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► **To cite this version:**

Philipp Braun, Georgios Tzortzopoulos, Ioannis Stefanou. Design of Sand-Based, 3-D-Printed Analog Faults With Controlled Frictional Properties. *Journal of Geophysical Research: Solid Earth*, 2021, 126 (5), 10.1029/2020JB020520 . hal-04395779

HAL Id: hal-04395779

<https://hal.science/hal-04395779>

Submitted on 15 Jan 2024

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1 **Design of sand-based, 3D-printed analogue faults with**
2 **controlled frictional properties**

3 **P. Braun¹, G. Tzortzopoulos¹, I. Stefanou¹**

4 ¹Institut de Recherche en Génie Civil et Mécanique, Ecole Centrale de Nantes
5 1 Rue de la Noë, Nantes 44321, France

6 **Key Points:**

- 7 • We design and test analogue fault interfaces using 3D-printing with sand parti-
8 cles
9 • We control the evolution of the friction coefficient with slip, by adequately design-
10 ing the printed interface geometry
11 • Wear and gouge production is enhanced by adjusting the 3D-printing settings

Corresponding author: Philipp Braun, philipp.braun@enpc.fr

Abstract

Laboratory experiments with surrogate materials play an important role in fault mechanics. They can improve the current state of knowledge by testing various scientific hypotheses in a repeatable and controlled way. Central in these experiments is the selection of appropriate analogue, rock-like materials. Here we investigated the frictional properties of sand-based, 3D-printed materials. Pursuing further recent experimental works, we performed uniaxial compression tests, direct shear and inclined plane tests in order to determine a) the main bulk mechanical parameters of this new analogue material, b) its viscous behavior, c) its frictional properties, and d) the influence of some printing parameters. Complete stress-strain / apparent friction-displacement curves were presented including the post-peak, softening behavior, which is a key factor in earthquake instability. The rate-and-state frictional parameters were also obtained.

Going a step further, we printed rock-like interfaces of custom frictional properties. Based on a simple analytical model, we designed the a) maximum, minimum and residual apparent frictional properties, b) characteristic slip distance, c) evolution of the friction coefficient with slip and d) dilatancy of the printed interfaces. This model was experimentally validated using interfaces following a sinusoidal pattern, which led to an oscillating evolution of the apparent friction coefficient with slip. Our approach could be used for simulating earthquake-like instabilities in the laboratory and mimic the periodical rupture and healing of fault sections. Additionally, our tests showed the creation of a gouge-like layer due to granular debonding during sliding, whose properties were quantified. The experimental results and the presented methodology make it possible to design new surrogate laboratory experiments for fault mechanics and geomechanics.

1 Introduction

The slow movement of tectonic plates continuously accumulates elastic energy in the earth's crust, which is suddenly released during earthquakes. A small part of this energy travels up to the surface in the form of seismic waves, which have catastrophic results for our built and shaped environment (Jones, 2018). Nevertheless, most of the energy is dissipated in the fault zone due to friction. Friction determines the nucleation of an earthquake, the evolution of seismic slip and the magnitude of seismic events (C. Scholz, 2002). Understanding friction is therefore a key element for studying earthquake nucleation, its possible mitigation and control (e.g. Raleigh et al., 1976; Barbot et al., 2012; Popov et al., 2012; Edwards et al., 2015; Bommer et al., 2006; Stefanou, 2019). Central in building understanding of induced/triggered earthquakes and their potential mitigation are in-situ measurements and laboratory testing.

Several experimental approaches have been developed for reproducing earthquakes in the laboratory. Laboratory experiments involve testing of natural rocks or rock-like, surrogate materials (e.g. Brace & Byerlee, 1966; Dieterich, 1979, 1981a; Power et al., 1988). A large variety of analogue materials has been employed in the literature. For instance, we refer to experiments with glass beads (Anthony & Marone, 2005), rubber (Schallamach, 1971), foam rubber (Brune, 1973), sandpaper (King, 1975), cardboard (Heslot et al., 1994), pasta (Knuth & Marone, 2007), and absorbent paper (Tzortzopoulos et al., 2020), among others (see Rosenau et al., 2017, for a comprehensive overview). Analogue materials permit not only to have better control over different parameters, but also to produce numerous specimens for repeatable experiments. *Repeatability* and *falsifiability* are of paramount importance for testing any theory or conjecture. This is especially important for systems where direct measurements are difficult to obtain or contain multiple sources of error. In this work, we propose a new analogue material for fault experiments, which enables the design of the apparent frictional parameters of rock-like frictional interfaces. This is achieved using 3D-printing with sand particles. This novel approach gives the advantage of controlling several properties such as the roughness, the exact geometry of the asperities, the maximum and minimum apparent friction coefficient, the exact evolution

of friction with slip and the characteristic slip-weakening distance, d_c^{sw} , of the frictional interfaces.

In literature, experiments on rock friction have not only been of interest in fault mechanics, but also in wider geo-engineering applications such as the stability in tunnelling and slopes. One can find a large number of studies discussing the contribution of joint roughness and asperities to the shear resistance of rocks, following the pioneering works of Newland and Allely (1957); Patton (1966). Analogue specimens have been created in this regard, as for instance for investigating the effects of triangle-shaped asperities on the shear resistance (Huang et al., 2002). These authors tested specimens made of a mix of chalk, sand and water, and analyzed the observed asperity friction and asperity cut-off in a theoretical model. Moreover, Asadi et al. (2013); Indraratna et al. (2015) showed experimentally on synthetic rocks, that the joint friction can be significantly reduced by asperity damage.

Analogue interfaces, resembling more closely to the geometry of natural rocks, have been replicated by 3D-printed molds (e.g. Fang et al., 2018) or 3D-printed acrylic resin specimens (Ishibashi et al., 2020). The aforementioned analogue materials permitted to carry out laboratory experiments and to infer properties that occur in real faults. Moreover, they allowed to explore the mechanisms behind various phenomena, such as asperity damage and gouge material creation, and their effect on apparent friction.

Here we go beyond that approach, by taking key fault characteristics and scale them down to the lab scale. These key properties can be local parameters, or average properties of an entire fault area, obtained through geodetic and seismological measurements. We use a recently developed, composite, analogue material, which gives a large scope for adjusting composition and micro-structural behavior of analogue rock-like frictional interfaces. More specifically, we employ sand-based 3D-printing, which enables us to adjust the geometry and roughness of analogue fault interfaces. Using Patton’s considerations on roughness (Patton, 1966), we succeed in generating desired frictional properties and reproduce the effects of asperity breakage and fault gouge creation. The latter is possible thanks to the applied 3D-printing technology, which uses sand particles of controlled size connected through resin bonds, that can break during shearing. Moreover, sand-based 3D-printing allows us to control the post-peak characteristic slip-weakening distance d_c^{sw} , which, together with the adjustable maximum and residual friction coefficient, enable us to control the frictional dissipation during slip. Note that this is central in the study of the earthquake phenomenon and its triggering (C. Scholz, 2002; Rattez et al., 2018a, 2018b; Stefanou, 2019).

The paper is organized as follows. In Section 2, we present the employed sand-based 3D-printing technology (S3DP). We characterize the basic mechanical properties of the S3DP material through element tests and investigate how the material composition and printing settings can influence its mechanical behavior. For this purpose, we perform Uniaxial Compressive Strength (UCS) tests on the bulk material and direct shear tests to 3D-printed flat interfaces, for characterizing the frictional properties including the angle of friction and the rate-and-state parameters. Then, in Section 4, we show how the frictional behavior is directly related to the designed geometry of the analogue fault asperities and we validate the predicted frictional behavior through shear experiments on sinusoidal interfaces. Finally, in Section 5, we discuss advantages, shortcomings, and perspectives of our approach for analogue experiments in fault mechanics.

2 3D-printed analogue rock

2.1 3D-printing technology

We use binder-jetting, a sub-category of 3D-printing technologies, for printing desired geometries of rock-like materials. Binder-jetting allows one to create composite ma-

114 materials by controlled mixing of two components: powder and binder. Among the vari-
 115 ous potential granular materials, we use here silica sand as the powder component. Be-
 116 fore the printing process, silica sand is mixed with an acidic activator. This activator serves
 117 later as a catalyst for the polymerization reaction of the binder. As shown in Figure 1a,
 118 a recoater and an inkjet head run over the build platform in alternating sequence. First,
 119 the recoater deposits a layer of the sand-activator mixture with a thickness of two times
 120 the mean grain diameter D_{50} of silica sand (here $D_{50} = 140 \mu\text{m}$). At the same time,
 121 it applies a small vertical pressure, in order to compact the new layer. Then, the inkjet
 122 head drops the binder (Furfurylic alcohol), which reacts with the activator and solidi-
 123 fies. Due to capillary forces, the binder is concentrated at the grain contacts and forms
 124 solid bridges, resulting in a rigid sand-binder matrix as depicted in Figures 1b,c. Grav-
 125 itational forces distribute the binder throughout the new sand layer and ensure binding
 126 to the previously deposited layer. Controlled amounts of binder are then deposited on
 127 each layer, under a given binder-to-sand ratio. Finally, the building platform moves down-
 128 wards and a new layer is printed, until the desired geometry is completed (for more de-
 129 tails on the printing procedure we refer to Prinkulov et al., 2017; Gomez et al., 2019;
 130 Mitra, Rodríguez de Castro, & El Mansori, 2019). The shape of the final object, which
 131 can be of arbitrary geometry (Figure 1d), is defined through an input CAD model. All
 132 principal printer settings for creating the specimens tested in this work are presented in
 133 Table 1a.

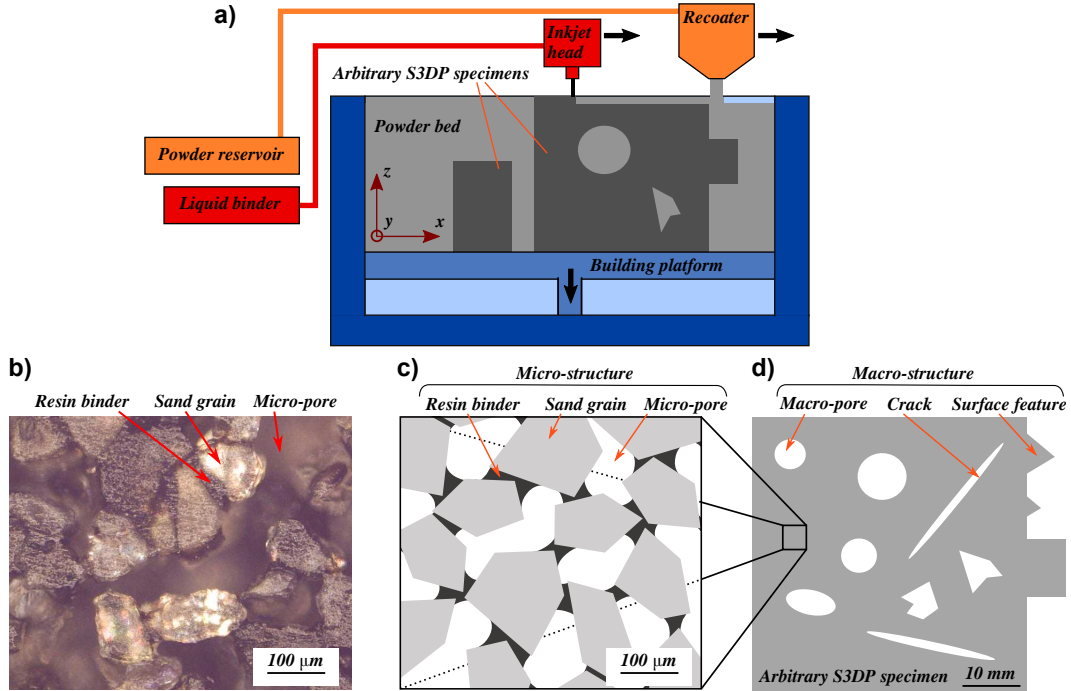


Figure 1. a) Schematic elements of a 3D printer for powder-binder composites, adapted from Upadhyay et al. (2017). b) Cross section of the S3DP material. c) Schematic representation of the micro-structure and d) of the macro-structure of the S3DP material.

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2.2 Micro-mechanical properties and analogies with natural rocks

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Specimens created by powder-based 3D-printing are characterized by their micro- and macro-structure (Figure 1b-d). The micro-structure describes the composition of the powder, binder and pore phases, and can be adjusted to a large extent to achieve desired

Table 1. a) Printer settings applied for specimen fabrication. b) Compositions for sand printing, representing different combinations of binder content b and recoating speed v_r . The resulting average porosity ϕ and its standard deviation (SD) are given.

(a)

Silica sand mean grain diameter	140 μm
Binder type	Furfurylic alcohol
Binder content	3.8 or 7.2 wt% of sand
Recoating speed	0.13 or 0.26 m/s
x resolution	20 $\mu\text{m}^{(1)}$ or 40 $\mu\text{m}^{(2)}$
y resolution	101.6 μm
z resolution (layer thickness)	280 μm
Activator content (sulfonic acid)	0.2 wt% of sand
Infra-red curing lamp temperature	32 $^{\circ}\text{C}$

⁽¹⁾ for high and ⁽²⁾ for low binder content

(b)

Composition	b [wt% of sand]	v_r [m/s]	ϕ [%]	SD [%]
R1	3.8	0.13	43.7	0.6
R2	3.8	0.26	47.6	1.0
R3	7.2	0.13	42.8	4.2
R4	7.2	0.26	45.1	2.2

138 macroscopic mechanical properties. More specifically, the macroscopic mechanical prop-
 139 erties of 3D printed analogues based on powder minerals (such as the S3DP material used
 140 herein) can be controlled by different process variables. For instance, phase composition,
 141 macroporosity and pore geometry have high impact on the compressive strength of 3D-
 142 printed specimens (Schumacher et al., 2010). Vaezi and Chua (2011) found that increas-
 143 ing the binder saturation of plaster-powder-based printed materials can improve mechan-
 144 ical resistance. They also observed that an increase of the printing layer thickness re-
 145 duces the tensile resistance, but increases flexural strength. Moreover, the printing layer
 146 orientation induces anisotropy in the microstructure (Vlasea et al., 2015), which can af-
 147 fect the apparent mechanical and hydraulic properties at the macro-scale. While hav-
 148 ing a minor effect on dimensional accuracy and pore structures, the printing speed can
 149 have a significant influence on the strength and structural accuracy of 3D-printed spec-
 150 imens. Farzadi et al. (2015) showed, that very fast printing prevents the binder from spread-
 151 ing and penetrating uniformly, resulting in lower mechanical resistance. Conversely, if
 152 printing is carried out too slow, the binder hardens before the subsequent layer is com-
 153 pleted, resulting in reduced adhesion between layers, leading to lower resistance. While
 154 the binder cures, heating the layer up to a certain temperature can improve the mechan-
 155 ical properties (Primkulov et al., 2017). Very high temperatures, however, can reduce
 156 the mechanical resistance. In addition, ageing, curing time and curing temperature can
 157 influence S3DP materials (Mitra et al., 2018).

158 Mechanical properties of S3DP analogues can be adjusted through the most im-
 159 portant printing parameters: a) the printing layer thickness, b) the layer orientation and
 160 c) the binder saturation (Gomez et al., 2019). According to Gomez et al. (2019), the print-
 161 ing layer thickness defines the thickness of new material added parallel to the building
 162 plane in each printing step. The layer orientation describes the angle between printing
 163 layers and loading direction, while the binder saturation denotes the percentage of sand

164 pore volume filled by binder. Moreover, Gomez et al. (2019) have found an increase of
 165 uniaxial compressive strength with increasing binder saturation. On the contrary, when
 166 they increased the layer thickness from 220 to 400 μm , they measured a significant de-
 167 crease of uniaxial compressive strength. Finally, Mitra, Rodríguez de Castro, and El Man-
 168 sori (2019) noted that a higher recoating speed leads to a lower grain packing density
 169 and therefore higher porosity. Furthermore, heterogeneities in density might increase due
 170 to the faster distribution of sand.

171 Even though literature examples of the use of sand-based 3D-printed materials in
 172 geomechanics applications are limited, Gomez (2017); Gomez et al. (2019) state that for
 173 given sand and binder properties, S3DP materials show similar behavior and mechan-
 174 ical characteristics with natural rocks. For instance, they measured an unconfined com-
 175 pressive strength between approximately 15 and 20 GPa, a Young modulus between 1.6
 176 and 1.9 GPa and a Poisson ratio between 0.19 and 0.25 on S3DP specimens with a poros-
 177 ity between 36 and 47%. Their cylindrical specimens had dimensions of 38.1 mm diam-
 178 eter and 76.2 mm height, and 63.5 mm diameter and 127 mm height, respectively (com-
 179 pared to our samples of 20 mm diameter and 40 mm height). These mechanical prop-
 180 erties are close to the ones found on weak sandstones, such as the Wildmoor or Water-
 181 stone sandstones (compressive strength of approximately 10 and 20 GPa, Young's mod-
 182 ulus of around 2 and 7 GPa, porosity of 25%, respectively, according to Dobereiner &
 183 Freitas, 1986; Papamichos et al., 2000).

184 Intact crustal rocks can have a large range of stiffness (Young's modulus up to tens
 185 of GPa), while the stiffness of the rock material in a fault core can be significantly re-
 186 duced down to 0.01 GPa, due to fracturing (Birch, 1966; Goodman, 1989; Schön, 2004;
 187 Jeanne et al., 2017). The stiffness of S3DP material is therefore in the range of damaged
 188 core material. Changing the printing composites, the printing ratios and further devel-
 189 opments in printing techniques (such as altering the grain size distribution, further im-
 190 pregnation with resin or printing under higher compaction) may permit to increase the
 191 stiffness of the printed material and adjust it to a desired rock material. Moreover, in
 192 certain experiments (King, 1975; Heslot et al., 1994; Scuderi et al., 2016, among others),
 193 the desired fault stiffness can be controlled by separate elastic components, so that the
 194 stiffness of the rock or surrogate material has minor importance. It is worth pointing out,
 195 that in many experiments it is not necessary to reproduce an identical rock stiffness, but
 196 to use adequate scaling laws to create surrogate faults (see also Sections 2.4 and 5.3).

197 **2.3 Printing material composition used in this study**

198 Given the important effects of various printing parameters discussed in the previ-
 199 ous section, we chose here to vary only two printing parameters, the recoating speed and
 200 the binder saturation. The layer orientation and layer thickness remained the same for
 201 all specimens. Our cylindrical samples were printed with the printing z axis along the
 202 cylinder axis, while the block samples were printed in such a way that the shear inter-
 203 face was aligned with the $x - y$ printing plane (see also Figure 1).

