

1 **Mechanical properties of quartz sand and gypsum powder (plaster) mixtures:**
2 **implications for laboratory model analogues for the Earth's upper crust**

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42 **Highlights**

- 43 - Density, tensile strength, shear strength of sand-plaster mixtures quantified
- 44 - Cohesion and friction coefficients from Coulomb and Griffith failure criteria.
- 45 - Sensitivity to emplacement technique and ambient humidity.
- 46 - Brittle to ductile behaviour depending on plaster content and applied normal load.
- 47 - Tensile strength of sand-plaster mixtures as a scalable experimental parameter.

48 **Abstract**

49 Granular materials are a useful analogue for the Earth's crust in laboratory models of
50 deformation. Constraining their mechanical properties is critical for such model's scaling and
51 interpretation. Much information exists about monomineralic granular materials, such as
52 quartz sand, but the mechanical characteristics of biminerale mixtures, such as commonly-
53 used quartz sand mixed with gypsum powder (i.e. plaster), are largely unconstrained. We used
54 several mechanical tests (density, tensile, extension, shear) to constrain the failure envelope of
55 various sand-plaster mixtures. We then fitted linear Coulomb and parabolic Griffith failure
56 criteria to obtain cohesions and friction coefficients. Tests of the effects of emplacement
57 technique, compaction and humidity demonstrated that the most reproducible rheology is
58 given by oven-drying, pouring and mechanically compacting sand-plaster mixtures into their
59 experimentation container. As plaster content increases, the tensile strength of dry sand-
60 plaster mixtures increases from near zero (pure quartz sand) to 166 ± 24 Pa (pure plaster). The
61 cohesion increases from near zero to 250 ± 21 Pa. The friction coefficient varies from
62 0.54 ± 0.08 (sand) to 0.96 ± 0.08 (20 weight% plaster). The mechanical behaviour of the
63 resulting mixtures shifts at 20-35 weight% plaster from brittle Coulomb failure along a linear
64 failure criterion, to more complex brittle-ductile Coulomb-Griffith failure along a non-linear
65 failure criterion. With increasing plaster content, the brittle-ductile transition occurs at
66 decreasing depth within a pile of sand-plaster mixture. We infer that the identified transitions
67 in mechanical behaviour with increasing plaster content relate to (1) increasing porosities, (2)
68 increasing grain size distributions, and (3) a decrease in sand-sand grain contacts and
69 corresponding increase in gypsum-gypsum grain contacts. The presented characterisation
70 enables a more quantitative scaling of the mechanical behaviour of sand-plaster mixtures,
71 including of their tensile strength. Sand-plaster mixtures can thereby realistically simulate
72 brittle-ductile properties of the Earth's crust in scaled laboratory models.

73

74 **Keywords:**

75 Laboratory modelling; Analogue materials; Quartz sand; Gypsum powder; Mechanical
76 properties; Tensile strength; Shear strength; Cohesion; Friction coefficient

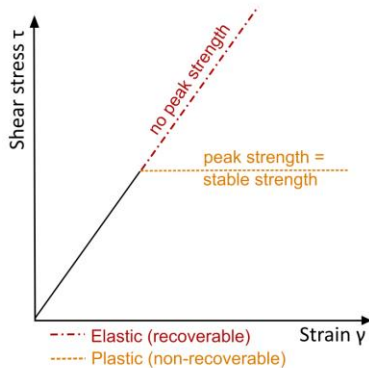
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78 **1. Introduction**

79 The Earth’s crust is a complex set of geological layers and structures, exhibiting a wide range
 80 of physical and mechanical properties. Properties such as rock density, porosity, tensile
 81 strength, shear strength, cohesion and internal friction control or relate to deformation of the
 82 crust during geological processes (Graveleau et al., 2012; Hubbert, 1951, e.g. 1937; Labuz et
 83 al., 2018). The mechanical response of rocks to a stress applied externally to the studied
 84 volume can take several idealised forms. For an ideal, linearly elastic material, the
 85 relationship between stress and strain follows a recoverable sloped linear trajectory, and the
 86 material resumes its initial geometrical state after the stress is removed (Figure 1A) (Jaeger et
 87 al., 2007). For an ideal plastic material, the relationship between stress and strain is initially
 88 similar to an elastic material, but at a certain shear stress threshold the plastic material
 89 undergoes ‘yielding’, after which the strain is non-recoverable (Jaeger et al., 2007). The strain
 90 vs. stress curve then becomes horizontal and defines a stable strength value (Figure 1A). Such
 91 idealised behaviours are widely used concepts for models of tectonic and magmatic crustal
 92 deformation (e.g. Scheibert et al., 2017; Vachon and Hieronymus, 2017).

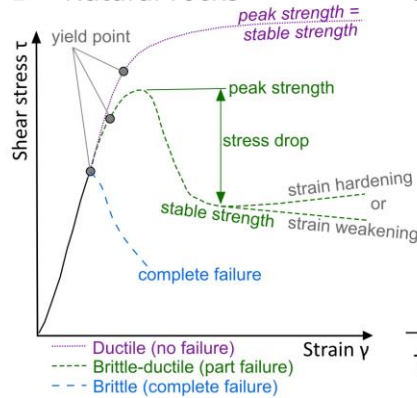
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94 **A Ideal material**



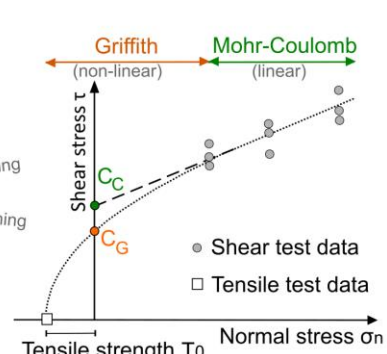
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101 **B Natural rocks**



102

103 **C Failure envelope**



104 **Figure 1** – **A** Shear stress (τ) in an ideal Coulomb material that is subjected to an angular shear (γ) increases
 105 linearly until failure occurs and a constant peak strength is reached; **B** Shear stress in natural rocks under low
 106 confining stress increases until the yield point is reached after which either shear stress increases towards a stable
 107 strength in the ductile regime, or until a peak strength where failure occurs and shear stress again decreases
 108 towards a lower stable strength in the brittle-ductile regime (the difference is the stress drop), or after which
 109 shear stress decreases until complete failure in the brittle regime; **C** Shear test results from samples subjected to
 110 different confining normal loads (σ_n), combined with tensile strength (T_0) obtained from tensile tests together
 111 define the two-dimensional Mohr failure envelope of a material; the intercept with the vertical axis (τ) is the
 material’s cohesion and can be estimated using e.g. a linear Coulomb (C_C) or non-linear Griffith (C_G) failure
 criterion (cfr. Jaeger et al. 2007).

112 Laboratory tests on natural rocks have shown a more complex behaviour (Byerlee, 1978;
113 Jaeger et al., 2007). Upon or after ‘yielding’, a peak strength may be reached, after which the
114 rock sample typically fails along a localised shear plane. The shear stress then decreases
115 towards a lower, stable – or ‘residual’– strength (Figure 1B, green). The difference between
116 the peak strength and stable strength is the so-called stress drop. The stable strength may
117 gradually increase or decrease at continued shearing, referred to as strain hardening or strain
118 softening respectively (Figure 1B). Upon brittle failure, a sharp stress drop leads to an abrupt
119 decrease in shear strength and – in the lab – can result in sample disintegration (Figure 1B,
120 blue). Brittle failure is typical for low lithostatic pressures in the upper part of the crust
121 (Paterson and Wong, 2005).

122 Ductile deformation, in contrast, is characterised by the absence of a stress drop (Figure 1B,
123 purple), and it typically occurs at higher lithostatic pressures (i.e. at greater depths in the
124 crust) (Byerlee, 1968; Jaeger et al., 2007; Schöpfer et al., 2013). Ductile materials can
125 undergo strain hardening or softening and this deformation is non-recoverable as well. The
126 brittle-ductile transition describes the level in the crust above which rock deformation is
127 brittle, and below which it is ductile.

128 These insights of rock mechanics have been used for decades in laboratory – or analogue –
129 experiments to study deformation processes in the Earth’s crust, such as tectonic faulting (e.g.
130 Dooley and Schreurs, 2012; Hubbert, 1937), seismo-tectonics (e.g. Reid, 1911; Rosenau et al.,
131 2017), magma intrusion (e.g. Galland et al., 2018; Kavanagh et al., 2018b; Mastin and
132 Pollard, 1988; Poppe et al., 2019) and gravitational collapse (e.g. Marti et al., 1994; Merle and
133 Borgia, 1996). The selection of analogue materials is guided by the aim of obtaining physical
134 similarity between the experiments and nature through dimensional analysis (Hubbert, 1937;
135 Merle, 2015). Such considerations have favored the use of low-cohesive, frictional granular
136 materials – dominantly sands (e.g. Cubas et al., 2013; Klinkmüller et al., 2016; Montanari et
137 al., 2017; Roche et al., 2000; Schreurs et al., 2016, 2006), although another type of laboratory
138 models use materials with simplified elastic or visco-elastic rheologies such as pigskin gelatin
139 or laponite gel (e.g. Bertelsen et al., 2018; Kavanagh et al., 2018a; Rivalta et al., 2015 and
140 references therein). Coulomb (1775) was the first to describe a linear relationship between
141 normal load and shear stress at failure for granular media. Like rocks, sand is considered to
142 deform largely according to a Mohr-Coulomb failure criterion (Figure 1C, green), with a
143 realistic strain weakening behaviour controlling localisation of deformation into shear zones
144 (Lohrmann et al., 2003; Ritter et al., 2016).

145 Studies using laboratory models traditionally focused on qualitative descriptions of structural
146 geometries (e.g. Eisenstadt and Sims, 2005; Holohan et al., 2013; Roche et al., 2000).
147 Recently, model deformation fields are routinely quantified by using advanced
148 photogrammetry and image analysis techniques (e.g. Adam et al., 2005; Galland et al., 2016;
149 Tortini et al., 2014) and most recently X-ray Computed Tomography (CT) (Adam et al., 2013;
150 Holland et al., 2011; Kervyn et al., 2010; Poppe et al., 2019; Schreurs et al., 2003; Zwaan and
151 Schreurs, 2017). Lately, such kinematic observations have been blended with both internal
152 “in-situ” stress measurements (Moulas et al., 2019; Nieuwland et al., 2000; Seropian and Stix,
153 2018) and constraints on externally applied forces (Cruz et al., 2010; Cubas et al., 2013;
154 Herbert et al., 2015; Ritter et al., 2018b, 2018a; Souloumiac et al., 2012) to derive a
155 quantitative dynamic picture of faulting or other deformation processes in laboratory models.
156 Different emplacement techniques (sieving, pouring) yield sand packings of variable
157 reproducibility, as demonstrated by mechanical tests (Lohrmann et al., 2003; Panien et al.,
158 2006). Moreover, benchmarking experiments using different sands have demonstrated that
159 variability in the granular characteristics (i.e. angularity, ellipticity) introduces uncertainties in
160 quantified model outcomes (Schreurs et al. 2016). The evolution towards a more quantitative
161 analysis of laboratory models requires quantified mechanical properties of granular
162 analogues, the reduction of reproducibility uncertainty and better scaling of laboratory models
163 to their natural prototypes (Gomes et al., 2006; Lohrmann et al., 2003; Montanari et al., 2017;
164 Panien et al., 2006; Ritter et al., 2016).

165 Density, cohesion and friction coefficient are the three main parameters that have been used in
166 dimensional analysis for scaling granular analogue materials; these properties can be obtained
167 from a granular material by using mechanical tests, such as direct and ring shear tests
168 (Abdelmalak et al., 2016; Galland et al., 2009; Merle, 2015; Montanari et al., 2017; Mourgues
169 and Cobbold, 2003; Schellart, 2000; Zorn et al., 2020). Compared to sand – which is near-
170 cohesionless –, more cohesive powders with finer grain sizes in the order of a few μm , such
171 as silica flour, crushed (feldspar) sand, alumina powder, ignimbrite powder, kaolin clay,
172 diatomite powder, powder sugar, wheat flour and gypsum powder, can be used purely or
173 mixed as a filler into coarser-grained sand to represent more complex crustal deformation
174 (e.g. Galland et al., 2018, 2006; Grosse et al., 2020; Mathieu et al., 2008; Montanari et al.,
175 2017; Reber et al., 2020; Schellart and Strak, 2016 and references therein). These powders are
176 able to form both tensile fractures and shear fractures, and they may follow a non-linear
177 Griffith-Mohr-Coulomb failure criterion (Figure 1C, orange), instead of a linear Coulomb
178 failure criterion (Figure 1C, green) (Abdelmalak et al., 2016; van Gent et al., 2010).

179 Abdelmalak et al. (2016) showed that, rather than relying on a single mechanical test, a
180 combination of mechanical tests can make cohesion and friction coefficient tunable
181 experimental variables for a range of mixtures of low-cohesion, low-friction with high-
182 cohesion, high-friction granular materials of similar grain sizes.

183 As example of fine-grained filler in sand, hemihydrate gypsum powder (i.e. plaster) has been
184 used in laboratory models of volcano-tectonic processes, such as magma intrusion, dome
185 building or gravitationally-driven deformation (Byrne et al., 2015, 2013; Donnadieu et al.,
186 2001; Holohan et al., 2008; Kervyn et al., 2010; Merle and Lénat, 2003; Poppe et al., 2019,
187 2015; Rincón et al., 2018; Roche et al., 2001; Zorn et al., 2020), and regional-tectonic
188 processes, such as the evolution of normal fault zones in high-strength rocks (van Gent et al.,
189 2010), near-surface gravitational instabilities, such as sinkhole collapse (Poppe et al., 2015)
190 and landslides (Paguican et al., 2014; Shea and van Wyk de Vries, 2008). Apart from limited
191 efforts (Donnadieu et al., 2001; Zorn et al., 2020), the physical and mechanical properties of
192 sand-plaster mixtures have not been systematically investigated, however.

193 This study quantifies the mechanical behaviour of quartz sand mixed with gypsum powder at
194 different weight ratios, by evaluating different mechanical testing methods. We first provide
195 the context for the scaling of mechanical properties of analogue granular materials. We test
196 the influence of the emplacement technique – pouring, sieving and compaction – on bulk
197 density and estimate the material porosities. We also test the effect of ambient humidity. By
198 using tensile tests, extensional tests, direct shear tests and ring shear tests, we constrain failure
199 envelopes for each of the end-member sand and plaster materials and mixtures thereof. By
200 assessing the goodness-of-fit of linear Coulomb versus parabolic Griffith failure criteria to the
201 failure data, we then estimate the cohesions and friction coefficients. Our results enable a
202 better understanding of modelling outcomes involving sand and plaster and their mixtures,
203 and allow more realistic dynamic scaling of laboratory experiments using such materials.

204

205 **2. Scaling of the mechanical properties of granular materials**

206 The concept of scaling and dimensional analysis implies two successive steps: (1) identifying
207 the dimensionless parameters that govern the modelled physical system, and (2) the
208 geometrical, mechanical and dynamical equivalence – i.e. similarity – of laboratory models to
209 their natural counterparts (Barenblatt, 2003; Gibbings, 2011; Hubbert, 1937). Abdelmalak et
210 al. (2016), Merle (2015) and Reber et al. (2020) summarise how this equivalence can be
211 reached for granular materials.

