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Antonio Rodríguez de Castro, Giovanni Radilla

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1 **Flow of Yield Stress and Carreau fluids through Rough-Walled Rock Fractures:**  
2 **prediction and experiments**

3 Antonio Rodríguez de Castro\* (1,2), Giovanni Radilla (1,3)

4

5 (1) Arts et Métiers ParisTech, 51006 Châlons-en-Champagne, France

6 (2) Laboratoire MSMP – EA7350, Rue Saint Dominique, 51006 Châlons-en-Champagne,  
7 France

8 (3) LEMTA, UMR 7563, CNRS, 54518 Vandœuvre-lès-Nancy, France

9

10

11

12 \*Corresponding author

13 Dr. Antonio Rodríguez de Castro

14 Arts et Métiers ParisTech

15 Rue Saint-Dominique

16 51006 Châlons-en-Champagne

17 France

18 Tel: +33 326699173

19 Email: [antonio.rodriguezdecastro@ensam.eu](mailto:antonio.rodriguezdecastro@ensam.eu)

20

21 **Abstract**

22

23 Many natural phenomena in geophysics and hydrogeology involve the flow of non-  
24 Newtonian fluids through natural rough-walled fractures. Therefore, there is considerable  
25 interest in predicting the pressure drop generated by complex flow in these media under a  
26 given set of boundary conditions. However, this task is markedly more challenging than the  
27 Newtonian case given the coupling of geometrical and rheological parameters in the flow  
28 law. The main contribution of this paper is to propose a simple method to predict the flow of  
29 commonly used Carreau and yield stress fluids through fractures. To do so, an expression  
30 relating the “*in-situ*” shear viscosity of the fluid to the bulk shear-viscosity parameters is  
31 obtained. Then, this “*in-situ*” viscosity is entered in the macroscopic laws to predict the flow  
32 rate-pressure gradient relations. Experiments with yield stress and Carreau fluids in two  
33 replicas of natural fractures covering a wide range of injection flow rates are presented and  
34 compared to the predictions of the proposed method. Our results show that the use of a  
35 constant shift parameter to relate “*in-situ*” and bulk shear viscosity is no longer valid in the  
36 presence of a yield stress or a plateau viscosity. Consequently, properly representing the  
37 dependence of the shift parameter on the flow rate is crucial to obtain accurate predictions.  
38 The proposed method predicts the pressure drop in a rough-walled fracture at a given  
39 injection flow rate by only using the shear rheology of the fluid, the hydraulic aperture of the  
40 fracture and the inertial coefficients as inputs.

41

## 42 **1. Introduction**

43

44 The flow of complex fluids through rough-walled rock fractures is involved in many  
45 economically important industrial applications, such as soil remediation, hydrogeology or  
46 Enhanced Oil Recovery (EOR) [*Radilla et al.*, 2013; *Tosco et al.*, 2013; *Coussot*, 2014].  
47 Numerous complex fluids are shear-thinning, showing a decrease in shear viscosity as the  
48 applied shear rate is increased. Shear-thinning fluids are extensively used in petroleum  
49 engineering and soil remediation to improve the microscopic sweep of the reservoir through  
50 stabilization of the injection front [*Lake*, 1989; *Silva et al.*, 2012; *Wever et al.*, 2011]. For  
51 instance, shear-thinning drilling fluids containing the biopolymer xanthan [*Zhong et al.*,  
52 2008; *Truex et al.*, 2015] and other polymers such as polyacrylamide [*Ball and Pitts*, 1984],  
53 carboxymethylcellulose [*Zhang et al.*, 2016] and guar gum [*Hernández-Espriú et al.*, 2013]  
54 are widely used in EOR.

55

56 In some cases, fluids with shear-rate dependent viscosity also present a yield stress, i.e. a  
57 threshold value in terms of shear stress below which they do not flow. Many complex fluids  
58 used in industrial applications exhibit yield stress behaviour, e.g. polymer solutions, waxy  
59 crude oils, volcanic lavas, emulsions, colloid suspensions, foams, etc. [*Coussot*, 2005;  
60 *Dimitriou and McKinley*, 2015; *Roustaei et al.*, 2016; *Talon et al.*, 2014; *Lavrov*, 2013;  
61 *Coussot*, 2014]. Common examples of yield stress shear-thinning fluids are the slurries or  
62 cement grouts injected to reinforce soils, the heavy oils or the drilling fluids injected into  
63 rocks for the reinforcement of wells [*Lavrov*, 2013; *Coussot*, 2014]. Indeed, drilling fluids are  
64 often designed so as to have a yield stress in order to prevent cutting from settling when  
65 circulation stops [*Lavrov*, 2013]. Also, a number of fracturing fluids used in hydraulic

66 fracturing exhibit a yield stress designed to enhance proppant transport [*Talon et al.*, 2014;  
67 Roustaei et al., 2016] and present shear-thinning behaviour [*Lavrov*, 2015; *Perkowska et al.*,  
68 2016].

69

70 For these reasons, the flow of shear-thinning fluids in porous media, and in particular that of  
71 yield stress fluids, has become a field of great research interest [*Chevalier et al.*, 2013;  
72 *Chevalier et al.*, 2014; *Coussot*, 2014; *Talon et al.*, 2014; *Rodríguez de Castro et al.*, 2016].  
73 However, although recent advances have been made [*Chevalier et al.*, 2013; *Chevalier et al.*,  
74 2014], obtaining a macroscopic law to predict pressure drop as a function of flow rate has  
75 proved to be a stumbling-block. Also, despite its broad interest, a serious lack of  
76 experimental works involving the flow of yield stress fluids was reported by *Lavrov* [2013]  
77 and *Coussot* [2014].

78

79 Inspired by the growing scope of industrial applications in which shear-thinning and yield  
80 stress fluids are injected through rough-walled fractures, the objective of this work is to  
81 present a simple method to predict the pressure losses generated during single-phase flow.  
82 The accuracy of the resulting predictions is then evaluated through comparison with  
83 experimental data. To do so, a series of flow experiments with concentrated aqueous  
84 solutions of xanthan biopolymer presenting a yield stress were carried out by measuring the  
85 pressure drop as a function of the injection flow rate during the flow through two replicas of  
86 rough-walled natural fractures (granite and Vosges sandstone). Furthermore, previously  
87 presented experimental data involving the flow of shear-thinning with no yield stress are also  
88 compared with the predictions obtained with the proposed method.

89

90 The single-phase flow of incompressible Newtonian fluids through porous media is governed  
91 by Darcy's law [*Darcy*, 1856]. In the case of one-directional steady flow through a horizontal  
92 porous media, this law is written as:

93

$$\nabla P = \frac{\mu Q}{KA} = \frac{\mu}{K} u \quad (1)$$

94  $\nabla P = \frac{\Delta P}{L}$  being the pressure gradient,  $\Delta P$  the absolute value of the pressure drop over a  
95 distance  $L$ ,  $Q$  the volumetric flow rate,  $A$  the cross-sectional area,  $u = Q/A$  the average  
96 velocity,  $\mu$  the viscosity of the injected fluid, and  $K$  the intrinsic permeability. This model is  
97 restricted to creeping flow in which inertial forces are negligible compared to viscous forces  
98 [*Schneebeli*, 1955; *Hubbert*, 1956; *Scheidegger*, 1960; *Chauveteau and Thirriot*, 1967].  
99 Nonlinearity of fluid flow stems from inertial pressure losses generated by the repeated  
100 accelerations and decelerations due to rapid changes in flow velocity and direction along the  
101 flow path. Both theoretical and empirical models taking into account the extra pressure losses  
102 due to inertial effects were presented in the literature [*Miskimins et al.*, 2005]. The results of  
103 these studies confirm the existence of a strong inertial regime and a weak inertial regime. The  
104 nonlinear behaviors associated to those regimes can be described respectively by a quadratic  
105 and a cubic function of the average velocity. Forchheimer's empirical law [*Forchheimer*,  
106 1901] is commonly used to model the strong inertial regime through addition of a quadratic  
107 flow rate term to Darcy's law:

108

109

$$\nabla P = \frac{\mu}{K}u + \beta\rho u^2 \quad (2)$$

110 where  $\rho$  is the fluid density and  $\beta$  is the inertial coefficient. Forchheimer's law has been  
 111 experimentally validated [*Dullien and Azzam, 1973; Geertsma, 1974; MacDonald et al.,*  
 112 *1979; Rasoloarijaona and Auriault, 1994; Javadi et al., 2014; Rodríguez de Castro and*  
 113 *Radilla, 2016a*] and has found some theoretical justifications [*Cvetkovic, 1986; Giorgi, 1997;*  
 114 *Chen et al., 2001*]. In the case of the weak inertial regime, which occurs at moderate values  
 115 of the Reynolds number, deviations from the linear relationship between flow rate and  
 116 pressure loss were shown to follow a cubic function of the mean velocity in the porous media  
 117 [*Mei and Auriault, 1991; Firdaouss et al., 1997; Fourar et al., 2004; Rocha and Cruz, 2010*].

118

$$\nabla P = \frac{\mu}{K}u + \frac{d\rho^2}{\mu}u^3 \quad (3)$$

119

120 where  $d$  is a dimensionless inertial coefficient. Reynolds number can be specifically defined  
 121 for weak inertia cubic law as [*Radilla et al., 2013; Rodríguez de Castro and Radilla, 2016a*].

122

$$Re_c = \sqrt{Kd} \frac{\rho Q}{\mu A} \quad (4)$$

123 Cubic law was obtained from numerical simulations in a 2D periodic porous medium  
 124 [*Barrère et al., 1990; Fidarous and Guermond, 1995; Amaral Souto and Moyne, 1997*] and  
 125 also by using the homogenization technique for isotropic homogeneous porous media [*Mei*



126 *and Auriault, 1991; Wodie and Levy, 1991*]. This law was shown to be in agreement with  
127 experimental data [*Firdaous et al., 1997; Rodríguez de Castro and Radilla, 2016a*].

128

129 Using the asymptotic expansions method in a thin cylindrical channel with oscillating walls  
130 and averaging over the channel diameter, *Buès et al. [2004]* and *Panfilov and Fouar [2006]*  
131 presented a macroscopic flow equation which proved to be in good agreement with numerical  
132 simulations in rectangular and cylindrical fractures at high flow rates. This flow equation was  
133 expressed in the form of a full cubic law:

134

$$\nabla P = \frac{\mu}{K} u + \beta \rho u^2 + \frac{d \rho^2}{\mu} u^3 \quad (5)$$

135 where  $\beta$  and  $d$  are the inertial coefficients which may be positive or negative, depending on  
136 the channel geometry.  $\beta$  and  $d$  were shown to be independent of the shear rheology of the  
137 injected fluid in previous numerical [*Firdaouss et al., 1997; Yadzchi and Luding, 2012; Tosco*  
138 *et al., 2013*] and experimental works [*Rodríguez de Castro and Radilla, 2016a; Rodríguez de*  
139 *Castro and Radilla, 2016b*]. In this full cubic law, the quadratic term describes the pure  
140 inertia effect caused by an irreversible loss of kinetic energy due to flow acceleration and the  
141 cubic term corresponds to a cross viscous–inertia effect caused by the streamline deformation  
142 due to inertia forces. This macroscopic flow equation is valid not only in the Darcian flow  
143 regime but also, to some limited extent, for the non-Darcian flow regimes.  $\beta$  and  $d$  can be  
144 obtained either through fitting to experimental data [*Dukhan et al., 2014; Rodríguez de*  
145 *Castro and Radilla, 2016a, 2016b*] or through theoretical predictions obtained from porosity,  
146 permeability and roughness of the porous medium [*Cornell and Katz, 1953; Geertsma, 1974;*  
147 *Neasham, 1977; Noman and Archer, 1987; López, 2004, Agnaou et al., 2016*].