204 Our S3DP specimens were fabricated using combinations of two recoating speeds,
 205 $v_r = 0.13$ and 0.26 m/s, and two binder contents, $b = 3.8$ and 7.2 wt% of sand (Ta-
 206 ble 1b). Further material and 3D-printer specifications are given in Table 1a. All four
 207 compositions show porosities close to 45%, calculated using the measured sample weight
 208 and volume. This porosity is close to the maximum porosity of 48 %, which corresponds
 209 to the loosest possible packing of spherical grains with uniform diameter and no binder.
 210 Note that we assumed a silica sand density $\rho_s = 2.65$ g/cm³ and a binder density $\rho_b =$
 211 1.15 g/cm³ (Mitra et al., 2018) for the porosity calculation.

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2.4 Analogue fault material

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Several applications could be envisaged with the presented technique of 3D-printing with sand. Here we focus on the possibility of designing surrogate experiments in the context of fault mechanics. The dynamic behavior of earthquakes is often idealized using the analogue spring-slider system as shown in Figure 2a (Rabinowicz, 1951, 1956, 1958; Dieterich, 1979; C. Scholz, 2002; Kanamori & Brodsky, 2004). Here the frictional interface between the block and the ground represents the fault zone, which is loaded with an effective normal force F'_n . The block is pulled with a slow, constant velocity, v_∞ , through an elastic spring of stiffness k , which progressively accumulates elastic energy, in a similar way as the rocks surrounding the fault zone do. The frictional behavior can be expressed either by adopting a slip-weakening friction law (Figure 2b) or a rate-and-state one (Figure 2c), or even more advanced frictional models (e.g. Reches & Lockner, 2010; Sammis et al., 2011; Rice et al., 2014; Viesca & Garagash, 2015; Rice, 2017; Rattetz et al., 2018a; Collins-Craft et al., 2020, among others).

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In the case of the slip-weakening frictional behavior see Figure 2b (Palmer and Rice (1973); Andrews (1976); C. Scholz (2002); Di Toro et al. (2011); Stefanou (2019)), the spring-slider analogue system is considered (Lyapunov) unstable, if the spring stiffness k is lower than the critical stiffness of the interfaces $k_c^{sw} = \Delta\mu \cdot F'_n / d_c^{sw}$, where $\Delta\mu \cdot F'_n$ is the frictional drop (corresponding to the static stress change of an earthquake) and d_c^{sw} is the characteristic slip-weakening distance (Dieterich, 1979; C. Scholz, 2002; Kanamori & Brodsky, 2004; Di Toro et al., 2011; Stefanou, 2019).

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On the other hand, when a rate-and-state friction law (Dieterich, 1981a; Ruina, 1983) is employed, the system is (Lyapunov) unstable if the stiffness of the equivalent spring k is lower than $k_c^{rs} = (b - a) \cdot F'_n / d_c^{rs}$ (necessary and sufficient condition for quasi-static motion), where a and b are empirical parameters, which can be obtained as indicated in Figure 2c. In this frictional law, d_c^{rs} is the characteristic rate-and-state distance (Dieterich, 1981a; Ruina, 1983; Marone, 1998; Scholz, 1998).

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In this study, printing interfaces with desired (macro-) roughness allows a direct control of the apparent slip-weakening properties of the interfaces (i.e. of the post-peak frictional response, characterized through $\Delta\mu$ and d_c^{sw}). This property is then exploited for the design of analogue experiments in the laboratory by controlling the post-peak frictional response. Earthquake-like instabilities can then be reproduced in the laboratory by adding a separate elastic component (e.g a spring) of desired stiffness (see Figure 2a, King, 1975; Heslot et al., 1994; Scuderi et al., 2016, among others).

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3 Sand-based 3D-printed material characterization

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To characterize the basic mechanical and frictional properties of the S3DP material, we carried out: a) unconfined compression tests on cylindrical S3DP specimens and b) shear tests on flat S3DP interfaces. The four different material compositions (Table 1b) were tested in order to analyze the effect of binder content and recoating speed on the mechanical parameters and to choose the most suitable composition for analogue faults.

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3.1 Unconfined compression tests

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For the unconfined compression test, we used a uniaxial compression frame, which is equipped with a 20 kN loadcell mounted on a servo-mechanical piston. The loading for the following experiments was carried out under displacement control with a rate of 0.1 mm/min, measured by an integrated encoder. The vertical displacement of the top of the specimen was recorded by an LVDT. Cylindrical specimens were printed with 20 mm diameter and 40 mm height. The cylinder axis was aligned with the printing direction z (Figure 1a). For the S3DP material, the weakness planes were aligned with the

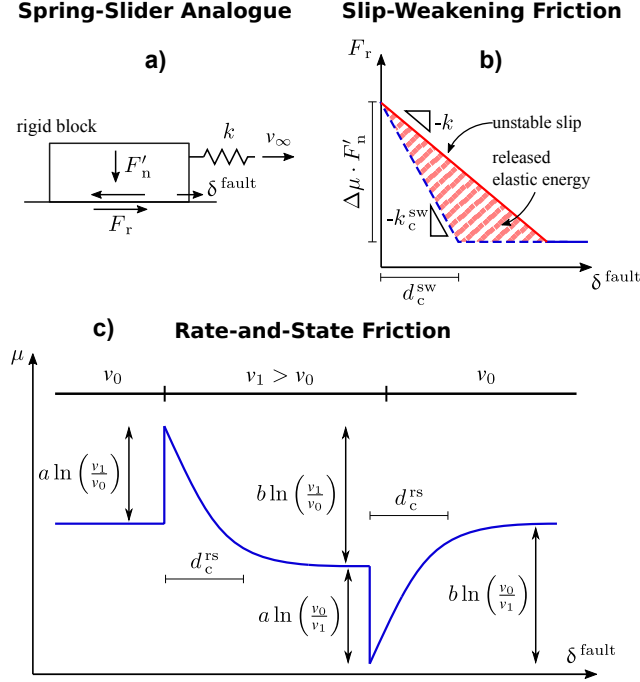


Figure 2. a) Schematic representation of the spring-slider dynamic system, consisting of a rigid block under a constant effective normal force F'_n , pulled with a slow velocity v_∞ through an elastic spring of stiffness k . b) Slip-weakening friction (cf. Palmer & Rice, 1973; Andrews, 1976; Dieterich, 1979; C. Scholz, 2002; Di Toro et al., 2011; Stefanou, 2019): Frictional force F_r over block displacement δ^{fault} . The system is unstable when $k < k_c^{\text{sw}} = \Delta\mu \cdot F'_n / d_c^{\text{sw}}$, where $\Delta\mu \cdot F'_n$ is the frictional drop due to slip-weakening and d_c^{sw} the characteristic slip-weakening distance. c) Rate-and-state friction (Dieterich, 1981a; Ruina, 1983): Coefficient of friction μ over block displacement δ^{fault} . The system is unstable when $k < k_c^{\text{rs}} = (b - a) \cdot F'_n / d_c^{\text{rs}}$, where a and b are empirical parameters and d_c^{rs} is the characteristic rate-and-state distance.

260 printing plane (Gomez, 2017; Gomez et al., 2019). The printing deposition leads to a trans-
 261 versely isotropic material which, to some extent, could mimic the natural, geological de-
 262 position mechanism.

263 For our direct shear specimens, shearing was carried out along this weakness plane.
 264 Notice that the layer orientation could influence the shear failure behavior of the S3DP
 265 matrix. In particular, this could influence wear, gouge production and the failure of as-
 266 perities along the printed interfaces (see also Section 5.2). As far as it concerns the bulk
 267 properties of the S3DP material, a comprehensive characterization of its anisotropy would
 268 require further compression tests, loaded parallel and inclined with respect to the print-
 269 ing layer (cf. Gomez, 2017; Gomez et al., 2019). In this study however, the aim of the
 270 compression tests was to get a first qualitative idea of the mechanical properties of the
 271 bulk material.

272 Typical stress-strain curves of the performed UCS tests are presented in Figure 3.
 273 More specifically, we are interested in the unconfined compressive strength (UCS), the
 274 Young modulus and the post-peak behavior (ductility/brittleness). Good repeatability
 275 was reported for tests of the same material composition.

276 In all of our experiments, we can observe a linear loading path above an axial stress
 277 of $\sigma_1 \approx 5$ MPa, leading to a relatively brittle failure. Below that stress level, the slope

278 of the stress-strain curve is much smaller, indicating a possible plastic compaction due
 279 to crack and/or pore closure. After failure, we detect a significant, but gradual soften-
 280 ing in the post-peak regime, which can be beneficial in some applications (ductility). No-
 281 tice that the initial loading section of composition R1 at $\sigma_1 \approx 2$ MPa shows a distinc-
 282 tive plateau, which could also be due to initial misalignment of the specimen or initial
 283 local compaction of asperities at the top and bottom end surfaces.

284 We note that compositions R1 and R3 (low recoating speed) behave similarly, with
 285 peak stresses close to 18 MPa. Likewise, compositions R2 and R4 (high recoating speed)
 286 show similar responses, but with lower peak strengths, i.e. at around 12 MPa. R2 and
 287 R4 specimens showed a more ductile behavior than the others (i.e. shallower and longer
 288 strain softening branch). The UCS values are summarized in Figure 4a, showing the in-
 289 crease of strength with lower recoating speed. Slower recoating induces higher packing
 290 density, which seems to favor mechanical strength. The binder content has negligible in-
 291 fluence on the compressive strength.

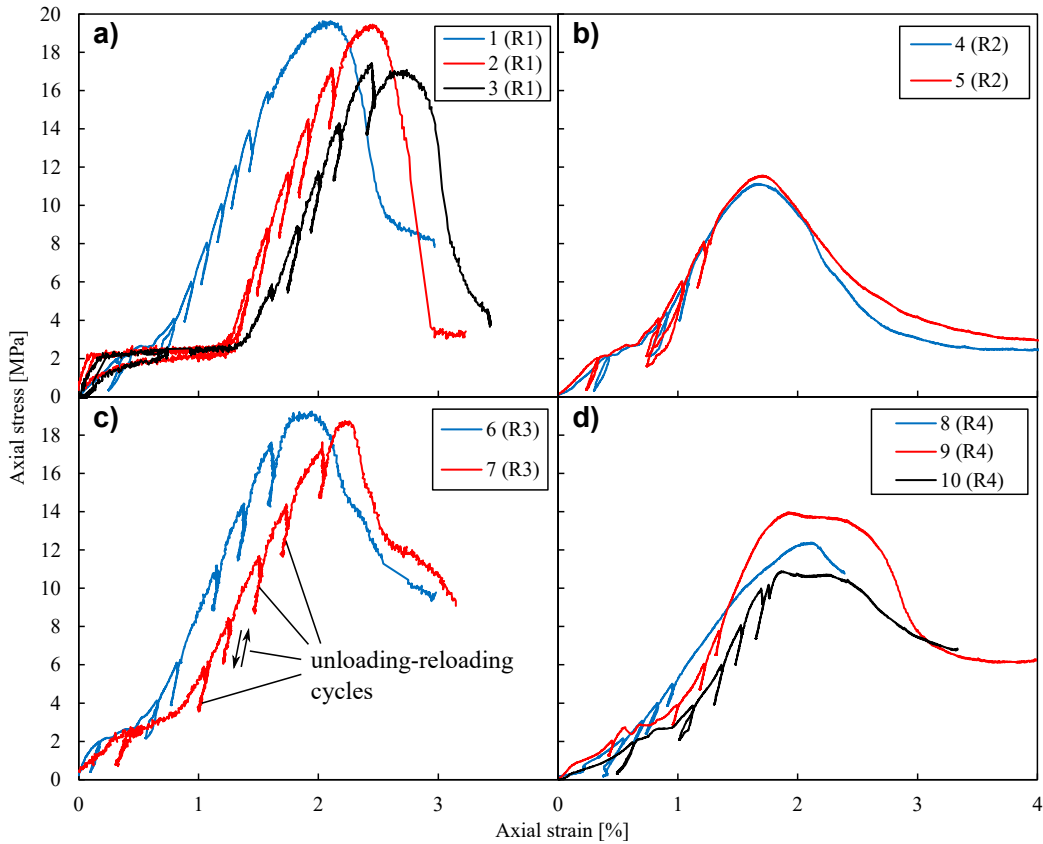


Figure 3. Experimental stress-strain behavior obtained from uniaxial compression tests on specimens with different compositions (Table 1b). The specimens were loaded with a constant displacement rate of 0.1 mm/min. We carried out subsequent unloading-reloading cycles before reaching the peak stress, by unloading each time for about 1.2 to 2.0 MPa, in order to determine the Young modulus from elastic deformations. Strain softening is observed after the peak.

292 During the loading paths, unloading-reloading cycles were carried out to measure
 293 the elastic Young modulus E . This parameter was evaluated through linear regression
 294 on the stress-strain curve of each cycle. In Figure 4b, we plot the Young modulus with
 295 respect to the vertical stress at the beginning of the respective cycle. We can observe

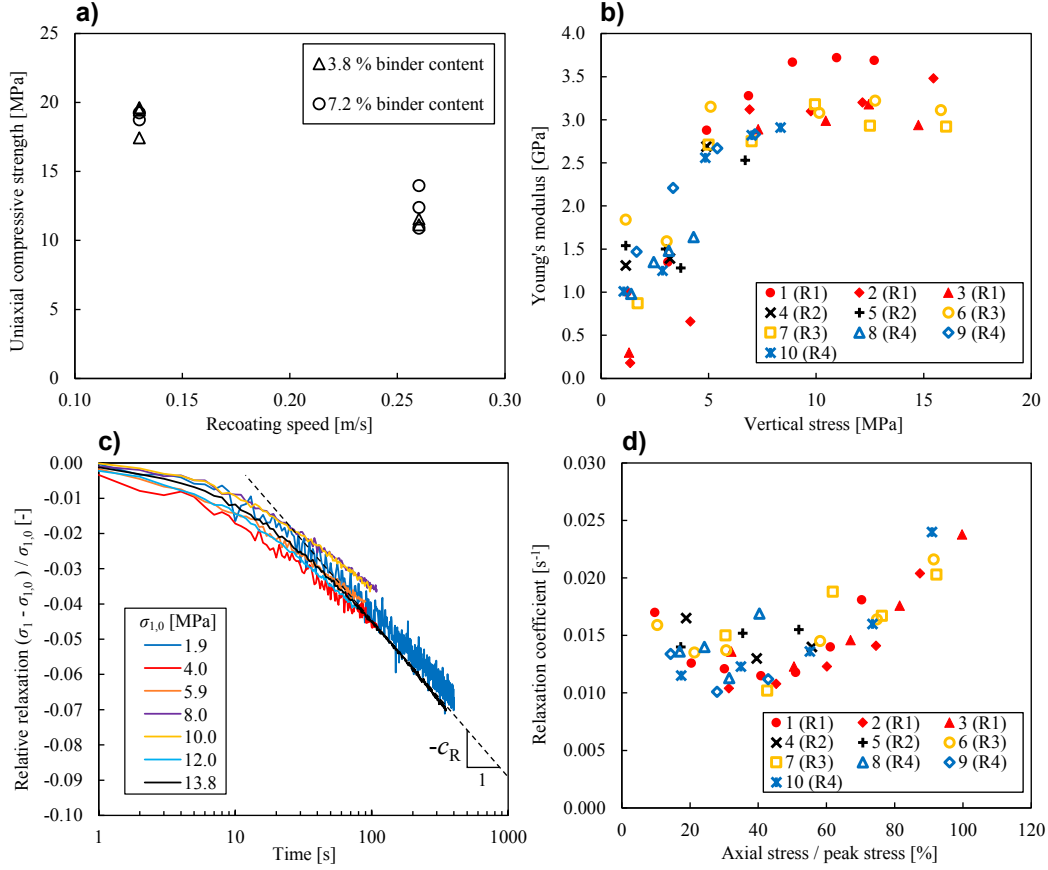


Figure 4. Data taken from the unconfined compression tests 1 - 10 in Figure 3: a) Influence of the recoating speed on the unconfined compressive strength. Different binder contents (Table 1b) have no significant effect. b) Young's modulus evaluated at unloading-reloading cycles at different axial stress levels. c) Relaxation coefficient c_R evaluated at constant displacement stages and under different stress levels. The indicated slope provides an estimation of the relaxation coefficient c_R . d) Relative relaxation with respect to time under various initial axial stress levels $\sigma_{1,0}$.

296 that E varies from around 0.2 up to 3.7 GPa. While the composition of the specimens
 297 does not notably affect the Young modulus E , the vertical stress has a significant im-
 298 pact on the stiffness. Even though we detect a rather large dispersion of values, we can
 299 observe an increase of the Young modulus with vertical stress. At $\sigma_1 = 2$ MPa, we meas-
 300 ured $E \approx 1.0$ GPa, which increases up to $E \approx 3.3$ GPa at $\sigma_1 = 6$ MPa. For higher
 301 stresses, the Young modulus remains practically constant.

302 Before each unloading-reloading cycle, the displacement was stopped for a certain
 303 time, which allowed us to measure the vertical stress relaxation. The decrease of verti-
 304 cal stress, starting from the initial value $\Delta\sigma_1 = \sigma_1 - \sigma_{1,0}$, was analyzed relative to the
 305 initial stress $\sigma_{1,0}$, giving the dimensionless relative relaxation. Figure 4c shows a typi-
 306 cal result of the relative relaxation with respect to time, measured on different stages
 307 for specimen 1 (composition R1). After a time of 30 s, we observe a linear behavior with
 308 respect to log-time. The relaxation coefficient c_R can be evaluated from the slope of the
 309 curve and its values are presented in Figure 4d in function of the normalized vertical stress
 310 (initial vertical stress over compressive strength). Independently of the sample compo-

311 sition, we find values of c_R varying between 0.010 and 0.017 s^{-1} at a vertical stress be-
 312 low 80 % of the compressive strength, while above that stress level, c_R increases up to
 313 0.024 s^{-1} at 100 % compressive strength.

314 In terms of compressive strength, we found a range of values between 10 and 20
 315 MPa, similar to the values obtained by Gomez et al. (2019) on a similar material. The
 316 observed values for compressive strength and Young's modulus are comparable to those
 317 of weak sandstones (porosity of approximately 25 %, Dobereiner & Freitas, 1986; Papami-
 318 chos et al., 2000). Interestingly, we can observe an evolution of Young's modulus with
 319 vertical stress, such as in natural sandstones (e.g. Pimienta et al., 2015). This behav-
 320 ior is often explained through the closure of micro-cracks, which increases the grain-to-
 321 grain contact area and consequently the stiffness.

