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1 Methods to evaluate earth slip cohesion to build with 2 light earth. 3

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17 Highlights.

- 18 • Cohesive behaviors of 6 earth are studied through yield stress measurement.
 - 19 • The study is based on samples representative of Brittany and Normandy earth natural
20 variability.
 - 21 • Existing or new rheological tests are compared to evaluate their accuracy and validity range.
 - 22 • Results allow to control an earth slip yield stress knowing its water content.
- 23
24
25

26 Abstract.

27 Bio-based materials are subject to a growing interest since the nineties to reduce the
28 environmental impacts of the building sector. Light earth is a low impact insulation material.
29 Light earth building methods are based on the use of earth slip, a mix of clayed earth and water,
30 and aggregates or fibers. The earth slip is characterized on site by mason by different means.
31 This study aims to compare different rheological measurements methods in laboratory
32 conditions, and then to define simple and robust tests adapted to any conditions. The study is
33 based on six soil samples. Geotechnical characterizations show that these soils cover a wide
34 range of natural variabilities. Their cohesive behaviors were investigated by measuring the yield
35 stress with a rheometer, a spread test, a dipping test and a rough wall cone test, both developed
36 for the study, and a Marsh cone test. Accuracy and the validity range of each test are presented
37 alongside the needs for light earth applications.
38
39

40 **Keywords:** clay, rheological behavior, yield stress, light earth
41

I Introduction

43 Earthen construction has been used for centuries with various building materials and methods,
44 mainly rammed earth, wattle and daub, cob, adobe, and plasters. Recently, it has attracted renewed
45 interest, especially due to its low environmental impact [1]–[5]. For instance, light earth is a
46 contemporary material based on wattle and daub, developed since the 1920s [6] in Germany and the
47 1990s in France, to obtain satisfactory thermal insulation with clay as a binder. It consists in a mix of a
48 large volume fraction (between 50 and 80%) of light aggregates bound together with a small quantity
49 of a liquid earth slip (i.e. earth and water). The aggregates mostly used currently are straw [6], [7] and
50 hemp [8], [9].

51 Even if the variability of the components can be tackled on site by experimented mason, it makes
52 more complex scientific studies. Bio-based aggregates might differ in terms of particle size
53 distributions and chemical compositions depending on the species, crop practices, harvesting, and the
54 primary transformation process [10]. In lime-hemp literature, hemp variability impacts on the material
55 performances are under studies [10].

56 On another hand, soils vary in composition and clayey behavior, even over short distances [11]. For
57 raw earth construction, assessment of the suitability of one material for a given building technic is a
58 subject of scientific studies [12]–[16].

59 Nowadays, the earth slip is qualitatively characterized on site by mason by different means. It is of
60 interest to supplement such analysis by a quantitative estimation of earth slip rheological behavior
61 with simple and rapid tests.

62 In unsaturated soils or dense earth building materials, the cohesion is defined by attraction
63 between particles. This attraction is in majority driven by capillarity and specific forces between clay
64 platelets [17]. Thus, soil cohesion appears to be a key parameter since the intrinsic cohesion of earth
65 particles and the water content drives the rheological behavior of the slips. High slip cohesion allows
66 a high volume fraction of bio-based aggregates and leads to good insulation properties in the hardened
67 state. Standard geotechnical tests as particle size distribution, Atterberg limits and Methylene Blue
68 Value (MBV) or Cation Exchange Capacity (CEC) [18]–[21] allow us to roughly estimate the cohesive
69 and physical behavior of soils. But further tests are needed to quantify the earth slip cohesion as a
70 function of its water content. An earth slip is a mix of fine particles (clay and silt), coarse particles
71 (sand), and water. Such a granular suspension behaves as a yield-stress material [22]–[25], with a yield
72 that depends on the cohesive behavior of clay and silt, particle size distribution, and solid volume
73 fraction[26].

74 Some studies [2], [27]–[31] evaluate the rheological behavior of earthen material that are
75 composed of a high solid volume fraction (mortars, rammed earth). Rheology is also used for the
76 development of 3D-printed earth [32] or earth concretes [33]. But no large comparative studies are
77 found on the evolution of the rheological behavior of different earth according to their content.

78 Even fewer studies deal with the development of simple rheological characterization tests [34]–[37].
79 For example, Alhaik et al. [38] use the flow test to characterize the impact of adding starch to earth
80 mortars. Here, the flow test is used to define the water content in order to aim a given workability. But
81 none of the studied mortars have the same rheological parameters and no link is done between the
82 flow test and the rheology of the suspensions.

83

84 The main purpose of the present study is to assess different methods to measure the rheological
85 behavior of the earth slips, in order to identify if a simple and robust test is adapted to field conditions.
86 In the present study, characterization made on suspensions are carried out with simple rheological
87 tests specifically developed for this study or from the literature [29]–[31], [34], and with a laboratory
88 rheometer equipped with a Vane geometry tool. Tests from different areas were considered in this
89 study: the spreading test is a well-used spread test in cement grout characterizations; the Marsh cone

90 is used for quarry sludge [35], [39]; the viscosity cups are used in the oil and painting industries [40] ;
91 the rough wall cone test is especially developed as an adaptation of the latter two tests; and finally,
92 the dipping cylinder test is derived from the plate test [41] used also for cement grout setting analyses.

93 Firstly, studied earth materials are presented along with their characteristics. In the second part,
94 the theoretical frame of each previously mentioned test is described in details. Then, results of earth
95 slip characterization are presented according each studied method. Finally, results are discussed
96 following the suitability of each test for yield stress measurement.

97

CEC	Cation Exchange Capacity	ρ_0	Perimeter of the cylinder
A_{CEC}	Clay activity calculated on CEC	h	Immersed height
H_0	Initial height of spreading flow container	h_0	Height of the sheet
R_{0max}	Initial maximum radius of spreading flow container	H_c	Height of the Rough wall cone, without extension
R_{0min}	initial minimum radius of spreading flow container	β	Slope angle
V	Volume of spreading flow container	R_{max}	Rough wall cone maximum radius
ρ	Density	R_{min}	Rough wall cone minimum radius
g	Gravity	A_{cone}	Slope area
τ_0	Yield stress	R_f	Maximum radius on Marsh funnel
τ'_0	Dimensionless yield stress	R	Minimum radius on Marsh funnel
S	Slump	L	Height of cylinder part in Marsh funnel
S'	Dimensionless slump	H_s	Height of remaining material
R	Final spread radius	H_f	Height of the conical part of the Marsh funnel
V_0	Initial sample volume	v	Ratio of vertical stability in rheometer tests with vane tool
a	Parameter in Pierre calculation	h_c	Vane tool height
b	Parameter in Pierre calculation	k	Number of particles
M	Mass	ϕ_{max}	Maximum particles diameter in earth slip
A	Plate area	I	Inertia
W'	Apparent weight	Cyl	Cylinder
W'	Weight	Sp	Sand paper
M_0	Sample Initial mass	λ	Thickness of sheared material in the air-material interfacial zone
A_0	Initial sheet area	α	Fitting parameter
t	Thickness of the remaining slip	w	Water content
T	Tensile force at inside/outside interface	ρ_e	Earth particles density
		ρ_w	Water density
		m	Sample mass

