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Influence of displacement rate on residual shear strength of clays

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Abstract

This paper reports on the results of direct shear tests carried out under controlled displacement rate in the range of 10^{-4} - 10^{2} mm/min, under different normal stresses, with different shear devices. The tests were carried out on a kaolin, a bentonite, their mixtures with sand at various percentages, and the clayey soil of the *Costa della Gaveta* earthflow. The tests were performed on specimens reconstituted with distilled water as well as with NaCl solutions at various concentrations. Positive rate effects were exhibited by mixtures with c.f. higher than 50% and, consistently, by the natural clayey soil the c.f. of which is about 50%. The residual shear strength increases significantly for shear displacement rate higher than about 1 mm/min. The rate effect increases with the pore solution concentration. The residual shear strength independence of displacement rate has been confirmed in the range 10^{-6} - 10^{-1} mm/min by the results of shear tests performed under controlled shear stress, with varying chemical conditions of the pore fluid.

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Keywords: Residual shear strength; displacement rate; clay; mixtures; ring shear.

1. Introduction

The residual shear strength is the minimum strength that a soil can offer to shear displacements under given effective normal stresses. It is the available strength of landslides which underwent large displacements on regular slip surfaces. The residual shear strength parameters depend on the composition of both the solid skeleton and the pore fluid[1-5]. In addition, several results reported in the technical literature[1,6-12] also point out a dependence on the displacement rate, showing that the residual shear strength can increase, decrease or remain constant with the displacement rate increasing.

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The rate effects are very important in the interpretation and in the forecasting of landslide behaviour. The temporal evolution of landslide displacements was attributed by Leroueil[13] also to the influence of the displacement rate on the residual shear strength. The Author highlighted that, for landslides in the reactivation stage, such influence can provide beneficial effect, preventing large movements. Similarly, Wang *et al.*[14], on the basis of laboratory test results, hypothesised that significant positive rate effect would have prevented catastrophic acceleration of a landslide system, experiencing repeated accelerating-decelerating cycles of movement, in Japan. Accounting for rate effects, Vuillet and Hutter[15] related the displacement rate of several landslides to the driving shear stresses.

The causes of rate effects were studied by several Authors. Lupini *et al.*[8] investigated the influence of clay type and grain size on the mode of shearing, identifying three mechanisms: turbulent, transitional and sliding, to which different energy dissipation corresponds. Tika *et al.*[11] showed that the shearing mode influences the rate effect. They observed three types of rate effect, corresponding to: fast residual strength higher than slow residual strength, fast residual strength lower than residual strength and constant residual strength, named positive, negative and neutral effect respectively. The relation between the types of displacement rate effect and the basic shearing modes of slow residual strength were considered, and the causes of the negative rate effect were investigated. Wang *et al.*[14], observed the shear zone of specimens of a Japanese landslide soil by means of laser microscope and scanning electron microscope. The examination of the shear-zone microstructure revealed that the change from sliding to turbulent shearing mode could have been the cause of the observed increase in shear strength. Furthermore, on different clayey soils, the Authors observed the same rate effect on both dry and water saturated specimens, thus excluding that excess pore water pressures played a significant role.

Tika *et al.*[11] also showed that rate effects depend on normal stress. Gratchev and Sassa[16] observed that negative rate effect decreases with normal stress increasing. Carrubba and Colonna[12] showed that even the type of effect (positive, neutral or negative) can depend on the normal stress.

Saito *et al.*[17] performed laboratory tests on sand, sand-illite mixtures and sand-montmorillonite mixtures with up to 20% c.f., by means of a ring shear apparatus[18] in undrained conditions and with pore pressure measurement. Their results show that the residual shear strength of their sand was independent of the displacement rate, consistently with the results reported by Tika *et al.*[11], while the residual shear strength of the mixtures was rate-dependent. For both c.f. = 10% and c.f. = 20%, a remarkable negative rate effect was evaluated for $v \geq 60$ mm/min. Although significant pore pressure variations were measured during the tests, the behaviour was also attributed, in part, to a decrease in the effective residual friction angle which, in turn, was considered the effect of the change in the shearing mode. Differently from Saito *et al.*[17], Li *et al.*[19] observed a positive rate effect on kaolin – glass beads mixtures with low clay content (c.f. ≤ 20%) and an opposite behaviour on mixtures with high clay content (c.f. ≥ 50%).