322 Note that the Young modulus, the peak strength and the relaxation characteris-
 323 tics were determined in this study always for a loading direction perpendicular to the
 324 printing layer. For loading parallel to the layer, one can expect different properties due
 325 to the anisotropic micro-structure of the material, but this exceeds the scope of the cur-
 326 rent work. For instance, Gomez (2017) showed for a similar S3DP material, that under
 327 loading parallel to the printing layer with respect to perpendicular loading, the strength
 328 decreased from 17.1 to 14.4 MPa, the failure characteristics changed from ductile to brit-
 329 tle and the Poisson ratio increased from 0.19 to 0.25, while the Young modulus remained
 330 at 1.7 GPa.

331 3.2 Direct shear experiments on flat interfaces

332 For direct shear experiments, we used the direct shear device shown in Figure 5a,
 333 which is designed for specimens composed of two blocks. The bottom one has dimen-
 334 sions equal to 140x100x10 mm³ and the top one equal to 100x100x25 mm³ (length x width
 335 x height). These blocks were printed with their height axis perpendicular to the print-
 336 ing layer.

337 The length of the bottom block is higher than the one of the top block, in order
 338 to assure constant contact area (100x100 mm²) during shearing. In the vertical direc-
 339 tion, the controlled normal force F_n results in a normal stress σ_n , which is quasi-uniform
 340 over the interface (Tzortzopoulos et al., 2019). The vertical displacement was measured
 341 by an integrated LVDT. In the horizontal direction, a ram permits to move the lower
 342 part of the device. We performed displacement controlled (δ) experiments. The horizon-
 343 tal displacement induces a shear stress τ_n , which is considered to be uniformly distributed
 344 over the interface. During shearing, loose material might detach from the blocks. How-
 345 ever, the sheared interface is 100 mm wide, prohibiting grain removal from the shear in-
 346 terface (plane-strain conditions). Moreover, the loading frame prevents loss of grains from
 347 the lateral sides of the specimen.

348 For each material composition R1 - R4, we tested two specimens under a normal
 349 stress of 500 kPa and a shear displacement rate of 0.5 mm/min. Two additional spec-
 350 imens of composition R1 were sheared under 100 kPa normal stress. The apparent fric-
 351 tion coefficient, presented for some typical results in Figure 5b, reached a constant resid-
 352 ual plateau for the investigated shear displacement up to 6 mm. The initial load-displacement
 353 branch includes elastic deformation, but also compression and sliding due to alignment
 354 of the sample blocks with the loading frame. Moreover, gouge is formed, which then un-
 355 dergoes steady-state shearing. Steady-state or critical-state shearing (Roscoe et al., 1958;
 356 Wood, 1991) is accompanied by gouge production due to grain detachment. Between the
 357 two phases a smooth transition is observed. The average values of this residual friction
 358 coefficient under 500 kPa normal stress are 0.58 for R1, 0.60 for R2 and 0.63 for R3 and
 359 R4. Decreasing the normal stress in tests on composition R1 did not change the appar-
 360 ent friction coefficient, confirming Coulomb's assumption of proportionality. The exper-
 361 iments showed good repeatability.

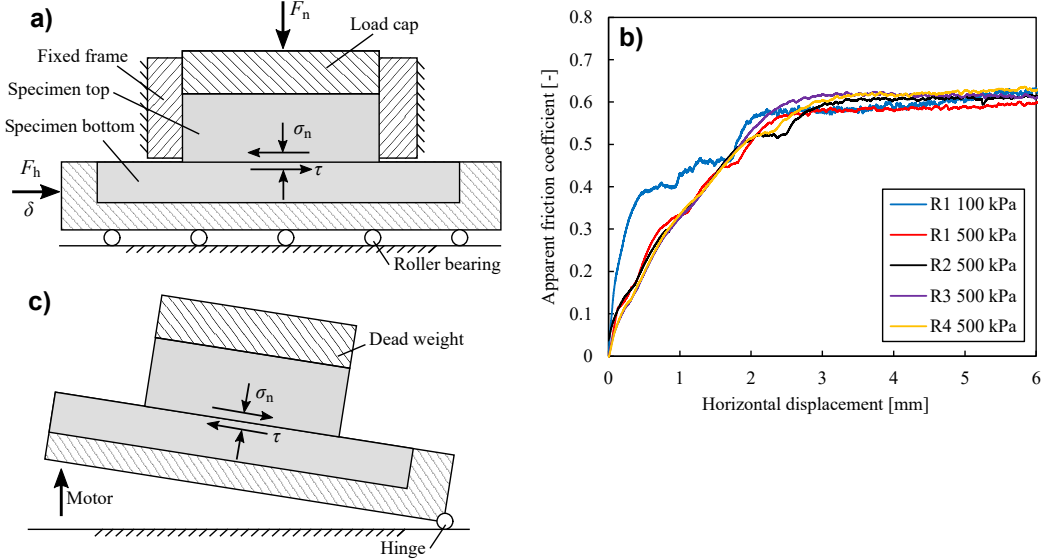


Figure 5. a) Schematic plan of the direct shear apparatus. The normal force F_n and the horizontal displacement δ are controlled. b) Evolution of the apparent friction coefficient shown on one representative result for each material composition and normal stress level. c) Configuration of the inclined plane shear test.

362 The measurements from the direct shear tests were verified through additional friction
 363 tests on composition R1, using an inclined plane configuration (Figure 5c). In these
 364 verification tests, specimens consisting of lower and upper blocks with flat interfaces (equiv-
 365 alent dimensions as the specimens used for direct shear tests), were placed on a horizon-
 366 tal metal plate. The lower block was prevented from sliding on the plate, while the upper
 367 block was unconstrained. An additional weight of 1.0 kg was placed on top of the
 368 upper block. The plate was slowly inclined, until the upper block started to slide. By
 369 measuring the inclination angle, the friction coefficient of the interface could be deter-
 370 mined. We carried out four tests in this way, showing an average friction coefficient $\mu =$
 371 0.62 (corresponding to a friction angle of 31.8°) with a standard deviation of 5.0 %. This
 372 friction coefficient is close to the value of 0.58 obtained on the R1 composition using the
 373 direct shear apparatus, which confirms the results of the more complex device. Zero co-
 374hesion was measured in all the tests.

375 Proceeding one step further with the characterization of the flat interfaces, we car-
 376 ried out velocity stepping experiments under constant normal load, in order to estimate
 377 the rate-and-state parameters a , b and d_c^{rs} (see Figure 2c). The same direct-shear ap-
 378 paratus and testing configuration were used as in Figure 5a. We performed two tests us-
 379 ing specimens made of R2 composition under 500 kPa of normal stress. Initially, the spec-
 380 imens were loaded for 5 mm with a constant shear displacement rate of $v_0 = 5 \mu\text{m/s}$
 381 in order to assure steady-state sliding of the mobilized block. An abrupt decrease of the
 382 velocity by one order of magnitude to $v_1 = 0.5 \mu\text{m/s}$ followed. This velocity was kept
 383 constant for a total displacement of 2 mm, until the velocity increased again instantly
 384 to v_0 . After 2 mm of sliding, a last abrupt velocity reduction to v_1 took place. The re-
 385 sponse of the specimens under these velocity steps can be observed in Figure 6.

386 More specifically, in Figure 6a, the time-history of the horizontal displacement is
 387 displayed, where the velocity steps, interchangeably between v_0 and v_1 , are easily dis-
 388 tinguishable. In Figure 6b, the apparent friction coefficient in terms of the horizontal dis-
 389 placement is plotted, along with a closer look to the frictional response due to an abrupt

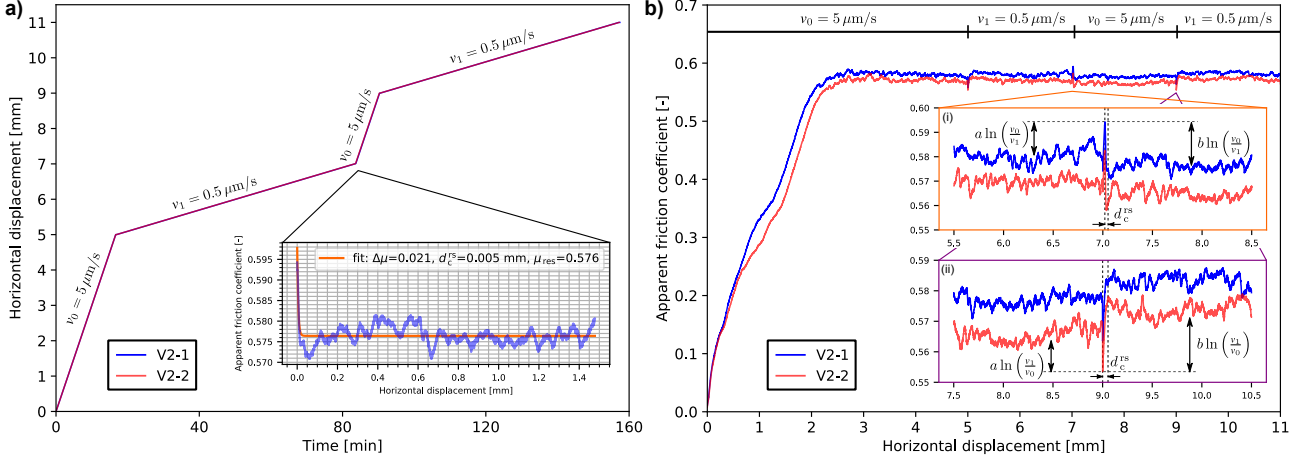


Figure 6. a) Horizontal displacement over time. The different applied displacement-rates are also illustrated indicating their duration. The inset shows an example of an exponential fitting which is employed for calculating d_c^{rs} for each velocity step. b) Apparent friction coefficient with respect to the horizontal displacement of the moving block. In the insets (i) and (ii), a closer look to an increase and decrease of velocity is presented, respectively.

390 (i) increase (orange framed inset) and (ii) decrease (purple framed inset) of block's
 391 velocity. In the case of a velocity increase (inset (i)), an instant frictional strengthening
 392 is observed of $\Delta\mu = a \ln(v_0/v_1)$ (from the steady-state). Then an exponential decay
 393 of the friction occurs leading to the next frictional steady-state value due to the faster
 394 velocity v_0 . The exact opposite happens for a velocity decrease as indicated in the
 395 inset (ii). The difference between the steady-state values before and after each velocity step
 396 is denoted as $\Delta\mu_{\text{ss}}$ and is equal to $(a-b) \ln(v_0/v_1)$. The distance that it takes for the
 397 friction to reach its new steady-state after a velocity change is noted as d_c^{rs} .

398 The parameters $a-b$ and d_c^{rs} are involved in the study of the stability of the analo-
 399 gous spring-slider model under the rate-and-state friction (see Section 2.4 and Figure
 400 2c). By taking into account the average steady-state friction before and after each ve-
 401 locity step and considering an order of magnitude increase of velocity, the average dif-
 402 ference $(a-b)_{\text{in}}$ is equal to -0.0019 , while for an equivalent decrease of velocity is $(a-
 403 b)_{\text{dcr}} = -0.0037$. For estimating the characteristic rate-and-state distance d_c^{rs} , we per-
 404 formed an exponential fitting to the frictional decay raw data utilizing the least-squares
 405 method, as it is illustrated in the inset of Figure 6a (Rice & Ruina, 1983; Gu et al., 1984;
 406 Bhattacharya et al., 2015). Consequently, the characteristic distance for the rate-and-
 407 state friction law following a factor of 10 rise of the velocity is $d_{c,\text{in}}^{\text{rs}} = 0.005 \text{ mm}$, while
 408 for an equivalent drop is $d_{c,\text{dcr}}^{\text{rs}} = 0.014 \text{ mm}$.

409 These results show that for relatively slow velocities and only if the sliding block
 410 has reached its steady-state, the S3DP material displays a rate-and-state dependency
 411 (Dieterich, 1981a; Dieterich & Kilgore, 1994; Hunfeld et al., 2019). Therefore, consid-
 412 ering the micro-behavior of this 3D-printed material, these experiments give birth to an
 413 additional small length-scale of the order of approximately $0.1D_{50}$. However, this rate-
 414 and-state behavior plays a secondary role in the design of interfaces with custom (slip-
 415 weakening) frictional properties. As shown in the next Sections, this is due to the possi-
 416 bility of adjusting the macro-roughness using 3D-printing.

4 Design of interfaces with controlled friction

Once the basic mechanical properties of the sand printed material are identified, it is possible to design the geometry of the printed interfaces, in order to give them the desired frictional properties. These properties include the peak friction, the residual friction, and the characteristic slip-weakening distance. Moreover, we can control the exact evolution of friction with slip, giving us important flexibility in experiments.

4.1 Joint friction model

Modeling the frictional behavior allows us to better understand the underlying physical mechanisms and enables us to design interfaces of desired frictional properties. According to Newland and Allely (1957); Patton (1966), and assuming Coulomb friction, the friction coefficient of rock joints is:

$$\mu = \frac{\tau}{\sigma_n} = \tan(\phi_b + i) \quad (1)$$

where ϕ_b is called basic friction angle and i effective roughness, or i -value in the case of rock joints (Barton, 1973). The effective roughness is the inclination of asperities along the interface.

According to Barton (1973), the value of ϕ_b corresponds to the residual friction angle, measured on saturated, planar rough-sawn or sand-blasted surfaces of the rock. This author has summarized literature data for sand-blasted and sawn surfaces, showing that most rocks have basic friction angles of approximately between 25° and 35° . The measured basic friction of the sand-based 3D printed material was found in the same range (around 30° , see Section 3.2), which makes it a good candidate for a rock analogue, as far as it concerns frictional properties.

By appropriately designing i in terms of slip, one can control the evolution of the apparent friction coefficient μ . In this way it is possible to imitate a great variety of frictional behavior in experiments. In order to demonstrate this idea, we apply Patton's friction relation (Eq. (1)) for periodic sine-wave asperities. This roughness profile is expressed as a function of the shear displacement δ , defined by an amplitude A_0 and a wavelength λ . In Figure 7, we present the geometry of the sinusoidal asperities. According to Eq. (1), the maximum friction is expected at the maximum profile angle i , where we set $\delta_{pp} = 0$. The profile height, h_p , can be expressed as a function of the shear displacement δ_{pp} , resulting in $h_p(\delta_{pp}) = A_0 \sin(2\delta_{pp}\pi/\lambda)$. The asperity inclination gives us the asperity friction coefficient μ_A , obtained through differentiation of h_p with respect to δ_{pp} :

$$\mu_A(\delta_{pp}) = \tan [i(\delta_{pp})] = \frac{dh_p(\delta_{pp})}{d\delta_{pp}} = 2\pi \frac{A_0}{\lambda} \cos \left(2\pi \frac{\delta_{pp}}{\lambda} \right) \quad (2)$$

where the maximum and minimum asperity friction μ_A are given by $\pm 2\pi A_0/\lambda$. Inserting Eq. (2) in (1), one can calculate the total apparent friction coefficient:

$$\mu(\delta_{pp}) = \frac{\mu_b + \mu_A(\delta_{pp})}{1 - \mu_b \mu_A(\delta_{pp})} \quad (3)$$

where $\mu_b = \tan \phi_b$ is the basic friction coefficient (see Section 4.3).

In addition, the oscillating vertical compaction-dilation $\delta_{v,A}$ due to the sliding over asperities (Figure 7) can be derived from the profile height $h_p(\delta_{pp}) = A_0 \sin(2\pi\delta_{pp}/\lambda)$. Therefore, dilatancy can be designed as well, which, for the sinusoidal asperities, is equal to:

$$\delta_{v,A}(\delta_{pp}) = A_0 \left[1 + \sin \left(2\pi \frac{\delta_{pp}}{\lambda} \right) \right] \quad (4)$$

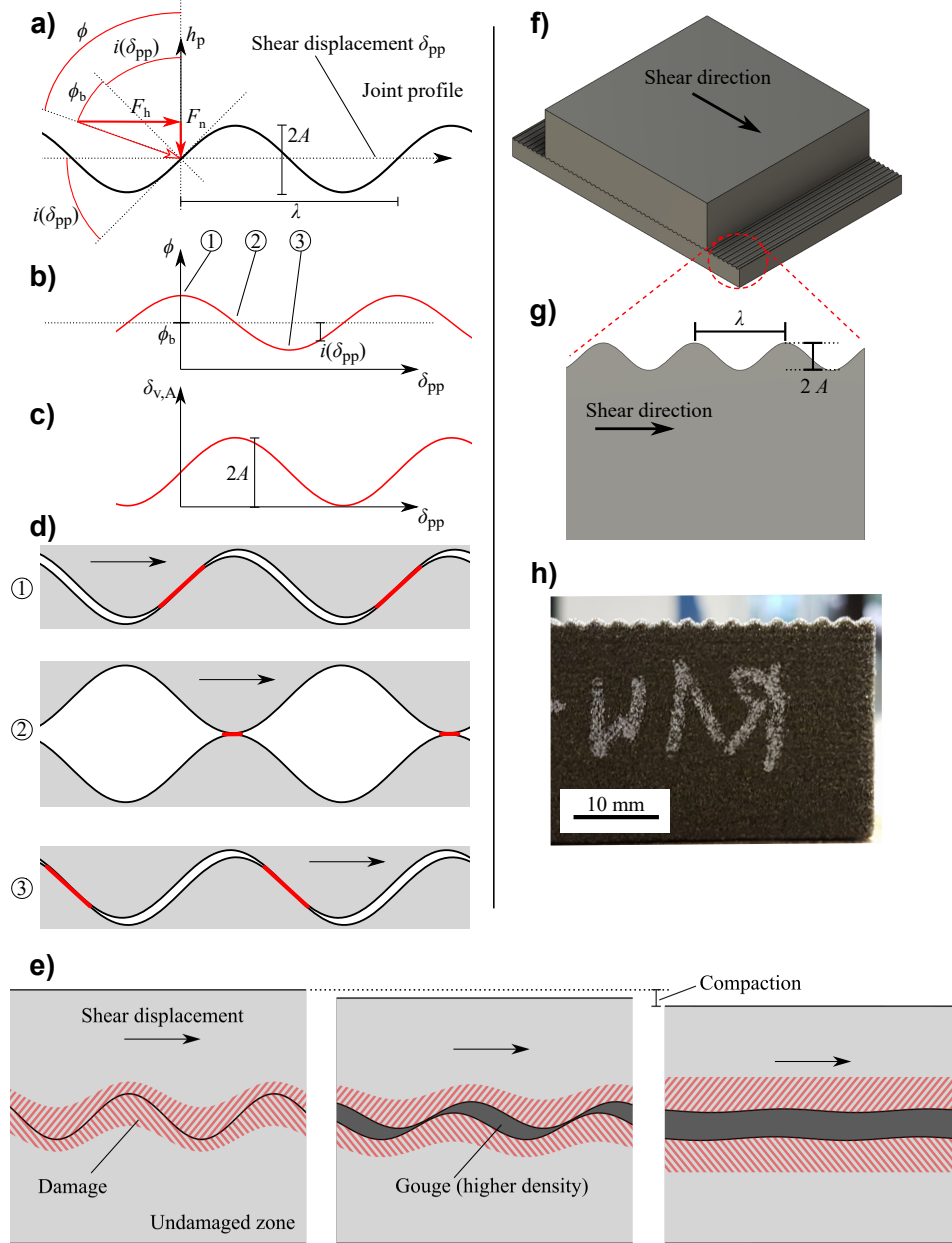


Figure 7. Friction model for a joint with periodic asperity geometry, illustrated using a sine-wave profile. a) Force diagram on the position $\delta_{pp} = 0$, where the asperity inclination i is the highest. The apparent total friction angle, which gives the relationship between F_h and F_n , is the sum of i and ϕ_b . b) Oscillation of the total friction angle ϕ around the basic friction angle ϕ_b with amplitude i , depending on the shear displacement. c) Vertical displacement of the top interface. d) Asperity contact orientation (red in online version), which changes with progressing displacement and affects the total friction. Wear and compaction is neglected in this schema, so that the interface geometry remains unchanged ($A = A_0$). e) Schematic representation of gradual wear of asperities. Abraded grains form a gouge layer between the interfaces. Total compaction can be due to the compaction in the damage zone and in the gouge layer. f) 3D model for printing the two direct shear specimen blocks with wave interfaces. g) Cross-section and zoom on the sine-wave interface with amplitude $A = 0.42$ mm and wavelength $\lambda = 2.80$ mm. h) Image of a printed specimen, zoomed on the interface.

