Rhone-Alpes region, France**

88
89 A collaboration was established with TERA, a local earth building professional organisation and
90 with various administrative services in charge of built heritage, in order to identify and select
91 appropriate constructions. About 20 of them were selected, and one or several samples were
92 collected in each building. Some examples of typical sampling sites are reported in Figure 3.

93 The sampling method was highly dependent of the context: it mainly involved shovel excavation
94 when the building was being demolished, or mechanical sawing in the case of renovation
95 operations (Figure 4). Some “intact” samples could sometimes be extracted, allowing density
96 measurements. A description sheet was established for each building, including spatial
97 localization, wall geometry, orientation, rammed earth aspect, type of coating, age of the
98 construction, etc. It made it possible to constitute a kind of “rammed earth” library that will be
99 associated with the test results presented hereafter.

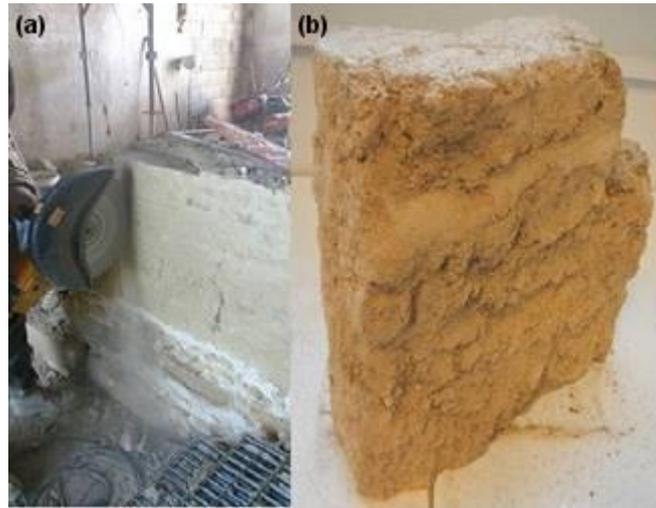


100

101 **Figure 3: An example of four typical sampling sites in the study area: (a) BLA, (b) QUE,**

102

(c) HAU, (d) CHA



104

105 **Figure 4: (a) earth sampling directly in a wall with a mechanical saw, and (b) example of a**
106 **collected 30 cm-high rammed earth sample**

107

108 *2.2 Earth identification*

109 Earth identification was mainly conducted through classical geotechnical testing procedures.

110 This approach was chosen instead of more complex chemical or mineralogical analyses
111 because it could be associated with a range of well-known, simple and representative laboratory
112 tests. These tests also remain reasonably close to the masons' practice, in the field, when they
113 need to assess soil suitability with limited means. Moreover, geotechnical and pedological
114 engineering has developed an interesting panel of classifications that may be used to
115 characterize rammed earth.

116 The testing procedures included: water content, particle size distribution (from sieving and
117 hydrometer test), methylene blue test, Atterberg limits (when possible) and dry density. These
118 tests are shortly described below, since various methods are usually encountered depending on
119 the countries. However, the reader is invited to refer to the corresponding standards for a
120 detailed explanation of each procedure.

121 The particle size distribution was assessed after French Standard NF P 94-056 [26]. In this
122 procedure, with a succession of washing and drying steps, the material is passed through
123 various sieve sizes ranging from 63 or 80 μm to the maximum particle size of the soil. For each
124 sieve size used, the percentage by mass of the soil sample that is finer than the sieve size is

125 computed. The finest grains (< 63 or $80 \mu\text{m}$) are then qualified through hydrometer testing, after
126 standard NF P 94-057 [27]. This test uses the Stokes law that specifies that the decantation
127 speed of spherical grains of equal density depends on their diameter. The decantation speed is
128 measured in a large test tube, on a solution of fine-grained soil and sodium
129 hexametaphosphate, by dipping a densimeter at predefined time steps. It is an approximate
130 indirect measurement but it usually yields reasonably reliable results compared to other
131 procedures such as laser diffraction analysers (see Loizeau et al. [28] for instance).

132 The argillaceous content and clay activity were qualified through two different techniques:
133 methylene blue test and Atterberg limits (when possible). The methylene blue test follows
134 standard NF P 94-068 [29] and consists in measuring the quantity of methylene blue that can be
135 adsorbed by a clayey soil. It is a very simple but reliable method to obtain information about the
136 properties of clay minerals: it relies on the replacement of the natural cations of clays by
137 methylene blue in a soil-water solution that is continuously stirred. The titration is performed by
138 adding successively small amounts of a methylene blue dye and by controlling adsorption after
139 each step. Adsorption is checked with the "spot technique": each time methylene blue is added
140 to the solution, a small drop is removed with a glass rod and dropped on a sheet of filter paper.
141 When a blue halo appears around the spot (instead of a distinct edge), it indicates that the clays
142 in the solution are saturated with methylene blue. The Methylene Blue Value (MBV) is
143 determined as the ratio (in percents) between the mass of methylene blue added in the solution
144 and the initial dry mass of the soil tested. The procedure is usually performed only on the 0/5
145 mm portion of the soil: if larger particle sizes exist, the MBV is lowered by multiplying it by the
146 0/5 mm vs. 0/50 mm ratio (after particle size analysis).