Thus, many experimental results show opposite, or at least inconsistent, behaviour for apparently similar conditions, suggesting the need of more systematic studies. In order to give a contribution in such direction, this paper shows the results of a large number of tests carried out on two different, almost pure, clays, on clay-sand mixtures at various percentages and on a natural clayey soil. The tests were performed under displacement rates varying in a wide range, and by means of different experimental devices.

2. Materials and methods

The laboratory tests were performed on reconstituted specimens of the *Costa della Gaveta* soil[20], a kaolin, a bentonite and mixtures of these two latter materials with a sand[21]. Some material properties and test conditions are summarised in Tab. 1, which shows that the *Costa della Gaveta* soil is characterised by high clay fraction. Its mineralogical analysis showed that illite-muscovite and kaolinite are the most abundant clay minerals[22]. However, relevant percentages of smectite are somewhere found[22]. The used kaolin is a practically pure kaolinite[23], and the tested bentonite is mainly composed of Na-montmorillonite[24].

The materials were reconstituted with distilled water, consolidated to given normal stresses and sheared in the range of displacement rates $0.00011 \leq v \leq 66.5$ mm/min. Some tests were carried out also on the soils reconstituted with – and submerged in – NaCl solutions at various concentrations. Most of the tests were carried out in the Bromhead ring shear apparatus. A number of tests was carried out by means of the Casagrande and the Bishop machines, thus the influence of the testing device on the results could also be investigated.

Table 1: Grain size fractions and liquid limit (w_L) of the investigated materials; test conditions of the specimens.

Material	Sample	Clay (%)	Silt (%)	Sand (%)	w_L (%)	Normal stress, σ'_n (kPa)	Displacement rate range (mm/min)
Costa della Gaveta soil	S9-A	47	40	13	64	150	0.00011-66.5
	S9-B1	48	49	3	-	150	0.018-0.45
	S9-B2	35	51	12	54	150	0.018-4.5
	S9-P5	45	42	13	56	150	0.005-3
	S9-P6	45	42	13	56	205	0.006-5.5
kaolin		74	25	1	67	120-350	0.018-11.1
sand*		0	0	100	-	150	0.089-44.5
bentonite		82	14	4	324	150	0.018-44.5

* coefficient of uniformity C_u=1.8 and median particle size D_{50}=0.2 mm

3. Experimental results

All specimens were first sheared to the residual condition under low displacement rate (v ≤ 0.018 mm/min), in different machines. Figs 1a and 1b show that the residual shear strength of the kaolin and bentonite - under given normal stresses - is independent of the used apparatus. The experimental points relative to the tested materials and to different normal stresses are plotted in a $\tau_r - \sigma'_n$ plane in Fig. 1c. The results relative to bentonite and kaolin are well interpreted by straight lines through the origin, providing residual friction angle $\varphi'_r \approx 5°$ and $\varphi'_r \approx 11°$ for the two clays respectively. A value of $\varphi'_r \approx 33°$ was obtained for the sand.

In order to investigate the influence of the displacement rate, two testing procedures were performed[25]. In a procedure, after the achievement of the residual state at low displacement rate, this latter was increased monotonically by steps. In the other procedure, the displacement rate was increased and then decreased alternatively, to check for test repeatability, and to observe if phenomena correlated to excess pore pressures were occurring. Actually, the "monotonic" procedure gave slightly lower values, probably because of excess pore pressures. Therefore, the results of the second procedure were considered more convincing to describe drained conditions.