455 Notice that this relation is purely geometrical and kinematic and neglects any deforma-
 456 tions due to high normal stress and/or hertzian contacts. These two factors could be taken
 457 into account in a more detailed analysis.

458 4.2 Wear and gouge formation

459 In our friction model, we intend to take into account the wear of asperities and the
 460 formation of gouge, due to the detachment of grains from the S3DP matrix (Figure 7e).
 461 Note that this gouge formation could mimic the creation of gouges in real faults (Marone
 462 & Scholz, 1989; Marone et al., 1990; Rattetz et al., 2018a, 2018b).

463 Queener et al. (1965) proposed a general law for wear, composed of an exponen-
 464 tial transient and a linear steady-state wear, which is compatible with wear observations
 465 in rock joint shear experiments (Power et al., 1988).

466 Abrasion gradually reduces the asperity amplitude (Li et al., 2016) (Figure 7e) and
 467 therefore the asperity friction affected by wear is denoted by $\mu_A^*(\delta_{pp})$. For very large dis-
 468 placements, $\mu_A(\delta_{pp})$ becomes zero and $\mu = \mu_b$ (Eq. (3)). We consider here exponen-
 469 tial abrasion, which reduces the apparent asperity friction coefficient $\mu_A^*(\delta_{pp})$:

$$\mu(\delta_{pp}) = \frac{\mu_b + \mu_A^*(\delta_{pp})}{1 - \mu_b \mu_A^*(\delta_{pp})} \quad (5)$$

$$\mu_A^*(\delta_{pp}) = \mu_A(\delta_{pp}) e^{-c_w \delta_{pp}} \quad (6)$$

470 The frictional behavior of this designed interface can therefore be adjusted through
 471 two asperity properties and two material parameters. These parameters are the wave-
 472 length λ , which governs the period in which the friction oscillates, and the amplitude A_0 ,
 473 which defines the asperity friction. Moreover, the material composition affects the ba-
 474 sic friction μ_b and the wear coefficient c_w .

475 In terms of vertical displacement, the maximum compaction $\delta_{v,max}(\delta)$ is a func-
 476 tion of the total shear displacement δ and can be described by an empirical exponential
 477 law (Power et al., 1988):

$$\delta_{v,max}(\delta) = \delta_{v,\infty} (1 - e^{-c_v \delta}) \quad (7)$$

478 where c_v is the vertical compaction coefficient and $\delta_{v,\infty}$ the final steady state compaction.

479 Moreover, we can superpose the oscillating vertical compaction-dilation $\delta_{v,A}$ due
 480 to the sliding over asperities (Eq. (4), see also Figure 7) to Eq. (7). As described above
 481 (Eq. (6)), the amplitude of the asperities decreases due to wear, governed by the wear
 482 coefficient c_w . The asperity dilation accounting for wear is then written as:

$$\delta_{v,A}^*(\delta_{pp}) = A_0 e^{(-c_w \delta_{pp})} \left[1 + \sin \left(\delta_{pp} \frac{2\pi}{\lambda} \right) \right] \quad (8)$$

483 The total vertical displacement is the sum of compaction and asperity dilation:

$$\delta_v(\delta_{pp}) = \delta_{v,max}(\delta) + \delta_{v,A}^*(\delta_{pp}), \quad \delta = \delta_{pp} + \delta_1 \quad (9)$$

484 where δ_1 is the total shear displacement at the first peak of the apparent friction coef-
 485 ficient. Power et al. (1988) stated that in laboratory shear tests, most of the wear oc-
 486 curs in the "transient wear phase". Laboratory specimens have a finite roughness scale,

487 and most of that initial roughness is destroyed during the initial, transient wear phase.
 488 Moreover, created gouge material often isolates the bare rock interfaces and reduces the
 489 apparent friction (Figure 7e). According to these authors, this first transient wear is fol-
 490 lowed by steady-state wear, which continues in laboratory tests under a relatively slow
 491 rate, as most of the asperities are flattened out. In real faults however, fault roughness
 492 is self-affine and covers a much larger range of scales (e.g. Schmittbuhl et al., 1993; Can-
 493 dela et al., 2012). As a result, the size of the asperities that must be broken increases
 494 approximately linearly with displacement. Hence, real faults never reach a steady state
 495 wear as experimental faults do (Power et al., 1988). However, similar to our experimen-
 496 tal results, the recent work of Dascher-Cousineau et al. (2018), using numerous samples
 497 from fault outcrops, showed that at a small scale (< 10 mm) fault surfaces indeed smoothen
 498 with slip. Note that in our experiments, we investigate a finite roughness scale, equal to
 499 the size of the sine-waves. Steady state wear is therefore expected to be negligible and
 500 not considered in the model.

501 4.3 Direct shear experiments with designed roughness

502 Direct shear experiments were performed on S3DP material with controlled rough-
 503 ness properties, to study the effectiveness of our theoretical friction design approach. For
 504 this purpose, we printed sine-wave interface asperities with a constant amplitude $A =$
 505 $3D_{50} = 0.42$ mm and constant wavelength $\lambda = 20D_{50} = 2.80$ mm, as shown in Figure
 506 7f-h.

507 A series of direct shear tests under a constant normal stress of 500 kPa was car-
 508 ried out on samples of the four different compositions. The specimens were initially loaded
 509 with a normal stress of 500 kPa and sheared under constant normal stress and constant
 510 displacement rate of 0.5 mm/min for 10 mm. After the maximum displacement was reached,
 511 the specimen was sheared in the reverse direction, until its initial position. In this way,
 512 a full loading cycle was performed, corresponding to a total of 20 mm of accumulated
 513 slip. Figures 8 (compositions R1 and R2) and 9 (compositions R3 and R4) present the
 514 evolution of the measured friction coefficient and the vertical displacement with progress-
 515 ing horizontal displacement. In particular, we show the apparent friction coefficient μ ,
 516 defined as the ratio of F_h/F_n . Negative values correspond to reverse shearing. One can
 517 clearly observe oscillations in the post-peak regime of the friction behavior, due to the
 518 wave geometry of the interfaces. The interlocking printed asperities induce a much higher
 519 peak friction, close to 1.0, compared to the one measured on the flat surface, close to 0.6.
 520 Once we exceed the peak, the friction decreases and drops to a lower level than the one
 521 determined on flat specimens (negative asperity friction angle i , see Eq. (1)). Then, the
 522 friction rises and falls in the form of damped oscillations, due to wear. In terms of ver-
 523 tical displacement, the specimens exhibit an overall compaction during shearing, com-
 524 bined with dilation peaks of decreasing amplitude.

525 In Table 2, we present different frictional properties evaluated from the experimen-
 526 tal results (Figures 8 and 9). The maximum friction coefficient measured at the first peak
 527 (μ_1) is shown along with the respective block's displacement (δ_1). At the end of the re-
 528 verse loading (negative apparent friction), the amplitude of friction oscillations becomes
 529 almost zero. Inspecting the specimens after the experiments confirmed that wear has flat-
 530 tened out the sine-wave asperities and left an almost flat interface. One can estimate the
 531 residual friction coefficient μ_∞ from the mean friction in this part of the experimental
 532 curve, which results in being almost identical to μ_b (asymptotical approximation for in-
 533 finite sliding). In theory, differences may arise due to a higher amount of gouge mate-
 534 rial present when evaluating μ_∞ . Comparing the values of μ_∞ with the results from flat
 535 interface shear experiments, no significant difference can be observed. The wavelengths
 536 λ_1 and λ_2 are the slip distances between two points of maximum and minimum friction,
 537 respectively. Their average value is λ , which corresponds in theory to the wavelength of
 538 the printed interface. It is important to note, that the characteristic slip-weakening dis-

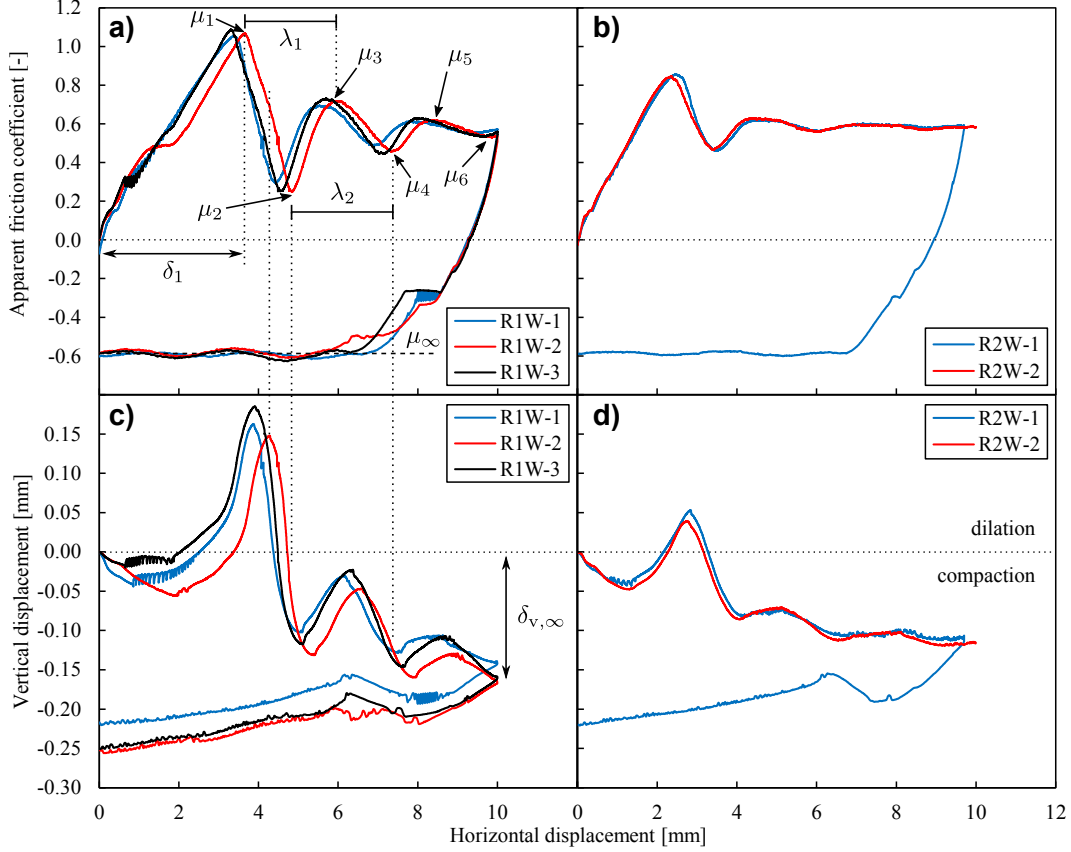


Figure 8. Results of direct shear experiments under 500 kPa normal stress on specimens R1 and R2 (Table 2). a), b) Friction coefficient and c), d) vertical displacement with respect to horizontal shear displacement. Note that due to technical problems, the reverse shearing of R2W-2 was not carried out.

539 tance d_c^{sw} (Figure 2b), over which the apparent friction decreases from its maximum to
 540 its minimum, is here equal to half of the wavelength λ (for sinusoidal interfaces).

541 **4.3.1 Effect of material composition**

542 For high binder content, the recoating speed (packing density) appears to have a
 543 minor influence on the friction, as we observe similar values $\mu_1 = 0.96$ and 0.93 for R3
 544 and R4, respectively. For low binder content, we measured $\mu_1 = 1.07$ for R1 and 0.88
 545 for R2. According to our results, higher density induces higher friction. Moreover, for
 546 high density, the friction is higher under low binder content. This is probably due to a
 547 higher possibility for grains to interlock in the absence of binder. The friction for large
 548 shear displacement μ_∞ does not appear to be significantly influenced by the material com-
 549 position, providing values close to 0.6 (Table 2), which is equal to μ_b measured on flat
 550 specimens in Section 3.2.

551 Regarding the average wavelength λ , we cannot see any clear influence of the material
 552 composition. These values are close to the designed geometric wavelength of the
 553 interface $\lambda = 2.40$ mm. Note that the vertical displacement shows the same wavelength,
 554 but, as expected, here the oscillations are shifted by $\approx \lambda/4$. This evidences that the beh-
 555 avior of vertical displacement is correlated with the asperity profile. In other words,
 556 the friction coefficient reaches its local extrema when the inclination of asperities (the

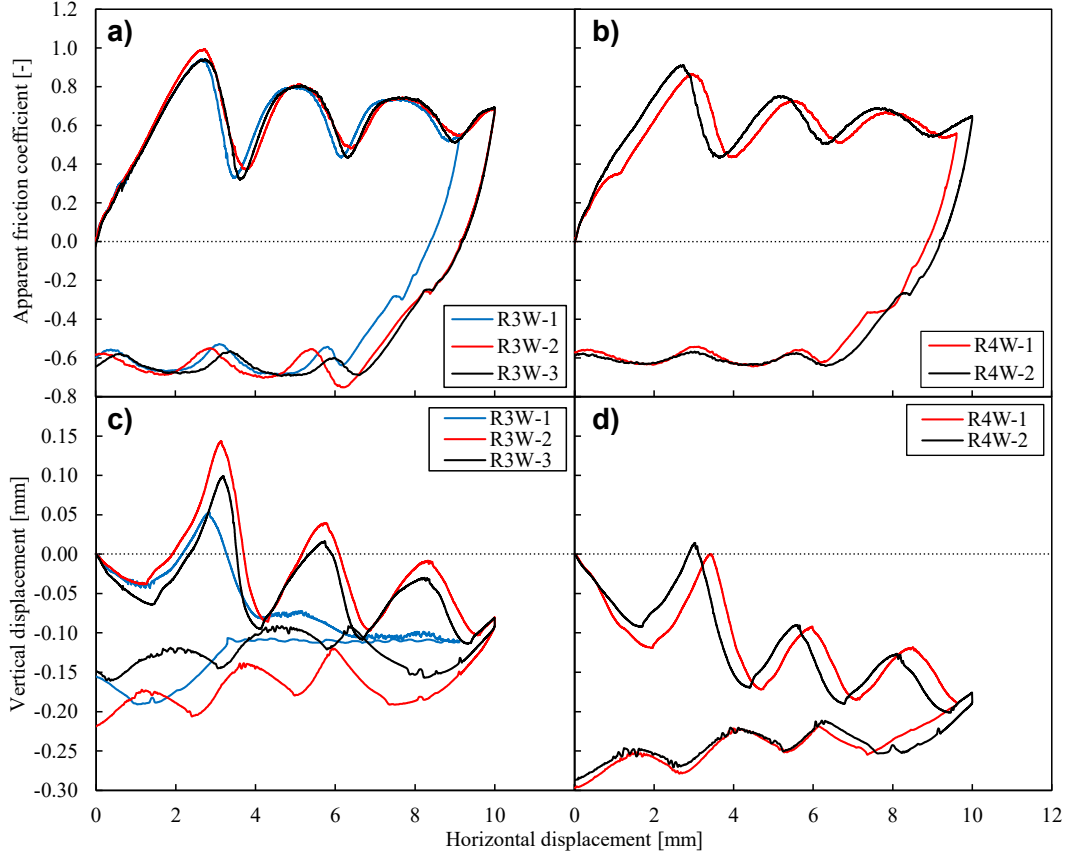


Figure 9. Results of direct shear experiments under 500 kPa normal stress on specimens R3 and R4 (Table 2). a), b) Friction coefficient and c), d) vertical displacement with respect to horizontal shear displacement.

557 slope of the vertical displacement over horizontal displacement) also has a local extremum
 558 (Figures 8 and 9).

559 The decrease of the friction amplitude differs between the compositions due to wear.
 560 For the R1 and R2 specimens (low binder content) the reduction of the amplitude is more
 561 prominent (Figure 8), and we observe a nearly constant friction at the end of the first
 562 loading phase and during the reverse loading. This residual friction coefficient corresponds
 563 to the one of a planar interface, due to complete abrasion of the asperities. This friction
 564 reduction can be approximated with an exponential law (Eq. (6)). Rewriting Eqs. (6)
 565 and (5), we can determine the relative asperity friction R_w , which is initially equal to
 566 1.0 and decreases to zero for progressing wear:

$$R_w = e^{-c_w \delta_{pp}} = \frac{(|\mu_i - \mu_\infty|)(1 + \mu_1 \mu_\infty)}{(\mu_1 - \mu_\infty)(1 + \mu_i \mu_\infty)} \quad (10)$$

567 The relative asperity friction is plotted for a typical experiment (R1W-1) in Fig-
 568 ure 10a, on which we can obtain the wear coefficient c_w through least square fitting (Ta-
 569 ble 2).