147 The Atterberg limits are a widespread testing procedure for clayey materials. They were
148 measured after standard NF P 94-051 [30] ; only plastic and liquid limits were considered. The
149 test is performed on the 0/400 μm portion of the soil. The water content corresponding to the
150 plastic limit is determined by the ability to roll a 10 cm-long and 3 mm-wide thread of the studied
151 soil on a flat impermeable surface. The liquid limit is obtained with the classical Casagrande cup
152 method. The plasticity index (PI) is then determined as the difference between the water
153 contents that characterize the liquid limit w_L and the plastic limit w_P . The PI indicates if the soil

154 exhibits a plastic behaviour over a wide range of water contents: this property depends on the
 155 proportion of the clay fraction but also on the nature of the clay minerals.
 156 Each sample collected in the vernacular buildings was subjected to most of these laboratory
 157 tests. It allowed drawing a representative survey of the regional diversity of earth material for
 158 construction, as shown in the following section.

159

160 *2.3 On-site initial state of the samples*

161 Before subjecting the specimens to the “earth identification” tests described above, a basic
 162 analysis of their on-site initial state was conducted, by measuring their water content and their
 163 dry density. The water content was determined by normalized oven drying, according to French
 164 standard NF P 94 050 [31]. The dry densities were calculated through the “hydrostatic weighing”
 165 procedure, in which the volume of an intact sample is obtained after water-proofing it with
 166 paraffin, and weighing it in immersed conditions, according to French standard NF P 94 053
 167 [32]. The results are shown in Table 1. Dry density and water content measurements were not
 168 possible for all the samples since they required the availability, on the sampling site, of a
 169 sufficient number of undisturbed blocks.

170 **Table 1: Dry density and water content measurements obtained on various "intact"**
 171 **samples from vernacular earth buildings. Mean and standard deviation are calculated**
 172 **only for buildings in use.**

Sample	Dry density ρ_d (Mg/m³)	Water content w (%)
<i>Ruins, abandoned or damaged buildings</i>		
CHO	1.56	2.9
RMN1	1.64	9.9
RMN2	1.70	6.1
STA	1.76	9.8
STR	1.77	5.4
TYR	1.73	2.5
<i>Buildings in use</i>		
BLA	1.75	0.4
CHA	1.84	0.3
CON1	1.82	0.5
DAG	1.57	0.7
DAR	2.14	0.3
DID	1.81	0.5
HAU	1.78	0.4
MAR	1.88	0.7
OLM	1.78	0.6
QUE	1.88	0.6
SOR	1.87	0.3
Mean (in use) :	1.78	0.48
Std deviation (in use) :	0.13	0.15

173

174 Most dry density values are in the range 1.70-1.90 Mg/m³ (mean 1.78 Mg/m³, standard
175 deviation 0.13) , indicating a good level of compaction. One value appears really higher (DAR,
176 $\rho_d \approx 2.14$ Mg/m³), but it corresponds to a very well graded earth that is likely to show a high
177 compaction ability (see 3.1). On the opposite, some low values are also recorded (DAG or CHO,
178 with $\rho_d \approx 1.56$ Mg/m³) on essentially fine-grained, and not very well graded earths.
179 The samples from buildings in use show very low water contents, in good agreement with
180 common statements on healthy earth buildings ($w < 1.0$ %). On the opposite, abandoned
181 buildings reveal a higher humidity (w up to 9.8 %): they correspond to constructions with no
182 more or deteriorated roofs, in which the walls were subjected to abnormal wetting. Finally, this
183 “initial state” characterisation shows that the samples were mostly in good agreement with the
184 expected properties for traditional buildings (see for instance similar ranges in Maniatidis et al.
185 [8]).