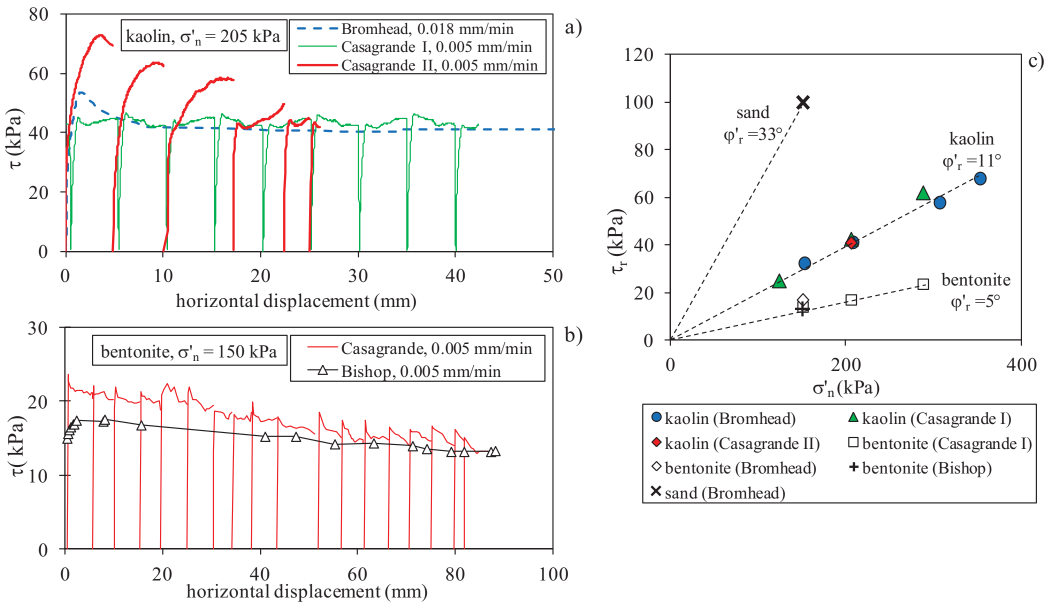

Fig. 1. Shear strength against horizontal displacement of specimens of kaolin (a) and bentonite (b) tested in different devices. Residual shear strength against applied normal stress (c) of specimens of sand, kaolin and bentonite.

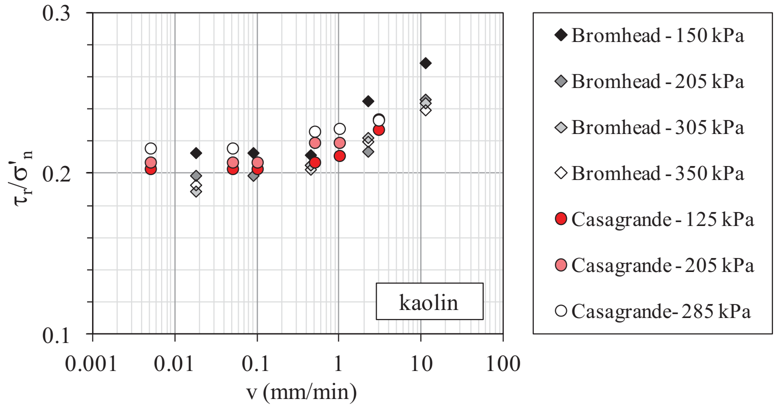

Fig. 2. Residual friction coefficient against displacement rate of specimens of kaolin tested in the Bromhead and Casagrande devices.

The results of the tests are shown in Figs 2 - 5. In particular, Fig. 2 plots, against the displacement rate, the ratio τ'_r/σ'_n evaluated by means of different devices and under several normal stresses, showing that the residual strength increases with the rate of displacement, and that the rate effect becomes significant for $v \geq 0.5 - 2$ mm/min, depending on the used apparatus. The apparent influence of σ'_n is currently under investigation.

A set of tests was carried out on mixtures kaolin - sand at various percentages. In the investigated rate range, for the mixtures with kaolin contents ≥ 50%, a positive effect was observed (Figs 3a, b). For lower percentages no rate effect was observed. Differently, Li *et al.*[19] found a noticeable negative rate effect on mixtures kaolin - glass beads with 40%-60% kaolin (Fig. 3b). However, it must be considered that the beads used by the Authors reached a size of 8 mm, much higher than the maximum, 0.4 mm, of the sand used in this study.