Table 1 Classification

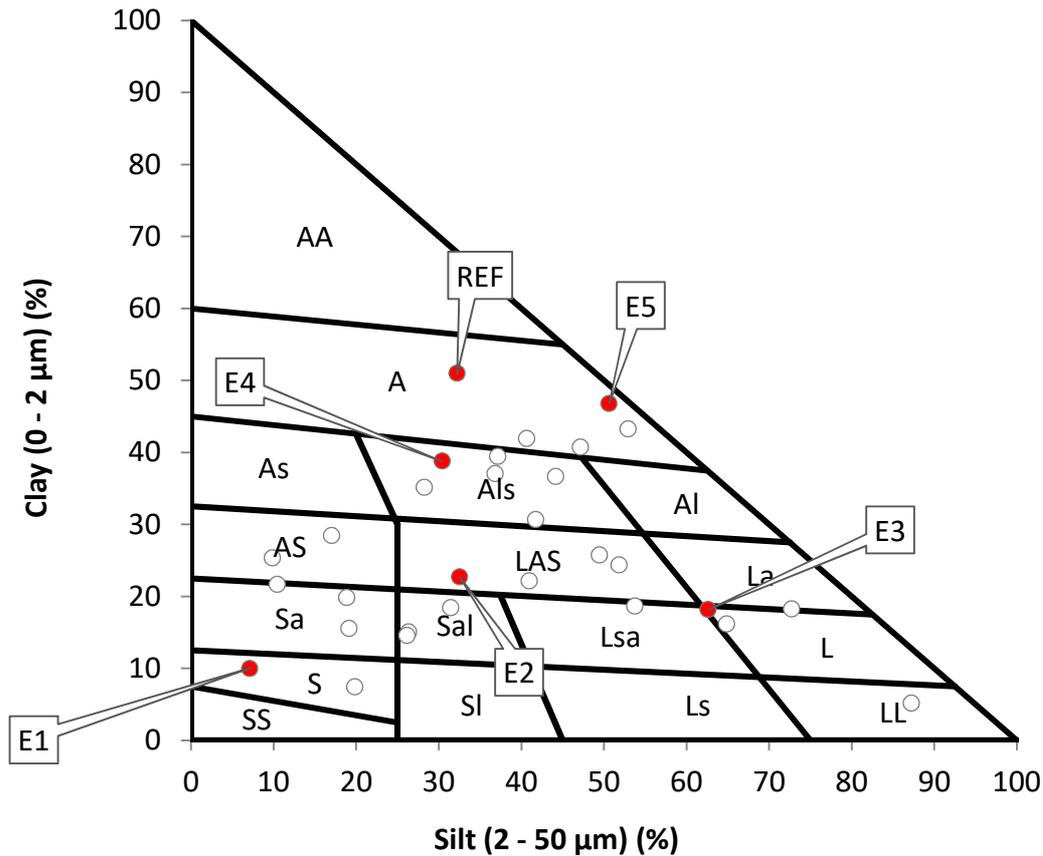
100 **2-1- Earth identification**

101 Six soil samples were chosen among 27 samples collected in Brittany and Normandy (France) in order
 102 to investigate a large range of variabilities. One reference had been used by builders on more than 15
 103 hemp-earth constructions, and the other five came from different locations, such as quarries, where it
 104 is possible to sample raw soils or washing sludge, or private lands, where the soil was used for
 105 construction, using the knowledge of experienced builders, which facilitated selecting soils with
 106 “extreme” characteristics. Apart from the reference (REF), the five other soil samples were given
 107 numbers. Each collected soil sample was examined using traditional geotechnical characterization
 108 methods. One goal was to evaluate if the selected samples cover a large variability range of soils that
 109 can be found in nature.

110
 111 Specific densities were measured using a water pycnometer according to the French standard NF P94-
 112 054 [42]. According to this standard, the soil is prepared by wet sieving at 2 mm, which is the sieve
 113 usually used for earth slips. Particle size distribution was quantified by dry sieving for the coarse
 114 fraction (above 80 μm), according to NF P 94-056 and by a hydrometer test for the fine fraction (below
 115 80 μm), according to NF P 94-057. The cation exchange capacity (CEC) was measured with cobalt
 116 hexamine according to NF ISO 23470. Atterberg limits were measured according to NF P94-051. All soil
 117 characterization results are summarized in Table 2. Density of the six soil range from 2575 kg/m^3 to
 118 2821 kg/m^3 . Particle size distributions are plotted in a texture triangle (Fig.1), and confirm that the
 119 collected samples cover a wide range of natural variability. It is to be noted that REF and E5 exhibit a
 120 clay content higher than 60%, which is rare [17]. The six chosen samples, marked in red in Fig.1, cover
 121 a wide range of soils. The CEC of the samples under investigation ranges from 0.5 to 22.3 $\text{cmol}^+.\text{kg}^{-1}$.
 122 Dividing these values by the clay fraction (below 2 μm) leads to clay activities A_{CEC} , ranging from 6.7 to
 123 117.8 $\text{cmol}^+.\text{kg}^{-1}$. The plasticity index of the samples goes from 11 to 32. E1 sample is too sandy to
 124 carry out Atterberg limits.

	REF	E1	E2	E3	E4	E5
Effective particle density (kg/m^3)	2661	2714	2821	2810	2806	2575
CEC ($\text{cmol}^+.\text{kg}^{-1}$)	14	4	5	7	13	21
A_{CEC}	28	39	20	14	34	118
Liquid limit (%)	53	-	43	58	51	58
Plastic limit (%)	27	-	29	37	19	47
Plasticity Index	26	-	13	21	32	11

Table 2 Geotechnical parameters of the six soil samples.



125

Fig.1 Clay silt and sand distribution of the 27 collected soil samples. The six red dots correspond to the six samples selected for slip making and rheological studies

126 2-2- Earth slip preparation

127 Raw samples at natural water content were prepared as follow:

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1. Earth was mixed with a small quantity of water (mass ratio of about 1 water for 1 of raw earth);
2. The mix was blended with a paddle mixer for 5 minutes;
3. The slip was sieved with a 2 mm square sieve (a mesh size commonly used by builders working with hemp-earth);
4. The slip was kept at rest for 24 hours in order to ensure the dilution of all earth clumps;
5. It was then blended again with a paddle mixer for 1 minute;
6. The water content was measured by oven drying (at 105°C, up to weight stabilization, according to XP CEN ISO/TS 17892-1).

The first earth slip, with a controlled water content, was then progressively diluted with water to vary the rheological behavior by controlling the water content.

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141 III Rheology measurement methods

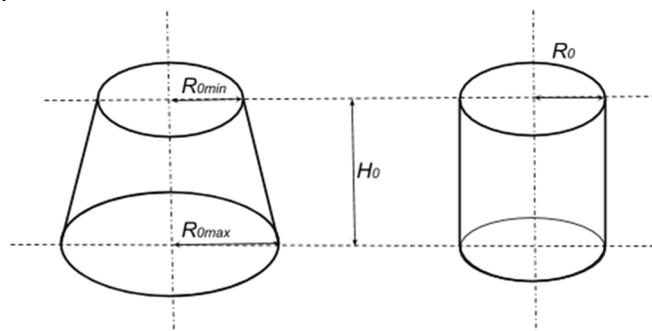
142 3-1- Rheometer

143 For the experimental validations, the yield stress values were measured using a rheometer
144 with vane geometry. The mixtures were poured into a cylindrical container and vigorously mixed by
145 hand to avoid thixotropy, segregation, and bleeding effects. The slip temperature was measured just
146 before each test. These precautions were taken to avoid the measurement bias that could be due to
147 temperature variations, sedimentation, or the structural build-up that occurs in the slips at rest. The
148 yield stress was measured using an Anton Paar Rheolab QC rheometer equipped with vane geometry
149 (four-bladed vane – 6 cm in height and 4 cm in diameter). The measurement procedure was similar to
150 the one used in [43], [44]. A strain growth was applied to the sample at a shear rate of 0.01 s^{-1} for 400
151 s. At such a low shear rate, viscosity effects are negligible, and the yield stress can be computed from
152 the measured torque peak value at flow onset. Each yield stress measurement was performed three
153 times to ensure procedure reliability. The curves obtained show a classical stress growth evolution.
154

155 3-2- Slump / spreading flow test

156 The slump flow/spreading flow test is widely used in the construction industry to assess the workability
157 of cementitious mixtures. It involves pouring and compacting the paste into a container (Fig. 2) using
158 a standard procedure and measuring the slump or the spreading diameter to estimate the workability
159 of the slip [45], [46]. The most commonly used geometries for these tests are the ASTM Abrams cone
160 (H_0 300mm, $R_{0\max}$ 100mm, $R_{0\min}$ 50mm) and the ASTM minicone (H_0 50mm, $R_{0\max}$ 50mm and $R_{0\min}$
161 35mm). For fluid pastes such as earth slips, a cylindrical container can also be used. In the present
162 study, both the cylinder and the cone were tested, with different aspect ratios and volumes:

- 163 - a cylinder with a radius R_0 of 27mm and a height H_0 of 90mm, for a volume V of 0.206 dm^3 and
164 an aspect ratio of 1,67;
- 165 - a cone with $H_0 = 150\text{mm}$, $R_{0\max} = 100\text{mm}$, $R_{0\min} = 50\text{mm}$, for a volume V of 2.75 L and an aspect
166 ratio around 2.