186

187 **3. Results**

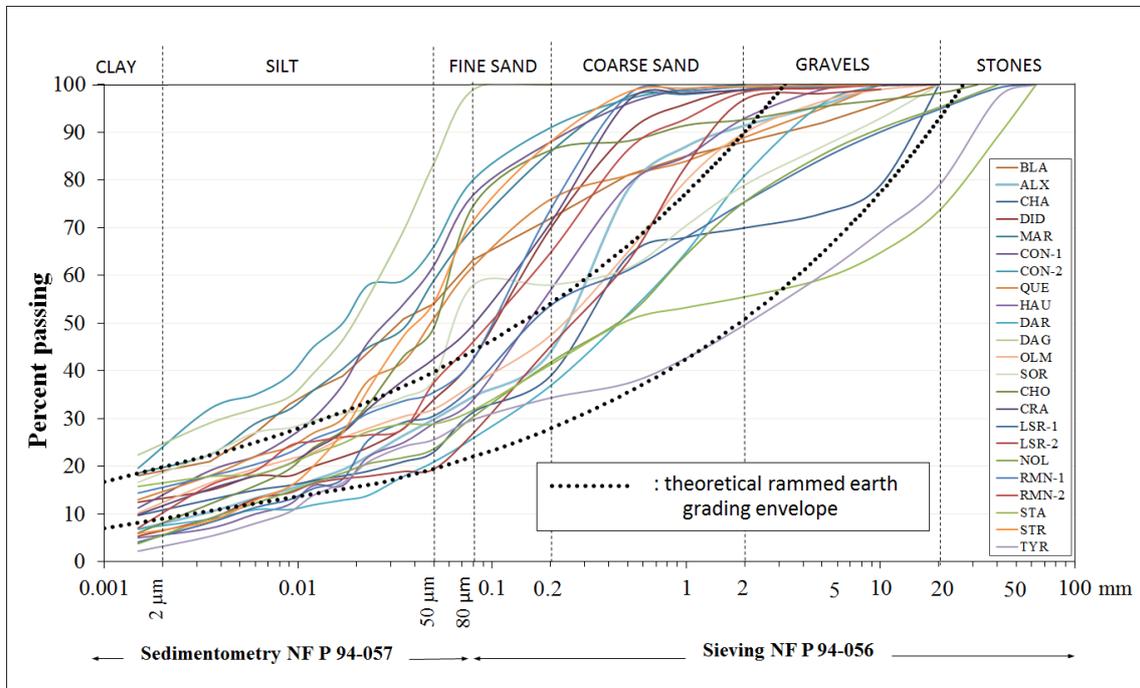
188 *3.1 Granularity*

189 The particle size distribution curves from the various samples are shown in Figure 5 that
190 includes both sieving and hydrometer testing. In dotted lines, recommended rammed earth
191 envelopes from Houben et al. [33] are shown in overlay. There are more curves than sampling
192 sites because sometimes several samples were taken on a building that showed different
193 rammed earth types (CON-1 & -2, LSR-1 & -2 and RMN-1 & -2). The graph yields a good
194 picture of the diversity of rammed earth but it cannot be used for statistical purposes because
195 the number of samples is not sufficient.

196 The curves show well graded soils, with an assembly of different particle sizes. The samples are
197 mainly composed of fine to coarse sands and always contain a proportion of clay (ranging from
198 5 to 25 %). Gravels or stones are encountered in various samples, but many samples have no
199 or little gravel contents, which is in contradiction with most grading envelopes available in the
200 literature [8] as stated also in previous studies for rammed earth from other regions [16].

201 Therefore, being included in these grading envelopes does not appear as a necessary condition
202 to determine if an earth can be used in rammed earth constructions. Moreover, a recent study
203 from Cuccurullo [34] tends to prove that it may not be sufficient either. Indeed, in this study, the

204 compressive strengths of compacted earth samples were found to drop when the raw material,
 205 whose grading was initially outside the theoretical envelope, was mixed with sand in order to
 206 reach the grading envelope criterion.
 207



208
 209 **Figure 5: A comparison between the theoretical grading envelope from Houben et al. [33],**
 210 **and grading curves of 23 samples from French vernacular rammed earth buildings**
 211 **measured in the present research program**

212

213 *3.2 Clay-water interactions: Atterberg limits and Methylene Blue Value (MBV)*

214 The results from MBV measurements are gathered in Table 2. As an indication, data from the
 215 grading analyses (including $P_{2\mu\text{m}}$ = percent passing $2 \mu\text{m}$) is also included in the table. Some
 216 Atterberg limits were performed on the samples too, but, as most samples had a small clay
 217 content, very low PI values were obtained (PI between 2 and 9), and the appropriate conditions
 218 to shape the 3 mm roll for plastic limit were rarely present. These cases correspond to poorly
 219 plastic materials that are cited for instance in section 5.5.11 of standard EN ISO 17892-12 (July
 220 2018 [35]), for which the test should be considered as poorly representative. Therefore, these PI
 221 values were not retained for further analyses and are not presented in the table. This

222 experiment tends to indicate that Atterberg limits are not the best tool to characterize most
 223 rammed earths because their clay content should not be too high to restrain shrinkage.
 224 The MBVs range from 0.01 to 1.69 g of MB per 100 g of soil, and are distributed quite evenly
 225 between these two extremes. The activity values ($A_{CB} = MBV/P_{2\mu m}$) are very scattered, with a
 226 minimum of 1 and a maximum of 23 (Table 2). The probable range of A_{CB} for each sample,
 227 which was derived from round-robin laboratory tests, is indicated also in the table. It shows that
 228 the inaccuracy on this parameter increases significantly when low $P_{2\mu m}$ values are measured.
 229 However, some general trends can still be drawn when sufficiently representative differences
 230 between values are observed. In this table, low values appear to be predominant, indicating
 231 poorly active clays and mostly silty minerals. However, some more active clays are also
 232 recorded, but they are associated with a low clay content ($P_{2\mu m}$). It leads to MBV values in the
 233 typical range of silty soils ($MBV < 1.5$) or of poorly active clays such as kaolinite ($MBV \approx 1$), and
 234 shows that the rammed earth compositions that were selected historically were expected to
 235 have a moderate specific surface as a whole. Therefore, the MBV test, that typically addresses
 236 the specific surface of the complete earth sample, should be an appropriate tool to analyse
 237 earth suitability for building purposes. Moreover, MBV values are more cost-effective than
 238 Atterberg limits.