212 Dynamic similarity is classically discussed by assuming that a Coulomb failure criterion is
213 representative of material failure in both model (*m*) and a natural prototype (*g*). The internal
214 friction coefficient μ is a direct dimensionless parameter. Similarity implies that the friction
215 coefficient must be equal in nature and in the laboratory:

$$216 \quad (1) \mu_m = \mu_g$$

217 The cohesion *C* is combined with density ρ , gravitational acceleration *g*, and depth or length *h*
218 (Hubbert, 1945; Merle, 2015) in the dimensionless parameter:

$$219 \quad (2) \Pi = \frac{\rho \times g \times h}{C},$$

220 This parameter quantifies the balance between the gravitational forces and the cohesive
221 forces; the system will be gravity-dominated if $\Pi \gg 1$ and cohesion-dominated if $\Pi \ll 1$.
222 Dynamic similarity of a laboratory model to a natural geological system is then usually
223 reached by ensuring the friction coefficient of the model material matches that in nature. In
224 addition, the model material cohesion C_m required for a model that is subjected to the natural
225 gravity field is calculated by rearranging equation (2):

$$226 \quad (3) C_m = \frac{C_g}{\rho_g \times h_g} \rho_m \times h_m,$$

227 Accordingly, the model cohesion dictates the length scale h_g of the model with respect to the
228 natural prototype. Different scales of observation, e.g. basin-scale vs. lithosphere scale,
229 therefore necessitate different model cohesions (Abdelmalak et al., 2016). The length scale h^*
230 represents the dimensionless scale ratio between model and nature and equals h_m/h_g (Table 1).
231 In laboratory models of lithosphere-scale processes, one centimeter typically represents 10
232 km, translating into $h^* \approx 10^{-6}$ (e.g. Davy and Cobbold 1991), while in those of basin-scale
233 processes, one centimeter most typically represents 100 to 1000 meters, translating into $h^* =$
234 10^{-4} - 10^{-5} (e.g. Dooley and Schreurs, 2012; Galland et al., 2018; Merle, 2015). Bulk densities
235 of most natural crustal rocks range between 2200 and 3000 kg.m^{-3} , while analogue granular
236 material bulk densities range between 1200 and 1800 kg.m^{-3} . This leads to model:nature
237 density ratios ρ^* of 0.4-0.8. Cohesions of natural rocks range broadly between 10^6 and 10^8 Pa
238 (e.g. Galland et al., 2018; Schellart, 2000; Schultz, 1996; Voight and Elsworth, 1997).

239 For lithosphere-scale processes, Π values then range between 2 and 300, and so cohesions of
240 model rocks should be considerably low, between 0.5 and 80 Pa. This is the case for pure
241 silica sand (Klinkmüller et al., 2016; Schellart, 2000). For basin-scale or volcano-scale
242 processes, Π values lie an order of magnitude lower, between 0.2 and 30, and cohesions of
243 model materials should have a range between 40 and 800 Pa. Granular materials with higher

244 cohesion compared to sand are thus needed, by using fine-grained powders or fillers in
 245 coarse-grained sand.

246

247 **Table 1:** Scaling parameters and dimensionless equation used to compare experiments to nature;
 248 natural values from (Galland et al., 2014; Merle, 2015; Schultz, 1996).

Parameter	Symbol and Unit	Model (m)	Nature(g)	Ratio*
Gravitational acceleration	g (m.s ⁻²)	~9.81	~ 9.81	~1
Overburden height	h (m)	1×10^{-2}	$1 \times 10^1 - 15 \times 10^3$	$10^{-4} - 10^{-6}$
Density	ρ (kg.m ⁻³)	1200-1800	2200-3000	0.4-0.8
Cohesion	C (Pa)	0.5-800	$10^6 - 10^8$	$10^{-4} - 10^{-8}$
Internal friction angle	Φ (°) = \square_3	25-45	25-45	~1
Internal friction coefficient	μ (radians)	0.43-0.79	0.43-0.79	~1
Gravitational stress:cohesion	$\square = \rho gh/C$	0.2-300	$0.015 \times 10^{-4} - 4 \times 10^3$	

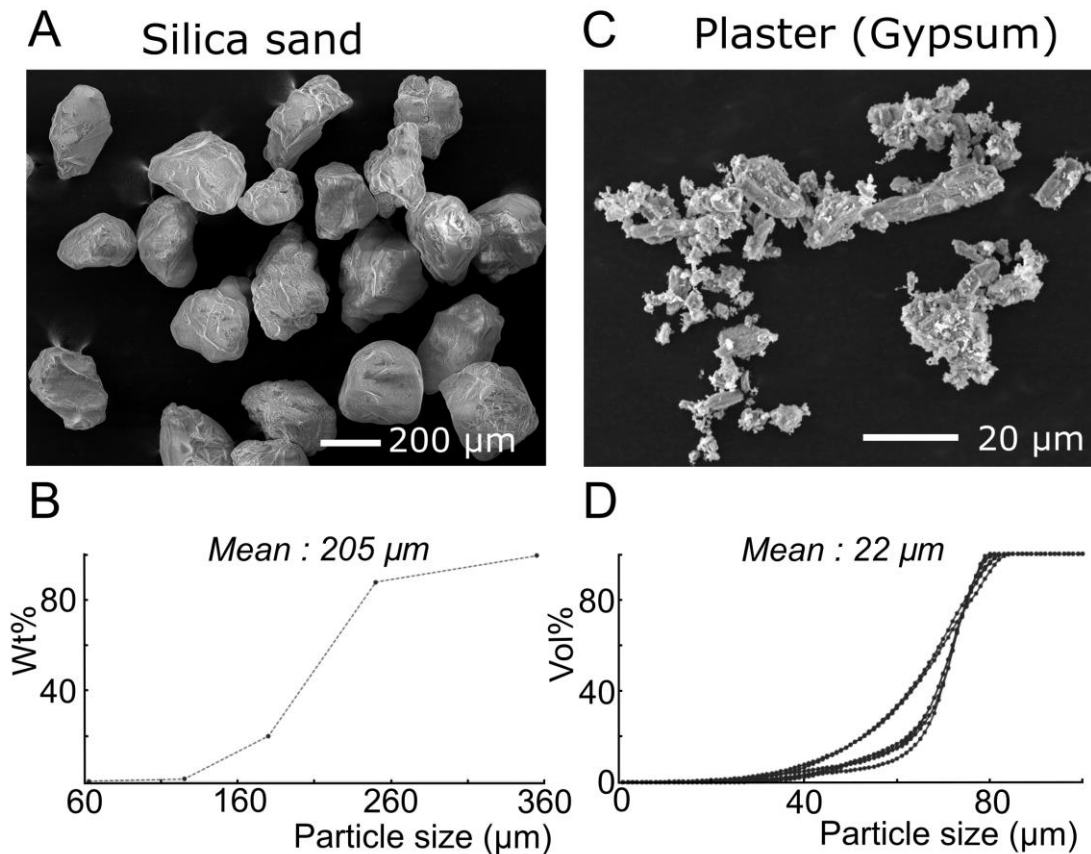
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250 3. Materials and Methods

251 3.1 Materials

252 We tested mixtures of dry sand and plaster. The sand is 99,8% chemically pure silica sand
 253 MAM1ST-300 (SiO₂; Sibelco, Mol, Belgium). Scanning Electron Microscope (SEM) images,
 254 carried out at Vrije Universiteit Brussel, show that the grains are subangular to poorly
 255 rounded (Figure 2A). The grain size is unimodal, with a mean ~205 μm (Figure 2B). The
 256 plaster is air-dried hemi-hydrate gypsum powder with the brand name Goldband (CaSO₄.1/2
 257 H₂O; Knauf). SEM images show the grains are tabular to plate-shaped, and clustered (Figure
 258 2C). Grain size measurements in water in a laser diffractometer without scintillation at Vrije
 259 Universiteit Brussel showed that the grain size distribution is unimodal, with a mean ~22 μm
 260 (Figure 2D), but this combines both 1-10 μm -sized individual crystals and 10-80 μm -sized
 261 clusters. The crystal hardness of quartz is 7 on the scale of Mohs, while that of gypsum
 262 crystals is 4.

263 The sand and plaster were mixed at 0, 5, 10, 20, 35, 50, 70 and 100 weight percent (wt%) of
 264 plaster. The quartz sand and gypsum plaster end-member materials and their mixtures are
 265 hereafter referred to as 'samples'. Ambient air temperature was registered in all laboratory
 266 environments to be 18-25°C.



267

268 **Figure 2** – **A.** Scanning Electron Microscope (SEM) image of MAM1ST-300 silica sand grains shows
 269 moderately rounded grain shapes and a unimodal grain size; **B.** Cumulative particle size measurements show the
 270 silica sand used in this study has a mean particle size of 205 μm (Sibelco); **C.** SEM image of Knauf gypsum
 271 powder – i.e. plaster - used in this study shows micrometer-sized, tabular and blocky crystals often in clusters of
 272 several tens of μm ; **D.** Cumulative particle size measurements show that the mean plaster particle size is about
 273 22 μm but clusters sizes are up to 80 μm .

274

275 3.2 Methods

276 3.2.1 Bulk density estimates and effects of emplacement method

277 The effects of three emplacement methods were assessed: (1) pouring, (2) sieving versus, and
 278 (3) pouring and compaction. The first two methods were assessed by systematically
 279 measuring the bulk density ρ of sand-plaster mixtures with 0, 10, 20, 50 or 100 wt% plaster
 280 in ring shear tests (see Section 3.2.3). The air-dried granular materials were placed into a ring-
 281 shaped shear cell, which is 4 cm high, 1.10^{-3} m^3 (1 liter) in volume and of a mass of 2186.5 g,
 282 either by sieving through a 400 μm mesh, or by pouring from an open pitcher. The samples
 283 were emplaced from ~20 cm height, which was previously found to be the most efficient
 284 height for obtaining a most compact quartz sand packing (Lohrmann et al., 2003). Surplus

285 material was scraped off the cell top manually and the emplaced sample mass was then
286 obtained by weighing the filled test cell on a balance.

287 The third emplacement method, and the effects of humidity, were examined through a second
288 set of identical mixtures that were oven-dried for 24 hours, poured in the shear cell from ~20
289 cm height and compacted by preloading with a normal load of 20000 Pa on the ring shear
290 tester. The ring shear test procedure includes the estimation of material density before and
291 during the test, which provided a means of assessing the effect of material compaction during
292 deformation (see Section 3.2.3).

293

294 **3.2.2 Porosity estimates**

295 The bulk porosity ϕ of each granular material was estimated through the equation:

296 (4) $\phi = (V_s - (((M_s \cdot F_q)/\rho_q) + ((M_s \cdot F_p)/\rho_p))) / V_s$

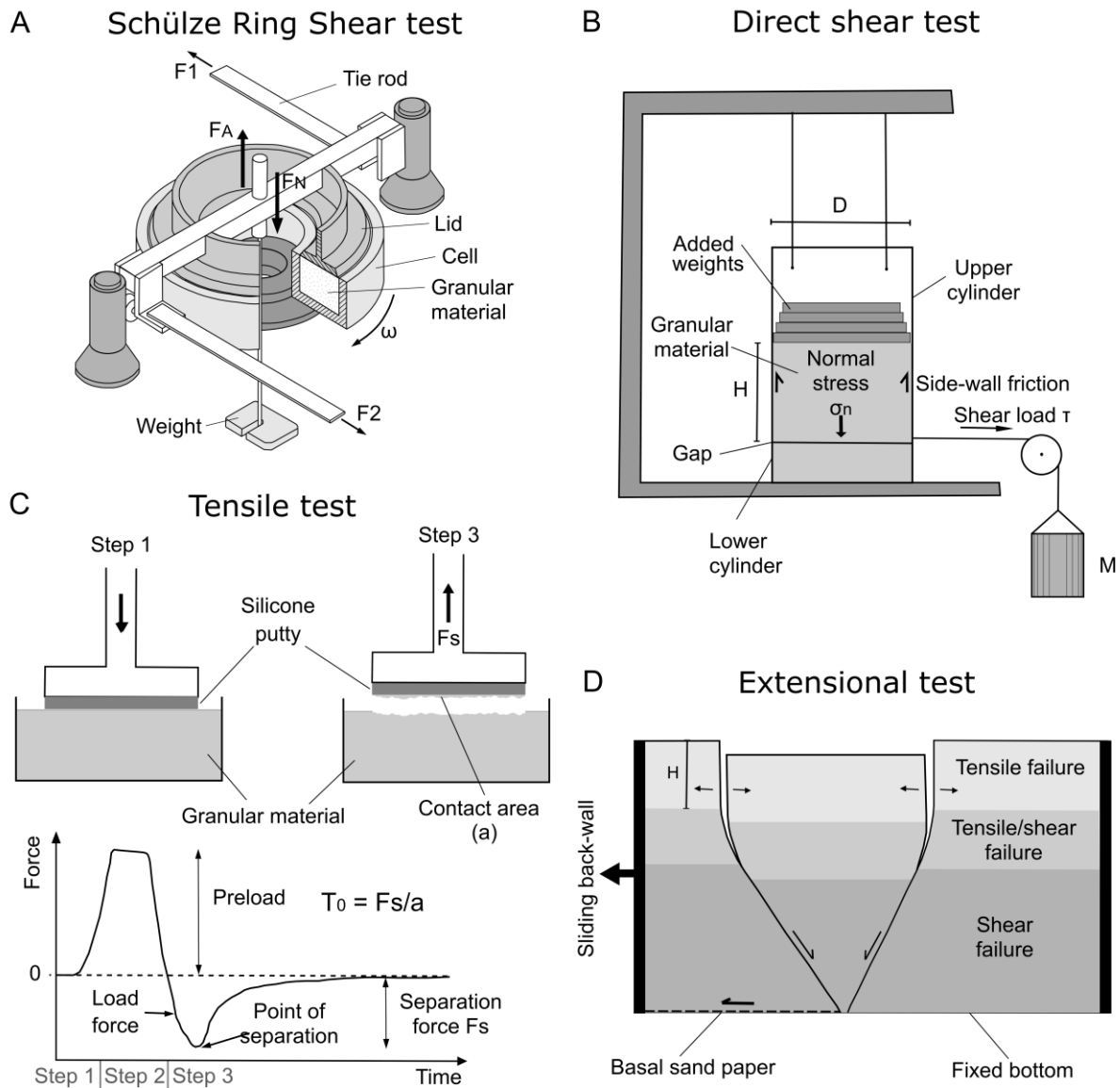
297 Here, F_q and F_p are the known bulk fractions of quartz sand and gypsum powder, respectively.
298 V_s is the sample bulk volume and M_s is the sample bulk mass. The individual crystal density
299 of quartz ρ_q is taken to be 2655 kg.m⁻³ and that of hemihydrate gypsum ρ_p is taken to be 2730
300 kg.m⁻³ (van Gent et al., 2010).

301

302 **3.2.3 Ring shear tests**

303 We generally followed the ring shear test protocol for measuring internal friction with the
304 RST01.pc as described in Klinkmüller et al. (2016). The shear cell containing the sample was
305 placed on the ring shear tester (Figure 3A) and the lid was lowered into the sample surface. A
306 normal load was then applied by the lid to the air-dried poured or sieved sample under rest,
307 that varied in separate test runs from 500, 1,000, 5,000, 10,000, 15,000 to 20,000 Pa. For
308 comparison with direct shear test data, oven-dried samples were poured and then compacted
309 in the ring shear cell by pre-loading with a normal load of 20,000 Pa for 5 seconds. Then, the
310 normal load was returned to respectively 250, 500, 1,000, 2,000 or 5,000 Pa in separate test
311 runs.