167

Fig. 2 Initial shapes for the slump/spreading flow test

168 Theoretical framework

169 An analytical relationship exists between the slump and the yield stress of a granular suspension [47],
 170 [48]. Four cases can be observed when lifting the container:

171

172 • No slump: there is a critical yield stress of the paste for which no slump occurs. Theoretically,
 173 if we assume that the paste should undergo a pure elongation deformation and that the Von
 174 Mises yield criterion is applied, this critical yield stress is equal to $\sqrt{3}\rho g H_0$, namely a
 175 dimensionless yield stress $\tau'_0 = \frac{\tau_0}{\rho g H_0} = \sqrt{3}$. It was confirmed by the numerical simulations
 176 and experimental results of Roussel and Coussot on the ASTM Abrams cone and the ASTM
 177 minicone [48]. Above this critical yield stress, the paste is too rigid to yield under its own
 178 weight, and this kind of experiment is not appropriate. In this case, a squeeze flow [49] or a
 179 dropping cylinder test [30] could be used to enforce the deformation.

180

181 • Slump flow, with no spreading: the final shape is close to the initial one, the stress and strain
 182 variations in the radial direction are small, yielding to a slightly barreling final shape. In this
 183 case, by considering a pure elongation flow, Roussel and Coussot [48] and Pierre, Lanos and
 184 Estellé [47] apply a Von Mises criterion to the paste, which leads to the following analytical
 185 expression for yield stress τ_0 as a function of the slump value S (or of the final height H):

186

$$187 \quad \tau_0 = \frac{\rho g H}{\sqrt{3}} = \frac{\rho g (H_0 - S)}{\sqrt{3}} \quad (1)$$

188 This theoretical expression is valid only with the assumption of a high initial height compared
 189 to the initial radius of the sample. Roussel and Coussot [48] show that it is accurate for a
 190 dimensionless yield stress τ_0' that ranges between 0.45 and $\sqrt{3}$, i.e. a dimensionless slump
 191 $S' = \frac{S}{H_0}$ lower than 0.1.

192

193 • Spreading (pure shear flow, with final height $H \ll$ final spreading radius R): in this case, Roussel
 194 and Coussot [48] propose a formula relating the yield stress and the spreading distance (radius
 195 R):

$$196 \quad \tau_0 = \frac{225\rho g V^2}{128\pi^2 R^5} \quad (2)$$

197 with V the volume of water, ρ its density and R the final radius of spreading

198

199 • Spreading, with a remaining cone or cylinder (mix of slump flow and spread regime): Pierre,
 200 Lanos and Estellé [47] propose an analytical formulation for this intermediate regime. They
 201 assume that the upper part of the deformed sample, which they call "hat", and the central
 202 zone of the lower part are subjected to elongation flow only (Eq.2). Inversely, they apply a pure
 203 shear flow theory to the spreading zone of the lower part, which leads them to resolve a
 204 second order polynomial equation and to take its positive solution:

205

$$206 \quad \tau_0 = \left(\frac{-b + \sqrt{b^2 + 4aV_0}}{2a} \right)^2 \quad (3)$$

207 With:

$$208 \quad a = \frac{\pi R_0^2 \sqrt{3}}{\rho g}$$

$$b = \left[\frac{8\pi}{15} (R - R_0)^{5/2} + \frac{4\pi}{3} R_0 (R - R_0)^{3/2} + \pi R_0^2 (R - R_0)^{1/2} \right] \sqrt{\frac{2}{\rho g}} \quad (4)$$

210 **Experimental method**

211

212 Apart from slip variabilities, the different parameters investigated in this study are as follows:

- 213 1. Geometry of the container: as presented above, two geometries are examined: a cone and a
214 cylinder, very different in volume and aspect ratio.
- 215 2. Surface roughness: according to Roussel [48], the wetting angle of the material on the solid
216 surface affects the measured yield stress. Improving the wetting of the surface (getting ϑ close
217 to zero) could theoretically provide an infinitely small yield stress measure. Furthermore, some
218 sliding could occur at the interface, due to the well-known lubricant property of muddy
219 suspensions. In order to examine these possible phenomena, two instances of surface
220 roughness were tested, one with sand-paper, the other with melamine wood.
- 221 3. Calculus method: two methods are available in the literature for yield stress measurement by
222 spread test [47], [48]. Both were applied to cementitious materials. In the present study, these
223 two methods are assessed for earth slips.

224 **3-3- Dipping test**

225 The plate cohesion meter was developed in the 1980s by Lombardi for cementitious materials [50]. It
226 involves a square metal plate, fitted with a balance that measures the weight of the paste remaining
227 on the plate surface after soaking. Sonebi, Svermova and Bartos [41] use it on cement slurries to
228 complement the test with a rheometer and do not use a cohesion parameter such as yield stress.
229 However, through knowledge of the mass M and the plate area A , a yield stress could theoretically be
230 estimated:

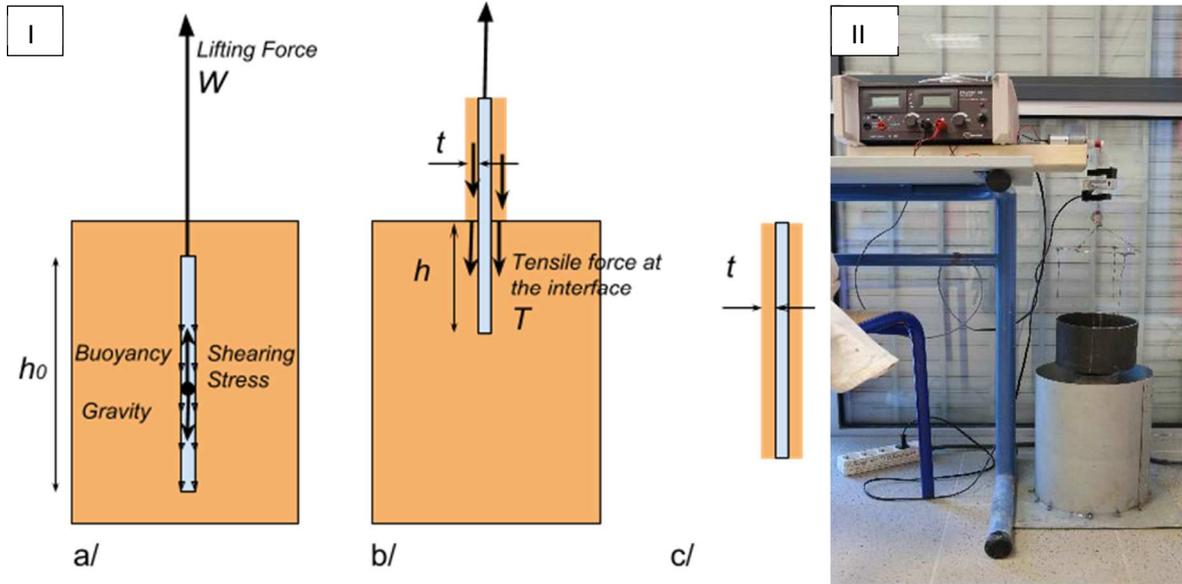
231

$$232 \quad \tau_0 = \frac{Mg}{A} \quad (5)$$

233 In practice, the results are varied: when the plate emerges from the mixture, some tensile stress and
234 flowing exist on the inside/outside interface. Hence, Eq.5 is no longer valid.