148

149 Analogously to the case of cubic law, Reynolds number can be defined for full cubic law as  
150 [*Radilla et al.*, 2013; *Rodríguez de Castro and Radilla*, 2016a]:

151

$$\text{Re}_{fc} = \frac{K\beta\rho u}{\mu} \quad (6)$$

152

153 Previous experimental works demonstrated that Darcy's law fails to predict pressure drops in  
154 fractures when inertial effects are relevant [*Zimmerman et al.*, 2004; *Radilla et al.*, 2013;  
155 *Javadi et al.*, 2014; *Rodríguez de Castro and Radilla*, 2016a, 2016b]. *Zimmerman et al.*  
156 [2004] presented experimental data on non-creeping flow through a rock fracture, showing  
157 good agreement with Forchheimer's model. The same authors also proved, via numerical  
158 solution of the Navier-Stokes equations, the existence of the weak inertia regime for  
159 moderate values of Reynolds numbers. *Radilla et al.* [2013] modelled single-phase flow  
160 experiments by means of the full cubic law and presented an elegant method to compare  
161 fractures in terms of hydraulic behaviour versus flow regime using the intrinsic  
162 hydrodynamic parameters. Besides, a geometrical model for non-linear fluid flow through  
163 rough fractures was proposed and evaluated through numerical simulations by *Javadi et al.*  
164 [2010]. More recently, *Roustaei et al.* [2016] numerically investigated the 2D-flow of a yield  
165 stress fluid along an uneven fracture, showing that important Darcy-type flow law lead to  
166 important errors in the case of short fractures due to self-selection of the flowing region and  
167 the existence of fouling layers of unyielded fluid.

168

169 Several authors showed that the intrinsic permeability  $K$  and the cross-sectional area  $A$  used  
170 in Eqs (1) to (5) can be written as functions of the hydraulic aperture of the fracture  $h$   
171 [*Witherspoon et al.*, 1980; *Brown*, 1987; *Zimmerman and Yeo*, 2000; *Brush and Thomson*,  
172 2003]:

$$K = \frac{h^2}{12} \quad (7)$$

174

$$A = hw \quad (8)$$

175 The aperture distribution of rough-walled rock fractures always presents a strong  
176 heterogeneity, due to the wide range of aperture sizes and the significant number of contact  
177 points [*Witherspoon et al.*, 1980; *Xiong et al.*, 2011; *Javidi et al.*, 2014; *Wang et al.*, 2016].

178 The hydraulic behaviour through a fracture is known to be heavily dependent upon the  
179 apertures distribution [*Isakov et al.*, 2001; *Javidi et al.*, 2014; *Wang et al.*, 2016]. This is  
180 explained by the tendency of the fluid to flow through the paths with the largest apertures.  
181 Moreover, within a given path, the hydraulic behaviour of fracture would be controlled by the  
182 small apertures and constrictions [*Tsang and Tsang*, 1987; *Neuzil and Tracy*, 1981].

183

184 Several attempts have been made to obtain a macroscopic law linking the injection flow rate  
185 to the resulting pressure drop during the flow of yield stress fluids in porous media [*Pascal*,  
186 1983; *Al-Fariss and Pinder*, 1987; *Chase and Dachavijit*, 2005; *Coussot*, 2014]. A major  
187 drawback of most available expressions is the existence of experimentally adjustable

188 parameters with no clear physical meaning as inputs, which impedes direct computational  
189 predictions. As an alternative, some pore-network approaches have also been proposed [*Chen*  
190 *et al.*, 2005; *Sochi and Blunt*, 2008]. The main advantage of pore-network models is that they  
191 provide a reasonably realistic description of the reality in which the number of flow paths  
192 through the porous media increases with the applied pressure gradient. Nonetheless, these  
193 effects need experimental validation. Also, pore-network methods do not lead to analytical  
194  $\nabla P$ - $u$  expressions, which is particularly aggravating in applications involving a wide range of  
195 injection flow rates. An important difference between Newtonian and complex fluids is the  
196 coupling of geometrical and rheological parameters in the flow law [*Roustaei et al.*, 2016].  
197 Indeed, a non-toxic method of porosimetry has been proposed, which is based on the  
198 injection of yield stress fluids through porous media and takes advantage of the mentioned  
199 coupling [*Ambari et al.*, 1990; *Malvault*, 2013; *Oukhlef et al.* 2014; *Rodríguez de Castro*,  
200 2014; *Rodríguez de Castro et al.*, 2014; *Rodríguez de Castro et al.*, 2016a].

201

202 The literature survey conducted by *Lavrov* [2013] revealed the severe lack of research on  
203 fracture flow of non-Newtonian fluids, especially regarding yield-stress fluids. The earlier  
204 works of Di Federico [*Di Federico*, 1997; *Di Federico*, 1998; *Di Federico*, 2001] mainly  
205 focused on defining and estimating the equivalent aperture for flow of a non-Newtonian fluid  
206 in a variable aperture fracture, without experimental validation. Also, *Silliman* [1989]  
207 provided different aperture estimates for variable aperture fractures. Only a few experimental  
208 works exist for the flow of yield stress fluids in porous media [*Al-Fariss and Pinder*, 1987;  
209 *Chase and Dachavijit*, 2005; *Chevalier et al.*, 2013; *Chevalier et al.*, 2014; *Rodríguez de*  
210 *Castro*, 2016a], and the ranges of variation of  $u$  are usually narrow. These experimental  
211 works show that the relationship between  $\nabla P$  and  $u$  is of the same form as the constitutive  
212 equation of the fluid, i.e.  $\nabla P = \nabla P_0 + Cu^n$  with  $\nabla P_0$  being the critical pressure gradient below

213 which no flow occurs,  $n$  being the flow index of the fluid and  $C$  being a parameter that  
214 depends on the porous medium and the boundary conditions. *Chevalier et al.* [2014] used an  
215 NMR imaging technique to show that the velocity density distribution of a yield stress fluid  
216 flowing through a packed bed was similar to that of a Newtonian fluid due to the minor role  
217 played by the constitutive equation of the fluid in rapidly varying pore geometry. On the basis  
218 of these results, the latter authors propose explicit (but complex) expressions with physical  
219 meaning to calculate  $\nabla P_0$  and  $C$ . Concerning multiphase flow, *Boronin et al.*, [2015]  
220 developed a model for the displacement of yield-stress fluids in a vertical Hele-Shaw cell and  
221 used it to investigate the joint effect of viscous fingering, yielding and gravitational slumping,  
222 showing that unyielded fluid zones develop as a result of viscous fingering generated when a  
223 yield stress fluid is displaced by a low-viscosity Newtonian one.

224

225 Recently, *Rodríguez de Castro and Radilla* [2016a] conducted non-Darcian flow experiments  
226 of shear-thinning fluids without yield stress in rough-walled fractures, showing that the  
227 inertial pressure losses do not depend on fluid's rheology. These authors proposed a method  
228 to predict the pressure losses generated during non-Darcian shear-thinning flow from the  
229 values of  $K$ ,  $\gamma$  and  $\beta$  obtained during creeping Newtonian flow and the shear-viscosity  
230 parameters of the fluid. Their predictions showed good agreement with experimental data.  
231 However, a major drawback was the use of an experimentally obtained shift parameter to  
232 relate the apparent viscosity of the fluid in the porous medium to its bulk viscosity. Indeed,  
233 the calculation of the mentioned shift parameter involved carrying out preliminary Darcian  
234 shear-thinning flow experiments, so predicting its value is of considerable interest. Another  
235 interesting prospect consisted in extending this prediction method to the case of shear-  
236 thinning fluids with yield stress. The same authors also proposed a simple method to predict  
237 non-Darcian flow of Carreau fluids through packed beads [*Rodríguez de Castro and Radilla*,

238 2016b]. However, the flow of yield stress fluids was not tackled in these works and no  
239 estimate of the shift parameter relating the apparent viscosity of the fluid in the porous  
240 medium to its bulk viscosity was provided either.

241

242 Many applications require the flow rate in a fracture to be predicted from the applied pressure  
243 gradient and known fracture size and fluid rheology. In particular, understanding the flow of  
244 drilling fluids with yield stress through a rough-walled fracture is of vital importance in order  
245 to design the additives used to stop the fluid loss when a fracture is hit during drilling  
246 [Lavrov, 2013]. In this work, a simple approach is proposed to extend Darcy's and full cubic  
247 laws to the case of yield stress and Carreau fluids. In order to achieve this goal, flow  
248 experiments with concentrated aqueous polymer solutions have been conducted using  
249 replicas of natural fractures. Particular attention will be paid to investigating how yield stress  
250 affects the relationships between flow rate and pressure losses in rough-walled rock fractures.

251

## 252 **2. Predicting the flow of yield stress fluids and Carreau fluids in porous media**

253

254 The shear-thinning behaviour of semi-dilute polymer solutions widely used in EOR and soil  
255 remediation is commonly represented by the empirical Carreau model [Carreau, 1972] based  
256 on molecular network theory [Sorbie, 1989; López et al., 2003; Rodríguez de Castro et al.,  
257 2016b]. The Carreau equation is often presented as  $\frac{\mu - \mu_\infty}{\mu_0 - \mu_\infty} = [1 + (\lambda\dot{\gamma})^2]^{\frac{n-1}{2}}$ , where  $\mu$  is the  
258 viscosity at a given shear rate  $\dot{\gamma}$ ,  $\mu_0$  and  $\mu_\infty$  are the zero shear rate and infinite shear rate  
259 viscosities, respectively,  $n$  is the power-law index, and  $\lambda$  is the time constant.  $n$  is inferior to  
260 unity for shear-thinning fluids. The values of  $\mu_0$ ,  $\mu_\infty$ ,  $n$  and  $\lambda$  are determined by the polymer

261 concentration under given pressure and temperature conditions. In the region far from the low  
 262 shear viscosity plateau, i.e. when  $\dot{\gamma} \gg \frac{1}{\lambda}$ , Carreau's law leads to the following expression  
 263 [*Rodríguez de Castro and Radilla, 2016a*]:

$$\mu \approx \mu_{\infty} + (\mu_0 - \mu_{\infty})\lambda^{n-1}\dot{\gamma}^{n-1} = \mu_{\infty} + c\dot{\gamma}^{n-1} \quad (9)$$

264 with  $c = (\mu_0 - \mu_{\infty})\lambda^{n-1}$ . Given that all the shear rates involved in the flow experiments with  
 265 Carreau fluids analysed in this work are sufficiently high, only the high shear rates version of  
 266 Carreau's equation (Eq. 9) will be considered subsequently.

267 Some concentrated polymer solutions present a yield stress, as shown in previous works  
 268 [*Song et al., 2006; Carnali, 1991; Withcomb and Macosko, 1978; Economides and Nolte,*  
 269 *2000; Khodja, 2008; Benmouffok-Benbelkacem et al., 2010*]. The steady-state shear flow of  
 270 concentrated polymer solutions has been proved to be well described by the Herschel–  
 271 Bulkley law [*Herschel and Bulkley, 1926*]. This empirical law can be written as follows:

272

$$\begin{cases} \tau = \tau_0 + a\dot{\gamma}^n & \text{for } \tau > \tau_0 \\ \dot{\gamma} = 0 & \text{for } \tau \leq \tau_0 \end{cases} \quad (10)$$

273 where  $\tau_0$  is the yield stress,  $a$  is the consistency and  $n$  is the flow index of the fluid. In the  
 274 case of shear-thinning yield stress fluids,  $n$  is inferior to unity. The three parameters are  
 275 generally obtained by fitting the data obtained by measuring the shear rate  $\dot{\gamma}$  as a function of  
 276 the applied shear stress  $\tau$  using a rheometer.

277

278 A practical approach to study the flow of complex fluids with shear-rate-dependent viscosity  
 279 through a porous medium consists in defining an equivalent viscosity  $\mu_{eq}$  as being the

280 quantity that must replace the viscosity in Darcy's law to result in the same pressure drop  
 281 actually measured [Tosco *et al.*, 2013]. In the case of a rectangular fracture,  $\mu_{eq}$  is expressed  
 282 as:

$$\mu_{eq} = K \frac{\nabla P}{u} = \frac{h^2}{12} \frac{\nabla P}{u} \quad (11)$$

284 It should be noted that both inertial and viscous effects are encompassed in  $\mu_{eq}$ . In order to  
 285 analyse the viscous effects separately, the “*in situ*” shear viscosity  $\mu_{pm}$  in the porous medium  
 286 must be calculated. To do such calculation from the constitutive equation of the fluid, an  
 287 apparent shear rate in the porous medium has to be determined first. The apparent shear rate  
 288  $\dot{\gamma}_{pm}$  of shear-thinning fluids flowing through a porous medium can be defined by dividing the  
 289 mean velocity  $u$  by a characteristic microscopic length of the porous media [Chauveteau,  
 290 1982; Sorbie *et al.*, 1989; Perrin *et al.*, 2006; Tosco *et al.*, 2013; Rodríguez de Castro *et al.*,  
 291 2016b]. This microscopic length is usually taken as  $\sqrt{K\varepsilon}$  with  $\varepsilon$  being the porosity of the  
 292 porous medium. From the definition of cross-sectional area (Eq. 7), it is expected that  
 293 porosity is close to unity in the particular case of fractures. Therefore,  $\dot{\gamma}_{pm}$  can be defined as:

$$\dot{\gamma}_{pm} = \alpha \frac{u}{\sqrt{K}} = \alpha \frac{2\sqrt{3}u}{h} \quad (12)$$

295  
 296 where  $\alpha$  is an empirical shift factor known to be a function of both the bulk rheology of the  
 297 fluid and the porous media [Chauveteau, 1982; Sorbie *et al.*, 1989; López *et al.*, 2003; López,  
 298 2004; Comba *et al.*, 2011]. Previous research showed that  $\dot{\gamma}_{pm}$  corresponds to the wall shear



299 rate in the average pore throat diameter [*Chauveteau and Zaitoun, 1981; Chauveteau, 1982;*  
300 *Sheng, 2011*].