312 The cell was then rotated clockwise at a constant angular velocity of 4.4°.min⁻¹, or 6 mm.min⁻¹
313 ¹ (with respect to the median line of the sample-contained ring of the shear cell) during 300
314 seconds (or 30 mm of shear). A set of 5-mm deep, vertical radial blades on the lid caused
315 localisation of shear inside the sample material and prevented shear at the interface between
316 the sample and the cell lid. During the test all signals from sensors (normal and shear load, lid
317 position and velocity) were recorded at 100 Hz and then down-sampled to 10 Hz to smooth
318 high-frequency noise.



319

320 **Figure 3** – Laboratory set-ups used for testing the physical properties of granular materials. **A.** Schülze ring
 321 shear tester (RST). The sample is placed in an annular cell and on top of the sample a lid is suspended to which a
 322 normal load is applied. During a test run the sample-bearing cell is rotated and tie rods measure the shear stress
 323 (F_1 , F_2) undergone by the lid. **B.** Hubert-type direct shear tester apparatus, in which a sample is placed in a
 324 cylinder consisting of an upper half suspended above a stable lower half. A shear load M is applied to the upper
 325 cylinder and is incrementally increased until sample failure occurs. Tests are repeated with constant sample
 326 height H but increasing normal loads by adding weights. **C.** Tensile test where the tensile strength of a
 327 compacted granular sample is obtained through a 3-step procedure in which a silicone pad is preloaded on the
 328 top of a granular sample and subsequently retracted until sample failure occurs at a measured separation force.
 329 **D.** Extensional test in which a compacted granular sample is extended horizontally until failure occurs by
 330 retracting a moving wall. The height H of the vertical upper part in the tensile failure domain of the induced
 331 fractures is a measure for the tensile strength of the material.

332

333 The registered shear stress curve is typical for granular materials (Figure 1B, green) and
334 consists of three parts (Lohrmann et al., 2003; Panien et al., 2006): (1) a peak shear strength
335 (i.e. static failure) that is reached shortly after test initiation, (2) a stress drop then reflects
336 localisation of shear into a shear zone; (3) a stable plateau is reached representing the steady
337 state stable shear strength; (4) after a short reversal of shear cell rotation direction to return
338 shear stress to zero, shearing anew in a clockwise direction returns the shear curve to a
339 dynamic shear strength which represents shear zone reactivation.

340 For each normal load, tests were repeated three times, amounting to 18 tests for each material
341 in total. Peak shear strengths were picked manually or automatically (Rudolf and Warsitzka,
342 2019; Warsitzka et al., 2019). Stable and dynamic shear strengths are not discussed further
343 here, but they are available in the accompanying data publication (Poppe et al., 2021).

344 During shearing, vertical lid movement is measured as a proxy for sample decompaction
345 (positive) or compaction (negative). This measurement allowed us to study the effect of
346 sample decompaction/compaction, and thus density variations, on sample frictional
347 properties.

348 An additional velocity stepping test was carried out on a 90 wt% sand – 10 wt% plaster
349 mixture to assess the dependency of measured shear strengths on the shear rate, by decreasing
350 the shear rate after reaching the steady state plateau incrementally from 5 mm.s⁻¹ to 2.5, 1,
351 0.5, 0.1 and 0.05 mm.min⁻¹.

352

353 **3.2.4 Humidity tests**

354 To estimate the humidity content, one air-dried sample of a mass of ~400g of each sand,
355 plaster, and sand-plaster mixtures containing 5, 10, 20, 35, 50 and 70 wt% plaster, all stored
356 previously in their original packaging at room temperature and ambient air humidity, were
357 weighed on a precision balance (precision = 0.01g). Then, the samples were placed in open
358 containers in an oven at a temperature of 90°C and weighed again after 24, 48 and 72 hours of
359 oven-drying. The drying process evaporated the sample's moisture, and the loss of sample
360 mass yielded a weight percentage (wt%) of humidity loss. Furthermore, to constrain the effect
361 of humidity on the mechanical properties of 100 wt% plaster, we carried out direct shear tests,
362 tensile and extensional tests both on oven-dried plaster and on air-dried plaster.

363

364 **3.2.5 Direct shear tests**

365 Pressures of <500 Pa are typical in sand-box experiments with a few centimeters of material
366 height (depending on material density - cf. equation 2). Because standard ring shear tests at

367 normal loads of < 500 Pa are possibly subject to bias (Ritter et al., 2016), we performed
368 Hubert-type direct shear tests at normal loads of ~ 100 to ~ 1200 Pa. The Hubert-type shear
369 apparatus consisted of an upper PVC cylinder suspended above a fixed lower PVC cylinder,
370 with a cardboard ring maintaining a gap of < 1 mm in between both cylinders (Figure 3B).

371 To avoid humidity effects on material properties, samples were first oven-dried at 90°C for at
372 least 24 hours, left to cool in a sealed container, weighed on a precision balance and poured in
373 the cylinders of the shear apparatus. A lid was placed on top of the sample, and by manual
374 tapping from above on the lid, the sample was compacted down until a height H of 2.5 cm
375 above the gap between both cylinders to obtain the density pre-determined for that material
376 ($\rho_{\text{Compacted}}$ in Table 2). The mass of material within the upper cylinder under gravity
377 represented an initial normal load on the horizontal plane passing between the cylinders. Up
378 to four weights could be added on top of the sample, to give a range of five normal loads. The
379 normal stress σ_n acting on the horizontal plane between the cylinders is obtained by dividing
380 normal load by the circular area of the plane. After sample emplacement, compaction and
381 vertical loading, the cardboard ring between both cylinders was carefully removed without
382 disturbing the sample. To obtain the shear strength τ , a shear load was applied to the upper
383 cylinder by pouring sand in a small container connected to the cylinder via a pulley (Figure
384 3B). This load was increased until an initial sample failure was detected by visual inspection
385 at the gap between both cylinders. The applied mass M causing shear failure was then
386 constrained by weighing. From this, the gravitational acceleration g , and the circular shear
387 plane area A (i.e. cylinder section), the sample's shear strength (i.e. the critical shear stress
388 acting on the shear plane) was calculated according to the equation:

389 (5) $\tau = gM/A$

390 This test was repeated three times for each of the five normal loads to ensure minimum
391 reproducibility. Thus, a total of 15 measurements were made for each mixture and end-
392 member granular material. In cases where the range of the obtained measurement values was
393 large, additional runs were carried out. The average shear strength value at each normal load
394 was used to construct failure envelopes in shear stress σ_s vs. normal stress σ_n diagrams,
395 following correction of the normal stress for the so-called silo effect.

396 The 'silo effect' or 'Janssen effect' is a reduction in the normal load on the shear plane due to
397 friction on the wall of the upper cylinder (Jansen, 1895; Mourgues and Cobbold, 2003). This
398 can be corrected empirically. The upper cylinder of the Hubbert-type shear apparatus was
399 suspended above a precision balance. A cardboard ring maintained a gap of < 1 mm between
400 the cylinder and the balance. A sample was then poured and compacted in the suspended

401 cylinder to obtain the same densities as used in the direct shear tests (Table 2). The cardboard
402 ring was then removed. The mass then registered by the balance was the effective normal load
403 exerted on the failure plane in the direct shear tests. These normal load measurements were
404 repeated at least three times for each of the five normal loads in the direct shear tests, and the
405 average ‘corrected normal load’ was used instead of the theoretical normal load to construct
406 failure envelopes.

407

408 **3.2.6 Tensile tests**

409 The tensile strength T_0 of oven-dried sand, plaster and sand-plaster mixtures containing 5, 10,
410 20, 35, 50 and 70 wt% plaster, and air-dried plaster was measured at the University of Maine,
411 France, following the method of Schweiger and Zimmerman (1999). Each material was
412 poured into a container of 108 cm³ in volume and with a square-shaped area of 6x6 cm². It
413 was then compacted by manually tapping a cover from above to obtain the required density
414 (Figure 3B). A pad of the silicone polymer polydimethylsiloxane (PDMS) with a viscosity of
415 $\sim 10^4$ Pa.s (Poppe et al., 2019) was attached to the bottom of a square-shaped load cell
416 measuring 4x4 cm², which was mounted on an EZ-SX tension apparatus.

417 The tensile strength test consisted of three steps (Figure 3C). In step 1, the sample was
418 vertically preloaded by the load cell for five seconds to allow the silicone to adhere to the
419 sample surface. In step 2, the loading was reduced until the tension force sensor measured 0
420 N. In step 3, an increasing vertical tensional force was exerted on the granular material by
421 moving the silicone pad upwards at a constant displacement rate until a peak tension force F_t
422 was reached at failure. A photograph of the post-test silicone pad was referenced in ArcGIS
423 software (ESRI). Here, the area of separated granular material A_s was traced and quantified.
424 The tensile strength T_0 was then obtained through the equation:

$$425 \quad (6) \quad T_0 = F_t/A_s$$

426 Tensile strength tests were reproduced ten times for the sand and plaster end-members and
427 each sand-plaster mixture.

428

429 **3.2.7 Extension tests**

430 On the assumption that the failure envelope of a material is non-linear at negative normal
431 loads and at small positive normal loads, the cohesion of granular materials can be estimated
432 by combining the tensile strength T_0 with a vertical cliff height H obtained from extensional
433 tests (Abdelmalak et al., 2016). H was measured at the Vrije Universiteit Brussel, Belgium, in
434 an extensional apparatus that consists of a box with three fixed glass walls and one moving

435 wall connected to a computer-controlled piston (Figure 3D). Attached to the moving wall was
436 sandpaper that covered half of the box bottom length.

437 A weighed amount of oven-dried sand, plaster or sand-plaster mixtures containing 5, 10, 20,
438 35, 50 and 70 wt% plaster, or air-dried plaster was poured in the box. Sample compaction to a
439 vertical height of 10 cm and the required density (see Table 2) was obtained by manual
440 tapping on a lid from above. By moving the wall laterally outwards at a constant rate of 10
441 cm/hr, the attached sandpaper imposed a velocity discontinuity to the base of the sample pack,
442 which extended until two or more fractures developed, forming a graben-like structure. At
443 and just below the surface, each fracture is vertical and opening mode in the tensile failure
444 domain; with depth the fracture becomes inclined and transitions to shear mode in the shear
445 failure domain (Figure 3D). We measured the height H of the opening-mode shallow part of
446 the fractures.

447

448 **4. Results**

449 **4.1 Effects of emplacement method**

450 We observed clear effects of the method of emplacement of sand-plaster mixtures – i.e.
451 sieving, pouring or pouring + compaction – on the heterogeneity, density and porosity of the
452 sample material.

453

454 **4.1.1 Material heterogeneity**

455 The dispersal of grainsize of a sand-plaster mixture, and thus of mineralogy, is strongly
456 affected by the emplacement method. Pouring a mixture quasi-instantaneously maintained a
457 homogeneous sand and plaster distribution (Figure 4A and Table 2). Sieving the mixture,
458 however, resulted in heterogeneous grain-size and mineralogical distribution as the sand and
459 plaster separated into thin layers (Figure 4A).

460

461 **4.1.2 Material density**

462 The pre-test bulk densities show systematic variation depending on the emplacement method
463 and sand-plaster mixing ratios (Figure 4B; Table 2). Firstly, the mean density of quartz sand
464 is significantly higher when sieved ($1410 \pm 5 \text{ kg m}^{-3}$) than poured ($1235 \pm 7 \text{ kg m}^{-3}$) ($\alpha =$
465 0.050 ; $p = 1.69 \times 10^{-25}$; $t\text{-statistic} = -127.61$; $t\text{-critical} = 2.12$), whereas the density of plaster is
466 significantly lower when sieved ($564 \pm 6 \text{ kg m}^{-3}$) than poured ($636 \pm 11 \text{ kg m}^{-3}$) ($\alpha = 0.050$; p
467 $= 4.40 \times 10^{-13}$; $t\text{-statistic} = 21.03$; $t\text{-critical} = 2.12$). At a 50:50 wt% sand:plaster ratio, the

468 density of sieved ($899 \pm 7 \text{ kg m}^{-3}$) and poured ($906 \pm 9 \text{ kg m}^{-3}$) samples is not significantly
469 different ($\alpha = 0.050$; $p = 6.67 \times 10^{-2}$; t-statistic = 1.97; t-critical = 2.12).

470 Secondly, pouring+compaction produced higher bulk densities than either sieving or pouring.
471 Compaction increased the bulk density of plaster to 900 kg m^{-3} regardless of whether done by
472 pre-loading (RST) or tapping (DST). Compaction by tapping more effectively increased the
473 bulk density for sand-rich mixtures (i.e. <35 wt% plaster) and produced a bulk density of
474 1700 kg m^{-3} for the sand end-member; this is approximately double that of plaster (Figure 4B;
475 Table 2).

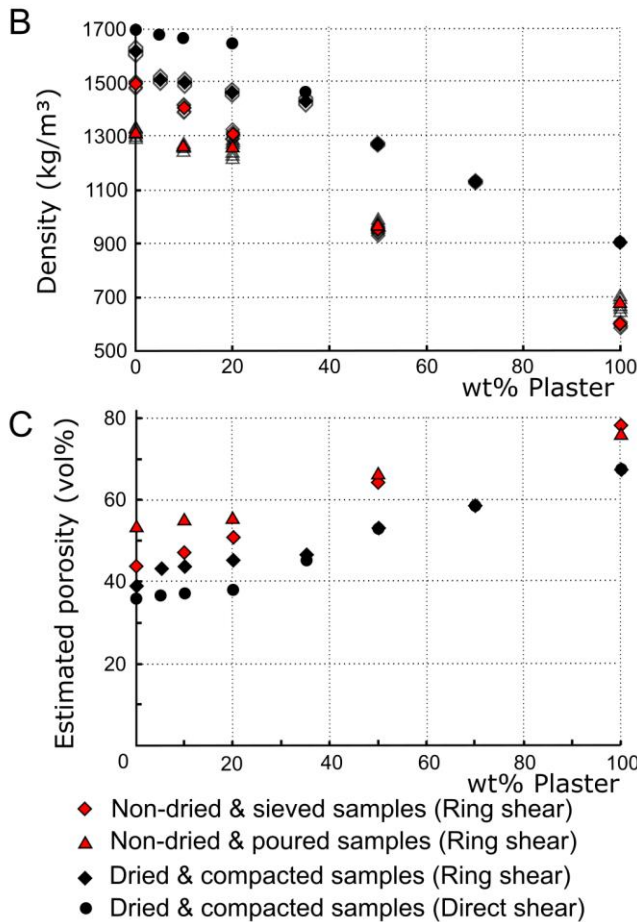
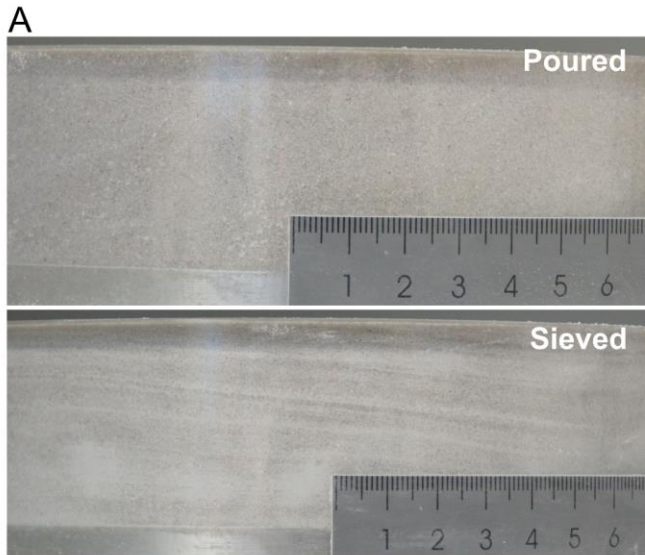
476 Thirdly, whether poured, sieved or poured+compacted, the bulk density of a sand-plaster
477 mixture systematically decreases with increased plaster content. This decrease is not linear –
478 bulk density decreases more rapidly for both the poured and the poured+compacted samples
479 after about 20 - 35 wt% plaster.