235

236 In the present study, to improve this experimental device in order to properly estimate the yield stress,
237 the tool was weighed with a 10N force sensor all the way from immersion to its complete exit from
238 the slip (Fig. 3.I). Thus, the validity range of the test depends on the test design. In the present case,
239 the upper limit is given by the force sensor capacity, leading to a maximum measurable yield stress of
240 100 Pa. Thus, the main difference with the work of Sonebi, Svermova and Bartos [41] is that in the
241 present case, a little actuator lifts the plate, at a rate of 2.5 mm/s, up to a complete exit. At the
242 beginning of the experiment, the slip is vigorously mixed by hand to avoid build-up and the
243 sedimentation bias, the force transducer is tared to cancel the proper weight of the plate, and the
244 plate is immediately immersed. Then, the motor starts raising the plate. The force transducer measures
245 only an apparent weight of matter, renamed W' , which opposes the rise of the sheet ($W' = W +$
246 *buoyancy* – *gravity*). In addition, we developed a cylindrical sheet rather than a plane geometry to
247 increase the contact surface (and the accuracy of the results), and we stuck rough sandpaper on its
248 surface to ensure that the shearing occurs into the slip and not at the sheet walls (Fig. 3.II). The
249 cylindrical sheet is 100 mm in height, 150 mm in diameter, with a thickness of the steel sheet plus
250 sandpaper of 4 mm.



251

Fig. 3 I) The dipping test: a/ initial state; b/ device partially emerged; c/ device totally out. II) The experimental device developed for the “plate” test

252 The theoretical frame is the same as for the plate test of Amziane, Perrot and Lecompte [51]. Three
 253 distinct phases have to be taken into consideration (Fig. 3I):

254

- The cylinder is totally immersed:

255

In this case, the slip shearing stress is the only apparent load:

256

257

258

$$\tau_0 = \frac{W + \rho g V_0 - M_0 g}{A_0} = \frac{W'}{A_0} \quad (6)$$

259 With A_0 , V_0 and M_0 respectively the sheet area, volume, and mass and ρ the density of the slip.

260

261

- The cylinder is partially out:

262

263

264 The immersed part bears the same shearing load as in the first case, and the outer part bears the
 265 weight of the slip remaining on the surface. Additionally, the buoyancy of the outer part of the plate
 266 no longer exists, and a tensile force at the inside/outside interface opposes the rising of the device:

267

$$W = \frac{\tau_0 A_0 h}{h_0} + \rho g t A_0 \left(1 - \frac{h}{h_0}\right) + T - \rho g V_0 \frac{h}{h_0} + M_0 g \quad (7)$$

268

$$W' = \frac{\tau_0 A_0 h}{h_0} + \rho g t A_0 \left(1 - \frac{h}{h_0}\right) + T + \rho g V_0 \left(1 - \frac{h}{h_0}\right) \quad (8)$$

269

270 With h_0 the height of the sheet, h the immersed height, t the thickness of the slip remaining on the
 271 outer part, ρ the slip density and T the tensile force at the inside/outside interface. In a first
 272 approximation, this tensile force is estimated by considering a simple Von Mises yield criterion:

273

$$T = 2\sqrt{3}\tau_0 t p_0 \quad (9)$$

274

275 With p_0 the perimeter of the cylinder.

276 It yields an analytical estimation of the slip yield stress when the cylinder is partially out:
277

$$278 \quad \tau_0 = \frac{W' - \rho g \left(1 - \frac{h}{h_0}\right) (V_0 + t A_0)}{A_0 \frac{h}{h_0} + 2\sqrt{3} \tau_0 t p_0} \quad (10)$$

279
280

281 • The cylinder is totally out:

282 We weigh the slip remaining on the cylinder surface, and we add the buoyancy effect that no longer
283 acts. As for the plate cohesion meter, we can deduce the mean remaining thickness t using this
284 measurement and the density of the slip:

$$285 \quad t = \frac{W - M_0 g}{\rho g A_0} = \frac{\frac{W'}{\rho g} - V_0}{A_0} \quad (11)$$

286 Where A_0 and V_0 are respectively the sheet area and volume, and ρ is the density of the slip. As
287 previously explained and shown by Maillard et al. [52], this thickness cannot be directly related to the
288 yield stress of the fluid. Gravity and the viscous effects stemming from the sheet velocity and
289 eventually the capillary effects yield to other analytical formulas for t . Maillard et al. [52] find that,
290 roughly, the thickness t at low velocities and few capillary effects (yield stress higher than 25 Pa) may
291 be expressed for yield stress fluids as:

$$292 \quad t \approx 0.3 \frac{\tau_0}{\rho g} \quad (12)$$

293 That is less than one third of the maximum thickness that the sheet could theoretically raise. This
294 equation is confronted to results in the next paragraphs.

295

296 The measurements of force and position of the cylinder relative to the mixture surface are used to
297 compute the yield shearing stress when the sheet is totally or partially immersed. Fig. 4 shows results
298 with the raw data W' and the estimation of the yield stress using Eq.6, Eq.7, and Eq.10.

299 The different parameters of the test are found mainly in the calculation method. In order to choose a
300 yield stress value, the two first phases are analyzed:

- 301 - The first phase curve is close to a vane rheometer measure: an elastic phase and then a plastic
302 phase with a maximum are observed.
- 303 - The second phase shows a variable yield stress value. It seems that the edge effect at the
304 fluid/air interface is not negligible and affects the measurement.

305

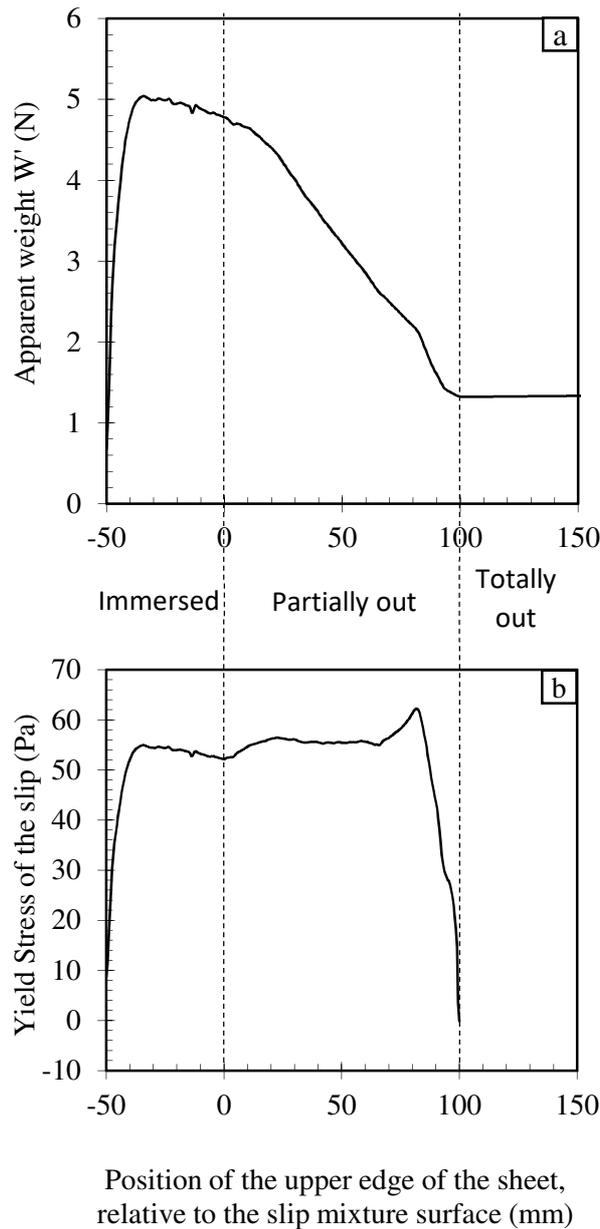


Fig. 4 Typical results of “Dipping test” measurements (a): raw data, (b): yield stress estimation

3-4- Rough wall cone

The inclined plane test was proposed by Coussot and Boyer in the 1990s [34], [53] to examine the possibility of predicting the free surface flow characteristics of non-Newtonian fluids such as mud and clay-water mixtures. Theoretically, it involves an infinite plane slope on which a mixture is poured slowly enough to avoid the effects of inertia and to obtain a uniform height of material. Practically, an approximately steady flow of mixture is imposed on a given slope and progressively stopped. Considering the no-wall slip at the surface of the device, a simple momentum balance leads to a yield stress calculation.