239

240 **Table 2: Proportions of gravel, sand, silt and clay (indicative value after $P_{2\mu m}$), MBV**
 241 **measurements, activity values ($A_{CB} = MBV/P_{2\mu m}$), obtained on various samples from**
 242 **vernacular earth buildings**

Sample	Gravel / stones > 2 mm (%)	Sand 50 μm – 2 mm (%)	Silt 2 - 50 μm (%)	Clay < 2 μm (%)	MBV (g of MB / 100 g of soil)	A_{CB}	Probable A_{CB} range
ALX	8.6	61.4	22.1	7.8	0.31	4	2.5 - 6.4
BLA	12	34	35.3	18.8	0.58	3	2.2 - 4.1
CHA	30	47	12.5	10.5	0.50	5	3.2 - 7.1
CHO	7.3	43.6	41.6	7.5	1.69	23	14.2 - 36.9
CON1	0	38	48.9	13.2	0.86	7	4.5 - 9.2
CON2	0	34	43.3	22.7	0.32	1	1.0 - 1.9
CRA	1.2	56.2	31.3	11.2	1.53	14	9.3 - 20
DAG	0	16.5	59.5	24	1.02	4	3.1 - 5.6
DAR	19	60	13.5	7.5	1.44	19	12.1 - 31.4
DID	1	65	20.9	13.1	0.99	8	5.2 - 10.7
HAU	7	64	23.5	5.5	0.80	15	8.5 - 27.4
LSR1	24.5	44.9	25.4	5.1	0.54	11	6.1 - 20.9
LSR2	3.1	77.4	13.1	6.3	0.04	1	0.4 - 1.1
MAR	1	40	39.4	19.6	1.37	7	5.1 - 9.3

NOL	24.5	51.8	18.5	5.2	0.04	1	0.4 - 1.5
OLM	10	58	20.2	11.8	0.85	7	4.9 - 10.4
QUE	11	38	36.8	14.3	0.94	7	4.6 - 9.2
RMN1	0.5	63.9	20.2	15.3	0.34	2	1.6 - 3.1
RMN2	1.5	60.9	28.2	9.4	0.59	6	4.1 - 9.6
SOR	21	41	19.9	18.1	0.66	4	2.6 - 4.9
STA	44.4	26.6	12.6	16.4	0.44	3	1.9 - 3.7
STR	0.4	45.3	47.9	6.5	0.65	10	6.1 - 17.3
TYR	50.3	24.1	22.6	3	0.37	12	5.9 - 44.4

243

244

245 4. Discussion

246

247 The data gathered on the samples presented previously can be analysed through various
 248 classification systems. These systems allow a synthetic view of the results that may help cross-
 249 analysing different parameters and identifying what the appropriate soil classes for construction
 250 could be. In particular, the following criteria are explored below:

- 251 • classification systems only based on granularity: grading curves or triangular
 252 classification for pedology;
- 253 • classification systems that include both granularity and clay behaviour: the classification
 254 from the French earthwork guide “GTR” [36] or from standard NF P 11-300 [37].

255 The primary aim of the classification system is to identify directly usable earths, without any
 256 correction such as sieving, additions, etc.

257

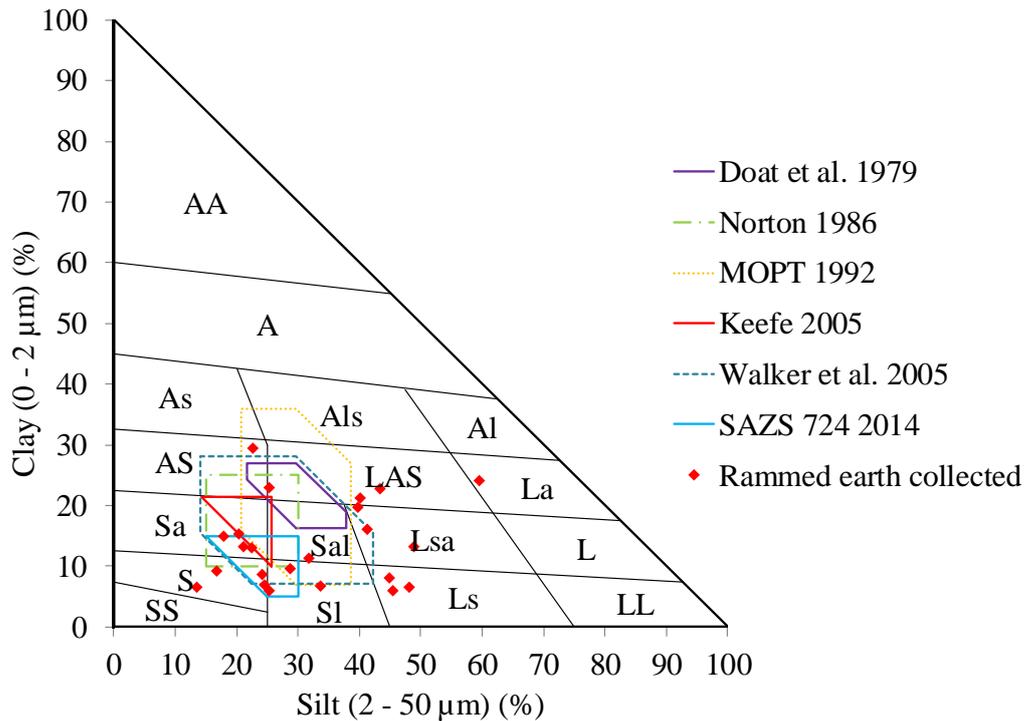
258 4.1 Classification systems based on granularity