570 We observe a stronger dependency of the wear characteristics on binder content
 571 than on recoating speed. Compositions with a binder content $b = 3.8\%$ show c_w between

572 approximately 0.4 and 0.6, while for $b = 7.2$, we measured c_w between approximately
 573 0.2 and 0.4. Increasing the recoating speed, from 0.13 to 0.26 m/s, the average value of
 574 c_w increases for about 0.1.

Table 2. Mean values of the parameters determined from the direct shear tests under $\sigma_n = 100$ and 500 kPa on wave interfaces (see also Figures 8, 9 and 11), and their standard deviation (SD). The amplitude A_0 is back-calculated using Eq. (12).

	σ_n [kPa]	μ_1		λ		δ_1		μ_∞		c_w		$\delta_{v,\infty}$		c_v		A_0 [mm]
		mean	SD [%]	mean [mm]	SD [%]	mean [mm]	SD [%]	mean [-]	SD [%]	mean [-]	SD [%]	mean [-]	SD [%]			
R1	100	1.03	6.0	2.67	1.6	2.13	6.1	0.50	2.8	0.14	17.1	-0.16	24.7	0.40	2.6	0.149
R1	500	1.07	1.8	2.41	4.4	3.45	5.4	0.57	2.0	0.45	26.0	-0.18	5.6	0.21	8.9	0.118
R2	500	0.85	0.8	2.45	2.0	2.41	2.9	0.58	1.2	0.60	4.7	-0.12	10.5	0.36	29.9	0.071
R3	500	0.96	3.2	2.55	0.8	2.71	2.0	0.61	1.9	0.19	12.7	-0.11	4.6	0.42	21.3	0.091
R4	500	0.89	3.6	2.54	1.1	2.86	5.7	0.60	1.2	0.26	0.8	-0.20	7.1	0.43	29.5	0.078

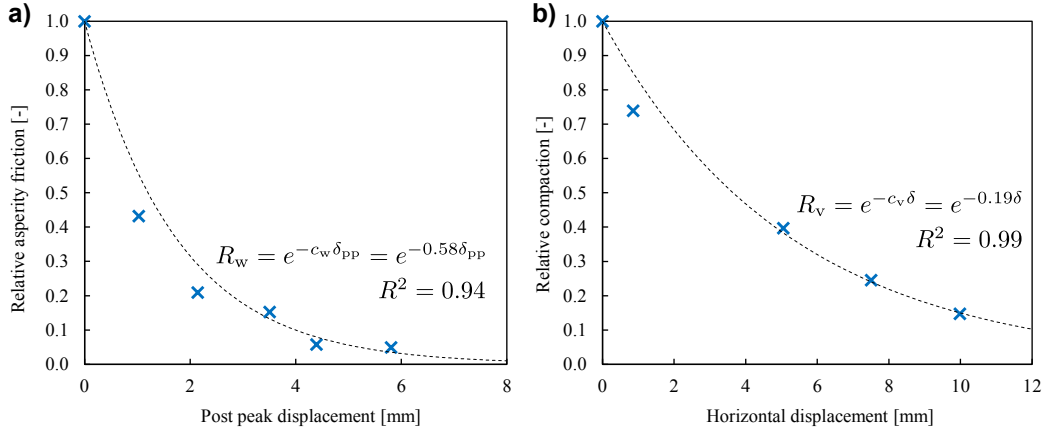


Figure 10. a) Decrease of relative asperity friction with progressing displacement and wear on a typical wave interface shear test (R1W-1). The wear coefficient c_w can be evaluated using an exponential fit. b) Measured relative vertical compaction on a typical wave shear experiment (R1W-1). The compaction is modeled through an exponential law, where the wear coefficient c_v can be evaluated using an exponential fit.

575 Evaluating the local minima $\delta_{v,i}$ of the vertical displacement evolution δ_v , one ob-
 576 serves a general compaction, which starts immediately at $\delta = 0$, before the first fric-
 577 tion peak. For large δ , the curves appear to approach a constant vertical displacement
 578 $\delta_{v,\infty}$ (cf. critical state, e.g. Wood, 1991). This global compaction is represented by the
 579 exponential law (Eq. (7)). Equation (7) can be rewritten, to introduce the relative com-
 580 paction R_v , which can be evaluated at the local peaks of vertical displacement:

$$R_v = e^{-c_v \delta} = 1 - \frac{\delta_{v,i}}{\delta_{v,\infty}} \quad (11)$$

581 The relative compaction values, determined on a typical experiment, are presented
 582 in Figure 10b. One can obtain the values of c_v and $\delta_{v,\infty}$ by a least square error fit. This

583 relationship captures only the overall vertical compaction, while in the experiments, we
 584 also observe significant oscillations due to asperities. In the following section, we are able
 585 to model these peaks of vertical displacement using Eqs. (7) - (9) with previously eval-
 586 uated properties. Consequently, no additional model parameters are required.

587 **4.3.2 Effect of normal stress**

588 In order to explore the influence of the applied normal stress on shear behavior,
 589 we carried out the same shear experiments under 100 kPa normal stress on specimens
 590 made of composition R1 (Figure 11, Table 2). The most important difference between
 591 the cases of 100 kPa and 500 kPa is observed on the wear, presented in terms of the wear
 592 coefficient c_w in Figure 11c. Otherwise, Coulomb's assumption of proportionality is valid.
 593 By reducing the normal stress, the decay of the friction oscillation is strongly reduced,
 594 giving a lower wear coefficient. Due to the lower normal stress, local stresses at the as-
 595 perities decrease, resulting in less breakage/chipping of the asperities. This becomes also
 596 clear on the measured specimen weight after the tests, which was almost two times higher
 597 for test under 500 kPa normal stress (average loss of ~ 1.7 g under 100 kPa and ~ 3.2
 598 g under 500 kPa).

599 No effect of the normal stress on the first peak friction coefficient μ_1 was reported
 600 (Figure 11d). Conversely, the residual friction μ_∞ appears to be slightly influenced by
 601 the normal stress (Figure 11e). Higher normal stress (500 kPa) leads to higher friction
 602 ($\mu_\infty \approx 0.57$), while under 100 kPa, we recorded $\mu_\infty \approx 0.50$.

603 **4.4 Validation of the design model**

604 We use the parameters evaluated on the five different test configurations (four com-
 605 positions, one additional normal stress level) and insert them in the model equations for
 606 calculating the apparent friction coefficient μ (Eq. (5)) and the vertical displacement δ_v
 607 (Eq. (9)) in function of the shear displacement δ . The effective amplitude A_0 is deter-
 608 mined indirectly from the wavelength, the basic friction and the first peak friction co-
 609 efficient $\mu = \mu_1$ (Eqs. (2) and (3)):

$$A_0 = \frac{\lambda(\mu_1 - \mu_b)}{2\pi(1 + \mu_1\mu_b)} \quad (12)$$

610 This model parameter A_0 can differ from the design amplitude A due to the print-
 611 ing resolution. Besides possible printing uncertainties, asperity abrasion could also oc-
 612 cur during transport and handling of the printed specimens. Moreover, during the mount-
 613 ing of specimens in the experimental devices, loose grains could deposit in the convex
 614 areas of the interface, which could prevent a complete interface contact and therefore re-
 615 duce the effective amplitude from A to A_0 . Given a printing resolution of $280 \mu\text{m}$ (cor-
 616 responding to two grain diameters), we expect an error of the amplitude A in this range,
 617 which is quite high. Therefore, the most reliable way for estimating the amplitude A_0
 618 for the interfaces designed herein is through Eq. (12).

619 Using the parameters presented in Table 2, we are able to calculate the expected
 620 friction behavior (Eq. (5)) and vertical displacement (Eq. (9)) of our laboratory exper-
 621 iments. The results of these calculations are presented in Figures 12, 13 and 14 together
 622 with the experimental curves. Notice that our main focus is on modeling the behavior
 623 after the first peak of friction. Before this point, in the loading branch, one could use
 624 a linear approximation for the shear force over shear displacement response and inter-
 625 polate the vertical displacement.

626 Our model mimics very well the measured friction behavior with its oscillations.
 627 In addition, the vertical displacement (compaction/dilatancy) can be reproduced well,
 628 requiring only the identification of the overall compaction curve (red dashed line) as ad-

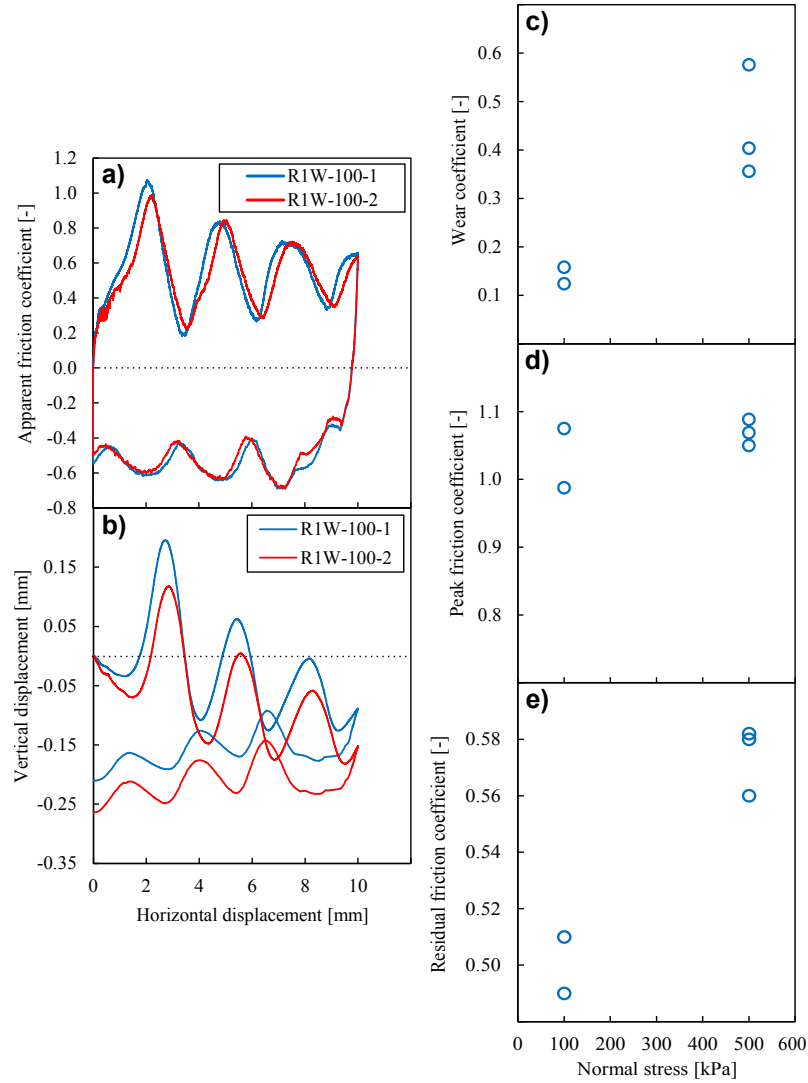


Figure 11. a), b) Friction experiments carried out on composition R1 under different 100 kPa of normal stress. c), d), e) Effect of normal stress on the friction characteristics: c) Wear coefficient, d) first peak friction and e) final friction of the abraded interface.

629 ditional model parameters. The additional oscillations (red solid line) are obtained from
 630 the relationships with the friction behavior, which confirm the model presented herein.
 631 As a result, this approach could be used for the design of interfaces of custom frictional
 632 properties (see Section 5).

633 5 Discussion

634 The presented experiments confirmed a good correspondence between the exper-
 635 imental behavior and our derived geometry-dependent friction law. The principal aspects
 636 and perspectives of this new method for creating analogue fault interfaces are discussed
 637 below.

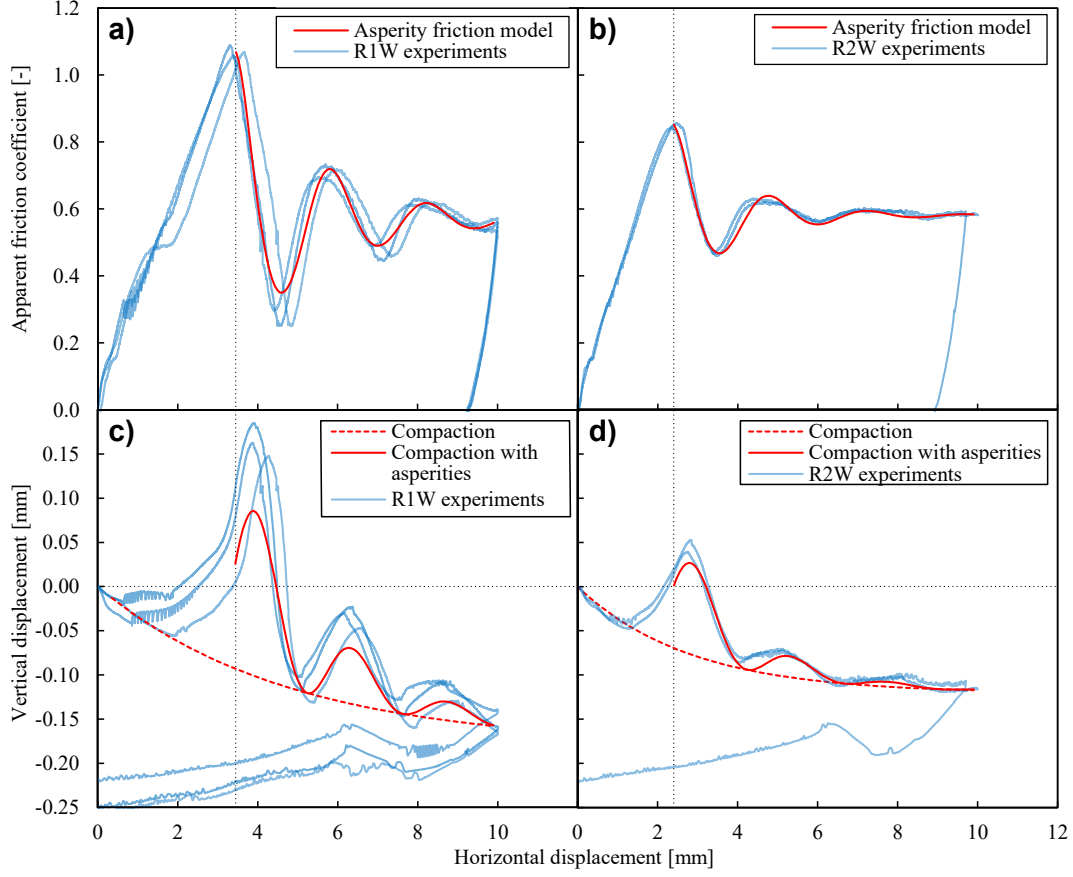


Figure 12. a), b) Evolution of friction and c), d) of vertical displacement with respect to the horizontal displacement, of R1 and R2 specimens under 500 kPa normal stress. The behavior calculated by our friction model (red solid lines) is compared with the experimental data (blue solid lines).

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5.1 Frictional weakening

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It is well-known how the stress drop (Noda et al., 2013) and the characteristic slip-weakening distance d_c^{sw} can lead to instabilities (see Figure 2 and also Dieterich, 1979; C. Scholz, 2002; Stefanou, 2019). Our surrogate experiments and model show that these properties can be adjusted by tuning the geometrical properties of the 3D-printed interfaces. For sinusoidal interfaces, we confirmed both theoretically and experimentally, that the characteristic slip distance d_c^{sw} is equivalent to half the asperity wavelength $d_c^{sw} = \lambda/2$ (see also Section 4.3). Using Eqs. (5) and (6), one can determine the friction drop $\Delta\mu = \mu(\delta_{pp} = \lambda/2) - \mu(\delta_{pp} = 0)$:

$$\Delta\mu = \left(1 + e^{-c_w\lambda/2}\right) \left(1 + \mu_b^2\right) \left[\frac{\lambda}{2\pi A_0} - \mu_b \left(1 + \frac{2\pi A_0}{\lambda}\right) + e^{-c_w\lambda/2}\mu_b \left(1 - \mu_b \frac{2\pi A_0}{\lambda}\right)\right]^{-1} \quad (13)$$

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In case of no wear, Eq. (13) simplifies to:

$$\Delta\mu = \frac{4A_0\pi}{\lambda} \frac{1 + \mu_b^2}{1 - 4\mu_b^2 A_0^2 \pi^2 \lambda^{-2}} \quad (14)$$

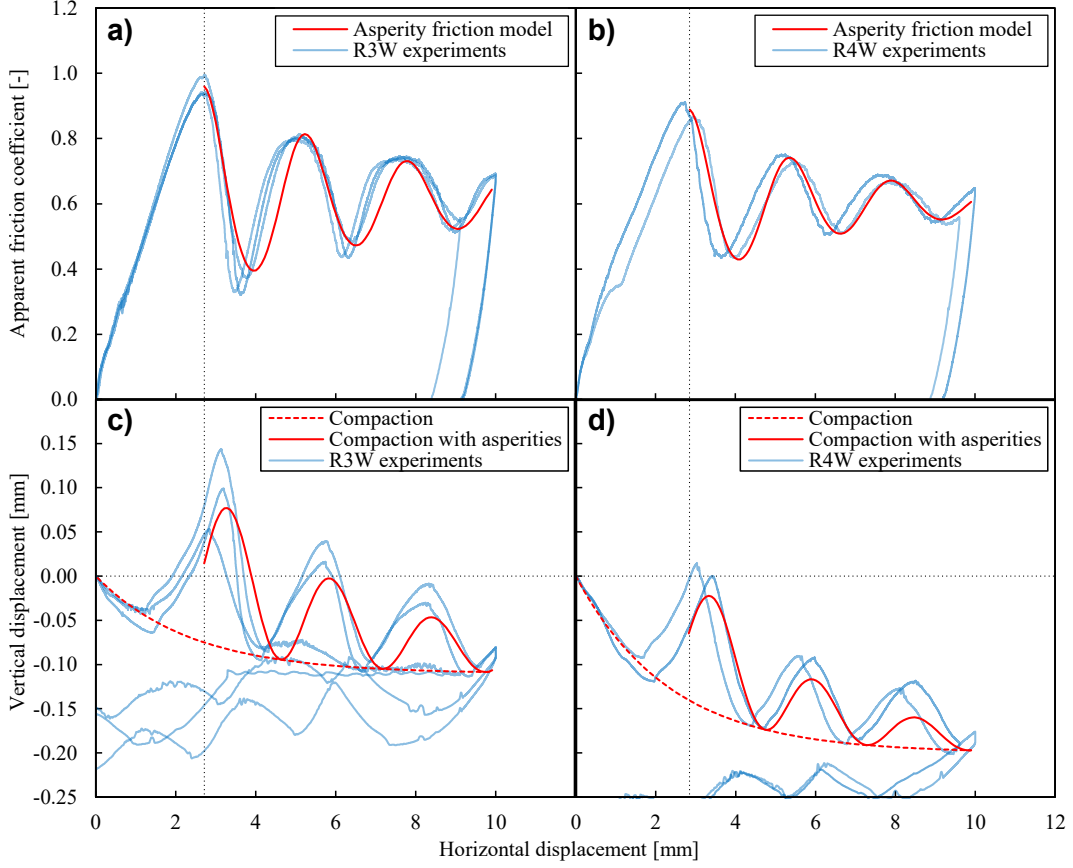


Figure 13. a), b) Evolution of friction and c), d) of vertical displacement with respect to the horizontal displacement, of R3 and R4 specimens under 500 kPa normal stress. The behavior calculated by our friction model (red solid lines) is compared with the experimental data (blue solid lines).