A similar experimentation was carried out, under the same normal stress (σ'_n = 150 kPa), on mixtures bentonite - sand. Fig. 3c shows, consistently with the results of other studies[3,26], that small percentages in dry weight of bentonite control the behaviour of the mixtures. The mixtures with bentonite contents equal to or higher than 50% exhibit a positive rate effect (Fig. 3d), small but significant percentage of the low rate shear strength.

The experimentation was carried out also on specimens of bentonite reconstituted with NaCl solutions at various concentrations. Figs 4a and 4b show how the ratio τ'_r/σ'_n depends on pore solution molarity and on displacement rate. The rate effect increases with the pore solution concentration. It is worth noting that the bentonite void ratio too is strongly dependent on such concentration, under given normal stresses, and it decreases as the solution concentration increases[27], probably making interparticle solid-solid contacts and interactions more numerous. In the higher number of contacts probably is the reason why the rate effects become more significant with the concentration increasing. For a concentration of 0.4 M, the behaviour of the bentonite is equal to that of the kaolin. For higher concentration values, besides the residual friction angle, also the rate effects of the bentonite are higher than those of kaolin. It is also worth observing that the hydraulic conductivity of the bentonite[27] increases greatly with pore solution concentration, thus the excess pore water pressures are less likely to occur during shearing.

Some tests were carried out on the *Costa della Gaveta* soil, reconstituted with water or with salt solutions and tested in various devices. Due to the soil heterogeneity, the results are unavoidably more dispersed (Fig. 5a). However, rather clearly, almost all the results show only negligible rate effects in the investigated range of displacement rates (Figs 5a and 5b).

The results of the experimentation are compared in Fig. 6 to those reported by Tika *et al.*[11] and by other Authors, in terms of residual shear strength normalised to the value at low displacement rate, against the displacement rate. In Fig. 6a the results are all referenced, in Fig. 6b they are classified according to the clay fraction. The two representations allow to observe that our kaolin behaved very similarly to the one tested by Tika *et al.*[11], and other sands, as our, did not exhibit rate effects. When a clay fraction is present, our results indicate that a positive rate effect can be expected for c.f. > 50%, however, literature results, as a whole, do not indicate a unique type of rate effect.