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In order to ease the on-field use of such a test, a new test was designed and inspired from viscosity cones. The main asset of a cone, compared to a plane, is that the slope is imposed by its shape. This test was designed for this study and called the “rough wall cone test”. All the geometry parameters are described in Fig. 5 (Left). A yield stress measurement is obtained from the following steps:

- Filling in a cone preliminarily fitted with rough sandpaper and closed at the lower part;
- Then, freeing the lower part and letting the fluid drop;
- Weighing the remaining fluid when the flow stops (Fig. 5, Right).

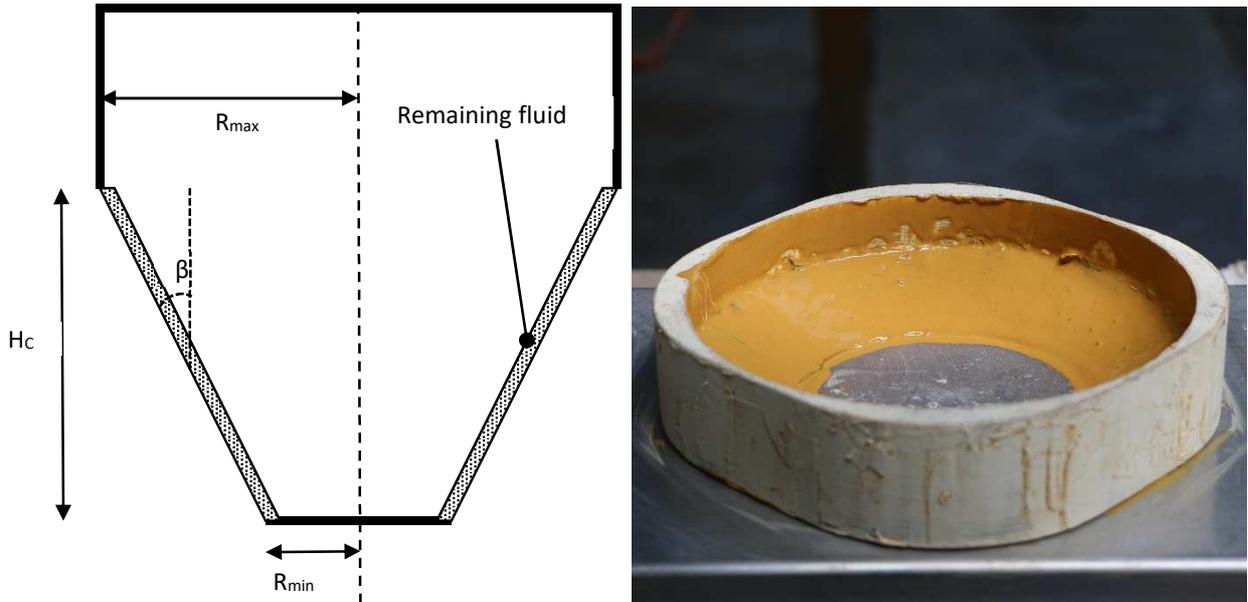


Fig. 5 Left : Cone geometry parameters ; **Right :** Remaining slip on cone surface after testing

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If we use a large cone, i.e. $R_{min} > (R_{max} - R_{min})$, with a very obtuse angle, we can assume that the flow is slow enough to avoid viscous effects, to be in a quasi-steady state, and that the initial fluid thickness is close enough to the equilibrium thickness to limit the surface tension effects. Then, the momentum balance can easily be deduced, as for the inclined plane (Eq. 13) when the flow stops:

$$331 \quad \tau_0 = Mg \frac{\cos\beta}{A_{cone}} = \frac{Mg \cos\beta}{\pi(R_{min} - R_{max})H_c} \quad (13)$$

332 **3-5 Marsh funnel and viscosity cups**

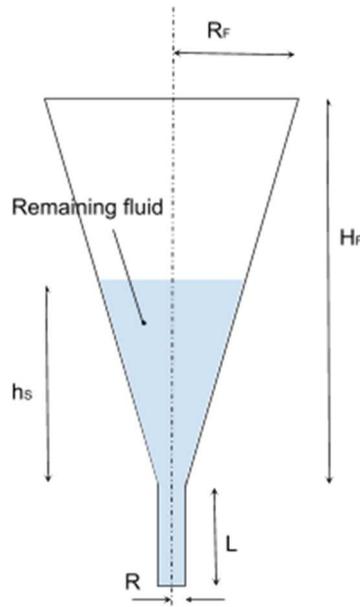
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Other devices sometimes recommended for earthen constructions are the viscosity cones, such as the Marsh funnel, or the viscosity cups. The test generally involves measuring the flow time necessary to empty the cone. This time corresponds to the fluidity of the material, which can generally be related to its viscosity [39]. The aim of the present study was to estimate not the viscosity of the fluid, but its yield stress. For yield stress fluids with a yield stress above 12.5 Pa, the Marsh funnel does not empty entirely. In this case, Balhof et al. [35] give a formula to estimate the yield stress using the remaining static height of fluid in the device (Fig. 6 and Eq.13). The authors assume that the tangential stress is sufficiently low in the cone part to let the fluid slip and that there is no slipping at the cylinder wall. This assumption, considering that the flowing mode only depends on the geometry of the wall, seems

342 quite strong. Hence, the Marsh funnel (4.76 mm and 8 mm opening) and flow cups (3, 4, 5, 6 and 8mm)
343 were also tested.

344
$$\tau_0 = \frac{\rho g (h_s + L)}{2 \left(\frac{L}{R} + \frac{H_F}{R_F} \right)} \quad (13)$$

345



346

Fig. 6 Marsh funnel geometry

347 IV Experimental results

348 Rheometer measurements can only be carried out in laboratory conditions. As this tool is
349 designed and used to give precise and accurate results, it was chosen as a reference to evaluate the
350 accuracy of the other tests.

351 First, to examine the effect of soil variability, several slips were prepared with each of the six
352 different soil samples by varying their water content. Apart from rheometer measurements, the yield
353 stress measures range from 0 to 250 Pa, depending on the water content and raw earth cohesion.
354 Then, following results will be plotted according to this range. Second, the following sections present
355 the design and calculus parameters of each test alongside characterization results, in order to assess
356 the suitability of the different tests.

357

358 4.1 Rheometer

359 In order to understand the variable rheological behavior of earth, an observation of the yield
360 stress versus water content results is needed. **Fig. 7** presents these results within a yield stress range
361 of 0 to 100 Pa. E1 shows a short evolution of the yield stress with a zero value close to a water content

362 of 1. At the opposite, E3 reach a yield stress of zero at a water content higher than 3. Most of the earth
 363 show similar curve shapes, but at different water content. Thus, the graph shows an important
 364 variation of cohesive behavior.