648 In addition, the slip-weakening slope, k_c , is highest at $\delta_{pp} = \lambda/4$, equal to (Eq. (5)):

$$k_c = -A_0 \frac{4\pi^2}{\lambda^2} (1 + \mu_b^2) \quad (15)$$

649 This slope is important for experiments focusing on reproducing the stick-slip behavior
 650 and earthquake-like events in the laboratory (see Section 2.4 and Dieterich (1978); Tinti
 651 et al. (2016); Scuderi et al. (2017); Stefanou (2019), among others).

652 Notice that by designing the roughness of the interfaces, we can adjust the slip-weakening
 653 behavior with great flexibility. Therefore, we are not limited by the intrinsic-fixed fric-
 654 tional properties (e.g. intrinsic rate-and-state friction) of the flat interfaces and we can
 655 design surrogate experiments with less constraints.

656 5.2 Wear, gouge production and dilatancy/compaction

657 Progressive sliding can influence the friction due to the wear of asperities, which
 658 is accompanied by gouge creation. The applied normal stress can have a non-negligible
 659 effect on the asperity wear. Higher normal stresses increase local shear and tensile stresses,
 660 which can lead to damage of the asperities and hence reduce the apparent friction. Our
 661 experiments showed that, while the material composition had a minor effect on the ini-

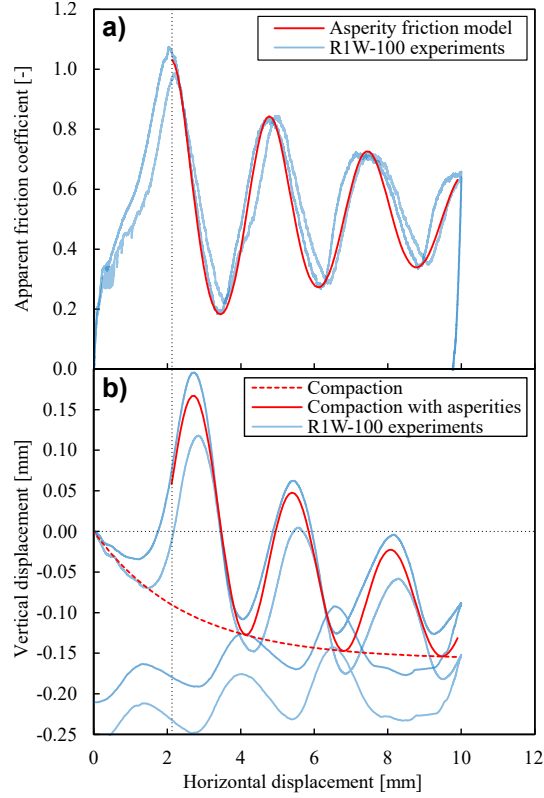


Figure 14. a) Evolution of friction and b) of vertical displacement with respect to the horizontal displacement, of R1 specimens under 100 kPa normal stress. The behavior calculated by our friction model (red solid lines) is compared with the experimental data (blue solid lines).

662 tial frictional behavior, it played a major role in wear. The resin binder is responsible
 663 for the material's tensile resistance and increased shear resistance due to grain bonding.
 664 Consequently, an increased binder content presumably reduces local failure of the asper-
 665 ities and preserves the designed and printed geometry of the interfaces.

666 In terms of dilatancy and compaction during shear, we observed a general compaction,
 667 accompanied by oscillating dilation due to the sinusoidal form of the interfaces tested
 668 herein. Wear is owed to the failure of the bonds between the grains, which progressively
 669 leads to the flattening of the interface, to the creation of gouge material and to compaction.
 670 The production of gouge material and compaction were evidenced by inspecting and weight-
 671 ing the specimens before and after shearing. The observed compaction reaches a con-
 672 stant value for large shear displacements, in accordance with the critical-state theory (Roscoe
 673 et al., 1958; Roscoe, 1970).

674 Notice that in their original state, the grains in the S3DP matrix have a very loose
 675 packing. After bond breakage, the grains are able to go into a denser packing causing
 676 a total volume reduction. Knowing the initial porosity (Table 1b), the measured verti-
 677 cal displacements $\delta_{v,\infty}$ (Table 2) and assuming a fault gouge density of 30%, we can roughly
 678 estimate the initial height of the damage/debonding zone. The thickness of this zone was
 679 equal to approximately $6D_{50}$. Due to denser packing at critical-state, this height reduces
 680 to approximately $4D_{50}$.

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5.3 Fault instabilities in the laboratory and their control parameters

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In order to transfer the behavior of an analogue experiment to the response of a real fault system, one has to employ scaling laws. By appropriate scaling of the lengths, the stresses, and the time (see Appendix A), one can simulate a real fault earthquake scenario in the laboratory. To this extent, the possibility of adjusting the frictional properties of the analogue fault interface as desired, gives a great flexibility for reproducing a wide spectrum of earthquake-like events in reduced scale in the laboratory.

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As an example, we consider two idealized faults. The first one has a length of $L_{ac}^{fault} = 3$ km, while the second one has 7 times smaller length, namely $L_{ac}^{fault} = 0.43$ km. Both are ideally oriented for slip and share the same properties. In particular, both faults have d_c^{fault} equal to 50 mm (see also Kanamori & Brodsky, 2004), an average in-situ effective normal stress σ_n^{fault} equal to 30 MPa that corresponds to a depth of 4-6 km, and an average shear stress drop $\Delta\tau^{fault}$ of 3 MPa (cf. Sibson, 2011). The apparent shear modulus G^{fault} of the rocks surrounding the fault is constant and equal to 30 GPa. For these parameters, the first case of a fault would result to an earthquake event of $M_w = 5.2$, while the second one would slide aseismically.

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Based on the frictional properties of the surrogate material presented in this work, the above two scenarios could be represented by two differently printed interfaces of the R1 composition. The first one has the same wavelength $\lambda_1 = 2.8$ mm, as the one studied in Section 4.3, while the second one has a wavelength of $\lambda_2 = 19.6$ mm, which is 7 times larger. In order to provoke the seismic instability in an analogue manner, one has to add a spring of stiffness $k_{spr}^{lab} = 441$ N/mm, as shown schematically in Figure 2. Using the scaling laws that are summarized in the Appendix A and by applying an effective normal stress, σ_n^{lab} , of 500 kPa over the printed interfaces of area 100×100 mm², the aforementioned idealized scenarios can be reproduced safely in the laboratory. Notice that the only difference in those tests is the geometry of the printed interfaces, i.e. the printed wavelength. Other adjustable model parameters could be the normal stress or the stiffness of the spring. However, being able to print the interfaces as desired gives an additional control parameter for the design of surrogate experiments. It is worth emphasizing that more complex configurations and tests could be conceptualized focusing also on the rupture propagation and slip direction along the printed curved interfaces following the studies of Marshall and Morris (2012); Romanet et al. (2020).

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Moreover, the observed frictional oscillations due to the printed geometry could be used for imitating sequences of healing and rupture during the seismic cycle. More generally, the frictional properties of any printed (also non-sinusoidal) interface profile with recurring geometrical features are controlled through the maximum and minimum profile angles i_{max} and i_{min} , the slip-weakening distance d_c^{sw} and the ‘‘healing’’ distance d_h as shown in Figure 15. The maximum and minimum angles govern the peak and minimum friction, respectively. The distance d_c^{sw} is equivalent to the displacement between the peak and the minimum friction (see also Figure 2b), while d_h defines the displacement from minimum to maximum friction. The sum $d_c^{sw} + d_h$ denotes the total displacement between recurring friction peaks. By connecting these two points of given angles using splines, one can obtain the complete interface profile with controlled properties. This pattern would lead to events of custom magnitude and periodicity, contrary to the ones that would appear due to the rate-and-state frictional properties of the flat interfaces, which are intrinsic to a given material.

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It is worth mentioning that in this study we investigated only interfaces with one (macro-) scale of asperities besides the micro-roughness owed to the grain-size. Our asperity scale was approaching the lower possible limit, due to the minimum printing resolution. Conversely, for larger asperity scales, the 3D-printing method is only limited by the printer’s size, and different scales could be combined in one specimen. Moreover, we used only a 2D height profile, while one could print interfaces with 3D profiles, includ-

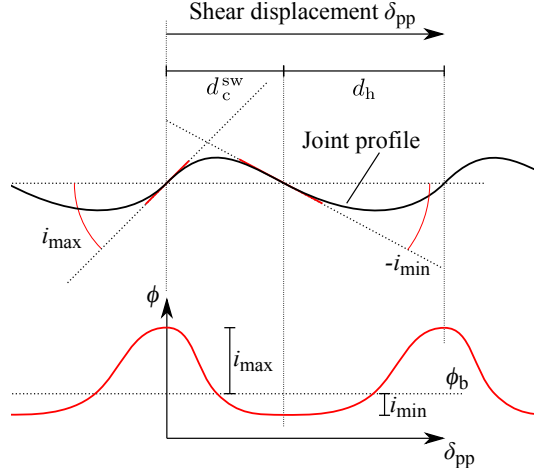


Figure 15. Schematic representation of a controlled joint friction behavior with adjustable maximum and minimum friction, slip and “healing” distance. Such interfaces could be used for mimicking earthquake cycles.

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ing for instance fault patches with different properties or in-situ roughness (Kirkpatrick et al., 2020). In addition, the permeability of the material could be adjusted through microstructural modifications (Mitra, El Mansori, et al., 2019) and printing of flow channels (Head & Vanorio, 2016), which would allow one to carry out experiments with the presence of fluid and to simulate anthropogenic injections around the fault zone.

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Other weakening mechanisms such as thermal pressurization, flash heating, melting or fluid injection at the fault were not considered in our approach and are worth of further investigation. These mechanisms could be potentially simulated in future experiments through fluid injection, heating, or shearing under high velocities and confinement, using the same or a modified S3DP material. Moreover, several effects, such as that of anisotropy, Poisson ratio, high confinement, porosity and fluid flow, to mention few, were not investigated in this work. Further works would be needed to address these issues.

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6 Conclusions

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Here we investigated, for the first time, the frictional properties of 3D sand-printed materials, which show a high potential for surrogate laboratory experiments involving frictional rock-like interfaces.

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Pursuing further the works of Gomez (2017); Gomez et al. (2019), we performed detailed uniaxial compression tests, in order to identify the main bulk mechanical parameters of this new surrogate material. For instance we measured the Young modulus which varies from around 0.2 up to 3.7 GPa. These values are close to the ones of weak sandstones (e.g. Dobereiner & Freitas, 1986; Papamichos et al., 2000).

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As far as it concerns the frictional properties, an apparent angle of friction of approximately 31° ($\mu \approx 0.6$) was determined based on direct-shear tests of flat sand-printed interfaces. This friction level is in the range of the friction angle of natural geomaterials and rock interfaces. The recoating speed and the binder saturation during printing showed to have a secondary role regarding the frictional behavior. However, these parameters did influence the creation of a thin gouge-like granular layer during shearing. Debonding of the granular particles are responsible for this thin layer, whose thickness was quantified in our experimental investigation.

762 The rate-and-state frictional parameters of flat 3D-printed interfaces were measured
 763 as well. It is worth mentioning that due to kinematics, the printed macro-roughness of
 764 other than flat interfaces was dominant over the measured rate-and-state frictional prop-
 765 erties measured on the flat interfaces. Therefore, for the design and modeling of the fric-
 766 tional response of the S3DP specimens with wave interfaces, the slip-weakening friction
 767 law was adopted.

768 Furthermore, we showed how to adequately design the printed geometry of the slid-
 769 ing interfaces, in order to obtain custom a) maximum, minimum and residual apparent
 770 frictional properties, b) characteristic slip-weakening distance d_c^{sw} , c) evolution of fric-
 771 tion coefficient with slip and d) dilatancy.

772 Experiments validated our design approach for achieving custom evolution of the
 773 apparent friction coefficient, which could be used to reproduce earthquake-like instabil-
 774 ities in the laboratory. Using adequate printing patterns, these earthquake-like instabil-
 775 ities could be designed to be periodic as well. Moreover, it is possible to control, to a cer-
 776 tain extent, the creation of a gouge-like layer by modifying the geometry of the asper-
 777 ities and the binder content. This could provide tools for future studies on the influence
 778 of gouge on frictional properties.

779 According to the above, this printing method gives new perspectives for the design
 780 of surrogate experiments in fault mechanics. For this purpose, adequate scaling laws can
 781 be developed for performing analogue experiments in the laboratory. An example of such
 782 an experiment was described in this work. This kind of experiments could shed light on
 783 open scientific questions related to induced/triggered seismicity and its control (Stefanou,
 784 2019, 2020). However, the use of this material is not limited in fault mechanics and can
 785 serve in other applications in geomechanics and geotechnics, such as tunneling, slope sta-
 786 bility and landslides, among others.

787 **Appendix A Scaling Laws for the S3DP material**

788 Using scaling laws, one could upscale experimental results to real earthquake events.
 789 The parameters that we scale in this study are the displacement, the normal stress, the
 790 constitutive friction law and the time. The effective normal stress in the laboratory σ_n^{lab}
 791 is scaled by the dimensionless factor \tilde{a} :

$$\sigma_n^{\text{fault}} = \tilde{a} \cdot \sigma_n^{\text{lab}} \quad (\text{A1})$$

792 The drop of the coefficient of friction $\Delta\mu^{\text{lab}}$ is scaled by the dimensionless factor \tilde{b} :

$$\Delta\mu^{\text{fault}} = \tilde{b} \cdot \Delta\mu^{\text{lab}} \quad (\text{A2})$$

793 Finally, the characteristic slip distance d_c^{lab} is scaled by the dimensionless factor \tilde{c} :

$$d_c^{\text{fault}} = \tilde{c} \cdot d_c^{\text{lab}} \quad (\text{A3})$$

794 Assuming slip-weakening frictional behavior (see Figure 2b), the normalized crit-
 795 ical post-peak stiffness \bar{k}_c ($= k_c/A$, where A is the area of the respective fault inter-
 796 face) of the S3DP material and the fault follows the same expression for both scales (Dieterich,
 797 1979; C. Scholz, 2002; Stefanou, 2019):

$$\bar{k}_c = \frac{\Delta\mu \cdot \sigma_n^{\text{lab}}}{d_c^{\text{sw}}} \quad (\text{A4})$$

798 If we combine Eqs. (A1)-(A5), we get the scaling relation between the normalized
799 critical post-peak stiffness in the laboratory and in the in-situ scales:

$$\bar{k}_c^{\text{fault}} = \frac{\tilde{a} \cdot \tilde{b}}{\tilde{c}} \bar{k}_c^{\text{lab}} \quad (\text{A5})$$

800 Analogously, we can scale the normalized elastic stiffness \bar{k} ($= k/A$, where k is the stiff-
801 ness of the spring) of the additional spring element (see Figure 2a) to the one of the rocks
802 surrounding the fault:

$$\bar{k}^{\text{fault}} = \frac{\tilde{a} \cdot \tilde{b}}{\tilde{c}} \bar{k}^{\text{lab}} \quad (\text{A6})$$

803 Consequently, the activated fault length $L_{\text{ac}}^{\text{fault}}$ can be calculated by the following expres-
804 sion (Dieterich, 1979, 1981b; C. Scholz, 2002):

$$L_{\text{ac}}^{\text{fault}} = \frac{G^{\text{fault}}}{\bar{k}^{\text{fault}}} \quad (\text{A7})$$

805 where G^{fault} is the apparent shear modulus of the rock material. The basic instability
806 condition of an analogue spring-slider model is given by $\bar{k} < \bar{k}_c$ (Dieterich, 1978; C. Scholz,
807 2002; Stefanou, 2019). Therefore, by using the obtained laboratory data and the ideal-
808 ized dip-slip fault properties for both examined scenarios in Section 5.3, we get:

$$\#1 : \quad \bar{k}^{\text{fault}} = 0.01 \text{ MPa/mm} < \bar{k}_c^{\text{fault}} = 0.06 \text{ MPa/mm} \quad (\text{A8})$$

$$\#2 : \quad \bar{k}^{\text{fault}} = 0.07 \text{ MPa/mm} > \bar{k}_c^{\text{fault}} = 0.06 \text{ MPa/mm} \quad (\text{A9})$$

809 Using Eq. (A7), the #1 scenario corresponds to a fault with length $L_{\text{ac},1}^{\text{fault}} = 3$ km,
810 while the #2 scenario to a fault with length $L_{\text{ac},2}^{\text{fault}} = 0.43$ km. As we can observe from
811 Eqs. (A8) and (A9), only in the #1 case, we experience a dynamic instability. In the #2
812 case, the respective fault slips aseismically. The estimated earthquake magnitude of the
813 nucleated instability of the #1 scenario can be derived by the following expression (Kanamori
814 & Brodsky, 2004):

$$M_w = \frac{2}{3} \log_{10} M_0 - 6.07 \quad (\text{A10})$$

815 where M_0 is the seismic moment of the event in [Nm], with $M_0 \approx \Delta\tau^{\text{fault}} (L_{\text{ac}}^{\text{fault}})^3$ (Kanamori
816 & Brodsky, 2004). Therefore, #1 fault scenario leads to an earthquake with magnitude
817 $M_w = 5.2$ (Eq. (A10)).