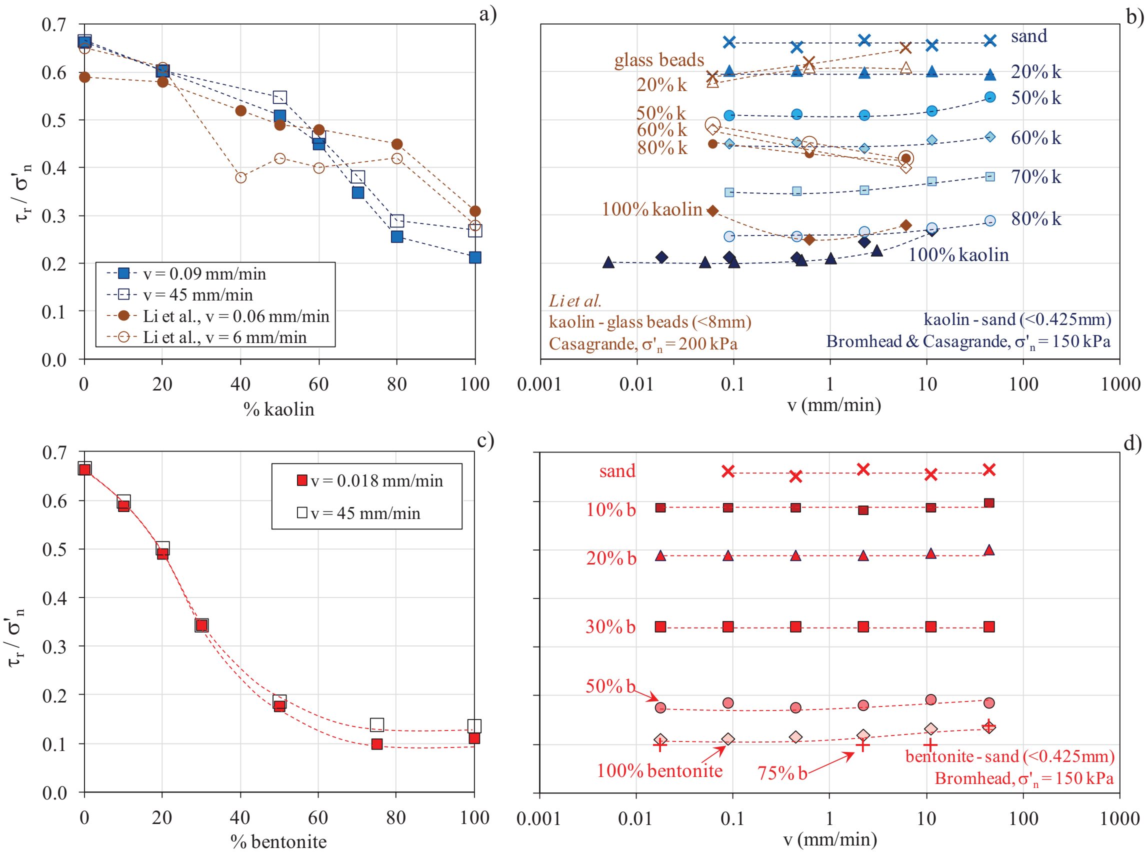

Fig. 3. Residual friction coefficient against kaolin (a) and bentonite (c) percentage in dry weight at two different displacement rates and against the displacement rate for the different tested mixtures (b and d). The results are compared to those obtained by Li *et al.*[19].

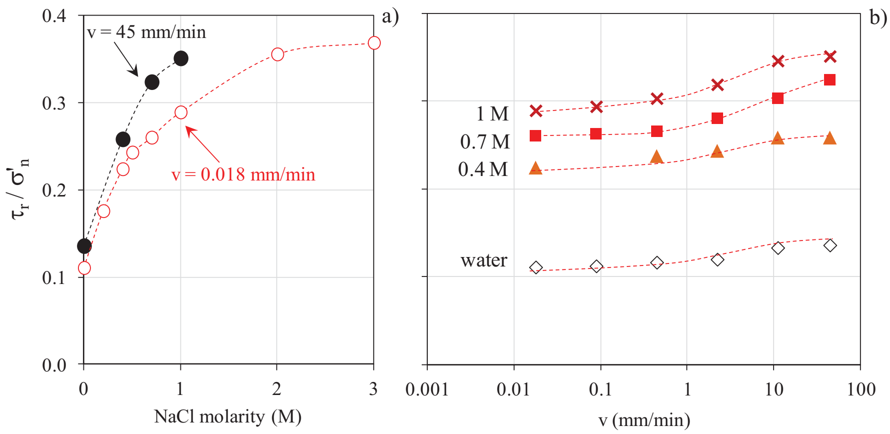

Fig. 4. Residual friction coefficient against pore solution molarity (a) and displacement rate (b) of specimens of bentonite reconstituted with water or with NaCl solutions at various concentrations. All specimens were tested in the Bromhead apparatus under σ'$_n$ = 150 kPa.