301

302 The usual approach to determine the value  $\alpha$  consists in overlaying the porous medium  $\mu_{eq}$   
303 vs.  $\dot{\gamma}_{app}$  with the bulk  $\mu_{eq}$  vs.  $\dot{\gamma}$  curves as closely as possible and noting the scale change in  
304 shear rate required to obtain the best fit. This criterion to select  $\alpha$  was proposed by *Sorbie et*  
305 *al.* [1989] as a pragmatic alternative to the original one previously proposed by *Chauveteau*  
306 [1982], and was subsequently used by other authors [*González et al., 2005; Amundarain et*  
307 *al., 2009*]. It should be noted that a good overlay between both curves is only possible in the  
308 low flow rates region where no significant inertial effects occur, assuming no wall slip [*Tosco*  
309 *et al., 2013; Rodríguez de Castro and Radilla, 2016a*]. Keeping in mind the objective to  
310 propose a prediction method, expressions for the calculation of  $\alpha$  must be provided so as to  
311 avoid the need to perform  $\alpha$ -determination experiments.

312

313 In the case of Carreau fluids flowing at moderate and high shear rates  $\mu_{pm}$  can be obtained  
314 from Eqs. (9) and (12):

315

$$\mu_{pm,Carreau} = \mu_{\infty} + c \left( \alpha \frac{2\sqrt{3}u}{h} \right)^{n-1} \quad (13)$$

316 Analogously, in the case of Herschel-Bulkley fluids,  $\mu_{pm}$  can be obtained from Eqs. (10) and  
317 (12):

318

$$\mu_{pm,ysf} = \frac{\tau_0 h}{\alpha 2\sqrt{3}u} + a \left( \alpha \frac{2\sqrt{3}u}{h} \right)^{n-1} \quad (14)$$

319

320 Although Eqs. (12-14), which are based on the bundle-of-capillaries model, were originally  
 321 proposed for the flow of non-Newtonian fluids through packed beads, the apparent viscosity  
 322 was found to correlate reasonably well in porous media with complex pre geometry and  
 323 topology [*Sorbie et al.*, 1989].

324 Let us focus now on the determination of the wall shear rate in rectangular channels. For the  
 325 steady 2D-flow of an incompressible fluid through a rectangular channel, the wall shear stress  
 326  $\tau_w$  is related to the pressure gradient  $\nabla P$  as follows [*Pipe et al.*, 2008]:

327

$$\tau_w = \frac{wh}{2(w+h)} \nabla P \quad (15)$$

328

329 For the calculation of  $\nabla P$  in Eq. (15), the fractures will be modelled as being rectangular  
 330 channels of width  $w$  and depth  $h$ . As explained above,  $\dot{\gamma}_{pm}$  corresponds to the wall shear rate  
 331 in the average pore throat diameter [*Chauveteau and Zaitoun*, 1981; *Chauveteau*, 1982;  
 332 *Sheng*, 2011]. In the case of a rough-walled fracture, the average pore throat diameter can be  
 333 assimilated to the hydraulic aperture. Therefore,  $\dot{\gamma}_{pm}$  can be interpreted as the wall shear rate  
 334 in a section of aperture  $h$ . The wall shear stress in a section of aperture  $h$  can be calculated  
 335 from Eq. (15), by using Eqs. (1) and (13) for the case of Carreau fluids:

336

337

$$\tau_w = \frac{6w}{(w+h)} \frac{u}{h} [\mu_\infty + c\dot{\gamma}_{pm}^{n-1}] = \frac{6w}{(w+h)} \frac{u}{h} \left[ \mu_\infty + 2^{n-1} 3^{\frac{n-1}{2}} c \left( \alpha \frac{u}{h} \right)^{n-1} \right] \quad (16)$$

338

339 And using Eqs. (1) and (14) for the case of Herschel-Bulkley fluids, Eq. (15) can be written

340 as:

$$\tau_w = \frac{6w}{(w+h)} \frac{u}{h} \left( \frac{\tau_0}{\dot{\gamma}_{pm}} + a\dot{\gamma}_{pm}^{n-1} \right) = \frac{\sqrt{3}w}{(w+h)\alpha} \left[ \tau_0 + 2^n 3^{\frac{n}{2}} a \left( \alpha \frac{u}{h} \right)^n \right] \quad (17)$$

341

342 For a constant viscosity fluid, the wall shear rate is given by  $\dot{\gamma}_{w,Newtonian} = \frac{6u}{h}$ . However, for

343 incompressible flows of liquids with a shear-rate-dependent viscosity, the calculation of  $\dot{\gamma}_w$  is

344 more complex given that the velocity profile is no longer parabolic [*Pipe et al.*, 2008]. An

345 apparent shear rate  $\dot{\gamma}_{app}$  can thus be defined as:

346

$$\dot{\gamma}_{app} = \frac{6u}{h} \quad (18)$$

347

348 The true wall shear rate can be found using the Weissenberg–Rabinowitsch–Mooney

349 equation [*Macosko*, 1994; *Pipe et al.*, 2008]:

350

$$\dot{\gamma}_w = \frac{\dot{\gamma}_{app}}{3} \left[ 2 + \frac{d(\ln \dot{\gamma}_{app})}{d(\ln \tau_w)} \right] \quad (19)$$

351

352 Therefore, the next equation can be obtained from Eqs. (16), (18) and (19) for a Carreau  
353 fluid:

$$\dot{\gamma}_{w,Carreau} = \frac{2u}{h} \left( 2 + \frac{2\sqrt{3}\alpha h^n \mu_\infty u + 2^n 3^{n/2} ah(\alpha u)^n}{2\sqrt{3}\alpha h^n \mu_\infty u + 2^n 3^{n/2} ahn(\alpha u)^n} \right) \quad (20)$$

354

355 Analogously, the next equation can be obtained from Eqs. (17), (18) and (19) for a Herschel-  
356 Bulkley fluid:

$$\dot{\gamma}_{w,ysf} = \frac{2u}{h} \left( 2 + \frac{a + 2^{-n} 3^{-n/2} \tau_0 \left( \alpha \frac{u}{h} \right)^{-n}}{an} \right) \quad (21)$$

357

358 For a Carreau fluid,  $\dot{\gamma}_{pm} = \dot{\gamma}_{w,Carreau}$ , so Eqs. (12) and (20) lead to the following expression:

359

$$\alpha = \frac{6\sqrt{3}\alpha h^n \mu_\infty u + 2^n 3^{\frac{n}{2}} ah(1 + 2n)(\alpha u)^n}{6\alpha h^n \mu_\infty u + 2^n 3^{\frac{n+1}{2}} ahn(\alpha u)^n} \quad (22)$$

360

361 In the case of a Herschel-Bulkley fluid ( $\dot{\gamma}_{pm} = \dot{\gamma}_{w,ysf}$ ), Eqs. 12 and 21 lead to:

362

$$\alpha = \frac{1}{\sqrt{3}} \left( 2 + \frac{a + 2^{-n} 3^{-n/2} \tau_0 \left( \alpha \frac{u}{h} \right)^{-n}}{an} \right) \quad (23)$$

363

364 From Eqs. (22) and (23), it can be deduced that  $\alpha$  is not a constant parameter in the case of  
 365 Carreau fluids and yield stress fluids, but depends on  $u$ . For the simpler case of a power-law  
 366 fluid ( $\tau_0=0$ ), Eq. (23) leads to:

367

$$\alpha = \frac{1}{\sqrt{3}} \left( 2 + \frac{1}{n} \right) \quad (25)$$

368 which becomes  $\alpha = \sqrt{3}$  for a Newtonian fluid. Therefore,  $\alpha$  is a constant parameter only if  
 369  $\tau_0 = 0$  and  $\mu_\infty = 0$ .

370

371 Given that  $\alpha$  depends on  $u$  for both Carreau and yield stress fluids, Eqs. (22) and (23) are  
 372 only relevant in the cases  $\mu_\infty = 0$  and  $\tau_0 = 0$ , respectively. For  $\mu_\infty \neq 0$  and  $\tau_0 \neq 0$ , Eq. (19)  
 373 becomes:

374

$$\dot{\gamma}_w = \frac{\dot{\gamma}_{app}}{3} \left[ 2 + \frac{\frac{d(\ln \dot{\gamma}_{app})}{du} du}{\frac{\partial(\ln \tau_w)}{\partial u} du + \frac{\partial(\ln \tau_w)}{\partial \alpha} d\alpha} \right] = \frac{\dot{\gamma}_{app}}{3} \left[ 2 + \frac{\frac{d(\ln \dot{\gamma}_{app})}{du}}{\frac{\partial(\ln \tau_w)}{\partial u} + \frac{\partial(\ln \tau_w)}{\partial \alpha} \frac{d\alpha}{du}} \right] \quad (26)$$

375 where  $\alpha$  is a function of  $u$ .

376

377 Therefore, for a Carreau fluid, Eq. (20) becomes:

$$\dot{\gamma}_{w,Carreau} = \frac{2u}{h} \left[ 2 + \frac{\alpha \left( 2\sqrt{3}\mu_{\infty}u\alpha + 2^n 3^{\frac{n}{2}} ah \left( \frac{u\alpha}{h} \right)^n \right)}{2\sqrt{3}\mu_{\infty}\alpha^2 + 2^n 3^{\frac{n}{2}} ahn\alpha \left( \frac{u\alpha}{h} \right)^n + 2^{n+1} 3^{\frac{n}{2}} ah(n-1)u \left( \frac{u\alpha}{h} \right)^n \frac{\partial\alpha}{\partial u}} \right] \quad (27)$$

378

379 Also, for a Herschel-Bulkley fluid, Eq. (21) becomes:

380

$$\dot{\gamma}_{w,ysf} = \frac{2u}{h} \left[ 2 + \frac{\alpha \left( \tau_0 + 2^n 3^{\frac{n}{2}} a \left( \frac{u\alpha}{h} \right)^n \right)}{2^n 3^{\frac{n}{2}} a n \alpha \left( \frac{u\alpha}{h} \right)^n - 2u \left( \tau_0 - 2^n 3^{\frac{n}{2}} a (n-1) \left( \frac{u\alpha}{h} \right)^n \right) \frac{\partial\alpha}{\partial u}} \right] \quad (28)$$

381

382 Consequently, the following differential equation has to be solved in order to determine  $\alpha$  as

383 a function of  $u$  for a Carreau fluid:

384

$$\alpha = \frac{1}{\sqrt{3}} \left[ 2 + \frac{\alpha \left( 2\sqrt{3}\mu_{\infty}u\alpha + 2^n 3^{\frac{n}{2}} ah \left( \frac{u\alpha}{h} \right)^n \right)}{2\sqrt{3}\mu_{\infty}\alpha^2 + 2^n 3^{\frac{n}{2}} ahn\alpha \left( \frac{u\alpha}{h} \right)^n + 2^{n+1} 3^{\frac{n}{2}} ah(n-1)u \left( \frac{u\alpha}{h} \right)^n \frac{\partial\alpha}{\partial u}} \right] \quad (29)$$

385

386 And for a Herschel-Bulkley fluid:

387

$$\alpha = \frac{1}{\sqrt{3}} \left[ 2 + \frac{\alpha \left( \tau_0 + 2^n 3^{\frac{n}{2}} a \left( \frac{u\alpha}{h} \right)^n \right)}{2^n 3^{\frac{n}{2}} a n \alpha \left( \frac{u\alpha}{h} \right)^n - 2u \left( \tau_0 - 2^n 3^{\frac{n}{2}} a (n-1) \left( \frac{u\alpha}{h} \right)^n \right) \frac{\partial\alpha}{\partial u}} \right] \quad (30)$$

388

389 Eqs. (29) and (30) can be numerically solved within a given range of  $u$  to obtain the relation

390 between  $\alpha$  and  $u$ . Then, the obtained relation can be used in Eq. (13) for a Carreau fluid and