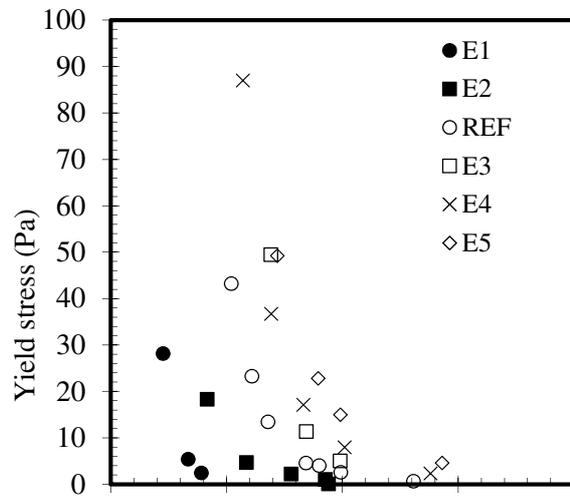
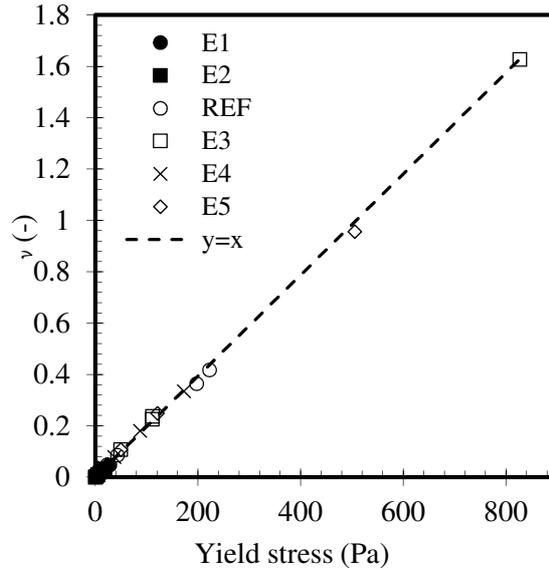


Fig. 1: Yield stress versus water content of the 6 studied earth

365 Attention was paid to the limits of vane geometry. Pierre et al. [54] define a ratio v that
 366 indicates the vertical stability/instability position in relation to the shear surface described by the vane
 367 tool in rotation:

$$v = \frac{1}{h_c} \frac{\sqrt{3}\tau_0}{\rho g} \quad (15)$$

369 With h_c the vane tool height, τ_0 and ρ resp. the paste yield stress and its density.
 370 If this ratio is close to or higher than 1, then the tested material is too stiff to flow. Moreover, if the
 371 tested earth has a swelling behavior, empty spaces around the tool can appear. To analyze the
 372 robustness of rheometer measurements, the recommendations of Pierre et al. [55] were used. The
 373 tested slips show yield stresses going from about 0 to about 850 Pa, with solid volume fractions
 374 evolving from 0.11 to 0.8. The v ratio was calculated for every rheometer measurement. Fig. 8 shows
 375 the evolution of this ratio versus the measured yield stress. Regardless of the earth type, the limit of v
 376 =1 is reached for a yield stress of 495 Pa. The analysis of the rheometer data confirms this
 377 phenomenon: under 495 Pa, the maximum standard deviation is 5% and above 495 Pa, the standard
 378 deviation can reach 95%.
 379



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Fig. 8 γ Ratio vs. vane tool yield stress measures

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4.2 Slump flow and spreading flow

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Influence of the apparatus design

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The effect of geometry and surface roughness were tested on the reference slip. The raw data were treated according to Pierre et al. formula (Eq.3 & Eq.4). Results are presented in Fig. 9a.

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First, the roughness of the surface does not affect the results: the matter flows of itself and sticks to the surface, even if clay pastes are known to act as a lubricant, even on a very smooth spreading surface. In contrast, the initial geometry of the sample showed a considerable influence on the measurements. It appears that the cone results match the rheometer values well between 0 and 50 Pa, whereas the cylindrical container seems to induce a divergence. Two parameters are involved in the influence of geometry: the volume and the shape of the container. Clayton et al. [56] tested the influence of these parameters on the slump of pigment pastes and mineral pastes and compared their results to those of the literature on clay pastes. They show that there is no influence of the shape (conical or cylindrical) on the slump, but when varying the heights with an aspect ratio of 1, they observe the strong influence of the volume of the container. How the volume affects the measure can be estimated through the limit of representative dimensions of the final spread. In this case, the limitative dimension is the final height H of the spread fluid, and the criteria can write as follows: $H > k\phi_{max}$ with ϕ_{max} the maximum particle diameter of the granular suspension and k the number of particles in the thickness for which the fluid remains representative. Generally $k \approx 6$. Considering a total spreading, we can rewrite the Roussel equation (Eq.2) in terms of the minimum volume:

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$$V > \left(\frac{225\rho g}{128\tau_0} \right)^2 \pi (k\phi_{max})^5 \quad (16)$$

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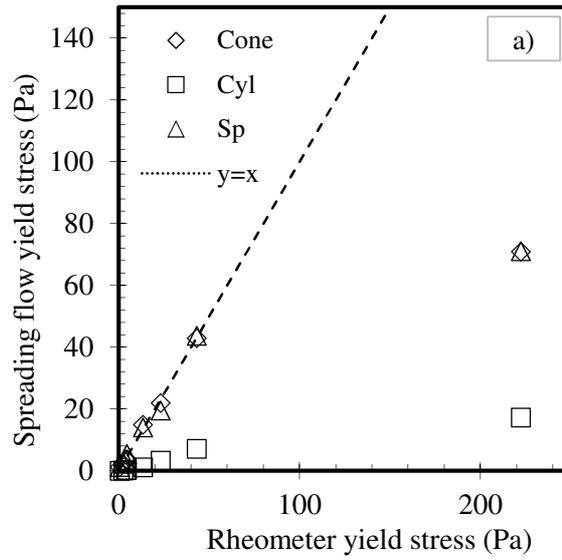
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Fig. 10 shows the container volume that should be aimed to measure a yield stress of 2 Pa and 10 Pa, as a function of the desired final fluid height. For the cylinder under investigation ($V_{cylinder}=0.21L$), a 10 Pa yield stress is hardly measurable as the final height will be 6mm (i.e. three maximum diameters of the slip particles), while for the cone ($V_{cone}=2.75L$) H should be higher than 10 mm. For such suspensions, with very low yield stress and containing quite coarse particles, a minimum volume of the container must be considered and is discussed below.

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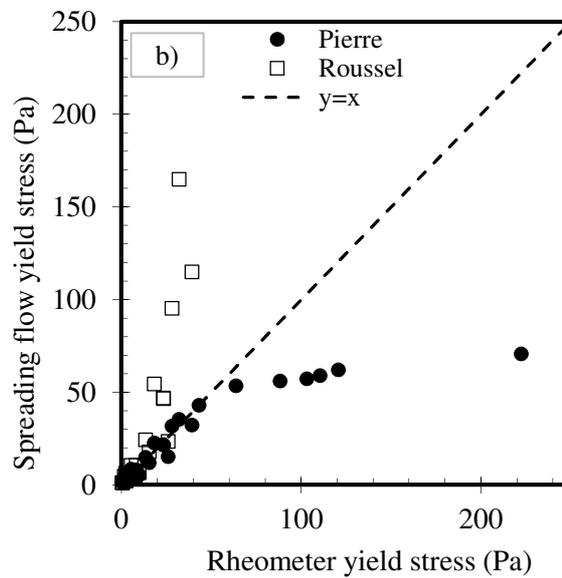
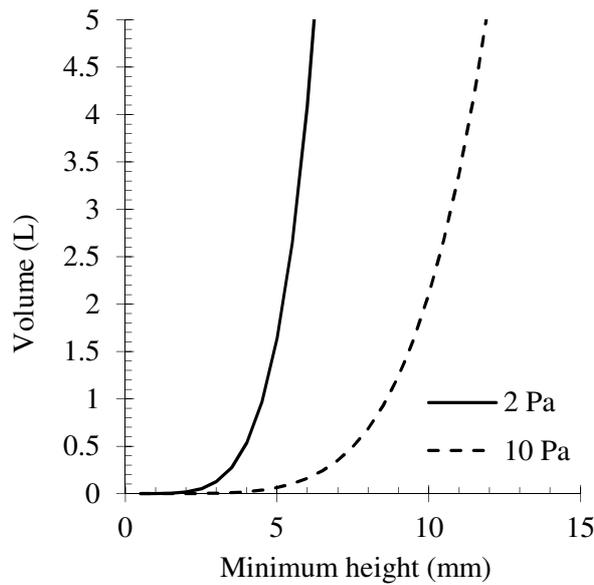


Fig. 9 a) Yield stress of one slip measured by spreading on sandpaper (Sp) or melamine wood, using a cone or a cylinder (Cyl), using Pierre et al.'s calculus compared with rheometer measurement. b) Yield stress of the six different slips measured by spreading

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Fig. 10 Container volume for the spreading test according to a minimum height at the end of the spreading test

413 The aspect ratio and the initial height of the container could also affect the results, due to inertia
 414 effects. Roussel et al. [48] indicate that the yield stress must remain higher than the inertia ($I =$
 415 $\rho(dR/dt)^2$) during the flow to avoid abrupt liquid–solid transitions. Then, the flow speed can be
 416 influenced by the height of the sample and the yield stress itself. A video analysis was conducted on
 417 two different slips and with cylindrical and cone containers to measure flow speeds. The results are
 418 given in Table 3. The $I < \tau_0$ criterion is not met for low yield stress, regardless of the container, which
 419 can explain the discrepancies for very fluid suspensions and stresses the differences due to the volume
 420 of the container.