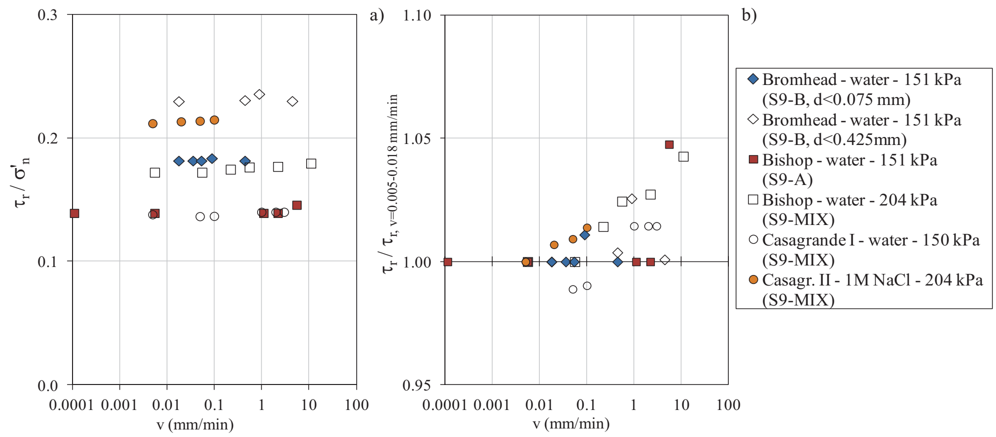

Fig. 5. Residual friction coefficient (a) and residual shear strength normalised by the value obtained at low displacement rate v = 0.005-0.018 mm/min (b) against the displacement rate for specimens of *Costa della Gaveta* soil tested in different machines.

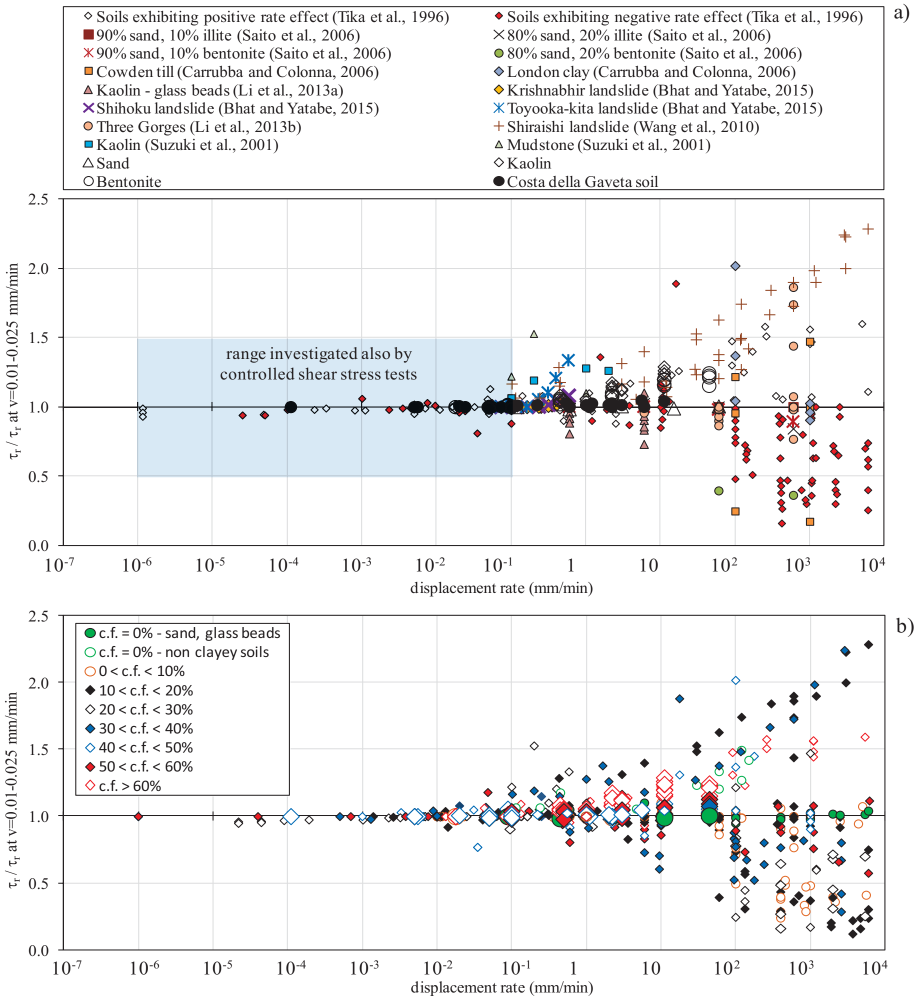

Fig. 6. Residual hear strength τ_r normalised by the value obtained at low displacement rate against the displacement rate: comparison among our data and data from literature. In (a) data are classified by reference, while in (b) by clay fraction (our data are indicated by larger markers).