480

481 **4.1.3 Material porosity**

482 The estimated bulk porosity of the samples relates inversely to the bulk density (Figure 4C;
483 Table 2). Depending on the emplacement technique, the inferred porosity of quartz sand was
484 varied between 36-54 vol%, whereas that of plaster varied between 67-78 vol%. In mixtures
485 of these end-members, the porosity increased systematically, but non-linearly, with increasing
486 plaster content by weight.

487



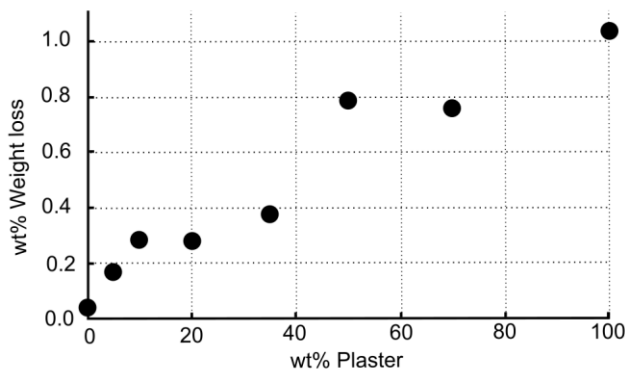
488 **Figure 4** – Effect of the emplacement technique on sand-plaster mixtures. **A.** Homogeneous grain size
 489 distribution in a poured 90-10 wt% sand-plaster sample vs. heterogeneous grain size distribution in a sieved 90-
 490 10 wt% sand-plaster sample with alternating coarser (sand-dominated) and finer (plaster-dominated) grain size
 491 layers; **B.** Densities of non-dried samples emplaced by pouring or sieving, or oven-dried samples poured and
 492 compacted into the ring shear cell, and oven-dried poured and compacted samples in direct shear tests, tensile
 493 tests and extension tests. The filled symbols indicate averages of the light-grey individual measurements. **C.**
 494 Inferred porosities of poured, sieved and poured+compact samples.

496 **Table 2** – Density, porosity and humidity of sand and plaster and their mixtures in function of the method of emplacement described in Section 3 and Figure 4B-C; sieved and
 497 poured samples were air-dried, poured+compacted samples were oven-dried; ρ = density; φ = porosity; uncertainties on sieved and poured densities are standard deviations
 498 (1σ), uncertainties on humidity indicate measurement precision relative to the total sample weight.

Sand:Plaster ratio (wt%)	Plaster (wt%)	ρSieved (kg.m⁻³)	ρPoured (kg.m⁻³)	ρCompacted (kg.m⁻³)	ρCompacted ring shear (kg.m⁻³)	φSieved (vol%)	φPoured (vol%)	φCompacted (vol%)	φCompacted ring shear (vol%)	Humidity Weight loss (wt%)
100:0 (Sand)	0	1410±5	1235±7	1700	1625±26	43.6	53.5	36.0	38.8	0.05±0.03
95:05	5	-	-	1680	1514±18	-	-	36.8	43.0	0.17±0.03
90:10	10	1327±6	1190±4	1666	1505±17	47.1	55.3	37.4	43.5	0.29±0.03
80:20	20	1237±8	1187±14	1650	1467±11	50.9	55.5	38.2	45.0	0.28±0.03
65:35	35	-	-	1465	1439±18	-	-	45.4	46.3	0.38±0.03
50:50	50	899±7	906±9	1268	1272±8	64.6	66.4	52.9	52.8	0.79±0.03
30:70	70	-	-	1125	1133±10	-	-	58.4	58.2	0.76±0.03
0:100 (Plaster)	100	-	-	900	901±2	78.1	76.7	67.0	67.0	1.03±0.03
0:100 (non-dried plaster)	100	564±6	636±11	900	-	-	-	67.0	-	-

500 4.2 Humidity tests

501 After 72 hours of oven-drying at 90°C, samples showed a cumulative weight loss that
502 increased roughly linearly ($R^2 = 0.93$) with increasing plaster content (Figure 5; Table 2).
503 While plaster lost a cumulative 1.05 wt% of moisture, quartz sand only lost 0.05 wt%. For all
504 samples, more than 90% of the weight loss occurred in the first 24 hours of oven-drying (see
505 data in Poppe et al., 2021), suggesting that drying overnight should be sufficient to remove
506 most of the humidity from granular materials prior to experimentation.
507



508 **Figure 5** - Weight loss of sand-plaster mixtures of varying weight ratios after 72 hours of oven drying as a proxy
509 for humidity contained within one sample per material.

510

511 4.3 Ring shear tests

512 4.3.1 *Effect of shear rate*

513 The shear stress in a 90:10 wt% air-dried sand-plaster mixture measured at a shear rate of 2.5
514 $\text{mm}\cdot\text{min}^{-1}$ increased by 2% compared to that measured at 25 $\text{mm}\cdot\text{min}^{-1}$ (see data in Poppe et
515 al., 2021). This observation indicates a weak dependency of the measured shear stress on
516 shear rate. While we consider this effect quantitatively marginal compared to reported error
517 margins, one may scale the friction coefficients reported here to the actual shear rate used or
518 observed in experiments by a correction factor of 2% per order of magnitude deviation from
519 the 6 $\text{mm}\cdot\text{min}^{-1}$ used in our ring shear tests.

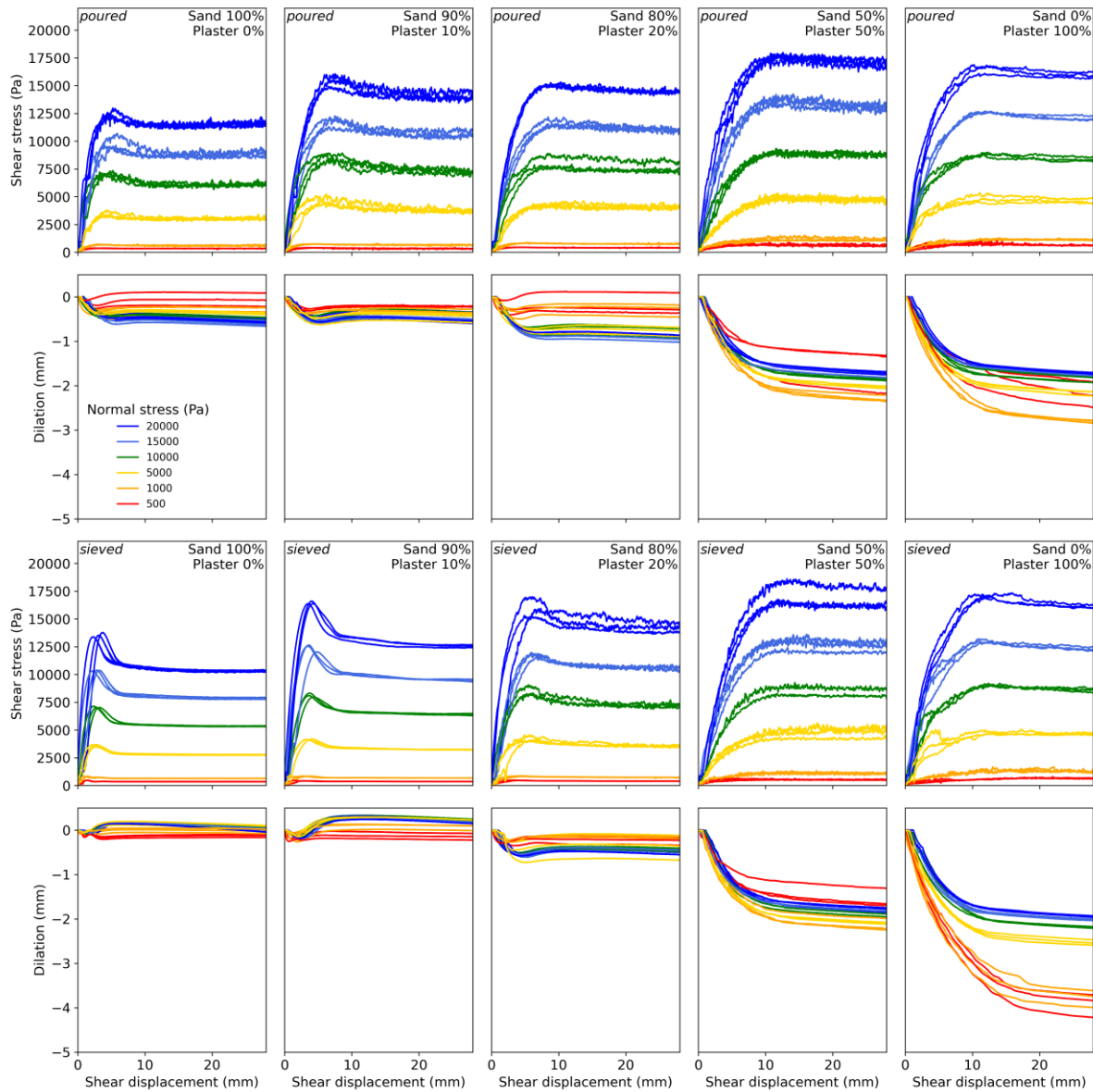
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521 4.3.2 *Stress and dilation curves for air-dried uncompacted samples*

522 We performed 300 individual ring shear tests on poured or sieved, air-dried sand, plaster and
523 sand-plaster mixtures with 10, 20 and 50 wt% plaster, and on oven-dried, poured+compacted
524 sand, plaster and mixtures with 5, 10, 20, 35, 50 and 70 wt% plaster (see data in Poppe et al.,
525 2021).

526 The shear stress and compaction curves for air-dried sieved or poured sand samples describe
 527 the effect of the emplacement technique on the mechanical behaviour of sand-plaster mixtures
 528 (Figure 6). Note that negative dilation by convention represents compaction (Lohrmann et al.,
 529 2003).

530



531

532 **Figure 6 – A.** Shear stress (τ) and sample dilation evolution as a function of time for air-dry poured versus
 533 sieved sand and plaster and 90:10, 80:20 and 50:50 mixing ratios. Ring shear test data (RST) at normal loads
 534 ranging between 500 Pa and 20,000 Pa at constant shear rate. Sample dilation is measured as RST lid uplift
 535 during shearing. Negative is compaction, positive is decompaction.

536

537 For sieved pure sand, shear stress and compaction evolution are qualitatively similar to what
538 was observed previously for other silica sands (Klinkmüller et al., 2016; Lohrmann et al.,
539 2003; Panien et al., 2006). After an initial phase of compaction during shear stress build-up,
540 decompaction accompanies shear zone localisation and failure occurs at a peak shear strength
541 value concurrent with the maximum decompaction rate. The measured shear stress then drops
542 to a dynamic plateau value without further decompaction. Overall, the peak strengths and
543 post-peak plateau strengths increase with increased normal loads.

544 As the plaster content increases in sieved samples, three alterations to this well-established
545 shearing behaviour are seen (Figure 6, bottom rows). Firstly, the initial peak is wider; i.e.
546 more strain is needed to localise a shear zone. Secondly, the associated stress drop gradually
547 decreases, and a peak is absent from a 50:50 sand-plaster ratio onwards; i.e. the behaviour of
548 plaster-dominated mixtures is more ductile. Additionally, the stable sliding strength at a given
549 normal load generally increases with increased plaster content. Thirdly, the compaction-
550 decompaction cycle observable in sand-dominated mixtures (≤ 20 wt% plaster) is replaced by
551 steady compaction during localisation in the plaster-dominated mixtures (≥ 50 wt% plaster).

552 For poured samples, the temporal evolution of shear stress and decompaction is qualitatively
553 similar to what has been observed for sieved samples (Figure 6, top rows). Nonetheless, there
554 are some quantitative deviations. First, the peaks are generally wider (i.e. localisation requires
555 more strain) and stress drops are smaller when poured compared to when sieved. Second,
556 high-frequency noise indicates stick-slip, except for pure sand, and such noise is typically
557 higher in amplitude compared to sieved samples. In sand-dominated samples, a clear initial
558 peak with stress drop occurs again, although it is accompanied by a more subtle compaction-
559 decompaction cycle (without net decompaction). In plaster-dominated poured mixtures, such
560 a peak stress is again absent and is replaced by strain strengthening and sample compaction
561 until the dynamic steady state is reached.

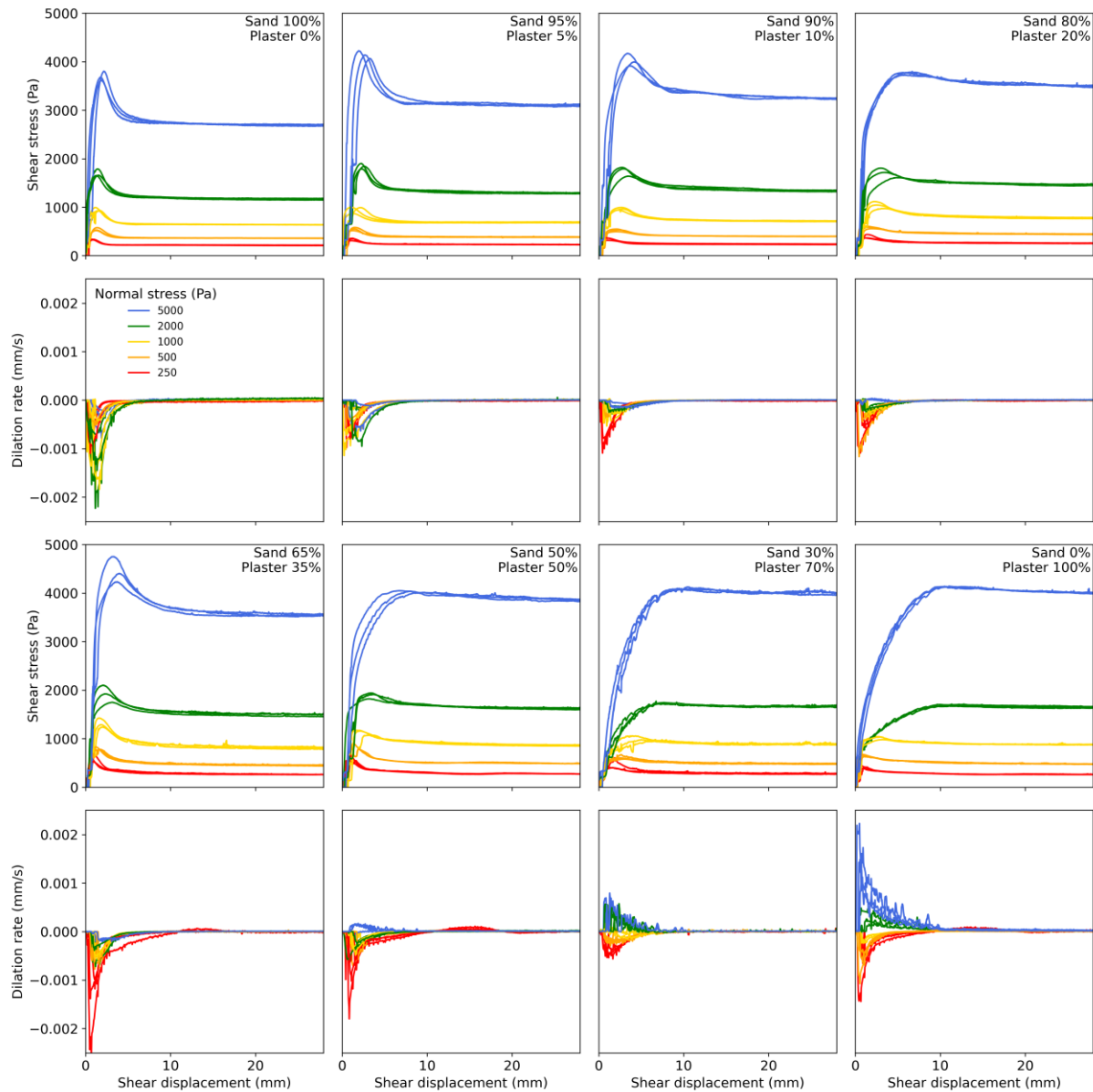
562

563 ***4.3.3 Stress and dilation curves for oven-dried compacted samples***

564 Figure 7 depicts the ring shear test results and dilation curves obtained for oven-dried sand,
565 plaster and sand-plaster mixtures that were poured and mechanically compacted prior to
566 testing. In general, the shear stress curves for these poured and pre-compacted samples are not
567 as noisy as those for their poured and uncompacted equivalents (see Figure 6).