		$\tau_0=62Pa$	$\tau_0=0,5Pa$
Density (kg/m ³)		1330	1285
Average radial speed (m.s ⁻¹)	Cone	0.16	5
	Cylinder	0.06	20
Inertia (Pa)	Cone	34.2	243
	Cylinder	5.4	500

Table 3 Inertia during spreading of two slips

421 **Influence of data processing**

422 Fig. 9b presents the yield stress calculated from spreading tests with the Pierre et al. formula
 423 [47] and the Roussel et al. formula [48]. The results with the Pierre et al. calculation method
 424 have a validity range going from 0 to about 50 Pa, while results with the Roussel et al.
 425 calculation method have a smaller validity range going from 0 to about 25 Pa. Roussel and his
 426 coworkers assume that all the material spreads by pure shearing, which is not true above 20
 427 Pa. Above this value, the Roussel et al. formula overestimates the yield stress.

428

429 Standard deviations have been calculated, but are not observable on this representation (Fig.
 430 9b), showing very good repeatability of the results. Average errors between the flow and

431 rheometer measurements have been estimated within the validity range expressed above. It
432 appears that these errors depend on the soil type: E1, E2, and E4 (respectively 34%, 56%, and
433 43% of average errors) slips show an average error higher than REF, E5 and E3 (respectively
434 19%, 5% and 14%).
435

436 **4.3 Dipping test**

437 The first phase, i.e. when the cylinder is totally immersed, provides the most reliable results,
438 as the calculus does not take into account the surface tension the thickness measurements of
439 the remaining slip measurements. As presented in Fig. 11, the first phase results are in line
440 with the rheometer measurements. Depending upon the soil type, average errors go from
441 18% to 51%. The highest errors are not found for the highest yield stress measurements.
442 Nevertheless, errors can be caused by a non-continuous shear surface, as expressed before
443 for the vane tool. When the slip is too stiff, empty spaces can be created while the cylinder is
444 lifted.
445

446 Second phase results, when the cylinder is partially out, always show an overestimation or an
447 underestimation of the yield stress. A slight inclination of the cylinder directly influences the
448 estimation of the mass of remaining slip on the cylinder and the surface tension effect.
449

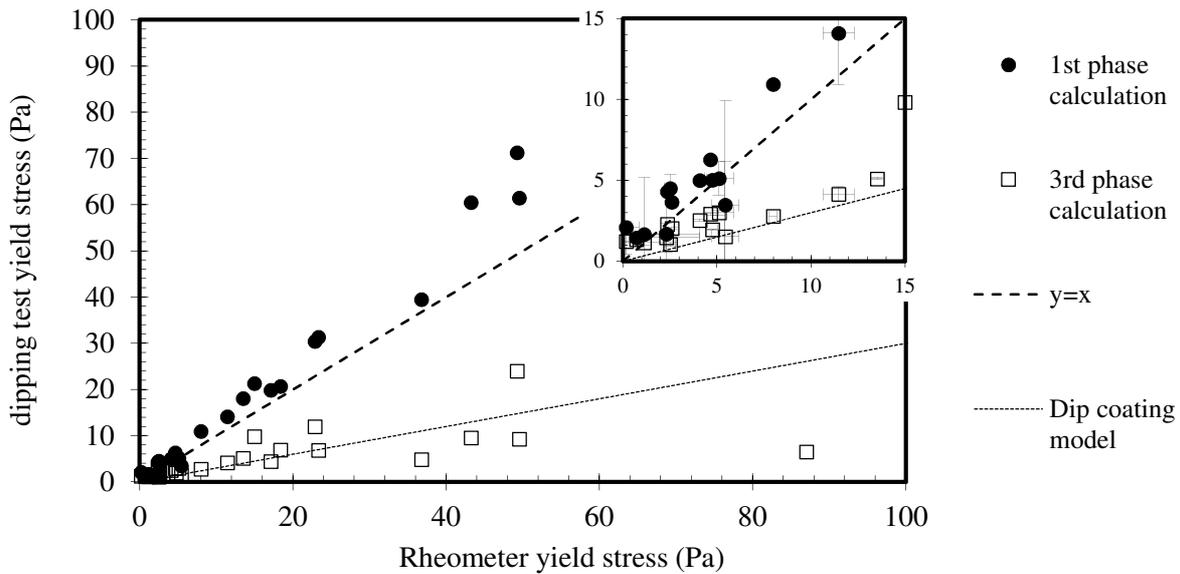
450 Then, Fig. 11 also presents results of a yield stress calculation based on the third phase, when
451 the cylinder is totally out of the slip. According to Maillard et al. [52], there should be a
452 proportionality coefficient between the thickness of the remaining material on the cylinder
453 and the real yield stress (Eq. 12). In the present case, this model does not fit the experimental
454 points. Taking all the results into account, the proportionality coefficient is 0.66 with a very
455 large total standard deviation (1.22).

456 In the same study [28], a more precise model estimates the thickness during the “partially
457 out” phase:

$$458 \quad t = \frac{\lambda}{2} - \frac{\alpha \rho g \lambda^2}{3\tau_0} \quad (15)$$

459
460 With t the thickness of the remaining material after the test, λ the thickness of the sheared
461 material in the air-material interfacial zone, α a fitting factor and τ_0 the material yield stress.
462 In the case of earthen material, the thickness of the sheared material (λ) depends on the
463 particle size distribution and clay activity of the tested material. The coarser the aggregates
464 are or the more cohesive the clay is, the larger this sheared zone will be. The differences of
465 granular distributions and the cohesiveness of the six slips of this study explain the high
466 discrepancies of the results.

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Fig. 11 Yield stress of the six different slips measured using the dipped cylinder test, from the 1st and 3rd phase of the test compared with the rheometer measurements. The 3rd phase results are compared to the dip coating model of Maillard et al. [28]

469

4.4 Rough wall cone

470 Fig. 12 shows the results of the yield stress measured using the rough wall cone for the six
 471 different slips and three different cone designs (see Fig. 6):

- 472 - $\beta=60^\circ$ - cone with a cylindrical upper part
- 473 - $\beta=60^\circ$ - cone without a cylindrical upper part
- 474 - $\beta=85^\circ$ - cone without an upper part

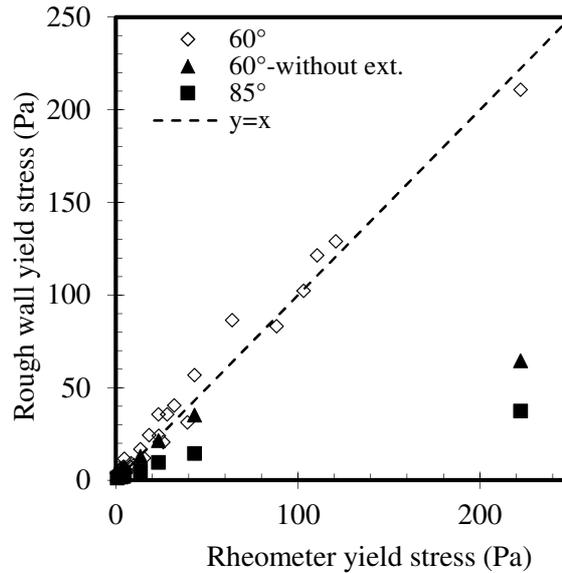
475 For every cone $R_{min}=6$ and $R_{max}=10$

476

477 The $\beta=60^\circ$ -cone with a cylinder upper part provides results in line with the rheometer
 478 measurements, regardless of the soil type. The upper limit in terms of yield stress is 230 Pa,
 479 above which no flow occurs. Around a yield stress of 200 Pa, results are disputable as there is
 480 no real flow occurring but a pure shearing of the central part of the sample. In addition,
 481 important errors are observed between 0 and 3Pa, where the yield stress measurements are
 482 highly overestimated. Because of the roughness of the cone wall, it is possible that coarse
 483 particles remain on the apparatus whereas they should have flown away. Then, the validity
 484 range of this test could go from 3 to 200 Pa. Within this range, average errors range from 8%
 485 to 58% depending on the soil type.