259 Granularity has been used for a long time to assess soil suitability for various practical
 260 applications. It only focuses on particle sizes, which does not allow taking fully into account
 261 other important parameters for soil behaviour such as interactions between clay particles and
 262 water. However, many authors proposed typical grading envelopes for construction. In Figure 5
 263 for instance, the typical envelope from Houben et al. [33] was presented. This figure clearly
 264 shows that the grading envelopes from the literature fail to represent the global diversity of
 265 rammed earths used in vernacular construction. Therefore, contrary to what is regularly
 266 assumed by many control or design offices, these envelopes should not be used as an isolate

267 criterion for earth suitability. This statement, which is a common criticism from masons in the
268 field about grading envelopes, is clearly confirmed here through quantified measurements.
269 Another way to analyse granularity is to compare the proportions of predefined particle sizes in
270 the soil. It can be made through a soil texture triangle for instance. In this classification,
271 commonly used in soil sciences, the proportions of sand, silt and clay are used to define soil
272 classes. In the graphic representation, the texture is symbolized by a point, contrary to the
273 conventional granular curve, which eases the comparison of a large number of soils. However,
274 depending on the authors and on the countries, many different triangles are referenced, without
275 any international standardization (see for instance Richer de Forges et al. [38] who listed about
276 30 different texture triangles in use around the world). In the present paper, a texture triangle
277 commonly used for French soils, defined by the French soil science organisation "GEPPA" [39]
278 is used. In this approach, only the fine fraction of the soil is taken into account, i.e. whatever the
279 gravel content, clay, silt and sand contents are calculated in order to represent 100 % of the fine
280 soil. The clay content is calculated from the percent passing 2 μm , the silt content is
281 conventionally the 2 – 50 μm fraction and the sand content covers particle sizes from 50 μm to 2
282 mm.

283 In Figure 6, the textures of fine soils collected in rammed earth buildings in Auvergne-Rhone-
284 Alpes region are confronted to recommendations available in the literature [12], [40]–[44] and
285 represented in a texture triangle. The majority of the earths collected fall outside the different
286 recommended textures. Even considering all these recommendations together, almost half of
287 the earths collected fall outside any predefined area available in the literature. Thus, current
288 texture recommendations fail to give full account of the diversity of the time-tested earths
289 employed by past masons for rammed earth in the southeast of France. At the opposite,
290 considering this entire diversity would lead to define a very large area of textures: this area
291 would represent the majority of available natural soils, which seems not realistic and would
292 contain soils that are not suitable for construction.

293



294

295 **Figure 6: Comparison of texture of collected rammed earth materials with literature**
 296 **recommendations** [12], [40]–[44]

297 Finally, the triangle presentation appears interesting due to its « compact » shape but it suffers
 298 the same defects as the grading curve, i.e. it does not take into account the soil-water or clay-
 299 water interactions that are an essential parameter for rammed earth strength.

300

301 4.2 About the quantification of clay-water interactions

302 Clay-water interaction is mostly linked to the Specific Surface Area (SSA) developed by colloids
 303 in the soil, i.e. clay, organic matter and colloidal silica.

304 In rammed earth practice, the higher the SSA the higher the cohesion but the higher the drying
 305 shrinkage. There is thus a minimum SSA to ensure a minimum cohesion for construction but
 306 also a maximum SSA to limit the shrinkage cracking [7], [19], [45]–[47]. Considering the 2μm
 307 passing is a way to estimate clay content, but it does not provide any information on clay type.

308 Since, for example, the SSA of a smectite is about 10 times higher than that of a kaolinite [48],
 309 clay type plays a major role in the soil-water interaction, and granularity is not sufficient to
 310 describe it properly.

311 SSA can be estimated via the Atterberg limits (Plastic and Liquid Limit, and Plastic Index),
312 measured by chemical titration (Methylene Blue Value or Cation Exchange Capacity) or
313 calculated after mineralogical identification and quantification (X-Ray diffraction combined with
314 chemical analysis). Among these tests, the Atterberg limits are the most employed ones [8],
315 [11], [49] even if their accuracy has been criticised for rammed earth [10]. The results of our
316 study (Table 2) highlight that suitable soils for rammed earth often have a low plasticity: it is
317 therefore most of the time impossible to determine their plastic limit and, as a consequence,
318 their plastic index. The liquid limit could be kept as an indicative value however, or correlated
319 with PI thanks to the Casagrande chart: but the scattering would be quite significant, and only
320 the fine part of the soil would be considered, contrary to MBV for instance that gives an
321 indication on the entire 0-50 mm fraction. Mineralogical identification and quantification is a very
322 long and expensive process and it cannot be used routinely. Methylene Blue Value (MBV) [18],
323 [21], [45], [50] and Cation Exchange Capacity (CEC) [7], [21], [47] can be regarded as good
324 estimators of the SSA of colloids of earth materials. Between these two tests MBV is easier and
325 cheaper to perform and it is already employed in numerous civil engineering laboratories.
326 Anyway, some correlations between MBV and CEC results [51] allow estimating the one from
327 the other. As a consequence, after identifying that Atterberg Limits were not truly appropriate,
328 the authors chose to use MBV tests preferentially in the classifications described below.

329 A last point that should be taken into account when dealing with clay-water interactions is the
330 question of organic matter. Indeed, the SSA of organic matter is about an order of magnitude
331 higher than the range of Methylene Blue Value usually measured for rammed earth (Table 2).
332 The presence of organic matter would dramatically increase the SSA, so that the SSA can be
333 regarded also as a good indicator of an excess of organic matter [47]. In the present study, only
334 mineral and sufficiently dry and un-weathered earths were sampled. Such conditions did not
335 allow clay-humic complexes to develop, and this assumption was confirmed by the low MBV
336 measured, as well as by olfactive and visual checking.