568 For sand-dominated mixtures (≤ 35 wt% plaster), initial shear stress peaks are again present at
569 all tested normal stresses. These materials thus display a similar strain hardening to strain

570 weakening behaviour, accompanied by compaction-decompaction cycles, as seen in the above
571 tests on air-dried samples and as described by (Panien et al., 2006).



572
573 **Figure 7:** Curves of shear stress versus shear displacement and of dilation rate for oven-dried,
574 poured+compacted sand, plaster and sand-plaster mixtures measured by using ring shear tests (n=120). Applied
575 normal stresses varied from 250 to 5000 Pa.

576 For plaster-dominated mixtures (≥ 50 wt% plaster), a peak stress and compaction-
577 decompaction behaviour is also seen at low normal loads. This is more brittle behaviour than
578 the generally ductile behaviour seen in equivalent mixtures that were uncompacted prior to
579 testing (see Figure 5). In addition, stick-slip behaviour is apparent in the stress-displacement
580 curves at intermediate to high normal loads (>1000 Pa). At high normal loads, the pre-
581 compacted plaster-dominated mixtures nonetheless again show pure strain hardening
582 behaviour without a stress drop and with compaction only (i.e. ductile behaviour). The

583 transition from somewhat brittle behaviour to entirely ductile behaviour occurs at decreasing
584 normal stresses for increasing plaster contents. For a 50:50 wt% sand-plaster mixture, the
585 transition lies between 2000-5000 Pa; for a 30:70 wt% mixture it lies between 1000-2000 Pa;
586 for pure plaster it lies between 500-1000 Pa.

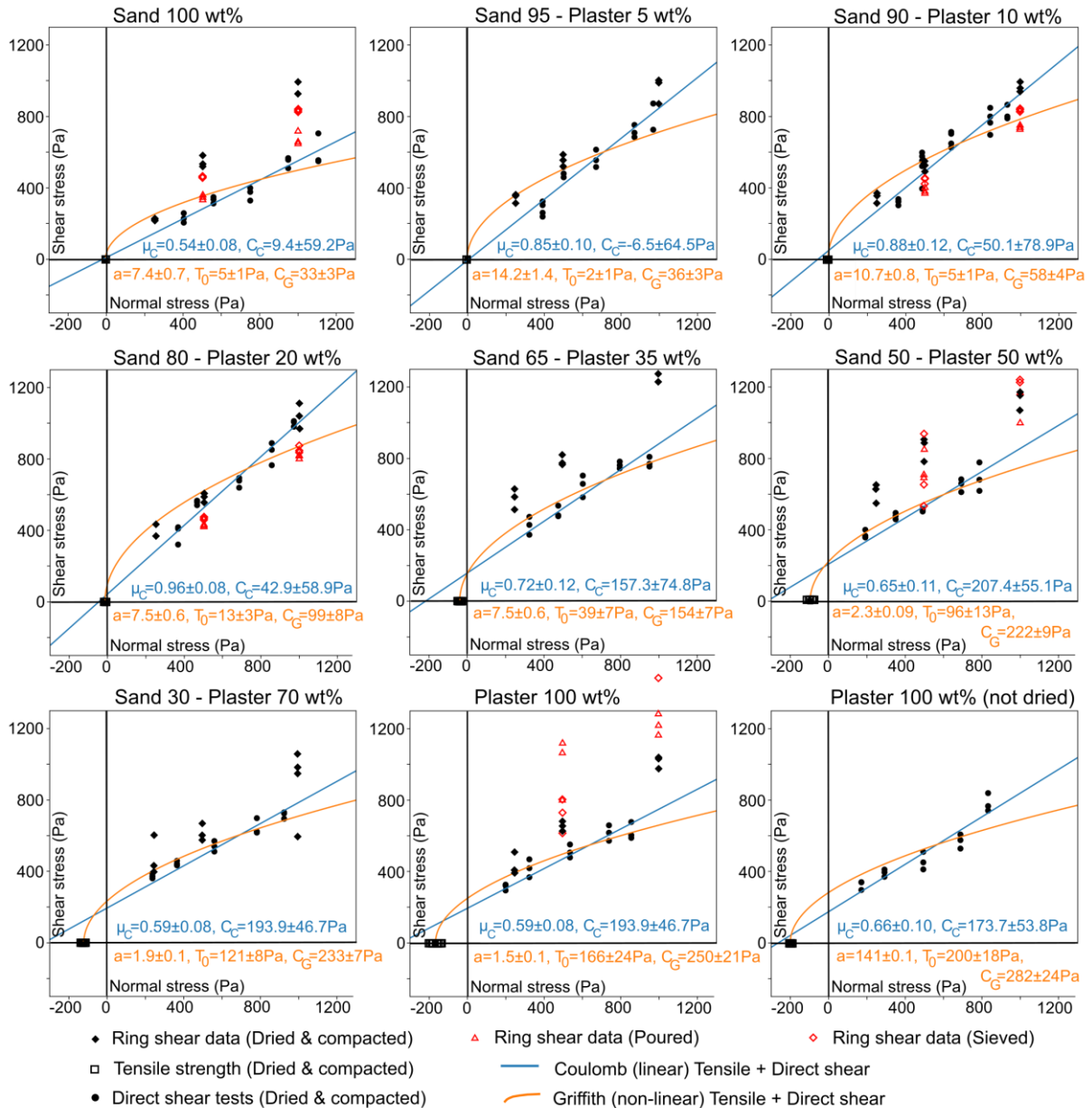
587

588 ***4.3.4 Peak stress data from ring shear tests***

589 Peak stress generally increases with increased normal load for all materials regardless of
590 emplacement procedure (Figure 8). The variation of peak strength with plaster content and
591 emplacement technique is more complex, however.

592 For air-dried uncompacted samples, peak shear stresses for a given normal load generally
593 increase with increased plaster content (Figure 8, red symbols). For sand-dominated sieved
594 mixtures (Figure 8, red diamonds), peak shear stresses are higher than for sand-dominated
595 poured mixtures (Figure 8, red triangles). For plaster-dominated sieved mixtures, on the other
596 hand, peak shear stresses are lower than for plaster-dominated poured mixtures.

597 For oven-dried and compacted samples, a general increase in peak stress for a given normal
598 load is not so clear (Figure 8, black diamonds). Rather, values generally increase up to 50
599 wt% plaster, the peak stresses are similar for compacted and uncompacted samples. For pure
600 plaster, however, the peak shear stress values of compacted samples are lower than those of
601 non-compacted samples.



602 **Figure 8** – Shear stress (τ) versus normal stress (σ_n) plots describing failure envelopes of oven-dried and
 603 compacted sand and plaster and their mixtures, composed of tensile strengths (T_0) obtained from tensile tests,
 604 direct shear test results (with normal loads corrected for the silo effect, see Supplementary Materials) and ring
 605 shear test results. Note that ring shear test data on sieved and poured samples were done on non-dried samples in
 606 equilibrium with ambient air humidity. Optimal failure envelopes shown here are based on fitting a Coulomb
 607 criterion (blue lines) or a Griffith criterion (orange curves) to direct shear and tensile test data on the oven-dried
 608 and poured+compacted samples.

609 610 **4.4 Direct shear tests**

611 We performed 143 direct shear tests on oven-dried poured+compacted sand, plaster and sand-
 612 plaster mixtures and on air-dried poured+compacted plaster (Figure 8).

613

614 **4.4.1 Correction for the silo effect**

615 The results of the empirical correction for the ‘silo effect’ (Jansen, 1895; Mourgues and
616 Cobbold, 2003) are shown in Supplementary Figure S1 and raw data in Poppe et al. (2021).
617 The tested range of normal stresses overlaps with that of the three lowest normal load steps in
618 the ring shear tests (250, 500 and 1000 Pa). The measured normal stress versus applied
619 normal stress curves deviate from a 45° slope. This deviation is greatest for mixtures with 35
620 and 50 wt% plaster. Therefore side-wall friction decreases the applied normal stress at the
621 shear failure plane in all samples, and these curves enable a correction to obtain the average
622 effective normal stress on the failure plane that was used to plot direct shear test data in
623 Figure 8.

624
625 **4.4.2 Shear strength of oven-dried and compacted samples**

626 The direct shear test results – i.e. shear strength values versus normal stress values that are
627 corrected for the side-wall friction effect – are displayed in Figure 8 (black circles). For all
628 mixtures, the shear strengths from the direct shear tests are lower than the peak strengths from
629 the ring shear test results on oven-dried and poured+compacted samples, except for mixtures
630 with 10 and 20 wt% plaster, where they are broadly similar for similar normal stresses.
631 Overall, the direct shear test results describe approximately linear failure envelopes in shear –
632 normal stress space. There is a general increase in shear strength at a given normal load as
633 plaster content increases to about 20 wt%. With higher plaster contents, however, the shear
634 strengths at the tested normal loads remain slightly higher than those of pure sand.

635
636 **4.5 Tensile tests**

637 We performed 89 unconfined tensile tests on oven-dried and compacted sand, plaster and
638 sand-plaster mixtures (Figure 9A; Table 3). Sand-plaster mixtures with < 20 wt% plaster
639 display average tensile strengths that are near-zero (2-5 Pa) with little to no data spread. From
640 20 wt% plaster upwards, the tensile strength increases with plaster content along a roughly
641 linear trend ($R^2 = 0.969$), up to a mean value 167 ± 23 Pa for pure, oven-dried plaster. The
642 data spread increases with increasing plaster content in a mixture. Non-dried plaster yields a
643 tensile strength of 200 ± 18 Pa, the mean of which is ~ 33 Pa. This is almost 20% higher than,
644 and statistically distinct from, the mean tensile strength value of oven-dried plaster ($\alpha=0.050$;
645 $p=0.004$; t -statistic=4.00, t -critical=2.31).

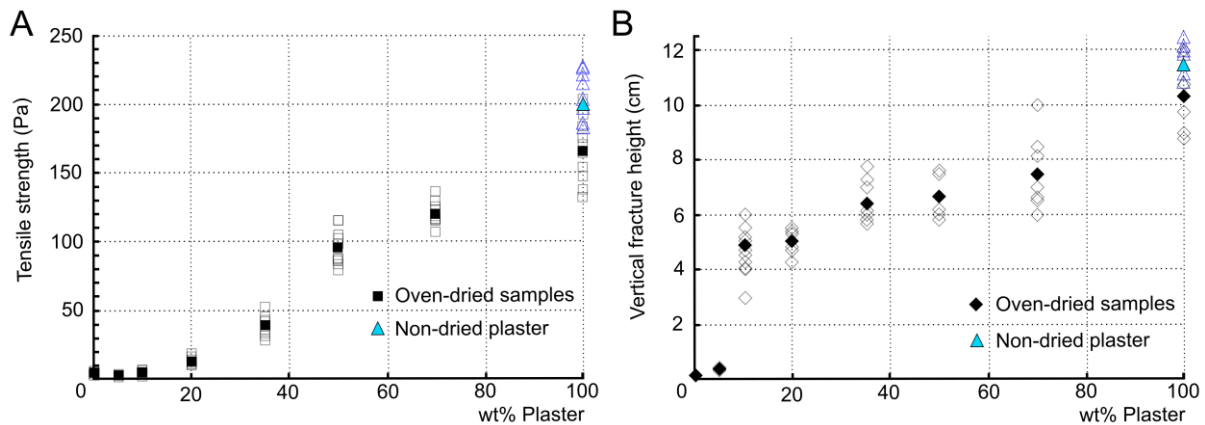
646
647 **4.6 Extension tests**

648 We performed 25 extensional tests on oven-dried and compacted sand, plaster and sand-
649 plaster mixtures, in which a total of 73 vertical opening-mode fracture portions were
650 measured (Figure 9B; Table 3). Quartz sand extended in a diffuse manner and developed
651 unmeasurably low cliffs. An arbitrary value of 0.1 cm, representing measurement limit, was
652 therefore assigned here to pure sand.

653 From 10 wt% plaster upwards, open fractures were observed. With increasing plaster content,
654 the height of the opening-mode fractures increases roughly linearly ($R^2 = 0.899$). The material
655 is able to develop opening-mode fractures to greater depths.

656 Non-dried plaster yielded vertical fracture heights that were on average 1.2 cm higher
657 compared to oven-dried plaster. Despite their ranges overlapping, these averages are
658 statistically distinct ($\alpha=0.050$; $p=0.046$; $t\text{-statistic}=2.36$, $t\text{-critical}=2.31$).

659



660

661 **Figure 9 – A.** Tensile strengths (T_0) of sand and plaster and their mixtures as measured in tensile tests on oven-
662 dried samples compacted by manual tapping. Unfilled symbols indicate individual measurements and therefore
663 the uncertainty on the averages represented by the filled icons; **B.** Heights H of the vertical upper portions of
664 normal (graben) faults formed in sand and plaster and their mixtures measured in extensional tests on oven-dried
665 samples compacted by manual tapping. Unfilled icons show individual measurements and therefore indicate the
666 uncertainty on the averages represented by the filled icons. Triangles in A. and B. represent individual
667 measurements on air-dried plaster in equilibrium with laboratory ambient air humidity (20-30%).

668

669

670

671

672

673

674 **Table 3** – Physical properties of mixtures of oven-dried and compacted mixtures of quartz sand and plaster:
 675 tensile strength, vertical height of opening-mode fractures measured in extension tests, and Griffith cohesion C_G
 676 derived from the former two parameters (bent lower part of failure envelope); * marks non-dried plaster in
 677 equilibrium with ambient air humidity.

Sand:Plaster ratio (wt%)	T₀ (Pa)	H (cm)
100:0	5±1	0.1±0.5
95:5	2±1	0.4±0.8
90:10	5±1	4.9±0.4
80:20	13±3	5.0±0.4
65:35	39±7	6.4±0.7
50:50	96±13	6.6±0.7
30:70	121±8	7.5±1.3
0:100	166±24	10.3±1.1
0:100*	200±18	11.5±0.6

678

679 **5. Failure criterion analysis: Cohesion and friction coefficients**

680 **5.1 Theoretical background**

681 While Coulomb proposed a linear failure criterion, the stresses at failure (peak strength) for
 682 most natural rocks of the upper part of the crust correspond to a non-linear failure envelope in
 683 shear stress - normal stress space (Byerlee, 1978; Jaeger et al., 2007 and references therein),
 684 especially at the lower normal loads governing laboratory experiments (Mourgues and
 685 Cobbold, 2003). We determined the optimal fit of failure envelope to sand-plaster mixtures,
 686 by applying a linear Coulomb failure criterion and a non-linear Griffith failure criterion to the
 687 combined results from tensile tests and direct shear tests.