391 in Eq. (14) for a Herschel-Bulkley fluid to obtain  $\mu_{pm,Carreau}$  and  $\mu_{pm,ysf}$ , respectively. Once

392  $\mu_{pm,Carreau}$  and  $\mu_{pm,ysf}$  have been determined, they can be entered in Eq. (1), Eq. (2), Eq. (3)  
 393 and Eq. (5), leading to the extension of Darcy's law (Eq. 31), Forchheimer's law (Eq. 32) and  
 394 full cubic law (Eq. 33) to Carreau and yield stress fluids:

395

$$\nabla P = \frac{\mu_{pm}}{K} u = \frac{12\mu_{pm}}{h^2} u \quad (31)$$

396

$$\nabla P = \frac{\mu_{pm}}{K} u + \beta \rho u^2 = \frac{12\mu_{pm}}{h^2} u + \beta \rho u^2 \quad (32)$$

397

$$\nabla P = \frac{\mu_{pm}}{K} u + \beta \rho u^2 + \frac{\gamma \rho^2}{\mu_{pm}} u^3 = \frac{12\mu_{pm}}{h^2} u + \beta \rho u^2 + \frac{\gamma \rho^2}{\mu_{pm}} u^3 \quad (33)$$

398

399 It is remarked that  $\frac{12\mu_{pm}}{h^2} u = \frac{2\sqrt{3}\tau_0}{h} \frac{1}{\alpha} + \frac{2^{n+1}3^{\frac{n+1}{2}}a}{h^{n+1}} \alpha^{n-1} u^n = C_1 \frac{1}{\alpha} + C_2 \alpha^{n-1} u^n$  in the case of  
 400 Herschel-Bulkley fluids, with  $C_1 = \frac{2\sqrt{3}\tau_0}{h}$  and  $C_2 = \frac{2^{n+1}3^{\frac{n+1}{2}}a}{h^{n+1}}$ . Therefore, Eqs. (31) to (33)  
 401 present a limiting pressure gradient [Roustaei *et al.*, 2016] of value  $C_1 \frac{1}{\alpha}$ . In the preceding  
 402 expressions,  $\mu_{pm}$  corresponds to  $\mu_{pm,Carreau}$  or  $\mu_{pm,ysf}$  depending on the type of fluid being  
 403 considered.

404

405

406

407 It should be noted that elongational flows during the injection of solutions of polymers  
408 presenting a certain degree of flexibility through porous media are known to induce extra  
409 pressure losses with respect to pure shear flow [*Rodríguez et al.*, 1993; *Müller and Sáez*,  
410 1999; *Nguyen and Kausch*, 1999; *Seright et al.*, 2011; *Amundarain et al.*, 2009). These extra  
411 pressure losses were attributed to the formation of transient entanglements of polymer  
412 molecules due to the action of the extensional component of the flow. In the present  
413 approach, we first hypothesize that the differences between the total pressure drops measured  
414 during the flow of the investigated complex fluids through rough-walled rock fractures and  
415 the viscous pressure drop as predicted from the shear viscosity of the fluid can be explained  
416 in terms of inertial effects generated in the porous medium flow. This hypothesis is then  
417 validated through analysis of the experimental results.

418

### 419 **3. Materials and Methods**

420

421 In this section, we present the experimental procedure and the materials used to carry out the  
422 flow experiments with a yield stress fluid specifically performed in the framework of the  
423 present study. However, the proposed method to predict  $\nabla P$  as a function of  $u$  in rough-  
424 walled fractures is also compared with previously presented experimental data [*Rodríguez de*  
425 *Castro and Radilla*, 2016a] in order to assess its efficiency in the case of Carreau fluids.

426

#### 427 **3.1. Experimental setup and procedure**

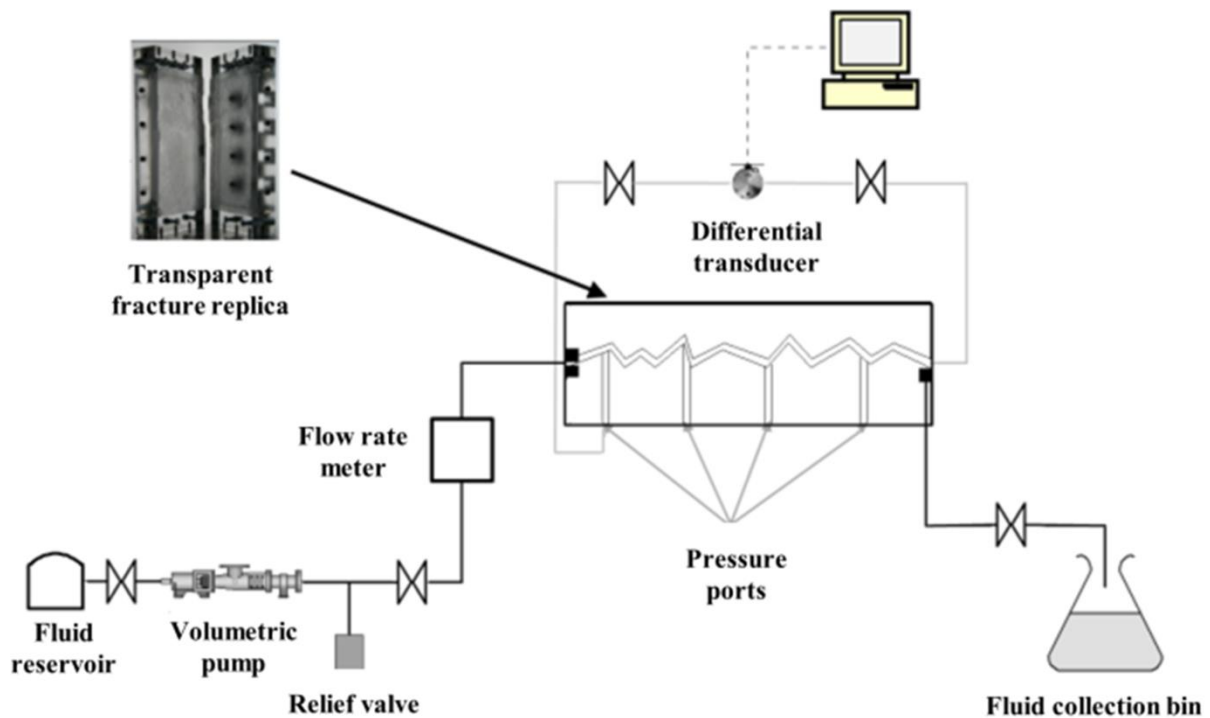
428



429 A series of experiments was conducted injecting a concentrated aqueous polymer solution  
430 through two transparent epoxy resin replicas of natural rough-walled rock fractures. The  
431 original fractures used in this work are a Vosges sandstone sample with dimensions 26 cm  
432 long and  $w = 14.8$  cm wide, and a granite sample with dimensions 33 cm long and  $w = 15.5$   
433 cm wide. Details of the fabrication process of these fracture replicas can be found elsewhere  
434 [Isakov *et al.*, 2001; Nowamooz *et al.*, 2013]. The aperture maps of both fractures obtained by  
435 Nowamooz *et al.* [2013] have been included as supporting information of the present article  
436 (Figures S<sub>1</sub> and S<sub>2</sub>), showing the high spatial variability. The latter authors analysed in detail  
437 the aperture variability and distribution of the fractures using an image processing procedure  
438 based on the attenuation law of Beer-Lamber. They showed that the smallest apertures are  
439 located at the centre and the largest apertures are located near the inlet and the outlet of the  
440 fractures. Moreover, the apertures of the Vosges sandstone fracture are more variable at  
441 lower half than at the upper half, while the spatial variability appears to be relatively high  
442 across the entire granite fracture area. This results in a more heterogeneous aperture map for  
443 the granite fracture. Moreover, Nowamooz *et al.* [2013] showed that the spatial variability of  
444 the fracture aperture field, especially the constricted areas at the centre of the fractures,  
445 resulted in the creation preferential paths for the flow of the fluid. These effects are expected  
446 to be more important in the case of shear-thinning fluids and yield stress fluids as the pressure  
447 loss sensitivity to aperture is higher (shear viscosity depends on the local aperture) [Roustaei  
448 *et al.*, 2016].

449  
450 Two different configurations were used depending on the involved flow rates. For the lowest  
451 flow rates, ranging from 0.06 L/h to 6 L/h, the injection circuit was open and the fluid was  
452 injected through the fractures at the selected flow rate using a dual piston pump (Prep Digital  
453 HPCL pump, A.I.T., France). For the highest flow rates, ranging from 9 L/h to 250 L/h, the

454 circuit was closed. In this case, the fluid was injected from a tank situated upstream of the  
 455 fracture using a volumetric pump (EcoMoineau M Series, PCM, France), and its flow rate  
 456 was measured with a positive displacement flow meter (Model LSM45, Oval, Japan). The  
 457 injected fluid was continuously recirculated to the upstream tank after passing through the  
 458 fracture. A differential pressure sensor (DP15 Variable Reluctance Pressure Sensor,  
 459 Validyne, USA) was used to measure the pressure drop over a distance of  $L = 20.5$  cm in the  
 460 case of the Vosges sandstone fracture and  $L = 27$  cm in the case of the granite fracture. A  
 461 sketch of the experimental setup is shown in Figure 1. The range of the piston pump was  
 462 from  $6 \times 10^{-3}$  to 6 L/h with an accuracy of  $\pm 2\%$  while the volumetric pump was able to  
 463 provide flow rates ranging from 0 to 300 L/h. The range of the flow meter installed at the  
 464 outlet of the volumetric pump was from 7 to 500 L/h with an accuracy of  $\pm 1\%$  and the range  
 465 of the pressure sensor was adjusted by installing different membranes from 0-1400 Pa to 0-  
 466 56000 Pa with an accuracy of  $\pm 0.3\%$  of the full scale  
 467



468

469 **Figure 1.** Sketch of the experimental setup used in the present experiments.

470

471 The procedure followed in our experiments was similar to the one followed by *Rodríguez de*  
472 *Castro and Radilla* [2016a], but the covered range of injection flow rates was considerably  
473 wider. In this procedure, the fractures were saturated with CO<sub>2</sub> (more water-miscible gas than  
474 air) prior to saturation with polymer solution in order to avoid air trapping during the  
475 experiments. Once saturated with polymer solution, a set of forty-five different flow rates  
476 ranging from 0.06 to 250 L/h were imposed for the flow through the fracture and the  
477 corresponding pressure drops were measured. It can be observed that the range of  $u$  used in  
478 this work is significantly wider than those used in some preceding works (Sabiri and Comiti,  
479 1994), which permits a better assessment of the proposed prediction methods (over  $\sim 3.6$   
480 orders of magnitude). Each step was repeated four times and the uncertainty related to the  
481 repeatability of the pressure drop and the accuracy of the involved instruments was calculated  
482 as  $\pm 2\sigma$ , with  $\sigma$  being an estimate of the relative standard deviation of the measurements (95%  
483 confidence interval). The room temperature during the experiments was  $20^{\circ}\text{C} \pm 1$ .

484

### 485 **3.2. Fluid Properties**

486

487 Filtered water and a xanthan gum aqueous solution with polymer concentration  $C_p = 7000$   
488 ppm were used as injected fluid in the present experiments. Xanthan gum is an important  
489 industrial biopolymer commonly obtained through fermentation of *Xanthomonas campestris*  
490 bacteria [*García-Ochoa et al.*, 2000; *Palarinaj and Javarman*, 2011; *Wadhai and Dixit*,  
491 2011]. This biopolymer is widely used as viscosity-enhancing additive in the food and  
492 cosmetics industries, as zerovalent iron for groundwater remediation and as part of the  
493 formulation of drilling muds in EOR [*García-Ochoa et al.*, 2000; *Amundarain et al.*, 2009;

494 *Palarinaj and Javarman, 2011; Wadhai and Dixit, 2011; Xin et al., 2015*]. In solution state,  
495 an isolated xanthan macromolecule is more or less rigid and is of typically 1  $\mu\text{m}$  of contour  
496 length [*Mongruel and Cloitre, 2003*] and a transverse size of approximately 2 nm. Song  
497 [2007] presented additional information about the chemical composition, structure and other  
498 physico-chemical properties of this biopolymer. Xanthan gum solutions are one of the main  
499 examples of inelastic, shear-thinning fluids in contrast to linear flexible polymers as  
500 polyacrylamide [*Jones and Walters 1989; Sorbie 1991a*] which are highly viscoelastic. Due to  
501 the stiffness of its molecule, xanthan semidilute aqueous solutions develop a high viscosity  
502 level and a very pronounced shear-thinning behavior. Therefore, xanthan gum solutions have  
503 been reported to present an apparent yield stress [*Song et al., 2006; Carnali, 1991; Withcomb*  
504 *and Macosko, 1978; Khodja, 2008; Benmouffok-Benbelkacem et al., 2010*] even if strictly  
505 speaking, they should be referred to as pseudo-yield stress fluids. The Herschel–Bulkley  
506 model [*Herschel and Bulkley, 1926*] has been proved to describe the steady-state shear flow  
507 of concentrated xanthan gum solutions [*Song et al., 2006; Rodríguez de Castro et al., 2014,*  
508 2016a].