337

338 *4.3 A classification system taking into account both granularity and clay-water interactions*

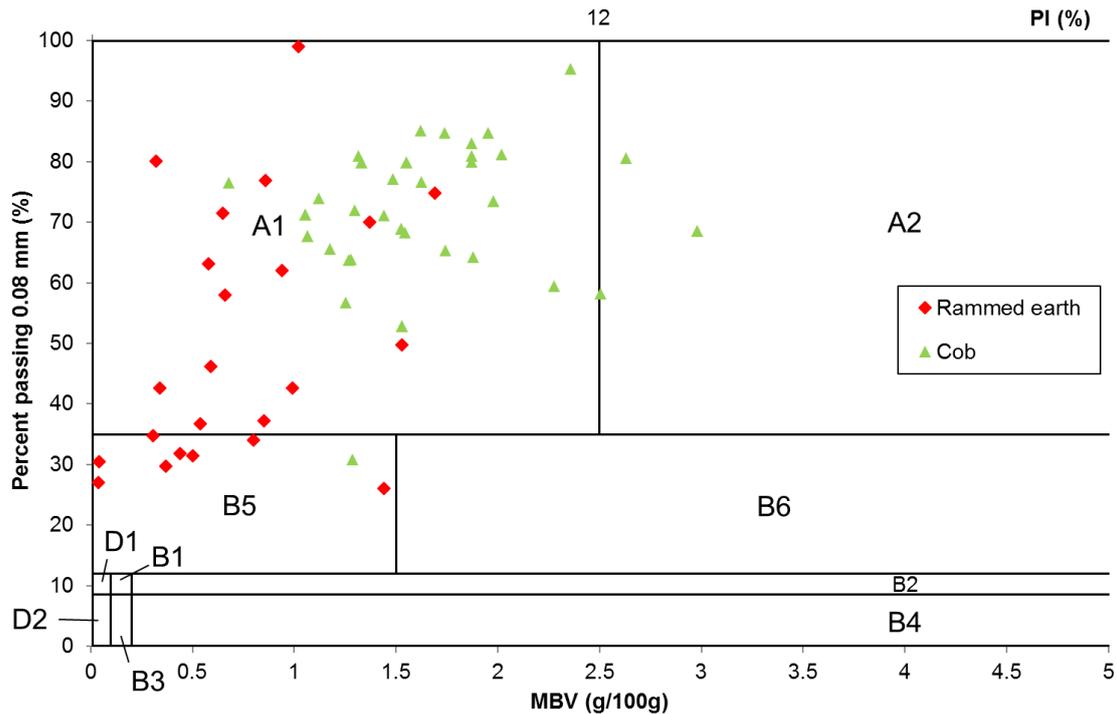
339 The French management system for road earthwork materials, called "*Guide des*
340 *Terrassements routiers*" (GTR) [36] is used here, for the first time, as a classification system for

341 earth building materials. It has the specificity to consider both granularity and clay activity
342 (through PI or MBV values). This classification was developed in France in the 1990's [36] ; it
343 takes into account the same basic characteristics as the common USCS soil classification (see
344 [52] for instance) but it includes a more precise focus on the behaviour of argillaceous particles
345 in order to define soil classes. This classification is also presented in the French Standard NF P
346 11-300 [37]. It is expected to be well adapted to rammed earth characterisation because it
347 originally aimed at obtaining long-lasting earthwork layers through compaction.

348 In this classification, soils with a maximum particle size of 50 mm are described after their fine
349 content (percent passing 80 μm), their MBV and/or their PI. When $\text{PI} < 12$, MBV should be used
350 as a preferential criterion, and reciprocally. It confirms that MBV should be the appropriate
351 testing procedure for the rammed earth samples presented in this paper. Fine silty or
352 argillaceous soils are called "A", and a number is added depending on clay-water interactions.

353 For instance, A1 stands for soils with over 35% passing 80 μm and $\text{MBV} < 2.5$ or $\text{PI} < 12$ (if
354 measurable). Soils B1 to B6 are mainly sandy and gravelly soils with fines, and D1 / D2
355 describe sandy or gravelly clean soils, mostly insensitive to the effects of water. This
356 classification can be pictured under a condensed form with the chart shown in Figure 7, on
357 which the various samples from rammed earth buildings have been represented. The figure also
358 presents typical points for cob after Hamard et al. [7], that will be explained further in the paper.

359



360

361 **Figure 7: The "GTR classification" chart for earthworks [36] and (in red) experimental**
 362 **points from rammed earth buildings and (in green) typical points for cob after Hamard et**
 363 **al. 2018. The right part of the original chart (PI > 25) is not shown.**

364

365 Concerning the rammed earth samples taken from the field, only A1 and B5 soils appear in the
 366 graph. Moreover, an interesting observation is that many A2 or B6 natural soils usually exhibit
 367 grading curves similar to A1 or B5 soils, but distinguish by the activity of their clay fraction. Such
 368 soils would have been considered as "suitable" after Figure 5 or Figure 6, but they would have
 369 been quite far from the area covered by the field samples in Figure 7.