688 The Coulomb failure criterion describes a linear relationship between the shear stress τ on the
 689 failure plane and the effective normal stress σ_n acting on that plane:

$$690 (7) \tau = \mu_C \sigma_n + C_C,$$

691 where μ_C is the Coulomb coefficient of internal friction or the slope of the line and C_C the
 692 Coulomb cohesion ('apparent' cohesion in Abdelmalak et al., 2016) derived from the
 693 intercept of the failure envelope with the $y(\tau)$ -axis in a Mohr space diagram (Figure 1C). Such
 694 a linear relationship is commonly used to describe shear failure at relatively high normal
 695 stresses (i.e. high confining pressures, and thus greater depth) acting on rocks in the upper
 696 crust (Byerlee, 1978).

697 At low and negative (tensile) normal stresses (i.e. low confining pressure, and thus depth or
 698 with high fluid pressures), a non-linear failure envelope has been invoked to account for

699 tensile and hybrid tensile/shear failure. One commonly used non-linear envelope is the
700 parabolic Griffith criterion (Jaeger et al., 2007; Labuz et al., 2018):

701 (8) $\tau^2 = aT_0 (\sigma_n + T_0)$,

702 Where a is a material-dependent constant and T_0 is the tensile strength determined by the
703 $x(\sigma_n)$ -axis intercept of the failure envelope in a shear - normal stress diagram (Figure 1C).
704 Where the criterion intercepts the $y(\tau)$ -axis of the failure envelope, it defines the Griffith
705 cohesion C_G of the material:

706 (9) $C_G = T_0 \sqrt{\frac{a}{T_0} + 1}$.

707 For some uncompacted cohesive powders used in laboratory experiments, $a \approx 2$ has been
708 found (Mourgues and Cobbold, 2003) but compacted silica powder shows $a \approx 3$ (Galland et
709 al., 2006), while for lactose and corn starch powders $a \approx 4$ (Schweiger and Zimmermann,
710 1998). Abdelmalak et al. (2016) provide a more general treatment of the origin of these
711 values.

712 Fitting of Coulomb and Griffith failure criteria to the shear strength and/or tensile strength
713 data was applied by using an adaptation of the ‘RST evaluation’ Python script (Rudolf and
714 Warsitzka, 2019). The Coulomb cohesion C_C and the Coulomb friction coefficient μ_c were
715 obtained by a 100-fold linear least-squares regression of the data plus noise to find the
716 optimal fit of the linear Coulomb failure criterion in equation (7). The Griffith cohesion C_G
717 was obtained by a 100-fold non-linear least-squares regression of the data plus noise to find
718 the optimal fit of parameters a and T_0 in equation (8).

719 In general, we used both direct shear test data and tensile test data to constrain optimal
720 Coulomb and Griffith criteria for each of the oven-dried and compacted end-member
721 materials and their mixtures, and for non-dried poured+compacted plaster (Figure 8). We then
722 choose the best-fitting of these criteria to derive either a Coulomb cohesion (C_C) or a Griffith
723 cohesion (C_G) value for each material. Since the slope of the Griffith criterion is non-unique,
724 we used by default the optimal Coulomb criterion to derive a friction coefficient (μ_C) for each
725 material.

726 We used only the peak strength data from the ring shear test results (poured, sieved, oven-
727 dried and poured+compacted) to constrain an optimal Coulomb criterion as that is a standard
728 approach in such tests (Klinkmüller et al., 2015; Montanari et al., 2017; Panien et al., 2006;
729 Schulze, 1994). For comparison to the ring shear test results, we used only the shear strength
730 data from the direct shear tests to constrain a Coulomb criterion for each material. This also
731 enabled us to evaluate the added value of tensile test results in the failure criterion fitting.

732 Finally, we combined average tensile strength from tensile tests with the vertical height of
 733 opening-mode fractures measured in extension tests to estimate the Griffith cohesion C_G of
 734 the materials. This approach follows the method proposed by Abdelmalak et al. (2016) and
 735 uses the approximation:

736 (10) $C_G = T_0 \sqrt{\frac{H \rho g}{T_0} + 1}$.

737

738 **5.2 Failure criterion fitting results**

739 A selection of the derived Coulomb (C_C) and Griffith (C_G) cohesions (Table 4) and friction
 740 coefficients (μ_C) (Table 5) is displayed in Figure 10. For sand and sand-plaster mixtures with
 741 plaster contents < 35 wt%, C_C values from combinations of tensile strength data and direct
 742 shear data (Figure 10A, green circles) yield the optimal fits (i.e. standard deviations are
 743 smaller with respect to the cohesion values, see Table 4). C_G values obtained from tensile and
 744 extension test data (Figure 10A, red squares), which are constrained only from data in the
 745 tensile field, lie within the double standard deviations of C_C values, and increase from < 10 Pa
 746 to ~105 Pa (Table 4).

747

748 **Table 4** – Cohesions of oven-dried and poured+compacted sand, plaster and sand-plaster
 749 mixtures obtained from optimal fitting of linear Coulomb (C_C , μ_C) and non-linear Griffith
 750 (C_G) failure criteria to various combinations of tensile strength, direct shear and ring shear test
 751 results, and tensile strengths T_0 and heights H of opening-mode fractures; * marks air-dried
 752 plaster.

Sand: Plaster ratio (wt%)	C_c direct shear + T_0 (Pa)	C_c direct shear (Pa)	C_c ring shear compact (Pa)	C_c ring shear poured (Pa)	C_c ring shear sieved (Pa)	C_G direct shear + T_0 (Pa)	C_G ($T_0 + H$) (Pa)
100:0	4±21	13±69	214±27	252±163	195±44	33±3	9.8±0.1
95:5	12±24	61±63	166±24	-	-	36±3	12.8±0.1
90:10	16±29	77±80	168±26	359±204	15±55	58±4	66.2±0.1
80:20	18±28	67±76	269±27	297±137	174±160	99±3	104.8±0.1
65:35	59±38	240±84	400±55	-	-	154±7	195.2±0.1
50:50	105±30	275±51	452±21	474±110	391±204	222±9	297.9±0.1
30:70	106±27	256±25	240±21	-	-	233±7	340.5±0.1
0:100	127±26	248±49	233±21	-	-	250±21	425.2±0.1
0:100*	157±22	192±68	-	672±105	615±85	282±24	494.9±0.1

753

754 For sand-plaster mixtures with plaster contents ≥ 35 wt%, C_C values systematically
 755 overestimate the lower part of the failure envelope, whereas C_G provides optimal fit (Figure
 756 10, orange circles). For direct shear test data alone in comparison, C_C provides larger standard

757 deviations and thus poorer fits (see Table 4). C_G values obtained from tensile strength and
758 direct shear data (Figure 10, orange circles) first continue increasing, albeit at a lower rate >
759 50 wt% plaster, until the maximum of ~280 Pa for pure plaster. C_G values obtained from
760 tensile and extension tests increase roughly linearly ($R^2 = 0.965$) with increasing wt% plaster
761 content until a maximum of ~500 Pa for non-dried compacted plaster (Table 4, Figure 10A).
762 Overall, the C_C values derived from ring shear data (Figure 10, green diamonds) are strongly
763 dependent on the higher normal stress data (5000 Pa) and their standard deviations are
764 systematically higher compared to those obtained from all other methods (Table 4). Their C_C
765 values are highest of all obtained values for mixtures with plaster content ≤ 50 wt%, but
766 abruptly decrease to values similar to C_G values derives from failure envelopes that combine
767 tensile and direct shear test data. C_C values derived from direct shear data alone do not show
768 obvious trends, but they systematically have higher standard deviations compared to those
769 obtained from failure envelopes that combine tensile and direct shear test data and are
770 therefore not displayed on Figure 10A. Air-dried plaster yielded a C_G value that is ~50 Pa
771 higher compared to oven-dried plaster, and displays relatively higher standard deviations
772 (Table 4, Figure 10A, blue-and-red circle).

773 Friction coefficient values can only be derived using a linear Coulomb criterion (Figure 10B,
774 Table 5). μ_C values derived from tensile strengths and direct shear data (Figure 10B, green
775 circles) increase with increasing plaster content up to ≤ 20 wt%. For mixtures with a plaster
776 content ≥ 35 wt%, μ_C values decrease again to about half of the value for plaster obtained
777 from ring shear data.

778 μ_C values obtained from ring shear data (Figure 10B, green diamonds) have much lower
779 standard deviations compared to those from combined tensile strengths and direct shear data
780 (Figure 10B, green circles), but produce no discernable trend. Values varie between 0.71 and
781 0.81, with an outlying minimum of 0.63 for non-dried plaster (Table 5).

782 μ_C values of non-dried plaster obtained either from direct shear data alone, or in combination
783 with tensile test data, agree very well (Table 5, Figure 10B, blue-and-red circle). These values
784 are slightly higher than those obtained for oven-dried plaster as constrained from tensile
785 strength and direct shear test data (Figure 10B, green circles), and they are lower than those
786 for oven-dried plaster as constrained from ring shear test data (Figure 10B, diamonds).

787

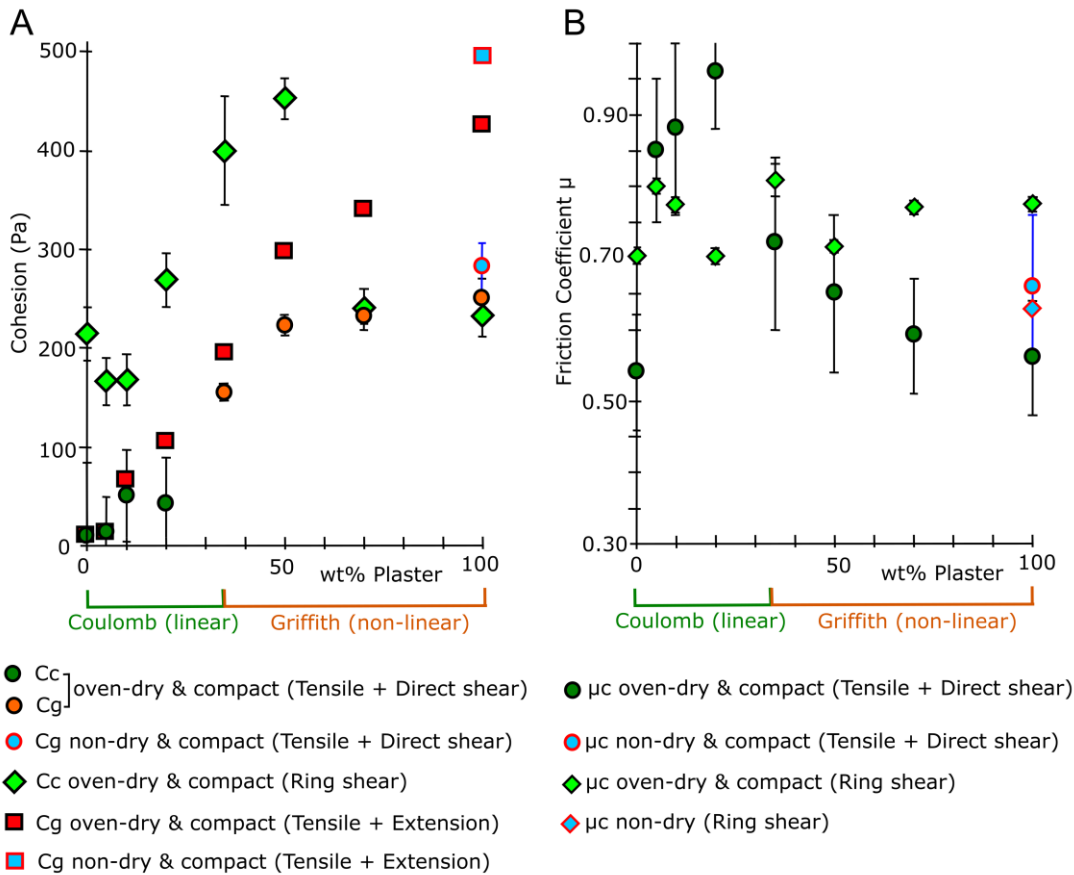
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789

790 **Table 5** – Friction coefficients of oven-dried and compacted mixtures of quartz sand and plaster obtained from
 791 optimal fitting of linear Coulomb (μ_c) failure criteria to failure envelopes of various combinations of tensile
 792 strength, direct shear and ring shear test results; * marks non-dried plaster in equilibrium with ambient air
 793 humidity.

Sand:Plaster ratio (wt%)	μ_c direct shear + T_0	μ_c direct shear	μ_c RST compact	μ_c RST poured	μ_c RST sieved
100:0	0.54±0.08	0.48±0.08	0.70±0.01	0.64±0.02	0.67±0.01
95:5	0.85±0.10	0.61±0.08	0.80±0.01	-	-
90:10	0.88±0.12	0.85±0.13	0.77±0.01	0.78±0.02	0.82±0.01
80:20	0.96±0.08	0.85±0.09	0.70±0.01	0.80±0.01	0.76±0.01
65:35	0.72±0.12	0.55±0.11	0.81±0.02	-	-
50:50	0.65±0.11	0.48±0.08	0.72±0.01	0.88±0.01	0.85±0.02
30:70	0.59±0.08	0.41±0.03	0.77±0.01	-	-
0:100	0.56±0.08	0.43±0.08	0.76±0.01	-	-
0:100*	0.66±0.10	0.63±0.06	0.63±0.06	0.80±0.01	0.83±0.01

794



795 **Figure 10** – Regression results based on failure envelope reconstructions in shear-normal stress space using a
 796 linear Coulomb failure criterion versus a non-linear Griffith one. **A.** Cohesion of compacted sand, plaster and
 797 sand-plaster mixtures. Best-fit C_C (< 35 wt% plaster) or C_G (> 20 wt% plaster) values are displayed for the
 798 combination of tensile and direct shear tests. Ring shear results are peak shear strengths. See Table 4. **B.** Friction
 799 coefficient values μ_c of compacted sand, plaster and sand-plaster mixtures for the combination of tensile and
 800 direct shear test data or ring shear test data. See Table 5.

801 **6. Discussion**

802 **6.1 Impact of material handling and humidity on material properties**

803 It is well established that the mechanical properties of quartz sand differ significantly when
804 emplaced into a sand-box by sieving or pouring. Sieving produces a sand pack with higher
805 density, higher internal friction coefficient and a more brittle stress-strain behaviour – i.e. a
806 sharper stress peak and a larger post-peak stress drop (Lohrmann et al., 2003; Panien et al.,
807 2006). For pure quartz sand, our tests reproduce such observations (Figures 4 and 6, Table 2).
808 This difference in behaviour between sieved and poured sand can be attributed to slower
809 sedimentation rates during sieving, which allows grains to saltate, creep and resettle in to a
810 tighter grain packing. Density of pure sand can be further elevated by compaction – either
811 through pressing (ring shear tests) or vibration (tapping). Our data indicate that compaction
812 does not give a discernable effect on cohesion (Table 4), but that it slightly increases the
813 friction coefficient of pure sand (Table 5).