818 In addition, we can implicitly scale the characteristic time of the instability event
819 by introducing an additional dimensionless scaling factor \tilde{z} for the densities, as follows:

$$\rho^{\text{fault}} = \tilde{z} \cdot \rho^{\text{lab}} \quad (\text{A11})$$

820 where ρ^{fault} represents the apparent density of the fault rocks and ρ^{lab} the density of
821 the S3DP moving block. The characteristic time of the instability of the spring-slider
822 can be given by:

$$t_c = 2\pi\sqrt{\frac{m}{k}} \quad (\text{A12})$$

823 where m is the mass of the equivalent sliding block. The mobilized mass of the surround-
 824 ing rocks during the instability scales with $(L_{ac}^{\text{fault}})^3$ and the density ρ^{fault} (Stefanou,
 825 2019):

$$m^{\text{fault}} = \zeta \cdot \rho^{\text{fault}} \cdot (L_{ac}^{\text{fault}})^3 \quad (\text{A13})$$

826 where ζ is a shape factor which can be considered approximately equal to ~ 1 . On the
 827 other hand, the mass of a S3DP block can be written as:

$$m^{\text{lab}} = \rho^{\text{lab}} \cdot A^{\text{lab}} \cdot h^{\text{lab}} \quad (\text{A14})$$

828 where A^{lab} is the area of the frictional interface and h^{lab} is the height of the mobilized
 829 S3DP block (for parallelepiped blocks). Taking into account Eqs. (A6) and (A11)-(A14),
 830 one can derive the scaling relation of the characteristic fast time-scale of the system:

$$t_c^{\text{fault}} = \sqrt{\frac{\tilde{c} \cdot \tilde{z} \cdot L_{ac}^{\text{fault}}}{\tilde{a} \cdot \tilde{b} \cdot h^{\text{lab}}}} \cdot t_c^{\text{lab}} \quad (\text{A15})$$

831 For the distinction between the inherent fast and slow time-scales of the dynamics of the
 832 system we refer to Stefanou (2019).

833 Data Availability Statement

834 Data archiving is underway in <https://svn.ec-nantes.fr/>.

835 Acknowledgments

836 Funding: This work was supported by the European Research Council (ERC) under the
 837 European Union Horizon 2020 research and innovation program (Grant agreement no.
 838 757848 CoQuake), <http://coquake.com>.

839 Contribution: All authors contributed to the analysis and writing the manuscript.

840 Competing interests: The authors declare that they have no competing interests.

841 References

- 842 Andrews, D. J. (1976). Rupture velocity of plane strain shear cracks. *Journal of Geophysical Research (1896-1977)*, *81*(32), 5679-5687. Retrieved
 843 from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/
 844 JB081i032p05679](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB081i032p05679) doi: 10.1029/JB081i032p05679
- 845 Anthony, J. L., & Marone, C. (2005). Influence of particle characteristics on granular friction. *Journal of Geophysical Research*, *110*(B08409), 1-14. doi: 10.
 846 1029/2004JB003399
- 847 Asadi, M. S., Rasouli, V., & Barla, G. (2013). A Laboratory Shear Cell Used
 848 for Simulation of Shear Strength and Asperity Degradation of Rough Rock
 849 Fractures. *Rock Mechanics and Rock Engineering*, *46*(4), 683-699. doi:
 850 10.1007/s00603-012-0322-2
- 851 Barbot, S., Lapusta, N., & Avouac, J.-P. (2012). Under the Hood of the Earthquake
 852 Machine : Toward Predictive Modeling. *Science*, *336*(6082), 707-710. doi: 10.
 853 1126/science.1218796

- 856 Barton, N. (1973). Review of a new shear-strength criterion for rock joints. *Engi-*
 857 *neering Geology*, 7(4), 287 - 332. Retrieved from [http://www.sciencedirect](http://www.sciencedirect.com/science/article/pii/0013795273900136)
 858 [.com/science/article/pii/0013795273900136](http://www.sciencedirect.com/science/article/pii/0013795273900136) doi: [https://doi.org/](https://doi.org/10.1016/0013-7952(73)90013-6)
 859 [10.1016/0013-7952\(73\)90013-6](https://doi.org/10.1016/0013-7952(73)90013-6)
- 860 Bhattacharya, P., Rubin, A. M., Bayart, E., Savage, H. M., & Marone, C. (2015).
 861 Critical evaluation of state evolution fault laws in rate and state friction: Fitting
 862 large velocity steps in simulated fault gouge with time-, slip-, and stress-
 863 dependent constitutive laws. *Journal of Geophysical Research: Solid Earth*,
 864 120(9), 6365-6385. Retrieved from [https://agupubs.onlinelibrary.wiley](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015JB012437)
 865 [.com/doi/abs/10.1002/2015JB012437](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015JB012437) doi: 10.1002/2015JB012437
- 866 Birch, F. (1966). Compressibility: Elastic constants. In P. S. CLARK (Ed.), *Hand-*
 867 *book of physical constants* (97th ed., pp. 97–173). Geological Society of Amer-
 868 ica.
- 869 Bommer, J. J., Oates, S., Cepeda, J. M., Lindholm, C., Bird, J., Torres, R., ...
 870 Rivas, J. (2006). Control of hazard due to seismicity induced by a hot
 871 fractured rock geothermal project. *Engineering Geology*, 83(4), 287 - 306.
 872 Retrieved from [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/S0013795205003108)
 873 [S0013795205003108](http://www.sciencedirect.com/science/article/pii/S0013795205003108) doi: <https://doi.org/10.1016/j.enggeo.2005.11.002>
- 874 Brace, W. F., & Byerlee, J. D. (1966). Stick-slip as a mechanism for earthquakes.
 875 *Science*, 153(3739), 990–992. Retrieved from [https://science.sciencemag](https://science.sciencemag.org/content/153/3739/990)
 876 [.org/content/153/3739/990](https://science.sciencemag.org/content/153/3739/990) doi: 10.1126/science.153.3739.990
- 877 Brune, J. N. (1973). Earthquake modelling by stick-slip along precut surfaces in
 878 stressed foam rubber. *Bulletin of the Seismological Society of America*, 63(6),
 879 2105–2119. doi: 10.1016/0148-9062(74)90186-7
- 880 Candela, T., Renard, F., Klinger, Y., Mair, K., Schmittbuhl, J., & Brodsky,
 881 E. E. (2012). Roughness of fault surfaces over nine decades of length
 882 scales. *Journal of Geophysical Research: Solid Earth*, 117(8), 1–30. doi:
 883 [10.1029/2011JB009041](https://doi.org/10.1029/2011JB009041)
- 884 Collins-Craft, N. A., Stefanou, I., Sulem, J., & Einav, I. (2020). A cosserat
 885 breakage mechanics model for brittle granular media. *Journal of the Me-*
 886 *chanics and Physics of Solids*, 141, 103975. Retrieved from [http://](http://www.sciencedirect.com/science/article/pii/S0022509620302106)
 887 www.sciencedirect.com/science/article/pii/S0022509620302106 doi:
 888 <https://doi.org/10.1016/j.jmps.2020.103975>
- 889 Dascher-Cousineau, K., Kirkpatrick, J. D., & Cooke, M. L. (2018). Smoothing of
 890 Fault Slip Surfaces by Scale-Invariant Wear. *Journal of Geophysical Research:*
 891 *Solid Earth*, 123(9), 7913–7930. doi: 10.1029/2018JB015638
- 892 Dieterich, J. H. (1978). Time-dependent friction and the mechanics of stick-slip.
 893 *pure and applied geophysics*, 116, 790–806. Retrieved from [https://doi.org/](https://doi.org/10.1007/BF00876539)
 894 [10.1007/BF00876539](https://doi.org/10.1007/BF00876539) doi: 0.1007/BF00876539
- 895 Dieterich, J. H. (1979). Modeling of rock friction: 1. experimental results and consti-
 896 tutive equations. *Journal of Geophysical Research: Solid Earth*, 84(B5), 2161-
 897 2168. Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/abs/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB084iB05p02161)
 898 [10.1029/JB084iB05p02161](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB084iB05p02161) doi: 10.1029/JB084iB05p02161
- 899 Dieterich, J. H. (1981a). Constitutive properties of faults with simulated gouge. In
 900 *Mechanical behavior of crustal rocks* (p. 103-120). American Geophysical Union
 901 (AGU). Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/GM024p0103)
 902 [abs/10.1029/GM024p0103](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/GM024p0103) doi: 10.1029/GM024p0103
- 903 Dieterich, J. H. (1981b). Potential for geophysical experiments in large scale
 904 tests. *Geophysical Research Letters*, 8(7), 653-656. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/GL008i007p00653)
 905 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/GL008i007p00653
 906 doi: 10.1029/GL008i007p00653
- 907 Dieterich, J. H., & Kilgore, B. D. (1994, Mar 01). Direct observation of frictional
 908 contacts: New insights for state-dependent properties. *pure and applied*
 909 *geophysics*, 143(1), 283-302. Retrieved from [https://doi.org/10.1007/](https://doi.org/10.1007/BF00874332)
 910 [BF00874332](https://doi.org/10.1007/BF00874332) doi: 10.1007/BF00874332

- 911 Di Toro, G., Han, R., Hirose, T., De Paola, N., Nielsen, S., Mizoguchi, K., . . . Shi-
 912 mamoto, T. (2011, Mar 01). Fault lubrication during earthquakes. *Nature*,
 913 *471*(7339), 494-498. Retrieved from <https://doi.org/10.1038/nature09838>
 914 doi: 10.1038/nature09838
- 915 Dobereiner, L., & Freitas, M. H. D. (1986). Geotechnical properties of weak sand-
 916 stones. *Géotechnique*, *36*(1), 79-94. Retrieved from [https://doi.org/10](https://doi.org/10.1680/geot.1986.36.1.79)
 917 [.1680/geot.1986.36.1.79](https://doi.org/10.1680/geot.1986.36.1.79) doi: 10.1680/geot.1986.36.1.79
- 918 Edwards, B., Kraft, T., Cauzzi, C., Kästli, P., & Wiemer, S. (2015). Seismic
 919 monitoring and analysis of deep geothermal projects in St Gallen and Basel,
 920 Switzerland. *Geophysical Journal International*, *201*(2), 1022-1039. Retrieved
 921 from <https://doi.org/10.1093/gji/ggv059> doi: 10.1093/gji/ggv059
- 922 Fang, Y., Elsworth, D., Ishibashi, T., & Zhang, F. (2018). Permeability Evolu-
 923 tion and Frictional Stability of Fabricated Fractures With Specified Rough-
 924 ness. *Journal of Geophysical Research: Solid Earth*, *123*, 9355–9375. doi:
 925 10.1029/2018JB016215
- 926 Farzadi, A., Waran, V., Solati-Hashjin, M., Rahman, Z. A. A., Asadi, M., &
 927 Osman, N. A. A. (2015). Effect of layer printing delay on mechanical
 928 properties and dimensional accuracy of 3D printed porous prototypes in
 929 bone tissue engineering. *Ceramics International*, *41*(7), 8320–8330. Re-
 930 trieved from <http://dx.doi.org/10.1016/j.ceramint.2015.03.004> doi:
 931 10.1016/j.ceramint.2015.03.004
- 932 Gomez, J. S. (2017). *Mechanical Properties Characterization of Printed Reser-
 933 voir Sandstone Analogues* (Master's thesis, University of Alberta). Retrieved
 934 from [https://era.library.ualberta.ca/items/49660e82-3446-4a9a-9a74](https://era.library.ualberta.ca/items/49660e82-3446-4a9a-9a74-e5ff2ab38470/download/7e82347e-42db-4031-bc32-12134e5441d7)
 935 [-e5ff2ab38470/download/7e82347e-42db-4031-bc32-12134e5441d7](https://era.library.ualberta.ca/items/49660e82-3446-4a9a-9a74-e5ff2ab38470/download/7e82347e-42db-4031-bc32-12134e5441d7)
- 936 Gomez, J. S., Chalaturnyk, R. J., & Zambrano-Narvaez, G. (2019). Experi-
 937 mental Investigation of the Mechanical Behavior and Permeability of 3D
 938 Printed Sandstone Analogues Under Triaxial Conditions. *Transport in
 939 Porous Media*, *129*(2), 541–557. Retrieved from [https://doi.org/10.1007/](https://doi.org/10.1007/s11242-018-1177-0)
 940 [s11242-018-1177-0](https://doi.org/10.1007/s11242-018-1177-0) doi: 10.1007/s11242-018-1177-0
- 941 Goodman, R. E. (1989). *Introduction to rock mechanics* (Vol. 2). John Wiley &
 942 Sons.
- 943 Gu, J.-C., Rice, J. R., Ruina, A. L., & Tse, S. T. (1984). Slip motion and stabil-
 944 ity of a single degree of freedom elastic system with rate and state dependent
 945 friction. *Journal of the Mechanics and Physics of Solids*, *32*(3), 167 - 196.
 946 Retrieved from [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/0022509684900073)
 947 [0022509684900073](http://www.sciencedirect.com/science/article/pii/0022509684900073) doi: [https://doi.org/10.1016/0022-5096\(84\)90007-3](https://doi.org/10.1016/0022-5096(84)90007-3)
- 948 Head, D., & Vanorio, T. (2016). Effects of changes in rock microstructures on per-
 949 meability: 3-D printing investigation. *Geophysical Research Letters*, *43*(14),
 950 7494–7502. doi: 10.1002/2016GL069334.Received
- 951 Heslot, F., Baumberger, T., Perrin, B., Caroli, B., & Caroli, C. (1994). Creep, stick-
 952 slip, and dry-friction dynamics: Experiments and a heuristic model. *Physical
 953 Review E*, *49*(6), 4973–4988. doi: 10.1103/PhysRevE.49.4973
- 954 Huang, T., Chang, C., & Chao, C. (2002). Experimental and mathemati-
 955 cal modeling for fracture of rock joint with regular asperities. *Engineer-
 956 ing Fracture Mechanics*, *69*(17), 1977 - 1996. Retrieved from [http://](http://www.sciencedirect.com/science/article/pii/S0013794402000723)
 957 www.sciencedirect.com/science/article/pii/S0013794402000723 doi:
 958 [https://doi.org/10.1016/S0013-7944\(02\)00072-3](https://doi.org/10.1016/S0013-7944(02)00072-3)
- 959 Hunfeld, L. B., Chen, J., Niemeijer, A. R., & Spiers, C. J. (2019). Temperature and
 960 gas/brine content affect seismogenic potential of simulated fault gouges derived
 961 from groningen gas field caprock. *Geochemistry, Geophysics, Geosystems*,
 962 *20*(6), 2827-2847. Retrieved from [https://agupubs.onlinelibrary.wiley](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GC008221)
 963 [.com/doi/abs/10.1029/2019GC008221](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GC008221) doi: 10.1029/2019GC008221
- 964 Indraratna, B., Thirukumaran, S., Brown, E. T., & Zhu, S.-p. (2015). Modelling
 965 the Shear Behaviour of Rock Joints with Asperity Damage Under Constant

- 966 Normal Stiffness. *Rock Mechanics and Rock Engineering*, 48, 179–195. doi:
 967 10.1007/s00603-014-0556-2
- 968 Ishibashi, T., Fang, Y., Elsworth, D., Watanabe, N., & Asanuma, H. (2020).
 969 Hydromechanical properties of 3D printed fractures with controlled surface
 970 roughness : Insights into shear-permeability coupling processes. *International
 971 Journal of Rock Mechanics and Mining Sciences*, 128(February), 104271.
 972 Retrieved from <https://doi.org/10.1016/j.ijrmms.2020.104271> doi:
 973 10.1016/j.ijrmms.2020.104271
- 974 Jeanne, P., Guglielmi, Y., Rutqvist, J., Nussbaum, C., & Birkholzer, J. (2017). Field
 975 characterization of elastic properties across a fault zone reactivated by fluid
 976 injection. *Journal of Geophysical Research: Solid Earth*, 122(8), 6583–6598.
 977 doi: 10.1002/2017JB014384
- 978 Jones, L. (2018). *The big ones: How natural disasters have shaped us (and what we
 979 can do about them)*. Doubleday. (ISBN 978-178578-436-1)
- 980 Kanamori, H., & Brodsky, E. E. (2004). The physics of earthquakes. *Reports on
 981 Progress in Physics*, 67(8), 1429–1496. doi: 10.1088/0034-4885/67/8/R03
- 982 King, C.-y. (1975). Model Seismicity and Faulting Parameters. *Bulletin of the Seis-
 983 mological Society of America*, 65(1), 245–259.
- 984 Kirkpatrick, J. D., Edwards, J. H., Verdecchia, A., Kluesner, J. W., Harrington,
 985 R. M., & Silver, E. A. (2020). Subduction megathrust heterogeneity charac-
 986 terized from 3D seismic data. *Nature Geoscience*. Retrieved from [http://
 987 dx.doi.org/10.1038/s41561-020-0562-9](http://dx.doi.org/10.1038/s41561-020-0562-9) doi: 10.1038/s41561-020-0562-9
- 988 Knuth, M., & Marone, C. (2007). Friction of sheared granular layers: Role of par-
 989 ticle dimensionality, surface roughness, and material properties. *Geochemistry,
 990 Geophysics, Geosystems*, 8(3). doi: 10.1029/2006GC001327
- 991 Li, Y., Oh, J., Mitra, R., & Hebblewhite, B. (2016). A constitutive model for a
 992 laboratory rock joint with multi-scale asperity degradation. *Computers and
 993 Geotechnics*, 72, 143–151. doi: 10.1016/j.compgeo.2015.10.008
- 994 Marone, C. (1998). Laboratory-derived friction laws and their application to seis-
 995 mic faulting. *Annual Review of Earth and Planetary Sciences*, 26(1), 643–696.
 996 Retrieved from <https://doi.org/10.1146/annurev.earth.26.1.643> doi: 10
 997 .1146/annurev.earth.26.1.643
- 998 Marone, C., Raleigh, C. B., & Scholz, C. H. (1990). Frictional behavior and con-
 999 stitutive modeling of simulated fault gouge. *Journal of Geophysical Research:
 1000 Solid Earth*, 95(B5), 7007–7025. doi: 10.1029/JB095iB05p07007
- 1001 Marone, C., & Scholz, C. (1989). Particle-size distribution and microstruc-
 1002 tures within simulated fault gouge. *Journal of Structural Geology*, 11(7),
 1003 799 - 814. Retrieved from [http://www.sciencedirect.com/science/
 1004 article/pii/0191814189900990](http://www.sciencedirect.com/science/article/pii/0191814189900990) (Friction phenomena in rock) doi:
 1005 [https://doi.org/10.1016/0191-8141\(89\)90099-0](https://doi.org/10.1016/0191-8141(89)90099-0)
- 1006 Marshall, S. T., & Morris, A. C. (2012). Mechanics, slip behavior, and seismic po-
 1007 tential of corrugated dip-slip faults. *Journal of Geophysical Research: Solid
 1008 Earth*, 117(B3). Retrieved from [https://agupubs.onlinelibrary.wiley
 1009 .com/doi/abs/10.1029/2011JB008642](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011JB008642) doi: 10.1029/2011JB008642
- 1010 Mitra, S., El Mansori, M., Rodríguez, A., Castro, D., & Costin, M. (2019). Study
 1011 of the evolution of transport properties induced by additive processing sand
 1012 mold using X-ray computed tomography. *Journal of Materials Process-
 1013 ing Tech.*, 227(116495), 1–15. Retrieved from [https://doi.org/10.1016/
 1014 j.jmatprotec.2019.116495](https://doi.org/10.1016/j.jmatprotec.2019.116495) doi: 10.1016/j.jmatprotec.2019.116495
- 1015 Mitra, S., Rodríguez de Castro, A., & El Mansori, M. (2018). The effect of ageing
 1016 process on three-point bending strength and permeability of 3D printed sand
 1017 molds. *International Journal of Advanced Manufacturing Technology*, 97(1-4),
 1018 1241–1251. doi: 10.1007/s00170-018-2024-8
- 1019 Mitra, S., Rodríguez de Castro, A., & El Mansori, M. (2019). On the rapid manufac-
 1020 turing process of functional 3D printed sand molds. *Journal of Manufacturing*