The dependence on displacement rate of the bentonite and the *Costa della Gaveta* soil residual shear strength, and in particular of their residual friction angle, can be also analysed through the results of shear tests that Di Maio *et al.*[30] and Di Maio and Scaringi[31] performed under shear stress-controlled conditions. The soils were reconstituted with a 1 M NaCl solution, sheared to the residual condition while in the solution, and subsequently subjected to shear tests under constant shear and effective normal stresses. The applied shear stresses were lower than the residual shear strength obtained with the salt solution but higher than that exhibited by the material when saturated with distilled water. In the said conditions, the applied shear stresses caused displacements with decreasing rate. The specimens were then exposed to distilled water, simply renewing the cell liquid, thus inducing ion flow outward from the clay pores. This caused a progressive increase in the shear displacement rate, with a displacement pattern typical of tertiary creep (Figs 7a and 7b). Given the apparatus constrains, the maximum recorded displacement rate was 10^{-1} mm/min.

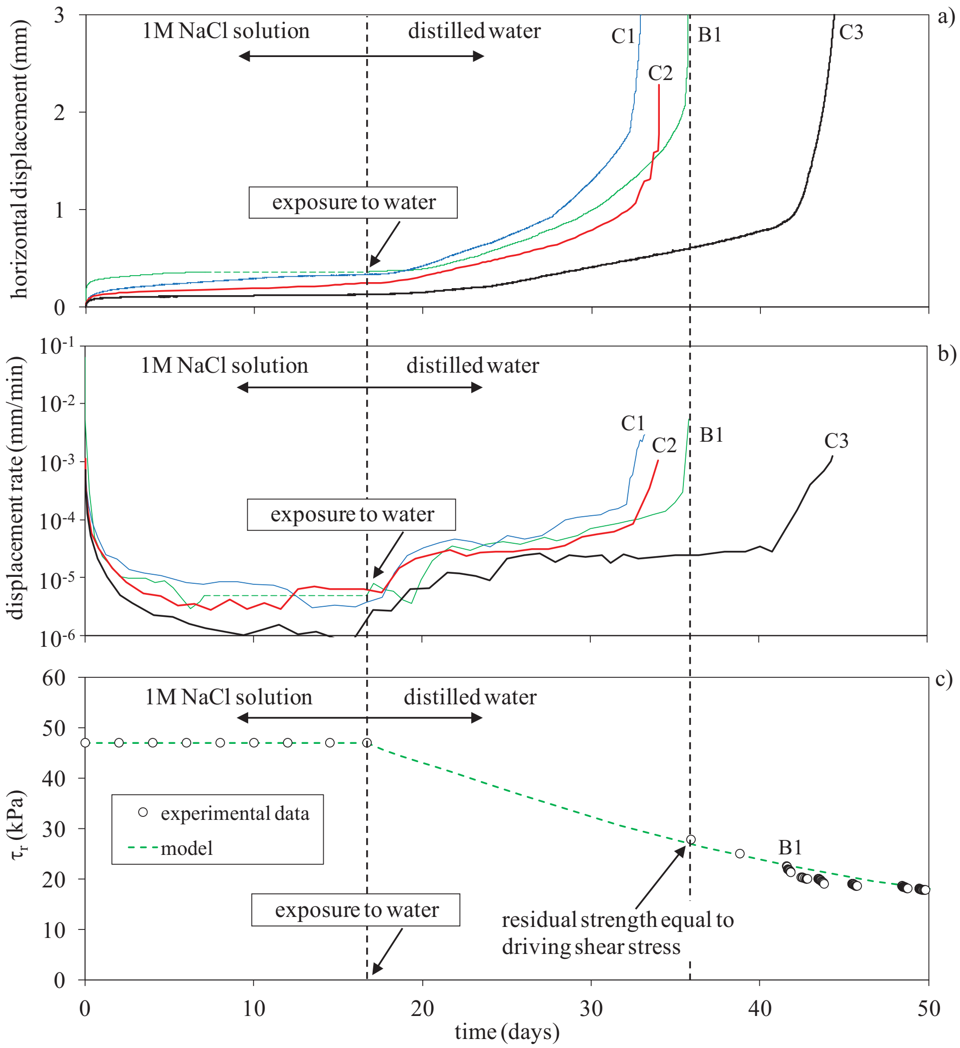

Fig. 7. Shear displacements (a) and shear displacement rate (b) under constant applied shear stresses before and during exposure to distilled water of specimens of bentonite; shear strength against time for specimen B1. Re-drawn from Di Maio and Scaringi[31].