814 For pure plaster, our tests document the opposite behaviour: sieved plaster is less dense,
815 poured plaster more dense (Figure 4B, Table 2). For a sand-plaster mixture with a plaster
816 content of 50 wt%, there is no significant difference in the density when sieved or poured. We
817 propose that friction with air during sieving might result in increased electro-static forces that
818 increase porosity between settled plaster grains (van Gent et al., 2010). On the other hand,
819 pouring plaster may reduce electrostatic forces and, if done at once, may make plaster-rich
820 packs more susceptible to compaction during emplacement. In terms of mechanical
821 properties, our data show that sieved plaster compacts more at low normal loads compared to
822 poured plaster (Figure 6). Sieving or pouring of pure, air-dried plaster did produce a
823 discernable difference in cohesion (Table 4), and sieving may slightly increase the friction
824 coefficient (Table 5). Compaction and drying in combination have a strong effect on the
825 mechanical behaviour of pure plaster, however. In addition to higher bulk density and
826 smoother stress-displacement curves, a more brittle behaviour is seen at low normal loads
827 compared to poured or sieved plaster (Figures 6 and 7), and cohesions and friction
828 coefficients are lower regardless of shear testing approach and failure envelope reconstruction
829 (Tables 4 and 5). This may be because compaction flattens more tabular gypsum crystals
830 toward alignment with the shear plane, thus making grain-grain sliding easier, and/or because
831 reduced moisture content reduces the electrostatic attractions between plaster grains.

832 For sand-plaster mixtures, and in addition to density differences, sieving results in layered,
833 non-homogeneous grain size distribution throughout packs (Figure 4A). Thus, sieving devices
834 that are designed to ensure an ideally dense packing of sand (e.g. Maillot 2013) would create

835 heterogeneous layering due to density differences between quartz sand and gypsum particles.
836 Similarly, Krantz (1991) showed that such density differences induced by the emplacement
837 technique affect the shear strength of mixtures of quartz sand and cement more than the grain
838 density differences between the sand and cement. Pouring is also not ideal as it creates
839 variations in grain packing density throughout sand-plaster mixtures. We surmise that these
840 effects of pouring or sieving could be seen in our data to some extent. Poured samples, as well
841 as sieved samples with high plaster content, generally show noisier stress-displacement curves
842 (Figure 6), although no clear trends or differences were seen in cohesion and friction values
843 (Tables 4 and 5). Compaction and oven-drying had a strong effect on pure plaster. Smoother
844 stress-displacement curves, a more brittle behaviour (stress drop) at low normal loads, and
845 lower friction coefficients are consistently seen compared to non-dried and non-compacted
846 equivalents (Table 4).

847 The problem of ambient humidity in granular analogues has received little attention, although
848 in quartz sand, moisture is known to increase the bulk strength (van Mechelen, 2004). Sand-
849 plaster mixtures in past studies have been used in equilibrium with ambient air humidity in
850 laboratories, which can vary strongly from day to day influenced by the weather. Our data
851 demonstrate that a sand-plaster mixture's humidity increases with increasing plaster content
852 (Figure 5). The moisture uptake by gypsum powder from ambient humidity was previously
853 measured to be ~2-2.5 wt% over 2.5 days under a constant air humidity of 75.2% (Lide,
854 1995). Undried plaster used here contains on average 1 wt% of water (Figure 5). Our data
855 further show that comparative test results of direct shear, tensile strength, and extension
856 fracturing of pure air-dried plaster are statistically distinct from those of oven-dried plaster
857 (Figures 8, 9 and 10). The strength of non-dried plaster is thus significantly affected by
858 humidity. Importantly, the measurement uncertainties of the mechanical properties of non-
859 dried plaster are higher as well. Our results establish that oven-drying sand-plaster mixtures to
860 remove excess humidity prior to emplacement in a modelling apparatus should be pursued to
861 increase reproducibility of the physical properties of the mixtures.

862 Except for Poppe et al. (2019), published experimental laboratory studies do not mention
863 oven-drying sand-plaster mixtures prior to experimentation. Poppe et al. (2015) invoked
864 variations in humidity of the sand-plaster mixtures from day to day to explain the occurrence
865 of overburden stability in some experiments and overburden collapse in other experiments. In
866 other experimental studies of geological deformation, the dip of fault planes formed in non-
867 dried, poured sand-plaster piles has been systematically measured (Holohan et al., 2013;
868 Rincón et al., 2018; Roche et al., 2001). That dip, however, depends on the angle of internal

869 friction, which our results demonstrate in turn depends on material humidity and compaction.
870 Furthermore, asymmetric development of model deformation in laboratory models of
871 volcanic processes where cones have been traditionally poured has been attributed to set-up
872 geometry asymmetry (e.g. Byrne et al., 2013; Delcamp et al., 2008; Kervyn et al., 2009;
873 Merle and Borgia, 1996; Rincón et al., 2018; Van Wyk De Vries and Merle, 1998). Our
874 results show that humidity and bulk density – i.e. porosity – variations may cause spatial and
875 temporal heterogeneities in the mechanical properties of sand-plaster mixtures that are
876 unaccounted for.

877 Based on our results, we recommend oven-drying and compacting sand-plaster mixtures prior
878 to their deformation in scaled laboratory models. Sand-plaster mixture ratios should be
879 calculated by weight% (this study; Poppe et al., 2019) rather than by volume% (e.g. Delcamp
880 et al., 2008; Poppe et al., 2015; Rincón et al., 2018; Roche et al., 2000; Zorn et al., 2020).
881 Immediately after drying, mixtures should be cooled in a sealed container to prevent
882 reabsorption of air moisture. During model set-up, a known mass of the mixture should be
883 instantaneously poured into the sand-box and mechanically compacted down to a pre-
884 determined bulk volume and thus a well constrained bulk density. That compaction can be
885 achieved by manual tapping as in our direct shear, tensile and extension tests, by pre-loading
886 and pressing the samples as in our ring shear tests, or by mechanical vibration (Galland et al.,
887 2009; Poppe et al., 2019). Such a more consistent approach to material handling should help
888 to better constrain bulk densities and porosities, to ensure homogeneous grain size and
889 mineralogy distribution, to provide better control on mechanical properties, and promote
890 greater confidence in the reproducibility of experimental outcomes involving sand-plaster
891 mixtures.

892

893 **6.2 The silo effect in direct shear tests : empirical versus theoretical correction**

894 In a silo, side-wall friction counteracts gravity forces; this ‘silo effect’ or ‘Jansen effect’
895 reduces the actual normal load acting on the shear plane in a direct shear test (Jansen, 1895).
896 Most often, the linear Coulomb failure criterion is assumed to adequately fit failure envelopes
897 of quartz sand that are reconstructed from direct shear tests, and quantify the sand’s cohesion
898 and friction coefficient (e.g. Galland et al., 2006; Krantz, 1991; Lohrmann et al., 2003;
899 Montanari et al., 2017; Schellart, 2000). When corrected theoretically for the silo effect, the
900 failure envelopes gain a steeper slope and their intercept with the vertical axis decreases in
901 absolute value (Mourgues and Cobbold, 2003). Mourgues and Cobbold (2003) set a
902 theoretical threshold of sample height to cylinder diameter ratio of 0.5 to avoid the silo effect.

903 That ratio is nevertheless as high as 1 in other studies (Abdelmalak et al., 2016; Schellart,
904 2000). If unaccounted for, the silo effect results in underestimated internal friction
905 coefficients and overestimated cohesions.

906 We have found empirically that side-wall friction progressively reduces the normal load at the
907 failure plane in direct shear tests, even at low normal loads below that theoretical threshold
908 value of 0.5 (see Supplementary Materials). Furthermore, we found that the silo effect
909 increases with increasing plaster content, up to about 50 wt% plaster and then it decreases
910 slightly, although it remain higher for pure plaster than for pure sand. Our empirical
911 correction method yielded reduced effective normal loads, and thus produced failure
912 envelopes with steeper slopes and with lower vertical axis intercepts in shear-normal stress
913 space. As a result, the cohesion values of granular materials in past studies that ignore the silo
914 effect are most likely overestimations (e.g. Abdelmalak et al., 2016; Lohrmann et al., 2003;
915 Schellart, 2000). Similarly, friction coefficients estimated previously from direct shear tests
916 without silo effect correction are likely underestimates. This empirical correction can be used
917 when establishing new granular analogue materials, or retrospectively to correct published
918 direct shear test results.

919

920 **6.3 Effects of plaster content on mechanical properties**

921 Our data show that for several measured physical or mechanical properties, such as bulk
922 density, porosity, tensile strength, derived cohesions and friction coefficients, as well as the
923 brittle or ductile behaviour of the material, are sensitive to the plaster content in a mixture
924 regardless of handling procedure. In addition, trends in these properties differ for sand-rich
925 mixtures (i.e. ≤ 20 wt% plaster content), compared to plaster-rich mixtures (i.e. ≥ 35 wt%
926 plaster contents).

927 With increasing plaster content, there is an overall decrease in bulk density of a sand-plaster
928 mixture and a corresponding increase in porosity (Figure 4B & C). Moreover, there is a
929 notable increase in the rate of change of density or porosity with increased plaster content at
930 20 wt% plaster content and higher. The bulk density of plaster is approximately half that of
931 quartz sand, for the same handling and humidity (Figure 4B). Conversely, the inferred
932 porosity of quartz sand is 35-55 vol% and that of plaster is 65-78 vol% (Figure 4C).
933 Previously, van Gent et al. (2010) found a similar porosity of ~ 75 vol% for gypsum powder.
934 SEM images and grain size distribution measurements showed that smaller gypsum crystals
935 (mean diameter of 2-10 μm) aggregate into clusters (Figure 2), which are too large to fill the
936 pore space in between the larger sand grains (mean diameter of 180-250 μm). Therefore,

937 although gypsum crystals have slightly greater density than quartz crystals (2730 kg.m^{-3} vs.
938 2655 kg.m^{-3}), the bulk density of a sand-plaster mixture decreases as the plaster content
939 increases because of the high micro-scale porosity of the gypsum aggregates (Figure 4B).

940 An increase in plaster content also generally leads to a more ductile behaviour of a sand-
941 plaster mixture (Figures 6 & 7). The stress drop seen for sand-rich mixtures diminishes and
942 ultimately disappears, especially at high normal stresses ($<1000 \text{ Pa}$). An exception is when
943 the mixture is oven-dried and pre-compacted; then a small stress drop persists in plaster-rich
944 materials at low normal stresses ($<1000 \text{ Pa}$). Irrespective of handling technique, the stress
945 drop diminishes from about 20-35 wt% plaster content and upward. This general shift to a
946 more ductile behaviour in stress-displacement curves as plaster content increases corresponds
947 to a change in dilation behaviour. Sand-rich mixtures ($<35 \text{ wt\% plaster}$) compact prior to
948 sample failure then de-compact, as previously observed for pure sand (Panien et al., 2006;
949 Ritter et al., 2016). Plaster-rich samples ($>35 \text{ wt\% plaster}$) undergo compaction throughout
950 shearing. Numerical simulations of deformation of granular materials produce a similar
951 transition to more ductile and compaction-dominated behaviour with increased porosity (cfr.
952 Figure 4 in Schöpfer et al., 2009). Therefore, we tentatively attribute the change to a more
953 ductile behaviour with increased plaster content to increased bulk porosity. This change may
954 occur with more distributed strain localisation in the more porous plaster-rich mixtures,
955 especially at high normal stresses, as the progressive collapse of pore-spaces in the gypsum
956 crystal aggregates inhibits the formation of well-defined shear zones.

957 Sand-plaster mixtures therefore have the capacity, like real rocks, to display a brittle-ductile
958 transition with depth. Considering the normal stress as equivalent to confining pressure of an
959 overburden and assuming the compacted bulk densities in Table 2, that transitional depth
960 would amount to 30 cm height (i.e. at $\sim 5000 \text{ Pa}$) in mixtures with 20 wt% plaster. This depth
961 would be shallower with increased plaster content, and it would lie at $\sim 16 \text{ cm}$ ($\sim 2000 \text{ Pa}$) with
962 50 wt% plaster and at 11 cm ($\sim 1000 \text{ Pa}$) in pure plaster. This brittle to ductile transition
963 primarily represents a change in strain-weakening or strain-strengthening behaviour, and does
964 not necessarily imply a major change in strain localisation (i.e. shear zone vs. distributed
965 flow) with depth within a material.

966 Associations between increased plaster content and a sand-plaster mixture's strength, in terms
967 of cohesion and friction coefficient, are complex and in part dependent on measurement
968 technique. In general, cohesion increases with increasing plaster content, up to about 50 wt %
969 plaster (Figure 10A, Table 4). Coulomb cohesions thereafter decrease or stabilize, whereas
970 Griffith cohesions continue to increase with increased plaster content. Friction coefficient

971 either shows no clear trend with increasing plaster content (ring shear test data) or shows an
972 initial slight increase at 0-20 wt% plaster followed by overall decrease at 20-100 wt% plaster
973 (Figure 10B, Table 5). Uniaxial compressive strength of quartz crystals at room temperature
974 and pressure is around 190-300 MPa (and references therein Scholz, 1972), whereas ultimate
975 shear strength of gypsum crystals is around 0.6 – 18 MPa (Williams, 1988). Such crystal
976 strengths far exceed the differential stresses applied in our material tests. The friction
977 coefficient of granular materials in a regime of no grain fracture is known to increase with
978 increased grain surface roughness (angularity) and particle size distribution (Mair et al.,
979 2002), however, and it is known to decrease with increased porosity (Schöpfer et al., 2009).
980 Moreover, stick-slip behaviour in deformed granular materials is associated with smoother
981 grain surfaces (Mair et al., 2002; Rosenau et al., 2009). Therefore, we interpret that cohesions
982 and friction coefficients at plaster contents of up to 20-50 wt % initially increase because of
983 increased particle size distribution on mixing relatively coarse quartz sand with relatively fine
984 gypsum powder (Figure 2). Increased inter-crystal attraction forces in gypsum may also play a
985 role in that initial strength increase (see below). Cohesion and friction coefficient
986 subsequently decrease or stabilize at plaster contents of up to 50-100 wt % because of
987 increased porosity (Figure 4) and possibly also the capability of gypsum grains to align and to
988 slip past each other along their relatively smooth crystal faces. The latter factor can also
989 account for the short-frequency noise and stick-slip events observed in plaster-rich mixtures
990 (Figure 6 & 7).

991 Increasing plaster content of sand-plaster mixtures is clearly associated with increased tensile
992 strength. This has been known qualitatively from the occurrence of opening mode fractures in
993 such mixtures compared to the absence of such fractures in pure quartz sand, and has formed
994 a main reason for use of plaster veneers or sand-plaster mixtures previously (e.g. Byrne et al.,
995 2013; Holohan et al., 2008; Poppe et al., 2015; Roche et al., 2001; Shea and van Wyk de
996 Vries, 2008; van Gent et al., 2010). Here, we quantify the tensile strength increase, and we
997 show again that its rate increases sharply at ≥ 20 wt% plaster content (Figure 9A). The high
998 tensile strength of plaster relative to quartz sand, and the corresponding increase in tensile
999 strength with increased plaster content in mixtures, are potentially related to the increased
1000 effectiveness of electrostatic attraction forces that bond gypsum crystals. Tensile strength has
1001 been shown to decrease slightly with porosity in numerical simulations of the deformation of
1002 granular material, but to increase greatly with increased proportion of bonded contacts
1003 between particles (Schöpfer et al., 2009). Atomic Force Microscopy experiments show that
1004 gypsum crystal faces are attracted to each other by van der Waal's forces and electrostatic

1005 forces, which are supplemented by capillary forces at high relative humidity (Finot et al.,
1006 2001). In general, therefore, an increase in such attraction forces with increased plaster
1007 content in sand-plaster mixtures can account for the increased tensile strength of such
1008 mixtures. The increase in inter-crystal force attraction with increased humidity also explains
1009 the still greater tensile strength of pure undried plaster. Overall, these data confirm that using
1010 plaster as a filler in sand is a valid strategy to increase and control such a mixture's tensile
1011 strength.