370 Moreover, even if the number of experimental points remains moderate, a rammed earth area
 371 may be guessed from Figure 7, independently of the already existing GTR subdivisions, and
 372 approximately delimited by: more than 25 % 80 µm passing, MBV < 1.7. The sampling points
 373 are well scattered in this area, which indicates that the complete range of granularity and MBV
 374 values may be appropriate for construction. However, as the number of collected earths is still
 375 not enough to be statistically representative and the soils of this study are only suitable under
 376 the climate and geological conditions of France, this proposition cannot be considered yet as an
 377 exclusive criterion for rammed earth. More data should be collected in other contexts. These

378 results may however be used as a “pre-decision tool”, yielding a first assessment of soil
379 suitability that should be validated afterwards with a scale-one experimental wall or laboratory
380 performance tests for instance.

381

382 *4.4 A comparison with earth suitability for cob in Brittany*

383 The characteristics of the soil horizons identified as suitable for cob in Brittany by Hamard et al.
384 [7] are used to calculate the 80 µm passing and the MBV, estimated from the CEC according to
385 the correlation proposed by Laribi et al. [51]. Soil horizons suitable for cob are presented
386 together with rammed earth material collected in built heritage in Figure 7.

387 The confrontation of data in the GTR classification system reveals that cob materials are finer
388 and have a higher specific surface area than rammed earth materials. Very few or no silty/sandy
389 soils (B5-type) are encountered. This is in agreement with the literature stating that cob
390 materials have a higher fine and clay content [12], [13] than rammed earth materials. Regarding
391 specific surface area (MBV/PI), no comparison can be found in the literature. Nonetheless, a
392 parallel can be made between wet techniques (cob and adobe) and dry techniques (rammed
393 earth and Compressed Earth Block (CEB)). The Plastic Index of CEBs is deemed to be lower
394 than the one of adobe [33], hence the PI of rammed earth should be lower than that of cob,
395 which is in line with the results of Figure 7.

396 Some cob points overlap with the “rammed earth area”, which is also in good agreement with
397 the common statement that some soils are appropriate for several techniques.

398

399 *4.5 An insight in the future: indications to build a decision tool*

400 Through confrontation with cob and rammed earth typical characteristics, the GTR classification
401 system based on two simple geotechnical tests (percent passing 80 µm and methylene blue
402 value) appears as a good candidate for earth suitability purposes. It can become a simple,
403 discriminant, and low-cost decision tool for contractors and planning authorities to assess the
404 reuse potential of their excavated materials in earth building.

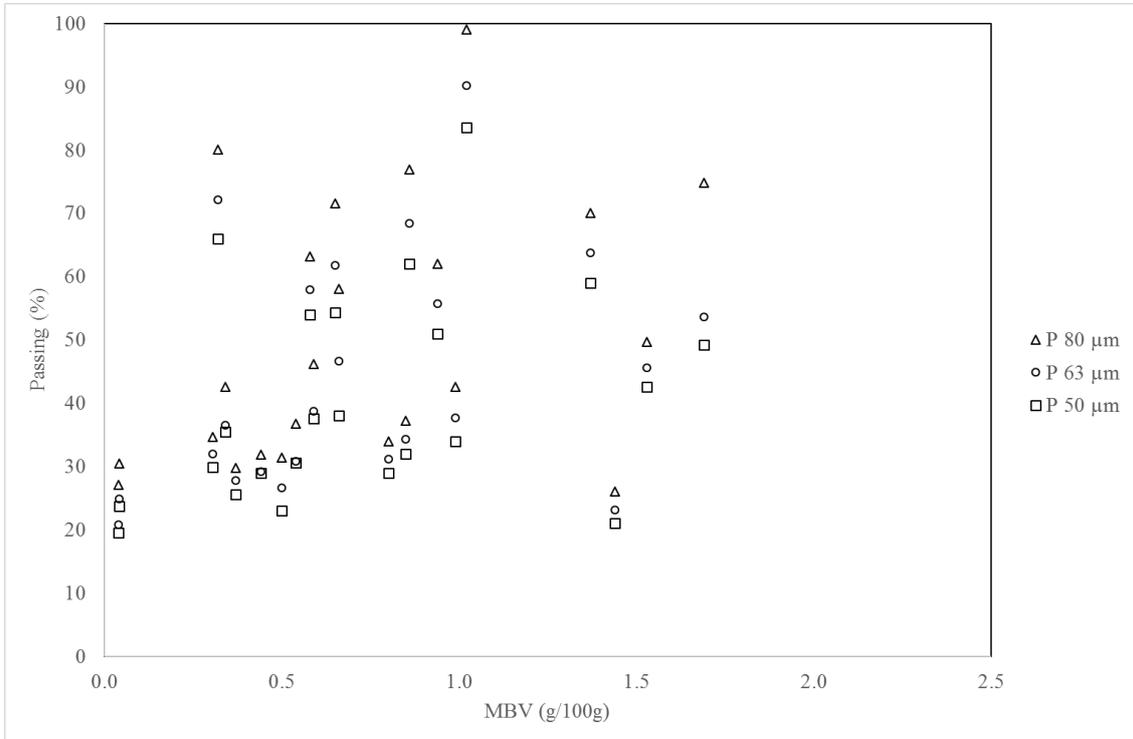
405 The authors believe that the present study constitutes the first step towards the definition of this
406 decision tool. The next step would be to gather more data on various building techniques