486 The other two designs do not give proper results. For the cone with $\beta=85^\circ$, the slope is not
 487 high enough to induce a flow. Regarding the design without an upper part extension, Coussot
 488 et al. [34] describe the importance of a stopped flow and a constant thickness of the material
 489 on the apparatus. In their case (inclined plane slope), the flow would occur in 30 to 40 minutes.
 490 In our case, the flow stops a few tens of seconds after the cone has been lifted. Thus, the lack
 491 of material above the beginning of the slope induces a non-continuous thickness of the flowing
 492 material. This phenomenon leads to a highly underestimated yield stress.

493



494

Fig. 12 Influence of the test design on cone yield stress measurement compared to rheometer measurements. The six earths were tested on the $\beta=60^\circ$ cone, while only REF was tested on the $\beta=85^\circ$ cone and the cone without extension

495 **4.4 Marsh funnel and viscosity cups**

496 The earth slips were also tested using the Marsh funnel and viscosity cups. First, these two
 497 tests are designed for viscosity measurement. The formula developed by Balhof et al. [35] was
 498 used to treat the Marsh funnel results. For the two tested openings, results show an important
 499 overestimation of about one order of magnitude. Furthermore, there are only one or two
 500 water contents at which the test works, in the range 12Pa-25Pa of yield stress for the standard
 501 funnel flow geometry. Outside these limits, the slip does not flow at all or flows completely
 502 through the device. We observed the same problems for the viscosity cups, with even less
 503 cases where measures are possible.

504 **V. Discussion**

505 **5.1 Comparison of yield stress measurement methods**

506 Table 4 summarizes the advantages and disadvantages of any tests considered in this study.
 507 Maximum measurement uncertainties are calculated from the sensors' accuracies and with
 508 the different yield-stress formulas (Eq.3 to Eq.11). The maximum average error is defined as
 509 the maximum of average differences for each water content and each soil type, between
 510 rheometer measurements and the compared test.

511 Whereas the spread test and the rough wall cone test are directly usable on site, the dipping
 512 test still requires adaptation. A proposal is presented in the following section. To compare the
 513 validity range of each test, it is necessary to consider the required yield stresses for different
 514 earthen construction methods:

- Light earth: knowledge about earth slips has been developed during this project. Following the know-hows of builders, earth slips with a yield stress between 2 and 80 Pa, according to the earth cohesive behavior, are considered to be valid.
- Earthen concrete: the same rheology as cement concrete is generally aimed at. For self-compacting earthen concretes, Ouellet-Plamondon et al. [33] defined an optimal yield stress between 200 and 500 Pa.

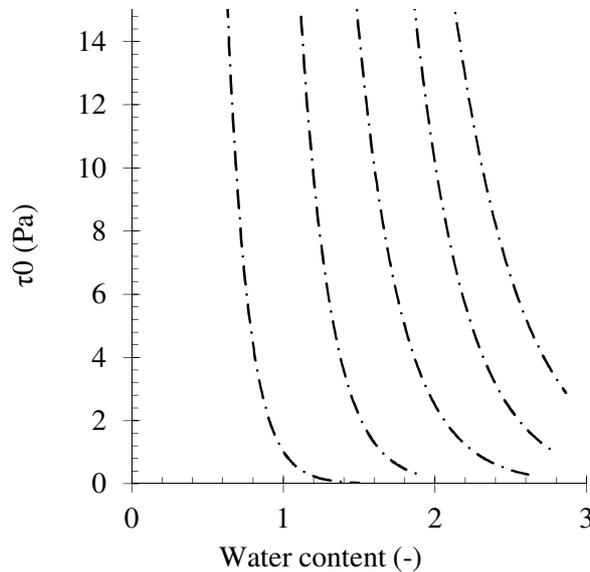
Test	Maximum measurement uncertainty (%)	Maximum error (%)	Validity range (Pa)	Advantages	Drawbacks
Rheometer	0.51	-	0 - 500 (with a 6 cm-in-height vane tool)	Sensitive, reference value	Laboratory apparatus, expensive and not adapted to field conditions
Spreading	0.2	56% - soil dependent	0-50	Fast and easy to process, very easy and cheap to design	Requires a plane and perfectly horizontal surface (not appropriate for earthen concretes); strong influence of the device volume
Dipping	0.05	51% - soil dependent	0-100	The most accurate test compared to rheometer; quite easy to process	First designed for the laboratory: a robust device has to be developed for field conditions; a large amount of slip is needed for the test; the data processing must be adapted to the device geometry (area).
Rough wall cone ($\beta=60^\circ$ -with extension)	0.2	58% - soil dependent	3-200	Fast and easy to process, more appropriate for high yield stress materials	The apparatus has to be machined or 3D printed, possibly user-dependent due to lifting rate and cone orientation
Marsh funnel and Viscosity cups	-	-	-	Easy to do and already used for other applications	Not appropriate for yield stress measurement of earth slips

Table 4 Summary of the comparison of yield stress tests

Measurement uncertainties are below the maximum average errors. Even if slips are mixed right before each test, for slips with coarse aggregates, sedimentation can occur before the test or the homogeneity of the slip can be impacted by the flow. Then, particle size distribution, clay activity, and particle swelling capacity could affect the results. Nevertheless, the maximum errors compared to reference values is sufficient for application in field conditions in the case of the spreading, dipping and rough-wall cone tests ($\beta=60^\circ$ -with extension).

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Fig. 13 shows the modelling of the experimental results showed in **Fig. 7** (without E5 which shows an evolution close to REF), following an exponential fitting. This abacus allows to quantify how much water should be added or removed to reach a targeted yield stress.



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Fig. 13: Modeled yield stress versus water content of 5 earth

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VI Conclusions

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This paper aims to demonstrate the possibility of measuring the rheological behavior of an earth suspension with simple tests. Firstly, the six earth chosen for sample manufacturing are representative of the large natural variability of 27 collected earth from Normandy and Brittany regions. With the six selected earth, different slips are manufactured with varying water contents. Soil suspensions behave like yield stress materials. Thus, their cohesive behavior is studied through the measurement of their yield stress. To do so, six different tests, of which two have been developed for this study, are compared: rheometer, spreading test, dipping test, rough wall cone, Marsh cone tests and viscosity cups.

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Rheometer measurements were used as the reference, in a yield stress range between 0 and 500 Pa. Results can be summed up as follows:

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- The six earth are very different in their geotechnical characteristics. Six different rheological behaviors are observed. Particle size distribution, clay activity and specific density affect the link between water content and yield stress;
- Marsh cone tests or viscosity cups are not adapted to the yield stress range of earth slips;
- Spreading test, dipping test and rough wall cone $\beta=60^\circ$ -with extension- gave satisfactory results respectively from 0 to 50 Pa, 0 to 100 Pa and 3 to 200 Pa. For these three tests, a 50% maximum discrepancy was observed. All these tests are easy to transfer to field conditions.

555 Along with yield stress versus water content model, these tests allow to evaluate how much
556 water should be added or removed to reach a targeted yield stress. This quantitative approach
557 can be used to characterize earth slip in laboratory conditions for light earth studies or in fields
558 conditions.

559 Finally, rheological results discrepancy level is slightly earth dependent. Further studies might
560 investigate the link between the rheological behavior and the geotechnical characteristics of
561 earth.

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