509

510 Sixty litres of polymer solution were prepared by dissolving xanthan gum in filtered water  
511 containing 400 ppm of  $\text{NaN}_3$  as a bactericide. The xanthan gum powders were progressively  
512 dissolved in water while gently mixing with a custom-made overhead device. Once prepared,  
513 the polymer solution was characterized by means of a stress controlled rheometer (ARG2, TA  
514 Instruments) equipped with cone-plate geometry at a constant temperature of  $19^\circ\text{C} \pm 1$ ,  
515 following a procedure previously presented in the literature [*Rodríguez de Castro et al., 2014,*  
516 2016a, 2016b]. The obtained rheograms are provided as supporting information (Figure S3).  
517 Eq. (10) was used to fit the rheograms following the procedure presented by *Rodríguez de*  
518 *Castro et al. [2014]* and obtaining  $\tau_0 = 7.4 \text{ Pa}$ ,  $a = 0.37 \text{ Pa s}^n$  and  $n = 0.52$ . A viscosity of

519 0.001 Pa s was measured for the solvent (water) and the densities  $\rho$  of both the water and the  
520 xanthan gum solution were taken as 1000 kg/m<sup>3</sup>.

521

522 Moreover, a set of effluent fluid samples were collected at the outlet of the fractures after  
523 injection at the highest flow rate. The effluent rheograms were determined and compared to  
524 that of the inflowing fluid in order to assess polymer degradation and retention of the  
525 polymer on the fracture walls. No significant difference was observed between the  
526 rheograms, so polymer degradation and significant polymer retention were proved to be  
527 negligible. Moreover, no air macro bubbles were observed in the injected fluid. Also, the  
528 rheograms of a degassed fluid sample and an undegassed fluid sample were measured and  
529 compared in order to evaluate the influence of residual air micro bubbles, showing no  
530 significant difference.

531

532 The Carreau fluids used in the non-Darcian shear-thinning flow experiments in rough-walled  
533 fractures performed by [Rodríguez de Castro and Radilla, 2016a] were three xanthan gum  
534 aqueous solutions with polymer concentrations of 200 ppm, 500 ppm and 700 ppm,  
535 respectively. The corresponding rheological parameters used in Eq. (9) for these fluids were  
536 [ $c = 4.8 \times 10^{-3}$  Pa s<sup>n</sup>,  $\mu_{\infty} = 1.1 \times 10^{-3}$  Pa s,  $n = 6.6 \times 10^{-1}$ ] for  $C_p = 200$  ppm, [ $c = 2.4 \times 10^{-3}$  Pa  
537 s<sup>n</sup>,  $\mu_{\infty} = 1.1 \times 10^{-3}$  Pa s,  $n = 5.8 \times 10^{-1}$ ] for  $C_p = 500$  ppm and [ $c = 4.2 \times 10^{-3}$  Pa s<sup>n</sup>,  $\mu_{\infty} = 1.1 \times$   
538  $10^{-3}$  Pa s,  $n = 5.2 \times 10^{-1}$ ] for  $C_p = 700$  ppm.

539

540 **4. Results**

541

542 The flow experiments were conducted for both fluids (water and yield stress fluid) and were  
543 repeated four times. For each fluid, a total of a hundred and eighty (four repetitions for each  
544 of the forty-five flow rates) were completed. The hundred and eighty measures for a given  
545 fluid-fracture pair were considered to be an experimental set.

546

547 **4.1. Non-Darcian flow of a Newtonian fluid: obtaining  $K$ ,  $\gamma$  and  $\beta$  from experiments**

548

549 The experimental sets of  $\nabla P$  as a function of  $u$  for water injection ( $C_p = 0$  ppm) through both  
550 fractures are included as supporting information (Figure S4). Higher pressure losses were  
551 obtained for the less permeable fracture (Vosges sandstone), as expected, and non-linear  
552 relations between  $u$  and  $\nabla P$  were observed in both cases stemming from inertial effects at high  
553 flow rates. It is known that directly fitting Eq. (5) to the whole set of data results in  
554 overestimation of permeability [*Du Plessis and Masliyah*, 1988; *Dukhan et al.*, 2014].  
555 Indeed, by fitting the whole set of data to the polynomial law, a part of the pressure drop  
556 would be attributed to inertial effects even at the lowest flow rates, which is not realistic.  
557 Consequently, the viscous pressure loss would be underestimated leading to permeability  
558 overestimation. To avoid this issue, the procedure proposed by *Rodríguez de Castro and*  
559 *Radilla* [2016a] was followed to determine  $h$  and  $K$  in the present experiments. This  
560 procedure is divided into two-steps:

561 1) In this step, the hydraulic apertures  $h_j$  obtained by only using the first  $j$  experimental data  
562 (starting with the lowest flow rates) are calculated by minimizing the sum  $\sum_{i=1}^j (\nabla P_i -$

563  $\left(\frac{12Q_i\mu}{h_j^3w}\right)^2$  for  $j = 1\dots N$ , with  $N$  being the number of experimental data and  $\mu$  being the  
 564 measured dynamic viscosity of water at the room temperature (0.001 Pa s).

565

566 2) Then, the quality of the  $N$  fits obtained by using the  $N$  values of  $h_j$  calculated in the

567 preceding step is evaluated by using the merit function  $F(j) = \frac{\sum_{i=1}^j \left| \frac{\nabla P_i - \frac{12Q_i\mu}{h_j^3w}}{\nabla P_i} \right|}{j}$  for  $j = 1\dots N$ .

568 After that, the value of  $j$  minimizing  $F(j)$  was determined. The corresponding  $h_j$  value was  
 569 selected as the hydraulic aperture of the fracture from which  $K$  was calculated using Eq. (7).

570

571 The obtained values for the granite fracture were  $K = 6.1 \times 10^{-8} \text{ m}^2$  ( $\pm 2\%$ ) and  $h = 8.5 \times 10^{-4}$   
 572  $\text{m}$  ( $\pm 2\%$ ), while for the Vosges sandstone fracture the computed values were  $K = 2.1 \times 10^{-8}$   
 573  $\text{m}^2$  ( $\pm 1\%$ ) and  $h = 5.0 \times 10^{-4} \text{ m}$  ( $\pm 1\%$ ). Once permeability was determined, the  $(Q_i, \nabla P_i, )$  data  
 574 were fitted to a full cubic law (Eq. 5) through a standard least squares method using the value  
 575 of  $K$  calculated in the previous step and obtaining the values of  $d$  and  $\beta$ . The computed values  
 576 were  $d = 2.5 \times 10^{-5}$  ( $\pm 5\%$ ) and  $\beta = 0 \text{ m}^{-1}$  for the granite fracture, and  $d = 2.2 \times 10^{-5}$  ( $\pm 2\%$ ) and  
 577  $\beta = 1.5(\pm 2\%) \text{ m}^{-1}$  for the granite fracture. Percentages represent  $\pm 2\sigma$ , with  $\sigma$  being an  
 578 estimate of the relative standard deviation of the measurements (95% confidence interval).

579

#### 580 **4.2. Equivalent and shear viscosity relations**

581

582 Eq. (30) was numerically solved within the involved range of  $u$  for both fractures using an  
 583 implicit Runge-Kutta method. From (23), it can be deduced that  $\alpha$  becomes the constant  
 584 value  $\frac{1}{\sqrt{3}}\left(2 + \frac{1}{n}\right)$  for Herschel-Bulkley shear-thinning fluids ( $0 < n < 1$ ) flowing at very high

585 values of  $u$ , i.e. when  $u \gg \frac{\tau_0 h^n}{2^n 3^{n/2} \alpha^n}$ . Given that the shift parameter is known to be greater than  
586 unity [Chauveteau, 1982; Sorbie *et al.*, 1989; López, 2003; Comba *et al.*, 2011], the  
587 preceding condition will be respected if  $u \gg u^* = \frac{\tau_0 h^n}{2^n 3^{n/2}}$ . Consequently, the boundary  
588 condition  $\alpha(u = 10^5 u^*) = \frac{1}{\sqrt{3}} \left(2 + \frac{1}{n}\right)$  was used to numerically solve Eq. (30). The resulting  $\alpha$   
589 versus  $u$  functions are presented in Figure 2(b) and 1(d).

590

591 Analogously, Eq. (29) was numerically solved within the range of  $u$  used by Rodríguez de  
592 Castro and Radilla [2016a] for both fractures. From (22), it can be deduced that  $\alpha$  becomes  
593 the constant value  $\sqrt{3}$  for Carreau shear-thinning fluids ( $0 < n < 1$ ) flowing at very high

594 values of  $u$ , i.e. when  $u \gg \left[ \frac{2^n \alpha^{n-1} h^{1-n}}{6\mu_\infty} \text{Max} \left( 3^{\frac{n-1}{2}}, 3^{\frac{n+1}{2}} c \right) \right]^{\frac{1}{1-n}}$ . Since the shift parameter is  
595 known to be greater than unity, the preceding condition will be respected if  $u \gg$

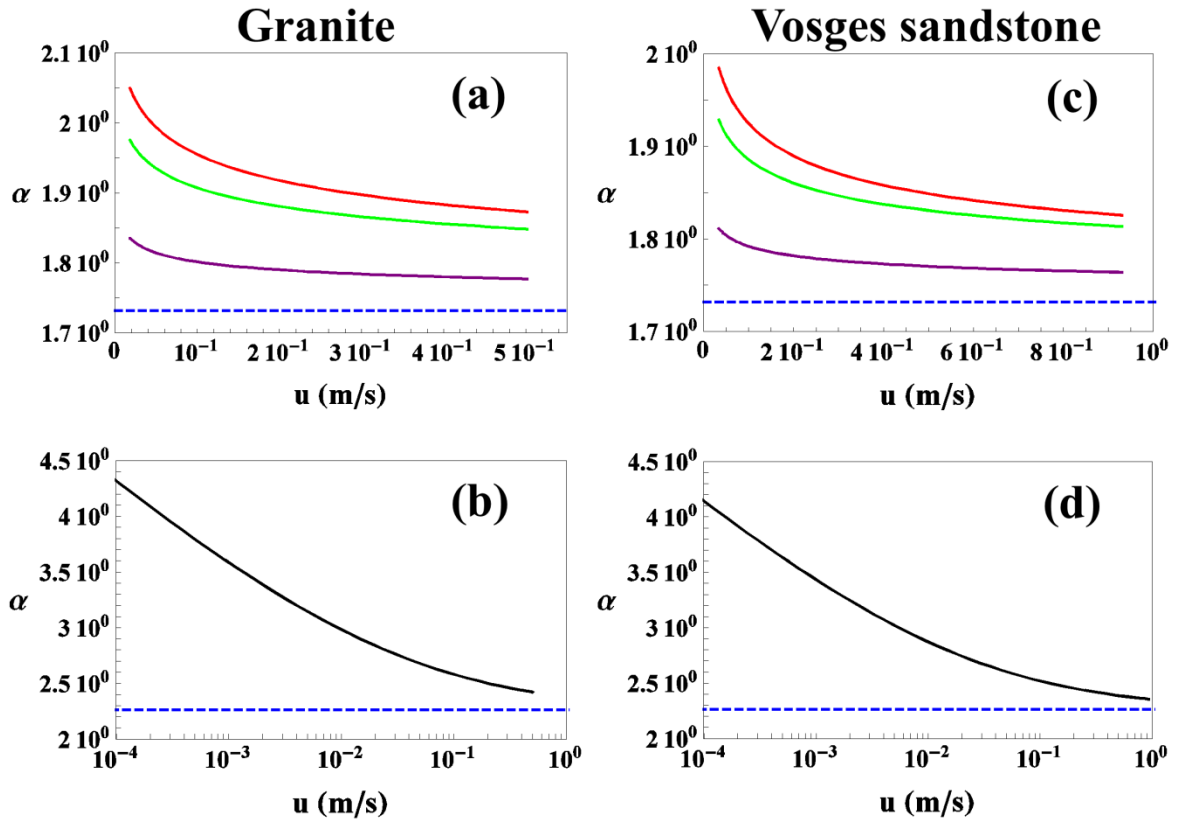
596  $u^* = \left[ \frac{2^n h^{1-n}}{6\mu_\infty} \text{Max} \left( 3^{\frac{n-1}{2}}, 3^{\frac{n+1}{2}} c \right) \right]^{\frac{1}{1-n}}$ . Therefore, the boundary condition  $\alpha(u = 10^5 u^*) = \sqrt{3}$

597 was used to numerically solve Eq. (29). The resulting  $\alpha$  versus  $u$  functions are presented in  
598 Figure 2(a) and 1(c).