407 (rammed earth, cob, adobes, CEB, wattle and daub, earth plasters) in order to define
408 statistically representative suitability areas in the classification chart (Figure 7).
409 Afterwards, the chart completed with typical areas for cob, rammed earth, adobes, etc. could be
410 used as a pre-decision tool in various situations. A first interesting application is the
411 identification of suitable earths for a predefined technique in a given territory. In this case,
412 planning authorities or investors can program extensive sampling campaigns, and analyse each
413 earth taken from the field with only two low-cost tests: MBV and percent passing 80 μm (the
414 complete grading curve is not even necessary). Representing the corresponding points in the
415 chart will immediately indicate what sampling sites have the highest probability to yield
416 convenient earth for a given technique. Another interesting application is the assessment of a
417 given earth, found on the field at the vicinity of a building project or in excess from an earthwork
418 project. With only two tests, the decision tool would indicate what the most suitable building
419 technique or techniques would be for this soil. In both cases, field or laboratory performance
420 tests will have to be conducted in the end to validate completely the chosen "earth / building
421 technique" pair.

422 A limitation of this classification system may appear in case of significant organic matter
423 contents that would disturb the material behaviour, and the MBV measurements. After the
424 earthwork practice gathered in the GTR guide [36] however, the classification principle should
425 remain fully valid as long as the organic matter proportion does not exceed 3 % in mass. As the
426 usual recommendations (see synthesis in [16] e.g.) for earth construction technologies are to
427 use mineral non-organic earths, and not topsoil, organic matter should not question the
428 applicability of the classification system when it is used to assess earth suitability before
429 building. It could however make it more difficult to conduct back analyses from existing buildings
430 when they incorporate significant amounts of large or microscopic vegetal fibers. For instance,
431 organic matter rates over 3% were reported in some existing buildings in South Portugal by
432 Gomes *et al.* [16].

433 Finally, it may be noticed also that the classification system of Figure 7 remains relevant if the
434 granulometric criterion for the fine content of the soil (i.e. 80 μm) is changed. Other limits
435 commonly used in European countries, i.e. 63 and 50 μm , can be used as well. A comparison is

436 shown in Figure 8. It shows that the rammed earth points from field sample remain gathered in a
437 comparable area with all three criteria.
438



439
440 **Figure 8: Rammed earth samples presented in the “MBV – soil fine percentage” diagram,**
441 **with 3 different granulometric criteria (80, 63, 50 μm)**

442
443 **5. Conclusions**

444 Built heritage constitutes a very interesting source of knowledge to identify the properties of
445 building materials used through history. These materials, that can be considered as “time
446 tested”, may be approached as a reference in order to specify appropriate earth characteristics
447 for fore coming rammed earth or cob buildings.

448 Through sampling or through cross-referencing of spatial data, a unique survey of earth
449 characteristics for construction was gathered. Such data is poorly present in the literature and
450 has, by itself, a strong scientific and historic interest. Moreover, it can be used to try to define
451 appropriate classification systems for earth suitability. Such criteria would help future
452 constructors choosing their material on the field.

453 The analyses conducted in the paper clearly show that grading envelopes or texture triangles
454 from the literature are inappropriate to select suitable earth characteristics. They do not reflect
455 the diversity of earth compositions encountered in the field, and if they were extended to a much
456 wider granularity range, they would include too many soil types. Moreover, they do not take into
457 account an important parameter for earth implementation, resistance and durability, that is the
458 activity of the clayey minerals.

459 The paper shows that classification systems based on both granularity and clay-water
460 interactions, such as the French "GTR" classification for earthworks, allow a more complete
461 description of earth properties and may allow differentiating the suitability for various building
462 techniques. The granularity criterion can be approached through only one value of soil fines
463 percentage, with a limit at either 50, 63 or 80 μm . The activity of clay minerals can be measured
464 through simple PI, CEC or MBV laboratory tests in order to achieve a simple and low-cost earth
465 analysis tool. In the paper, MBV appeared as the most relevant tool for techniques such as
466 rammed earth, because of its low cost and easy implementation, and because the
467 corresponding soils often exhibit low clay contents and/or specific surface areas, leading to
468 poorly representative PI tests. The same should be valid for CEB technologies.

469 Such a classification system is expected to be a very good candidate for the assessment of
470 earth convenience for building purposes: it would be discriminant, low-cost (only one sieving
471 and one MBV per tested soil) and user-friendly. It may be completed by an organic matter
472 content measurement when rates over 3% are suspected (which should be also an exclusion
473 criterion after most existing recommendations). It would be possible to use it as a pre-decision
474 tool before conducting scale-one or laboratory performance tests for validation. It is strongly
475 expected that, by continuing the sampling and testing approach of this paper on various
476 widespread earth construction techniques (such as adobes, wattle-and-daub, etc.), a complete
477 vision of earth suitability could be obtained.

478 As a consequence, the authors encourage other labs from other countries to gather and publish
479 similar data on various building techniques, in order to establish a complete international
480 reference set of earth characteristics, based on granularity and clay activity, that will allow a
481 reliable and statistically representative decision tool for professionals.

482

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488

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619 **Figure captions (images as individual files separate to your MS Word text file).**

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628 Figure 1.

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