1012

1013 **6.4 Empirically reconstructed failure envelopes and theoretical failure criteria**

1014 Ring shear tests and direct shear tests on oven-dried and pre-compacted samples give slightly
1015 different failure envelopes in the compressive stress field and consequently give different
1016 values of cohesion and friction coefficient (Tables 4 & 5, Figure 10). While ring shear tests
1017 reportedly yield accurate estimates of friction coefficients of sands with low standard
1018 deviations, the method has yielded unrealistically high cohesions with large standard errors
1019 from linear Coulomb extrapolations (Klinkmüller et al., 2015; Montanari et al., 2017; Panien
1020 et al., 2006; Ritter et al., 2016). Furthermore, ring shear tests are difficult to operate at small
1021 normal loads (<500 Pa), whereas direct shear tests are better suited to constrain this lower
1022 part. Ritter et al. (2016) inferred that in ring shear tests the through-going shear zone likely
1023 develops via the linkage of several shear zones, each initiated at one of the intruding lid
1024 blades. In contrast, a through-going shear zone likely develops more readily as a single shear
1025 failure plane in direct shear tests. This contrast in test methodology may at least partially
1026 explain the mismatch between failure envelopes derived from ring shear test results and direct
1027 shear test results (Figure 8), and consequently the values of cohesions and friction coefficients
1028 derived from the linear Coulomb criterion (Figure 10).

1029 Cohesion values obtained for oven-dried and pre-compacted sand-plaster mixtures by
1030 extrapolation of shear strength only (C_C) shows different trends to those obtained by
1031 extrapolation of tensile strength and extensional test data only (C_G) (Table 4). Cohesions from
1032 direct shear test or ring shear tests, despite differences in absolute values, show a similar
1033 initial increase at low plaster contents followed by a decrease or levelling off at high plaster
1034 contents (Figure 10). In comparison, cohesions obtained from combining tensile strength data
1035 with extension tests yield a more monotonic linear increase of cohesion from near-zero for
1036 sand to >400 Pa for plaster. The latter method is based on a non-linear Griffith criterion that
1037 ignores data in the compressive field (Abdelmalak et al., 2016), however, and the resultant

1038 monotonic increase in cohesion that it yields is highly dependent on the measured value of
1039 tensile strength (Equation 10), which itself increases linearly with plaster content (Figure 9).
1040 In general, we therefore regard the cohesion and friction values constrained by interpolation
1041 between data in both tensile and compressive fields to be more reliable than those constrained
1042 by extrapolation from data in one field only. We find that linear Coulomb failure criteria more
1043 optimally fit the combined tensile strength and direct shear data of sand-rich mixtures (<35
1044 wt% plaster), whereas non-linear Griffith failure criteria better fit the combined tensile and
1045 shear data of sand-plaster mixtures with ≥ 35 wt% plaster content. The addition of tensile
1046 strength data in criterion fitting considerably helps to constrain the lower – negative – part of
1047 the failure criteria (Table 4, Table 5). The resulting ‘preferred’ cohesion values (Figure 10A)
1048 increase from near-zero for pure quartz sand to 200-250 Pa for sand-plaster mixtures with \geq
1049 50 wt% plaster. Similarly the ‘preferred’ friction coefficient values derived from Coulomb
1050 criteria fitted to data in both tensile and compressive fields (Figure 10B) increase from ~ 0.54
1051 for pure quartz sand to ~ 0.96 for mixtures with 20 wt% plaster and then decrease to ~ 0.56 for
1052 pure plaster. The more optimal fit of a non-linear Griffith failure criterion to sand-plaster
1053 mixtures with a plaster content ≥ 35 wt%, shows that, in detail, the internal friction coefficient
1054 of such mixtures is not constant throughout a sandbox model, but rather varies with depth – as
1055 is the case for rock masses in nature. The fit of other non-linear failure criteria, such as that of
1056 Hoek-Brown (Jaeger et al., 2007; Labuz et al., 2018) for such mixtures could be explored in
1057 the future.

1058

1059 **6.5 Implications for scaling analogue models of crustal deformation**

1060 The combination of mechanical laboratory tests has shown that by systematically controlling
1061 the weight ratio of quartz sand to plaster, analogue granular materials of varying strengths but
1062 also brittle to complex brittle-ductile shear stress behaviour can be obtained. Compared to
1063 pure sand, these properties allow analogue modelers to simulate a greater range of tensile to
1064 shear fracturing, brittle to ductile behaviour, similar to how natural rocks are known to behave
1065 in the shallow crust (e.g. Byerlee, 1978, 1968; Jaeger et al., 2007). Our characterisation now
1066 quantifies values of cohesions and friction coefficients for sand-plaster mixtures (Tables 4 and
1067 5) and shows that they are suitable to simulate natural rock strengths in scaled laboratory
1068 models (Table 1). The comparison of failure criteria fits, however, also exposes the
1069 uncertainties related to applying theoretical models to describe the complex, non-linear
1070 rheology of granular analogue materials. Tensile strengths, in addition, might provide a
1071 complementary or more direct means to scale laboratory experiments where opening-mode

1072 failure is important. This is the case for example in simulations of magma-filled fracture
1073 opening that forms sheet intrusions (Galland et al., 2018; Poppe et al., 2019; Rivalta et al.,
1074 2015), or in some tectonic extension experiments (e.g. Reber et al., 2020; Schreurs et al.,
1075 2006). The newly quantified values of tensile strength, cohesion and friction coefficient of
1076 sand-plaster mixtures now allow to systematically explore the effect of analogue granular
1077 material strength as an experimental parameter.

1078

1079 **7. Summary and conclusions**

1080 Our study confirms that mixtures of quartz sand and gypsum powder – i.e. plaster – possess
1081 brittle to brittle-ductile behaviour that is analogue to that of crustal rocks. Using density
1082 measurements and ring shear tests, we have constrained the effect of the emplacement
1083 technique – i.e. sieving, pouring and pouring+compaction – and humidity on the physical
1084 properties of a range of sand-plaster mixtures. Ring shear tests allowed a detailed
1085 characterisation of the stress-displacement behaviour. We used complementary direct shear
1086 tests, tensile tests and extensional tests to constrain the shear and tensile strengths of density-
1087 controlled, oven-dried samples of sand, plaster and sand-plaster mixtures.

1088 When emplacing an experimental volume of sand-plaster granular material, we found that:

- 1089 - Sieved sand is denser and less porous compared to poured sand; sieved plaster is
1090 conversely less dense and more porous compared to poured plaster; the effects for
1091 sand-plaster mixtures lie in between their two end-members.
- 1092 - Sieving sand-plaster mixtures introduces compositional and bulk density heterogeneity
1093 in the form of layering. Pouring sand-plaster mixtures leads to under-compaction and
1094 very high porosity and possibly to lateral variations in these. Pouring followed by
1095 mechanical compaction produces more controlled and laterally consistent density
1096 while minimizing mineralogical heterogeneity.
- 1097 - Plaster contains at least 1 wt% moisture.
- 1098 - Humidity increases the strength of plaster and increases the uncertainty in the
1099 measured mechanical properties.

1100 To obtain reproducible composition and mechanical properties, we recommend that sand-
1101 plaster mixtures should be oven-dried for at least 24 hours to remove ambient humidity and
1102 be poured and compacted mechanically to a controlled bulk density.

1103 The stress-displacement behaviour of sand-rich sand-plaster mixtures (≤ 20 wt% plaster) is
1104 dominantly brittle, while plaster-rich sand-plaster mixtures (≥ 35 wt% plaster) exhibit more
1105 complex, brittle-ductile behaviour. The documented brittle-ductile transition is thus

1106 constrained by the plaster content and the applied normal stress. We infer that this transition is
1107 ultimately controlled by a porosity increase with increasing plaster content.

1108 For oven-dried, poured and compacted sand-plaster mixtures, a linear Coulomb failure
1109 criterion fits most optimally to failure envelopes for ≤ 20 wt% plaster as constrained by both
1110 tensile strength and direct shear test data. A non-linear Griffith failure criterion most
1111 optimally fits the failure envelopes for sand-plaster mixtures with ≥ 35 wt% plaster. Our
1112 comparison of empirical mechanical testing methods suggests that the best-fit cohesions most
1113 likely range from ~ 0 Pa for quartz sand to ~ 250 Pa for pure plaster, while friction coefficients
1114 estimated from a linear Coulomb criterion range from 0.50 to 0.94, respectively. The more
1115 optimal fit to a non-linear failure criterion suggests that in detail friction coefficients likely
1116 vary with depth within a sand-plaster mixture with ≥ 35 wt% plaster. The relationship of
1117 cohesion and friction coefficient to plaster content is non-linear, and likely reflects a complex
1118 interplay of factors controlling material strength, such as porosity, grain shape, grain
1119 smoothness, particle size distribution and attraction forces between gypsum crystals.

1120 We found that absolute tensile strength of a sand-plaster mixture increases near-linearly with
1121 increased plaster content from near-zero for pure quartz sand to 166 ± 24 Pa for pure plaster.
1122 This value also increased with increased humidity. The tensile strength of sand-plaster
1123 mixtures likely derives from attractive forces (van der Waal's, electrostatic and capillary)
1124 acting between gypsum crystals.

1125 Overall, this detailed characterisation effort quantifies the range of tensile, shear-failure,
1126 brittle to ductile behaviour of natural rocks in the Earth's upper crust that can be simulated by
1127 analogue sand-plaster mixtures in scaled laboratory experiments. Using the best-practice
1128 recommendations for mechanical testing of granular sand-filler materials, material handling
1129 and emplacement, and the characterised mechanical properties, will provide a more robust
1130 basis for using sand-plaster mixtures in laboratory-scale simulation of natural rock-mass
1131 deformation.

1132

1133 **Author contributions**

1134 SP led all phases of this study, including writing the manuscript as part of his PhD research
1135 defended in 2019 at VUB, Belgium. SP's thesis was co-supervised by MK and EPH. EPH, OG,
1136 MR, MR, AD and MK contributed to the experimental planning, interpretation of the results
1137 and revision of the manuscript. EPH and MRo provided advice and access to the RST
1138 machine at GFZ Potsdam, Germany. MRu collected RST data on compacted sand-plaster
1139 mixtures at GFZ Potsdam and produced figures 6 and 7, SP collected all other data.

1140 **Declaration of interest statement**

1141 The authors declare that no conflict of interest exists with this work.

1142 **Data availability**

1143 The original data collected for this study is available as part of the GFZ open-access data
1144 publication Poppe et al. (2021), <https://doi.org/10.5880/fidgeo.2021.005>, completed with
1145 mechanical test data for garnet sand and kaolin clay powder mixed with quartz sand as used in
1146 Grosse et al. (2020).

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1156

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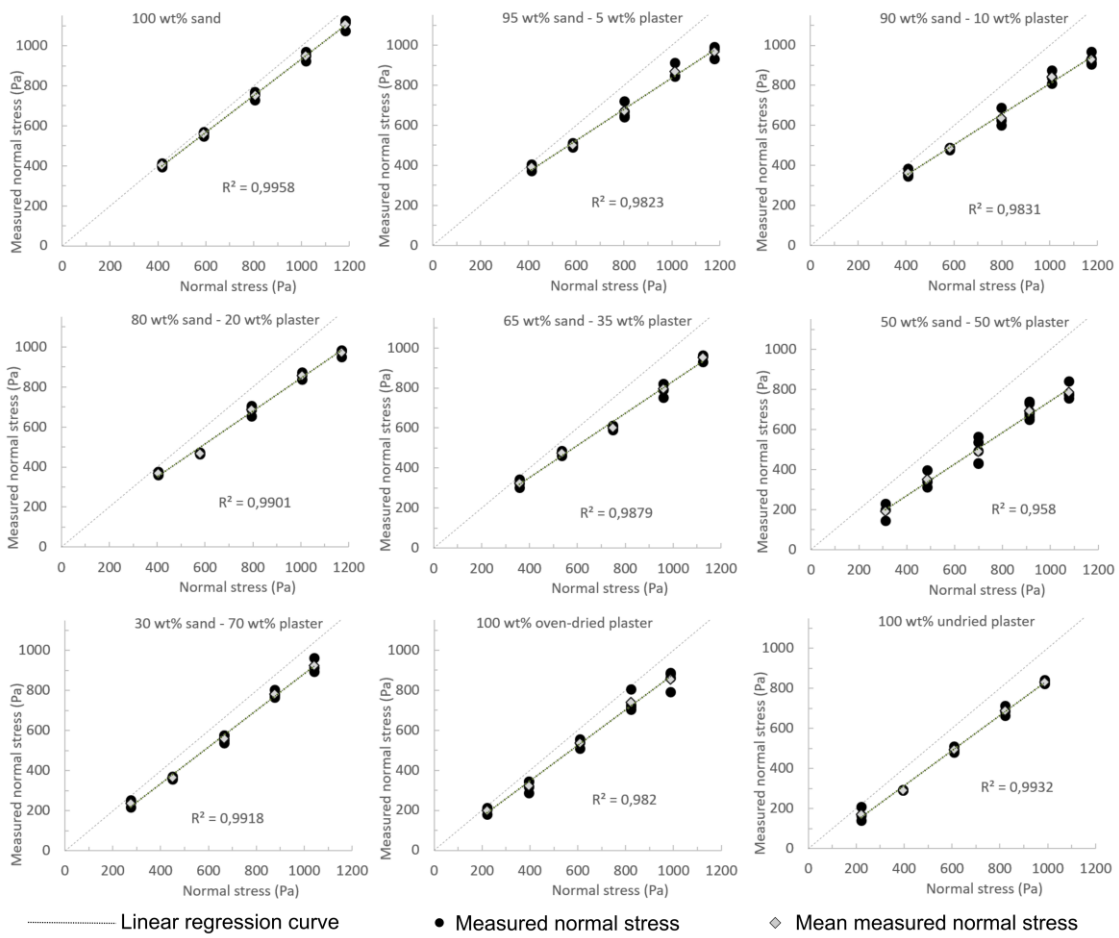
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1461 **SUPPLEMENTARY MATERIAL**

1462 **Normal load correction of direct shear test data**

1463 Part of the normal stress applied on the horizontal shear plane by the sample and additional
1464 loads in the upper cylinder is counteracted by friction between the granular sample and the
1465 plastic of the upper cylinder, also called the ‘silo effect’ or ‘Janssen effect’ (Jansen 1895). The
1466 method of Mourgues and Cobbold (2003) was used to measure the silo effect empirically, and
1467 correct the normal loads used to construct the failure envelopes (Figure 8 in main text). The
1468 upper cylinder was suspended <1 mm above a precision balance, each granular material was
1469 emplaced and compacted in the same manner as for complete direct shear tests to obtain the
1470 same densities (Table 2 in main text). The weight then registered by the balance was the
1471 effective normal load exerted on the failure plane in the direct shear tests. These normal load
1472 measurements were repeated at least three times for each applied normal load (Figure S1). For
1473 all materials, these measurements fell on a linear trend with a slope lower than that of the
1474 zero-friction diagonal line. To ensure reproducibility of the measurements, more runs were
1475 added if necessary to reach a $r^2 > 0.990$ linear regression value of the data in a measured
1476 normal load vs. theoretical normal load (i.e. zero friction between material and cylinder wall)
1477 plot.



1479

1480 **Figure S1** – Measured normal stress versus theoretical (i.e. zero-friction) normal stress (σ_n) plots for sand and
 1481 plaster and their mixtures. The means were used as normal load values in the direct shear test results that
 1482 reconstruct the failure envelopes of Figure 6.

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