599

600 It can be noted that the relation between  $\alpha$  and  $u$  strongly depends on polymer concentration  
601 as shown in Figure 2. Indeed, the dependence of  $\alpha$  on  $u$  is weaker for the low polymer  
602 concentration as expected from their less pronounced shear-thinning behaviour. It is also  
603 remarked that this dependence of  $\alpha$  on  $u$  is less significant as  $u$  increases and  $\alpha$  approaches  
604 the limit value  $\lim_{u \rightarrow \infty} \alpha(u)$ . This implies that assuming a constant value of  $\alpha$  should lead to  
605 acceptable levels of accuracy in the prediction of the  $\nabla P$ - $u$  relations within the high- $u$  region.





607

608 **Figure 2.**  $\alpha(u)$  functions as numerically obtained from Eqs. (29) and (30). (a,c) correspond to  
 609 the Carreau fluids used by *Rodríguez de Castro and Radilla* [2016a]. (b,d) correspond to the  
 610 7000 ppm solution used in the present experiments. Solid lines represent the computed  $\alpha(u)$   
 611 functions and dashed lines represent  $\lim_{u \rightarrow \infty} \alpha(u)$ . Purple lines correspond to the 200 ppm  
 612 Carreau fluid, green lines to the 500 ppm Carreau fluid, red lines to the 700 ppm Carreau  
 613 fluid and black lines to the 7000 ppm yield stress fluid.

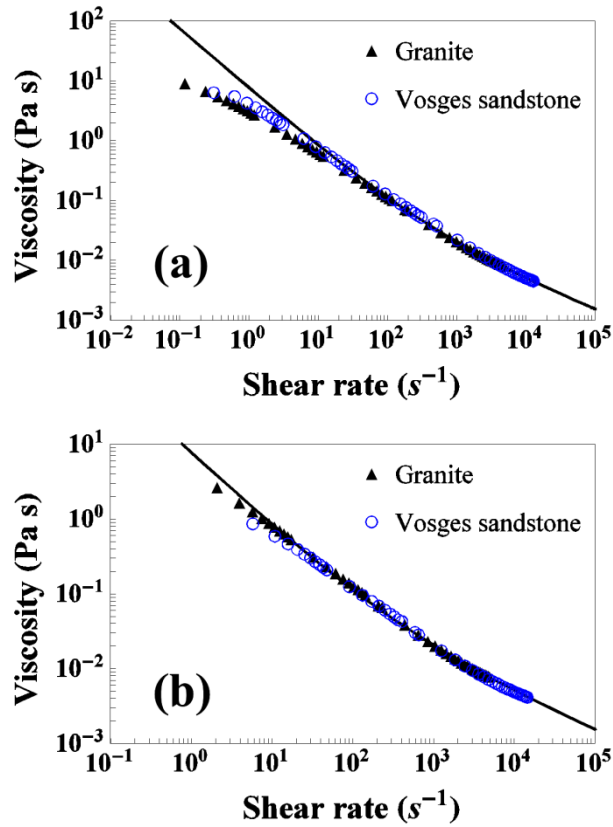
614

615  $\mu_{pm,ysf}$  was computed for the flow of the 7000 ppm solution through each fracture using Eq.  
 616 (13). Two different approaches were followed: 1) the constant value  $\alpha = \frac{1}{\sqrt{3}} \left( 2 + \frac{1}{n} \right)$  was used  
 617 in Eq. (13) and 2) the  $\alpha(u)$  function obtained as explained above was used in Eq. (13). The  
 618 results of both approaches are presented in Figure 3, together with  $\mu_{eq}$  as obtained with Eq.

619 (11) from the  $\nabla P$ - $u$  measurements. In this figure, it can be observed that  $\mu_{eq}$  is close to  
620  $\mu_{pm,ysf}$  at high values  $u$  for both the constant  $\alpha$  and the variable- $\alpha$  methods. However, this is  
621 not the case at low and moderate values of  $u$  for which  $\mu_{eq}$  approaches clearly better  $\mu_{pm,ysf}$   
622 with the variable- $\alpha$  method. It should be highlighted that xanthan gum may induce a depleted  
623 layer close to pore walls with a lesser concentration in that region. This produces an apparent  
624 wall slip which leads to a reduced average viscosity in the pores, mainly at low values of  $u$   
625 [*Chauveteau*, 1982; *Sorbie*, 1991b]. However, in the case of the present fractures, the  
626 dimensions of the macromolecules is negligible with respect to the fracture apertures so this  
627 effect is not observed and  $\mu_{eq}$  is very close to  $\mu_{pm,ysf}$  even at low values of  $u$ . This shows that  
628 that the effect of fluid-solid interactions (e.g. polymer mechanical degradation and apparent  
629 wall slip) on the relationship between viscosity and shear rate is negligible [*González et al.*,  
630 2005; *Amundarain et al.*, 2009; *Rodríguez de Castro et al.*, 2016b]. Also, it is expected that  
631  $\mu_{eq} > \mu_{pm,ysf}$  at high values of  $u$  in the presence of important inertial effects [*Tosco et al.*,  
632 2013; *Rodríguez de Castro and Radilla*, 2016a]. The fact that no important deviation of  $\mu_{eq}$   
633 with respect to  $\mu_{pm,ysf}$  is observed in the present experiments reflects that inertial effects are  
634 not significant. Moreover, Figure 3 shows that the shear rates involved in the flow through  
635 the Vosges sandstone fracture are higher than those involved in the flow through the granite  
636 fracture. This is coherent with the highest values of  $u$  and the lowest permeability of the  
637 Vosges sandstone fracture.

638

639



640

641 **Figure 3.**  $\mu_{eq}$  and  $\mu_{pm,ysf}$  for the yield stress fluids used in the present experiments. Symbols  
 642 represent  $\mu_{eq}$  and solid lines represent  $\mu_{pm}$ . (a) Corresponds to  $\alpha = \frac{1}{\sqrt{3}}\left(2 + \frac{1}{n}\right)$ . (b)  
 643 Correspond to the  $\alpha(u)$  functions presented in Figure 2.

644

645 It should be noted that the two-parameter power law model used in most of the preceding  
 646 works dealing with shear-thinning fluids [Chhabra and Srinivas, 1991; Rao and Chhabra,  
 647 1993; Sabiri and Comiti, 1994; Smit and du Plessis, 1997; Tiu et al. 1997; Machac et al.,  
 648 1998; Chhabra et al., 2001; Broniarz-Press et al., 2007] is not appropriate to study non-  
 649 Darcian flow as the involved shear rates are high and close to the upper Newtonian plateau of  
 650 viscosity [Woudberg et al., 2006; Fayed et al., 2016], which is not taken into account by this  
 651 model. In contrast, the empirical Carreau model [Carreau, 1972] can accurately predict the  
 652 variation in the viscosity at all shear rates and is known to successfully represent the shear-

653 thinning behaviour of xanthan gum semi-dilute solutions [Sorbie et al., 1989; López et al.,  
654 2003; Rodríguez de Castro et al., 2016b; *Rodríguez de Castro and Radilla*, 2016a]. Although  
655 Herschel-Bulkley model does not include an upper Newtonian plateau viscosity, there is less  
656 concern in the case of this type of fluids. Indeed, as can be observed in figures 3 and S<sub>3</sub>, the  
657 high levels of viscosity presented by the concentrated solutions injected in the present  
658 experiments are far from the upper plateau in all cases. This is in contrast with the results of  
659 *Rodríguez de Castro and Radilla* [2016a] for less concentrated xanthan gum solutions.

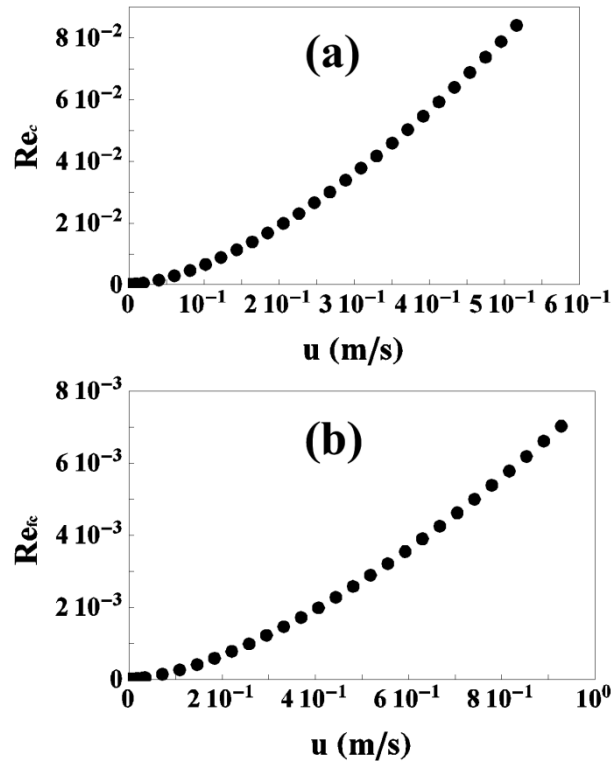
660

### 661 **4.3. Effects of yield stress on Reynolds number**

662

663 In previous works, it was shown that Reynolds number is not directly proportional to  $u$  for  
664 shear-thinning fluids, in contrast to the Newtonian case [*Rodríguez de Castro and Radilla*,  
665 2016a, 2016b]. Indeed, according to Eqs. (13) and (14), an increase in  $u$  implies a decrease in  
666 viscosity which implies in turn an extra increase in Reynolds number. In this work, the effect  
667 of yield stress on the  $Re$ - $u$  relationship was also analysed. To do so, the Reynolds numbers  
668 obtained for the imposed values of  $u$  were calculated through Eq. (4) in the case of the granite  
669 fracture and Eq. (6) in the case of the Vosges sandstone fracture.  $\mu_{pm}$  was used for the  
670 calculation of Reynolds number. It is highlighted that  $\mu_{pm}$  accounts only for viscous effects  
671 and is consistent with the definition of Reynolds number as the ratio of inertial to viscous  
672 forces, in contrast to  $\mu_{eq}$  that accounts also for inertial effects. The results are presented in  
673 Figure 4. In this figure, it can be observed that Reynolds number is close to zero at low values  
674 of  $u$  for the flow of the yield stress fluid in both fractures.

675



676

677 **Figure 4.** (a)  $Re_c$  vs.  $u$  for the granite fracture (b)  $Re_{fc}$  vs.  $u$  for the Vosges sandstone fracture.

678

679 From Figure 4, one can also deduce that the non-linear dependence of  $Re$  on  $u$  previously  
 680 reported for Carreau fluids is also observed for shear-thinning yield stress fluids.