- 1021 *Processes*, 42(March), 202–212. Retrieved from [https://doi.org/10.1016/j](https://doi.org/10.1016/j.jmapro.2019.04.034)
 1022 [.jmapro.2019.04.034](https://doi.org/10.1016/j.jmapro.2019.04.034) doi: 10.1016/j.jmapro.2019.04.034
- 1023 Newland, P. L., & Allely, B. H. (1957). Volume changes in drained triaxial tests on
 1024 granular materials. *Géotechnique*, 7(1), 17–34. Retrieved from [https://doi](https://doi.org/10.1680/geot.1957.7.1.17)
 1025 [.org/10.1680/geot.1957.7.1.17](https://doi.org/10.1680/geot.1957.7.1.17) doi: 10.1680/geot.1957.7.1.17
- 1026 Noda, H., Lapusta, N., & Kanamori, H. (2013, 03). Comparison of average stress
 1027 drop measures for ruptures with heterogeneous stress change and implica-
 1028 tions for earthquake physics. *Geophysical Journal International*, 193(3),
 1029 1691–1712. Retrieved from <https://doi.org/10.1093/gji/ggt074> doi:
 1030 [10.1093/gji/ggt074](https://doi.org/10.1093/gji/ggt074)
- 1031 Palmer, C., & Rice, J. R. (1973, April 03). The growth of slip surfaces in the pro-
 1032 gressive failure of over-consolidated clay. *Proceedings of The Royal Society A*
 1033 *Mathematical Physical and Engineering Sciences*, 332(1591), 527–548. doi:
 1034 <http://doi.org/10.1098/rspa.1973.0040>
- 1035 Papamichos, E., Tronvoll, J., Vardoulakis, I., Labuz, J. F., Skjærstein, A., Unan-
 1036 der, T. E., & Sulem, J. (2000). Constitutive testing of Red Wildmoor
 1037 sandstone. *Mechanics of Cohesive-Frictional Materials*, 5, 1–40. doi:
 1038 [10.1002/\(SICI\)1099-1484\(200001\)5](https://doi.org/10.1002/(SICI)1099-1484(200001)5)
- 1039 Patton, F. D. (1966). Multiple modes of shear failure in rock. In *Proc.*
 1040 *1st congr. int. soc. rock mech.* (pp. 509–513). Lisbon. Retrieved from
 1041 <https://www.onepetro.org/conference-paper/ISRM-1CONGRESS-1966-087>
- 1042 Pimienta, L., Fortin, J., & Guéguen, Y. (2015). Experimental study of Young’s
 1043 modulus dispersion and attenuation in fully saturated sandstones. *Geophysics*,
 1044 80(5), L57–L72. Retrieved from <https://doi.org/10.1190/geo2014-0532.1>
 1045 doi: 10.1190/geo2014-0532.1
- 1046 Popov, V. L., Grzempa, B., Starcevic, J., & Popov, M. (2012). Rate and state
 1047 dependent friction laws and the prediction of earthquakes: What can we
 1048 learn from laboratory models? *Tectonophysics*, 532–535, 291–300. doi:
 1049 [10.1016/j.tecto.2012.02.020](https://doi.org/10.1016/j.tecto.2012.02.020)
- 1050 Power, W. L., Tullis, T. E., & Weeks, J. D. (1988). Roughness and wear during
 1051 brittle faulting. *Journal of Geophysical Research: Solid Earth*, 93(B12), 15268–
 1052 15278. Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB093iB12p15268)
 1053 [abs/10.1029/JB093iB12p15268](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB093iB12p15268) doi: 10.1029/JB093iB12p15268
- 1054 Primkulov, B., Chalaturnyk, J., Chalaturnyk, R., & Narvaez, G. Z. (2017). 3D
 1055 Printed Sandstone Strength : Curing of Furfuryl Alcohol Resin-Based Sand-
 1056 stones. *3D Printing and Additive Manufacturing*, 4(3), 149–155. doi:
 1057 [10.1089/3dp.2017.0032](https://doi.org/10.1089/3dp.2017.0032)
- 1058 Queener, C., Smith, T., & Mitchell, W. (1965). Transient wear of machine parts.
 1059 *Wear*, 8(5), 391 – 400. Retrieved from [http://www.sciencedirect.com/](http://www.sciencedirect.com/science/article/pii/0043164865901705)
 1060 [science/article/pii/0043164865901705](http://www.sciencedirect.com/science/article/pii/0043164865901705) doi: [https://doi.org/10.1016/](https://doi.org/10.1016/0043-1648(65)90170-5)
 1061 [0043-1648\(65\)90170-5](https://doi.org/10.1016/0043-1648(65)90170-5)
- 1062 Rabinowicz, E. (1951). The nature of the static and kinetic coefficients of friction.
 1063 *Journal of Applied Physics*, 22(11), 1373–1379. doi: 10.1063/1.1699869
- 1064 Rabinowicz, E. (1956). Stick and slip. *Scientific American*, 194(5), 109–119. Re-
 1065 trieved from <http://www.jstor.org/stable/26122743>
- 1066 Rabinowicz, E. (1958). The intrinsic variables affecting the stick-slip process. *Pro-*
 1067 *ceedings of the Physical Society*, 71(4), 668–675. doi: 10.1088/0370-1328/71/4/
 1068 316
- 1069 Raleigh, C. B., Healy, J. H., & Bredehoeft, J. D. (1976). An Experiment in
 1070 Earthquake Control at Rangely, Colorado. *Science*, 191(4233), 1230–
 1071 1237. Retrieved from [http://www.sciencemag.org/cgi/doi/10.1126/](http://www.sciencemag.org/cgi/doi/10.1126/science.191.4233.1230)
 1072 [science.191.4233.1230](http://www.sciencemag.org/cgi/doi/10.1126/science.191.4233.1230) doi: 10.1126/science.191.4233.1230
- 1073 Rattez, H., Stefanou, I., & Sulem, J. (2018a). The importance of Thermo-Hydro-
 1074 Mechanical couplings and microstructure to strain localization in 3D con-
 1075 tinua with application to seismic faults. Part I: Theory and linear stability

- 1076 analysis. *Journal of the Mechanics and Physics of Solids*, 115(March), 54–
 1077 76. Retrieved from [https://linkinghub.elsevier.com/retrieve/pii/](https://linkinghub.elsevier.com/retrieve/pii/S0022509617309626)
 1078 [S0022509617309626](https://linkinghub.elsevier.com/retrieve/pii/S0022509617309626) doi: 10.1016/j.jmps.2018.03.004
- 1079 Rattez, H., Stefanou, I., Sulem, J., Veveakis, M., & Poulet, T. (2018b). The
 1080 importance of Thermo-Hydro-Mechanical couplings and microstructure
 1081 to strain localization in 3D continua with application to seismic faults.
 1082 Part II: Numerical implementation and post-bifurcation analysis. *Jour-*
 1083 *nal of the Mechanics and Physics of Solids*, 115, 1–29. Retrieved from
 1084 <https://linkinghub.elsevier.com/retrieve/pii/S0022509617309638>
 1085 doi: 10.1016/j.jmps.2018.03.003
- 1086 Reches, Z., & Lockner, D. A. (2010, Sep 01). Fault weakening and earthquake in-
 1087 stability by powder lubrication. *Nature*, 467(7314), 452-455. Retrieved from
 1088 <https://doi.org/10.1038/nature09348> doi: 10.1038/nature09348
- 1089 Rice, J. R. (2017). Heating, weakening and shear localization in earthquake rup-
 1090 ture. *Philosophical Transactions of the Royal Society A: Mathematical, Physi-*
 1091 *cal and Engineering Sciences*, 375(2103), 20160015. Retrieved from [https://](https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2016.0015)
 1092 royalsocietypublishing.org/doi/abs/10.1098/rsta.2016.0015 doi: 10
 1093 .1098/rsta.2016.0015
- 1094 Rice, J. R., Rudnicki, J. W., & Platt, J. D. (2014). Stability and localization
 1095 of rapid shear in fluid-saturated fault gouge: 1. linearized stability analysis.
 1096 *Journal of Geophysical Research: Solid Earth*, 119(5), 4311-4333. Retrieved
 1097 from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JB010710)
 1098 [2013JB010710](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JB010710) doi: 10.1002/2013JB010710
- 1099 Rice, J. R., & Ruina, A. L. (1983, 06). Stability of Steady Frictional Slipping. *Jour-*
 1100 *nal of Applied Mechanics*, 50(2), 343-349. Retrieved from [https://doi.org/](https://doi.org/10.1115/1.3167042)
 1101 [10.1115/1.3167042](https://doi.org/10.1115/1.3167042) doi: 10.1115/1.3167042
- 1102 Romanet, P., Sato, D. S., & Ando, R. (2020, 06). Curvature, a mechanical link be-
 1103 tween the geometrical complexities of a fault: application to bends, kinks and
 1104 rough faults. *Geophysical Journal International*, 223(1), 211-232. Retrieved
 1105 from <https://doi.org/10.1093/gji/ggaa308> doi: 10.1093/gji/ggaa308
- 1106 Roscoe, K. H. (1970). The influence of strains in soil mechanics. *Géotechnique*,
 1107 20(2), 129-170. Retrieved from [https://doi.org/10.1680/geot.1970.20.2](https://doi.org/10.1680/geot.1970.20.2.129)
 1108 [.129](https://doi.org/10.1680/geot.1970.20.2.129) doi: 10.1680/geot.1970.20.2.129
- 1109 Roscoe, K. H., Schofield, A. N., & Wroth, C. P. (1958). On the yielding of soils.
 1110 *Géotechnique*, 8(1), 22-53. Retrieved from [https://doi.org/10.1680/geot](https://doi.org/10.1680/geot.1958.8.1.22)
 1111 [.1958.8.1.22](https://doi.org/10.1680/geot.1958.8.1.22) doi: 10.1680/geot.1958.8.1.22
- 1112 Rosenau, M., Corbi, F., & Dominguez, S. (2017). Analogue earthquakes and seismic
 1113 cycles: experimental modelling across timescales. *Solid Earth*, 8(3), 597-635.
 1114 Retrieved from <https://hal.archives-ouvertes.fr/hal-01553120> doi: 10
 1115 .5194/se-8-597-2017
- 1116 Ruina, A. (1983). Slip instability and state variable friction laws. *Journal*
 1117 *of Geophysical Research: Solid Earth*, 88(B12), 10359-10370. Retrieved
 1118 from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB088iB12p10359)
 1119 [JB088iB12p10359](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB088iB12p10359) doi: 10.1029/JB088iB12p10359
- 1120 Sammis, C. G., Lockner, D. A., & Reches, Z. (2011, Dec 01). The role of adsorbed
 1121 water on the friction of a layer of submicron particles. *Pure and Applied Geo-*
 1122 *physics*, 168(12), 2325-2334. Retrieved from [https://doi.org/10.1007/](https://doi.org/10.1007/s00024-011-0324-0)
 1123 [s00024-011-0324-0](https://doi.org/10.1007/s00024-011-0324-0) doi: 10.1007/s00024-011-0324-0
- 1124 Schallamach, A. (1971). How does rubber slide? *Wear*, 17(4), 301 - 312. Re-
 1125 trieved from [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/0043164871900330)
 1126 [0043164871900330](http://www.sciencedirect.com/science/article/pii/0043164871900330) doi: [https://doi.org/10.1016/0043-1648\(71\)90033-0](https://doi.org/10.1016/0043-1648(71)90033-0)
- 1127 Schmittbuhl, J., Gentier, S., & Roux, S. (1993). Field measurements of the rough-
 1128 ness of fault surfaces. *Geophysical Research Letters*, 20(8), 639–641. doi: 10
 1129 .1029/93GL00170
- 1130 Scholz. (1998, Jan 01). Earthquakes and friction laws. *Nature*, 391(6662), 37-42. Re-

- 1131 trieved from <https://doi.org/10.1038/34097> doi: 10.1038/34097
- 1132 Scholz, C. (2002). *The Mechanics of Earthquakes and Faulting* (2nd ed.). New York:
- 1133 Cambridge University Press. doi: 10.1017/CBO9780511818516
- 1134 Schön, J. H. (2004). *Physical properties of rocks: Fundamentals and principles of*
- 1135 *petrophysics*. Elsevier.
- 1136 Schumacher, M., Deisinger, U., Detsch, R., & Ziegler, G. (2010). Indirect rapid pro-
- 1137 totyping of biphasic calcium phosphate scaffolds as bone substitutes : influence
- 1138 of phase composition , macroporosity and pore geometry on mechanical prop-
- 1139 erties. *Journal of Materials Science: Materials in Medicine*, *21*, 3119–3127.
- 1140 doi: 10.1007/s10856-010-4166-6
- 1141 Scuderi, M. M., Collettini, C., & Marone, C. (2017). Frictional stability
- 1142 and earthquake triggering during fluid pressure stimulation of an exper-
- 1143 imental fault. *Earth and Planetary Science Letters*, *477*, 84–96. doi:
- 1144 10.1016/j.epsl.2017.08.009
- 1145 Scuderi, M. M., Marone, C., Tinti, E., Di Stefano, G., & Collettini, C. (2016).
- 1146 Precursory changes in seismic velocity for the spectrum of earthquake failure
- 1147 modes. *Nature Geoscience*, *9*(9), 695–700. doi: 10.1038/ngeo2775
- 1148 Sibson, R. H. (2011, 01). The scope of earthquake geology. In *Geology of the Earth-*
- 1149 *quake Source: A Volume in Honour of Rick Sibson*. Geological Society of Lon-
- 1150 don. Retrieved from <https://doi.org/10.1144/SP359.18> doi: 10.1144/
- 1151 SP359.18
- 1152 Stefanou, I. (2019). Controlling anthropogenic and natural seismicity: Insights
- 1153 from active stabilization of the spring-slider model. *Journal of Geophys-*
- 1154 *ical Research: Solid Earth*, *124*(8), 8786–8802. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB017847)
- 1155 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB017847 doi:
- 1156 10.1029/2019JB017847
- 1157 Stefanou, I. (2020). Control Self-Organized Critical behavior and incite slow-slip in
- 1158 generalized Burridge-Knopoff models. *submitted for publication*.
- 1159 Tinti, E., Scuderi, M. M., Scognamiglio, L., Di Stefano, G., Marone, C., & Col-
- 1160 lettini, C. (2016). On the evolution of elastic properties during laboratory
- 1161 stick-slip experiments spanning the transition from slow slip to dynamic rup-
- 1162 ture. *Journal of Geophysical Research: Solid Earth*, *121*(12), 8569–8594.
- 1163 Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/abs/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JB013545)
- 1164 [10.1002/2016JB013545](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JB013545) doi: 10.1002/2016JB013545
- 1165 Tzortzopoulos, G., Braun, P., & Stefanou, I. (2020). Absorbent porous paper re-
- 1166 veals how earthquakes could be mitigated. *submitted to Geophysical Research*
- 1167 *Letters, manuscript 2020GL090792*.
- 1168 Tzortzopoulos, G., Stefanou, I., & Braun, P. (2019). Designing Experiments for Con-
- 1169 trolling earthQuakes (CoQuake) by Fluid Injection. In *12th hstam 2019 inter-*
- 1170 *national congress on mechanics*. Thessaloniki, Greece.
- 1171 Upadhyay, M., Sivarupan, T., & El Mansori, M. (2017). 3D printing for rapid sand
- 1172 casting—A review. *Journal of Manufacturing Processes*, *29*, 211–220. Re-
- 1173 trieved from <http://dx.doi.org/10.1016/j.jmapro.2017.07.017> doi: 10
- 1174 .1016/j.jmapro.2017.07.017
- 1175 Vaezi, M., & Chua, C. K. (2011). Effects of layer thickness and binder satu-
- 1176 ration level parameters on 3D printing process. *The International Jour-*
- 1177 *nal of Advanced Manufacturing Technology*, *53*, 275–284. doi: 10.1007/
- 1178 s00170-010-2821-1
- 1179 Viesca, R. C., & Garagash, D. I. (2015, Nov 01). Ubiquitous weakening of faults due
- 1180 to thermal pressurization. *Nature Geoscience*, *8*(11), 875–879. Retrieved from
- 1181 <https://doi.org/10.1038/ngeo2554> doi: 10.1038/ngeo2554
- 1182 Vlasea, M., Pilliar, R., & Toyserkani, E. (2015). Control of Structural and Me-
- 1183 chanical Properties in Bioceramic Bone Substitutes via Additive Manufac-
- 1184 turing Layer Stacking Orientation. *Additive Manufacturing*, *6*, 30–38. Re-
- 1185 trieved from <http://dx.doi.org/10.1016/j.addma.2015.03.001> doi:

1186 10.1016/j.addma.2015.03.001
1187 Wood, D. M. (1991). Plasticity and yielding. In *Soil behaviour and critical state soil mechanics* (p. 55–83). Cambridge University Press. doi:
1188 10.1017/CBO9781139878272.004
1189