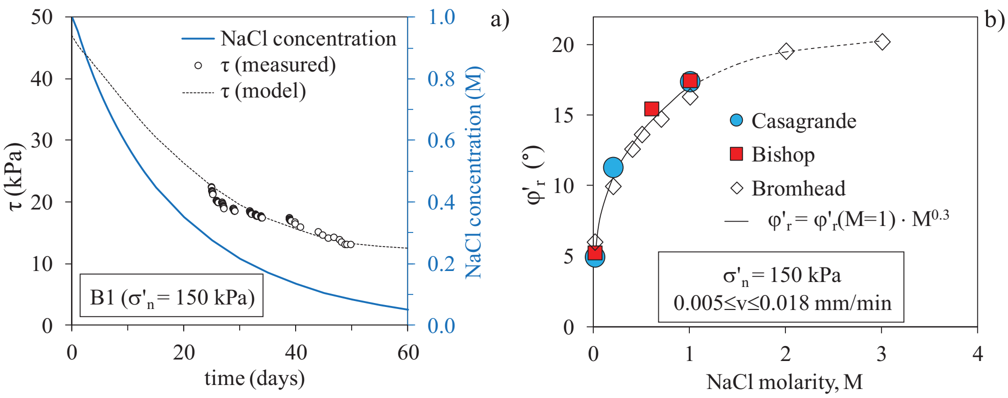

Fig. 8. a) shear strength measured and shear strength calculated on the basis of pore solution concentration and φ'_r of Fig. 8b, during exposure to water of a specimen of bentonite previously in 1M NaCl solution; b) residual friction angle against NaCl molarity of specimens of bentonite tested in absence of chemical gradients under constant displacement rate v = 5 μm/min (Di Maio and Scaringi[31]).

The observed behaviour was explained with a reduction in the residual shear strength (Fig. 7c) which progressively decreased until the value of the applied shear stress, thus causing "failure" (Figs. 7a and 7b). The residual strength decrease was caused by the decrease in pore solution concentration induced by exposure to distilled water. The decrease is satisfactory interpreted (Figs 7c and 8a) by using the relation between φ'_r and pore solution concentration determined by tests carried out at different solution concentrations (Fig. 8b), at very low displacement rate (v = 5 μm/min) and in the absence of chemical gradients (pore solution equal to cell solution), i.e. in drained conditions. Thus, in the range $10^{-6} < v < 10^{-2}$ mm/min ($10^{-6} < v < 10^{-1}$ for *Costa della Gaveta*), in which experimental data fall (Fig. 7b), no rate effects must be invoked to explain the soil behaviour.

4. Discussion and Conclusion

Shear tests under controlled displacement rates were carried out on a kaolin, a bentonite, on their mixtures with sand at various percentages, and on the clayey soil of the *Costa della Gaveta* earthflow. The range 10^{-4}-10^{2} mm/min of displacement rate was investigated. The results relative to the material mixed with distilled water show that the mixtures clay-sand with c.f. ≥ 50% exhibit positive rate effects which increase with the c.f. content. The rate effect becomes significant for rate v in the order of mm/min, with slight differences dependent on the used experimental shear apparatus. Results consistent with those of artificial mixtures are found on the *Costa della Gaveta* soil, the c.f. of which is about 50%.

The results relative to the material mixed with NaCl solutions at various concentrations show that the rate effect increases with the pore solution concentration. Since the increase in salt concentration also makes the material void ratio decrease greatly, the observed strength improvement could be reasonably attributed to the increasing number of solid-solid contacts, that probably endeavours the turbulent shearing mechanism. This aspect is currently under further examination.

The independence of residual shear strength on the displacement rate in the range 10^{-6}-10^{-1} has been confirmed by the results of shear tests performed under controlled shear stress conditions. This latter procedure can be promisingly improved for the evaluation of rate effects in a wider rate range.

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