681 Furthermore, as reflected in the same figure, there is a threshold value in terms of  $u$  below  
 682 which  $Re$  is very close to zero for the injection of yield stress fluids. This threshold value

683 arises from the yield stress of the fluid. In fact, for a yield stress fluid, viscosity approaches  
 684 infinity at low shear rates leading to very low values of  $Re$ . Also, the critical value of  $Re$  for

685 the transition to non-Darcian regime was reported to be close to  $Re_c = 0.3$  for the granite  
 686 fracture and  $Re_{fc} = 0.05$  for the Vosges sandstone fracture [Rodríguez de Castro and Radilla,

687 2016a]. As can be seen in Figure 4, the  $Re$  obtained for the present experiments are lower  
 688 than these critical values in both fractures, so no important inertial effects are expected. The

689 ratio between inertial and viscous pressure losses was calculated from Eq. (33) as  $\frac{\Delta P_{inertial}}{\Delta P_{viscous}} =$

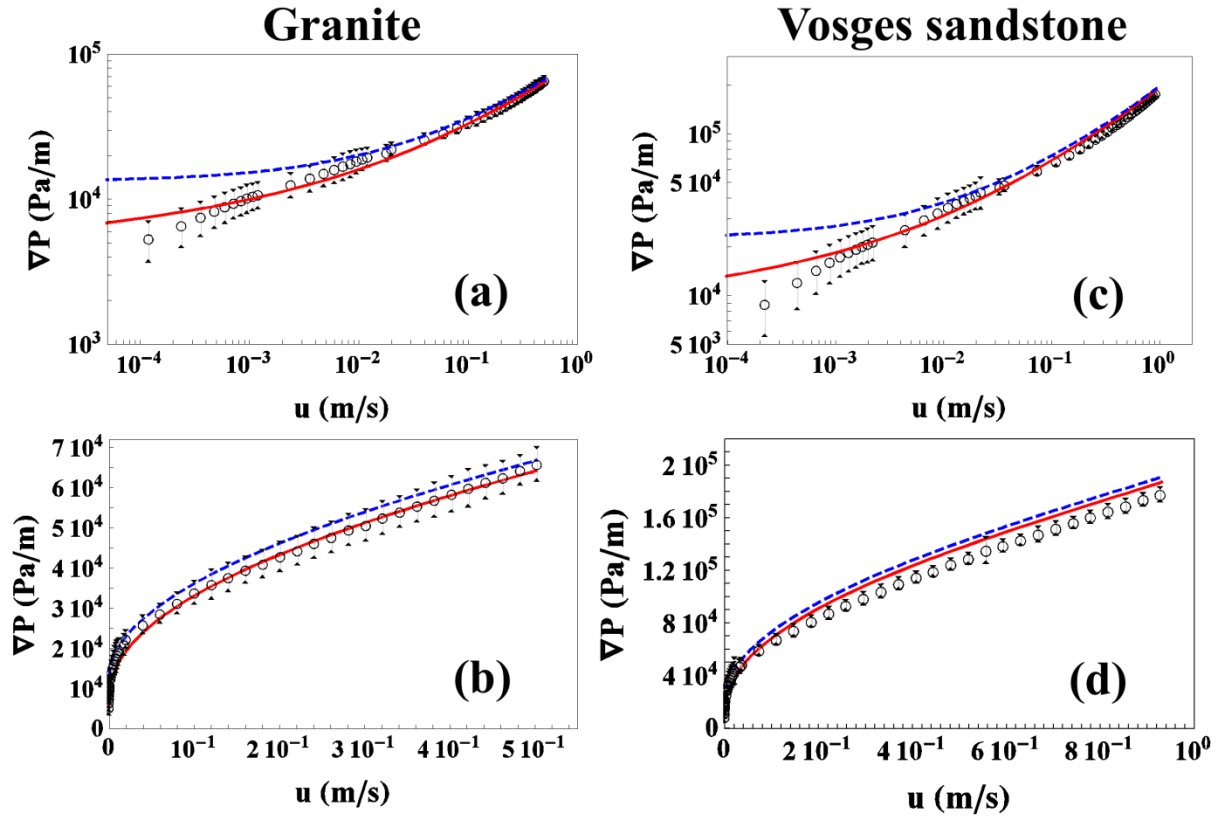
690  $\frac{\beta \rho u + \frac{\gamma \rho^2}{\mu_{pm}} u^2}{\frac{12 \mu_{pm}}{h^2}}$  leading to values of  $\frac{\Delta P_{inertial}}{\Delta P_{viscous}} < 7.1 \times 10^{-3}$  for the granite fracture and  $\frac{\Delta P_{inertial}}{\Delta P_{viscous}} < 3.1$   
691  $\times 10^{-2}$  for the Vosges sandstone fracture. This confirms that inertial pressure losses are not  
692 relatively important, in contrast to the experiments with Carreau fluids performed by  
693 [Rodríguez de Castro and Radilla, 2016a].

694

#### 695 **4.4. Experimental validation of the proposed prediction methods**

696

697 Eq. (33) was used to predict the relation between  $\nabla P$  and  $u$  for the injection of the 7000 ppm  
698 solution through the fractures. The  $\beta$  and  $d$  values in Eqs. (2-5) do not depend on polymer  
699 concentration as shown by Rodríguez de Castro and Radilla [2016a, 2016b], so the values  
700 obtained from water injection (subsection 4.1) were used. The obtained predictions are  
701 presented in Figure 5 together with the experimental results of measurements performed in  
702 the present work. In this figure, the errors bars correspond to a 95% confidence interval as  
703 explained in subsection 3.1. The results are presented in a log-log scale in order to allow  
704 visibility of all the range of measurements and in a linear scale so as to show that the form of  
705 the curves is the same as that of the rheogram of a yield stress fluid (Figure S3). From these  
706 results, the accuracy of the proposed methods for the prediction of  $\nabla P$  as a function of  $u$   
707 during the flow of yield stress fluids through rough-walled fractures can be assessed. Figure 5  
708 shows that the variable- $\alpha$  approach provides more accurate predictions within the low and  
709 moderate  $u$  regions, which is in agreement with the arguments presented above. However, a  
710 less important difference is obtained between both methods for the highest values of  $u$ . It is  
711 observed that the variable- $\alpha$  method successfully predicts the  $\nabla P$ - $u$  relationship for the flow  
712 of the yield stress fluid through both fractures, even though the obtained predictions are  
713 slightly less accurate in the case of the Vosges sandstone.



715

716 **Figure 5.**  $\nabla P$  as a function of  $u$  corresponding to (a,b) Granite and (c,d) Vosges sandstone  
 717 fractures. Symbols represent experimental data, red solid lines represent predictions using Eq.  
 718 (33) with the  $\alpha(u)$  functions presented in Figure 2 and blue dashed lines represent predictions  
 719 using Eq. (33) with  $\alpha = \frac{1}{\sqrt{3}} \left( 2 + \frac{1}{n} \right)$ .

720

721 With the objective of assessing the accuracy of the proposed predictions in the case of  
 722 Carreau fluids, Eq. (33) was also used to predict the  $u$ - $\nabla P$  relations for the injection of the  
 723 three Carreau fluids used by *Rodríguez de Castro and Radilla* [2016a], and the results were  
 724 compared to their experimental data in Figure 6. The average deviations between predictions  
 725 and experiments corresponding to the whole range of explored  $u$  for all tested fluids and  
 726 fractures are included as supporting information of this article (Table S1). As can be seen in

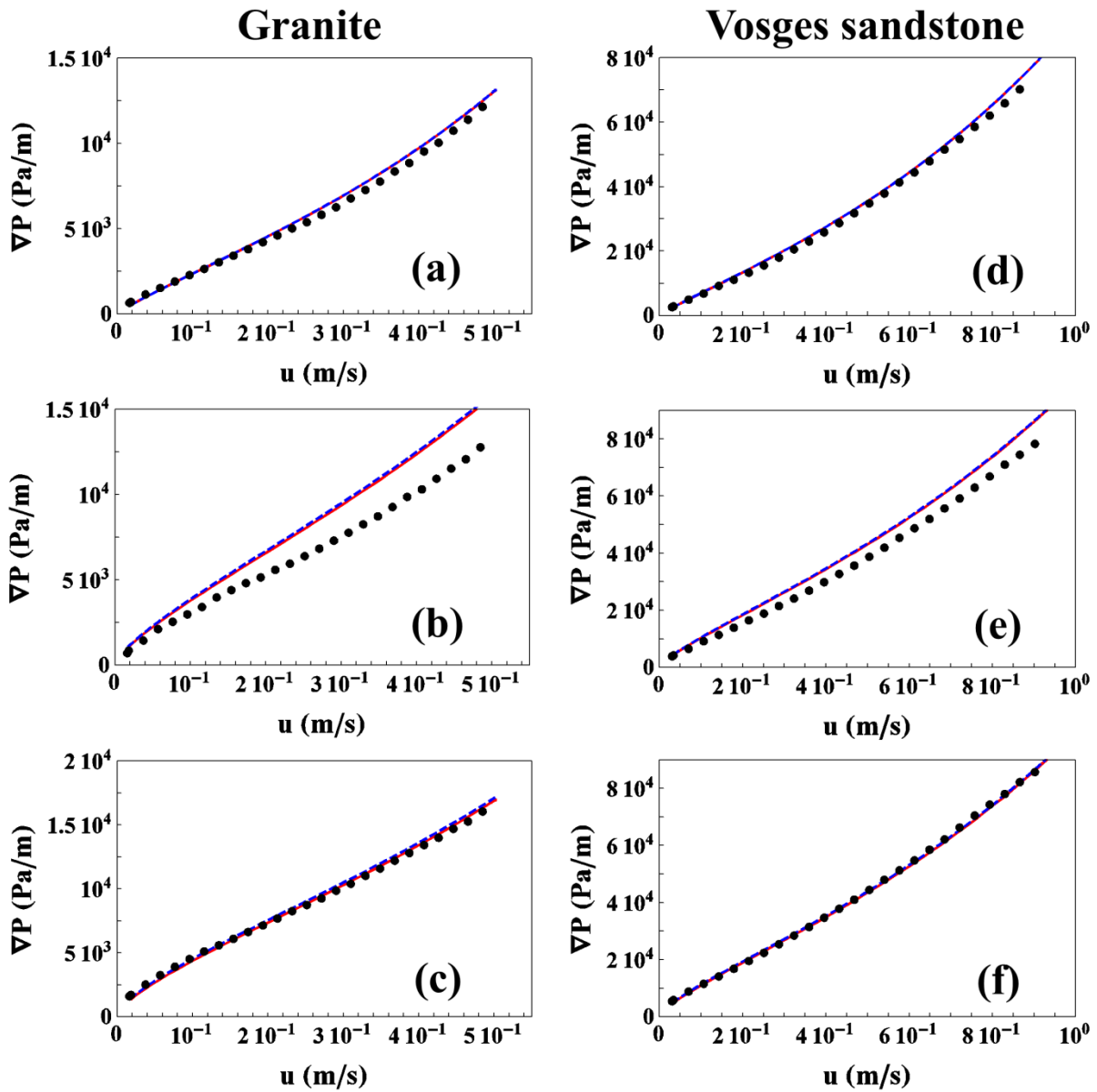
727 Figure 6, the predictions coming from both methods (constant- $\alpha$  and variable- $\alpha$ ) methods are  
728 almost identical in all cases. This is explained by the proximity of all the  $\alpha$  values to the limit  
729 value  $\sqrt{3}$  (Figure 2) within the range of imposed  $u$ . Furthermore, the low and moderate  $u$   
730 regions were not explored by [Rodríguez de Castro and Radilla, 2016a], while it is precisely  
731 in these regions where more important differences are expected between both approaches.  
732 However, the predictions obtained for the covered range of  $u$  is in very good agreement with  
733 the experimental data, apart from the 500 ppm – granite pair which will need further study.  
734 Moreover, it is also remarked that Eq. (33) successfully takes into account the inertial effects,  
735 which are important for the flow of the injected Carreau fluids at the involved values of  $u$ .

736

737

738





739

740 **Figure 6.**  $\nabla P$  as a function of  $u$  corresponding the injection of the three Carreau fluids used  
 741 by *Rodríguez de Castro and Radilla* [2016a] through (a,b,c) Granite and (d,e,f) Vosges  
 742 sandstone fractures. Symbols represent experimental data, red solid lines represent  
 743 predictions using Eq. (33) with the  $\alpha(u)$  functions presented in Figure 2 and blue dashed lines  
 744 represent predictions using Eq. (33) with  $\alpha = \sqrt{3}$ .

745

746

747 **5. Discussion**

748

749 As explained in subsection 3.2., the concentrated xanthan gum solutions used in our  
750 experiments present an apparent yield stress, so they should be referred to as pseudo-yield  
751 stress fluids. In this regard, *Lipscomb and Denn* [1984] showed that the classical lubrication  
752 approximation, which essentially assumes that flow is locally fully-developed, can be applied  
753 to this type of fluids, while it cannot be successfully applied to ideal yield stress fluids with a  
754 real yield stress. These authors argued that rigid plug regions should not exist in complex  
755 geometries according to classical lubrication. Indeed, this theory predicts that plug-velocity  
756 changes slowly as aperture varies, so the plug region cannot be truly unyielded for continuity  
757 reasons. The latter is known as lubrication paradox [*Lipscomb and Denn*, 1984; *Frigaard and*  
758 *Ryan*, 2004; *Lavrov*, 2013]. However, as showed by *Lipscomb and Denn* [1984], both real  
759 and pseudo-yield stress fluids may exhibit a near-plug-like region in a complex flow field.  
760 For fully developed flows, the depth of the plug as a function of  $\nabla P$  is given by [*Lipscomb*  
761 *and Denn*, 1984]:

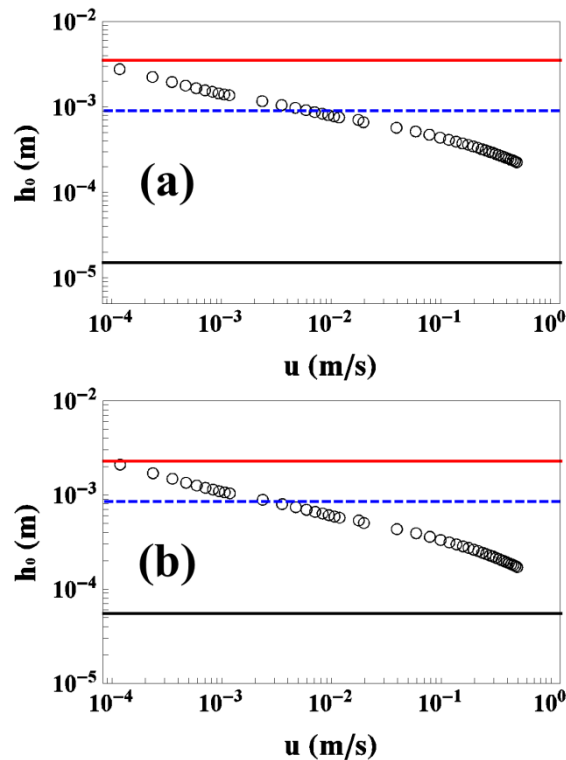
762

$$h_0 = \frac{2\tau_0}{\nabla P} \tag{34}$$

763 As a first simple approach similar to the one presented by *Auradou* [2008], we will assume  
764 that the fracture space can be modelled as being a bundle of parallel rectangular canals of  
765 length  $L$ , width  $w_i$  and aperture  $h_i$ , with  $w_i \gg h_i$ .  $h_i$  is expected to vary along the flow paths.  
766 However, given the strong dependence of  $\nabla P$  on the canal aperture in the case of shear-  
767 thinning fluids, we will also assume that the pressure drop along a percolating path is located

768 exclusively in the section of smallest aperture  $h_0$ . By doing so, it can be deduced that the  
 769 fluid will flow through a percolating path only if the minimum local aperture is superior to  $h_0$   
 770 as given by Eq. (34). Therefore, the number of percolating pathways is expected to increase  
 771 as  $\nabla P$  and  $u$  increase.  $h_0$  has been presented as a function of  $u$  for the present flow  
 772 experiments with yield stress fluids in Figure 7. This figure shows that  $h_0$  decreases with  $u$ ,  
 773 as expected. Indeed, only the pathways with the highest apertures participate in the flow at  
 774 the lowest values of  $u$ , while pathways with smaller values of  $h_0$  are progressively  
 775 incorporated as  $u$  increases. According to this simple approach, the flow pathways including  
 776 the minimum apertures of the fracture would not participate in the flow, even at the highest  $u$ ,  
 777 so unyielded fluid regions would exist (in agreement with *Frigaard and Ryan [2004]*).

778



779

780 **Figure 7.**  $h_0$  as a function of  $u$  for the flow of the yield stress fluid through the (a) granite  
 781 fracture and the (b) Vosges sandstone fracture. The experimental data are represented as void

782 symbols. Red solid lines represent the maximum fracture apertures, black solid lines  
 783 represent the minimum fracture apertures and blue dashed lines represent the average fracture  
 784 apertures as measured by *Nowamooz et al.* [2013] (see complementary figures).

785

786 If we focus on the Darcian flow of a yield stress fluid ( $\mu_{pm} = \mu_{pm,ysf}$ ), Eq. (31) gives the  
 787 pressure gradient through a rough-walled fracture of hydraulic aperture  $h$  as a function of the  
 788 Herschel-Bulkley law parameters:  $\tau_0$ ,  $a$  and  $n$ . This equation can be re-written as:

789

$$\nabla P = \frac{C_1}{\alpha} + C_2 \alpha^{n-1} u^n \quad (35)$$

790

791 with  $C_1 = \frac{2\sqrt{3}\tau_0}{h}$  and  $C_2 = \frac{2^{n+1}3^{\frac{n+1}{2}}a}{h^{n+1}}$ .

792

793 In the high flow rates region, i.e. when  $u \gg \frac{\tau_0 h^n}{2^n 3^{n/2}}$ ,  $\alpha$  can be considered a constant value  $\alpha =$

794  $\frac{1}{\sqrt{3}} \left( 2 + \frac{1}{n} \right)$  and Eq. (31) leads to:

795

$$\nabla P = \nabla P_0 + C u^n \quad (36)$$

796

797 with  $\nabla P_0 = \frac{6n\tau_0}{h(2n+1)}$  and  $C = \frac{6an(\frac{2+4n}{hn})^n}{h+2hn}$ . This is in agreement with the results of *Talon et al.*  
798 [2014], who stated that  $u$  scales linearly as  $(\nabla P - \nabla P_0)$  in the case of a Bingham fluid ( $n = 1$ )  
799 flowing at high  $u$  through a one-dimensional channel. Also, *Nash and Rees* [2017] showed  
800 that the manner in which flow begins once the threshold pressure gradient is exceeded  
801 strongly depends on the channel size distribution of the porous media. The same authors  
802 [*Talon et al.*, 2014; *Nash and Rees*, 2017] proved that  $\nabla P_0$  is higher than the actual threshold  
803 pressure, which is consistent with our results given that  $\alpha$  increases as  $u$  tends to zero (Figure  
804 2). *Roustaei et al.* [2016] numerically showed that unyielded plug regions appear close to the  
805 fracture wall and in the deeper layers (fouling layers) when injecting yield stress fluids in  
806 short fractures, especially at low values of  $u$ . These researchers showed that Darcy-type flow  
807 laws are limited to  $H/L \ll 1$ ,  $H$  being a half of the difference between the maximum and the  
808 minimum aperture of the fractures. In the case of the granite sandstone used in the present  
809 work  $H/L = 6.2 \times 10^{-3}$  while  $H/L = 5.5 \times 10^{-3}$  for the granite sandstone as shown in supporting  
810 figures, so a Darcy-type approach is expected to be valid.

811

812 Lavrov [2015] developed analytical solutions for the flow of truncated power law fluids  
813 through smooth-walled fractures. Truncated power-law fluids, unlike Carreau fluids, enable a  
814 closed-form solution for the flow between plane parallel walls while exhibiting more realistic  
815 behaviour than simple power-law fluids for commonly used polymer solutions. However,  
816 truncated power-law fails to model the real behaviour of these complex fluids at shear rates  
817 lying within the transition region between the shear-thinning region and the upper Newtonian  
818 plateau. Therefore, this model is not expected to provide accurate predictions in the wide  
819 range of shear-rates explored in the present experiments.

820

821 One may wonder whether the proposed procedure is simpler than performing a numerical  
822 solution to the actual flow equations, without invoking a bundle-of-capillaries approximation.  
823 In this sense, it should be highlighted that performing a numerical solution to the actual flow  
824 equations would imply using the size distribution of the flow paths as an input for the model.  
825 This information on the size distribution of the flow paths is rarely available in real  
826 applications, while the average aperture of the fracture can be more easily estimated or  
827 measured from water flow experiments. It is reminded that the objective of this work is to  
828 present a simple method to predict the pressure drop for the flow of shear-thinning fluids  
829 through tough-walled rock fractures. Therefore, using hardly accessible inputs as needed to  
830 perform a numerical solution to the actual flow equations is not a valid approach.

831

832 Also, it is noted that in our experiments with yield stress fluids, the total pressure drop  
833 through the fractures was successfully predicted from the values of  $K$ ,  $\gamma$  and  $\beta$  obtained from  
834 water injection without any significant deviation. Therefore, elongational viscosity effects  
835 have been shown to be negligible in the case of the present experiments with yield stress  
836 fluids as they were with the Carreau fluids used by [Rodríguez de Castro and Radilla,  
837 2016a].

## 838 6. Summary and conclusions

839

840 A simple method to extend Darcy's law, weak inertia cubic law and full cubic law to the flow  
841 of yield stress fluids and Carreau fluids in rough-walled natural fractures has been presented  
842 in the present work. In this method, the values of the shift parameter  $\alpha$  between the  $\mu_{pm}$   
843 measured in the rheometer and the  $\mu_{eq}$  observed during the flow in the porous media is  
844 predicted through identification of the apparent shear rate with the maximum wall shear rate  
845 in a section with aperture  $h$ . The inputs of the method are only the shear rheology parameters  
846 of the fluid, the hydraulic aperture of the fracture and the inertial coefficients  $\gamma$  and  $\beta$ . On the  
847 basis of our results, an efficient protocol to predict  $\nabla P$  as a function of  $u$  is proposed here:

848 1) Determine the shear-rheology parameters of the fluid:  $(\tau_0, a, n)$  for Herschel-Bulkley  
849 fluids or  $(\mu_\infty, c, n)$  for Carreau fluids.

850 2) Measure  $h$ ,  $\beta$  and  $\gamma$  from Newtonian-flow experiments. Alternatively,  $h$  can be deduced  
851 from the aperture distribution [Zimmerman *et al.*, 1991], which can be obtained  
852 through image analysis [Nowamooz *et al.*, 2013].

853 3) Calculate the values of  $\alpha(u)$

854 3.1) When low and moderate values of  $u$  are involved, solve the differential  
855 equation (29) or (30) to obtain  $\alpha(u)$ .

856 3.2) When only high values of  $u$  are involved ( $u \gg \frac{\tau_0 h^n}{2^n 3^{n/2}}$  for yield stress

857 fluids or  $u \gg \left[ \frac{2^n h^{1-n}}{6\mu_\infty} \text{Max} \left( 3^{\frac{n-1}{2}}, 3^{\frac{n+1}{2}} c \right) \right]^{\frac{1}{1-n}}$  for Carreau fluids), use a constant

858 value  $\alpha = \frac{1}{\sqrt{3}} \left( 2 + \frac{1}{n} \right)$  for Hershel-Bulkley fluids or  $\alpha = \sqrt{3}$  for Carreau fluids.

859 4) Use Eq. (13) or (14) to calculate  $\mu_{pm,Carreau}$  Or  $\mu_{pm,ysf}$

860 5) Use Eq. (33) to calculate  $\nabla P$  as a function of  $u$ , with  $\gamma = 0$  in the case of  
861 Forchheimer's law (strong inertia regime),  $\beta = 0$  in the case of a cubic law (weak  
862 inertia regime),  $\beta = 0$  and  $\gamma = 0$  in the case of Darcy's law (creeping flow).

863

864 Flow experiments of yield stress fluids covering a wide range of  $u$  ( $\sim 3.6$  orders of  
865 magnitude) have been performed and compared with the predictions of the proposed method,  
866 showing good agreement. It has been observed that the existence of a yield stress reduces  
867 significantly the value of Reynolds, so the inertial effects are negligible within the explored  
868 range of  $u$ . Consequently, Darcy's law provide accurate  $u$ - $\nabla P$  predictions in contrast to the  
869 case of less concentrated solutions with no yield stress [Rodríguez de Castro and Radilla,  
870 2016a]. Also, the experimental results obtained in the non-Darcian shear-thinning flow  
871 experiments through rough-walled fractures conducted by [Rodríguez de Castro and Radilla,  
872 2016a] have been compared with the predictions of the proposed method, showing good  
873 agreement also in the case of Carreau fluids. It should be noted that good predictions of the  
874 pressure drop-flow rate relations are obtained by only using the global parameters  $h$ ,  $\beta$  and  $\gamma$   
875 as inputs. Therefore, no significant effects of the aperture distributions of the fractures have  
876 been observed.

877

878 The variable- $\alpha$  approach leads to a very good overlap between  $\mu_{pm}$  and the  $\mu_{eq}$  over the wide  
879 range of  $u$  investigated in this work. Our results can be included in computational studies of  
880 large-scale nonlinear flow in fractured rocks, as suggested in the works of Javadi *et al.*  
881 [2014]. These conclusions must now be extended to other types of rough-walled rock  
882 fractures.



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884

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886 setup.

887

888 Supporting data are included as four figures and a table in SI files; any additional data may be  
889 obtained from the authors ([antonio.rodriquezdecastro@ensam.eu](mailto:antonio.rodriquezdecastro@ensam.eu)).

890

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