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A new apparatus for testing the delayed mechanical behaviour of interfaces: The Shearing Interfaces Creep box (SInC box)

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ABSTRACT

A new experimental apparatus is presented for testing the time-dependent behaviour of interfaces, including in particular interfaces of geomaterials, under constant loading. This apparatus allows the application of two orthogonal loads normal and tangential to the mean plane of the interface, as well as the measurement of the axial and tangential relative displacements. The sample is moulded inside two half shear boxes and the system is designed in such a way that the shear force is applied along the mean plane of the interface. Some preliminary testing was carried out on a clay rock/concrete interface, under a controlled temperature environment. Preliminary results are presented, showing the evolution of the delayed displacements.

1. Introduction

It is well known that the mechanical behaviour of geotechnical structures such as dams, underground nuclear waste storage facilities, foundations, etc. is mainly governed by the behaviour of the various interfaces, present either within the structure itself or at the contact between the structure and the hosting rock or soil. The study of the mechanical behaviour of these interfaces, being the weakest points in terms of mechanical resistance, is of great importance for evaluating the stability or predicting a tentative life-time of such infrastructures.

Since Barton et al. [1], several constitutive models have been developed in order to describe the behaviour of joints in geomaterials on various direct shear paths ([2–6]). However, the predictability of any model depends on the quality of the tests performed in the laboratory, taking into account possible scale effects ([7]). In the literature, several shear devices can be found performing shear tests under various conditions. Desai et al. [8] employed a direct shear apparatus for the displacement-controlled cyclic testing of concrete/sand interfaces. Huck et al. [9] developed a ring simple shear device for interface testing, which can provide a relatively uniform shear-stress distribution. A modified direct shear apparatus was used by Fioravante et al. [10], allowing shear tests under constant normal stiffness, which can be considered as an intermediate situation between traditional constant normal load and constant normal volume tests. Boulon [11,12] introduced an original 3D testing device, called BCR3D ("Boîte de Cisaillement direct pour joints Rocheux en 3 Directions" in French),

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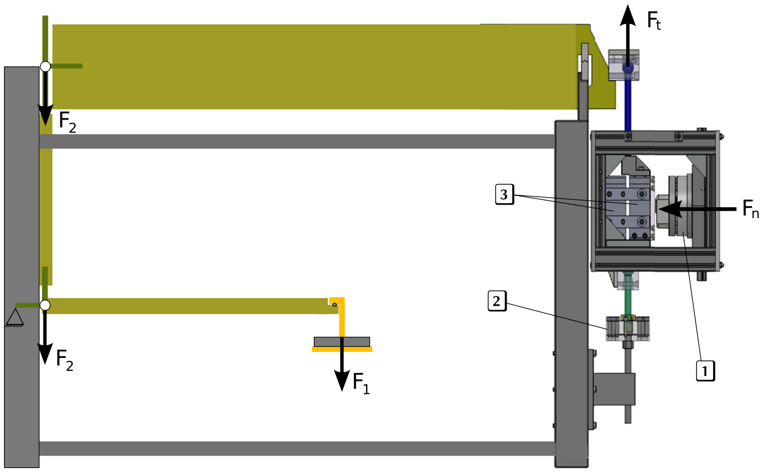

Fig. 1. 2D concept of creep apparatus. (1) Normal axis load cell – F_n, (2) shear axis load cell – F_t, (3) shear box.

which consists of three independent orthogonal axes: one normal to the joint, two in shearing directions. The BCR3D can perform shear tests under controlled normal stress, constant normal volume or constant normal stiffness, allowing no relative rotation between the two shear boxes.

Shear tests, not only for geomaterials interfaces, but also for interfaces of construction materials, have been developed. Kishida and Uesugi [13] used a simple shear box in a series of cyclic tests on interfaces between dry sand and steel. A test device, called annular shear device, was proposed by Brumund and Leonards [14] in order to conduct interface testing between sand and typical construction materials under static and dynamic loading conditions. For the testing of the concrete–steel bond, pull-out tests are widely used under various configurations ([15–17]).

It is obvious that several experimental approaches have been developed for the study of various types of interfaces under different loading conditions (static, dynamic, cyclic). However, for geotechnical structures as named previously, not only the study of the instantaneous mechanical behaviour is important, but also of the delayed one. Indeed, the physics at the level of the interface is different than in the core of intact materials; a geometrical wall effect perturbs the granular assembly of materials, bonding properties are different, so on. Therefrom comes the need to measure the relative displacement along an interface in time, in order to evaluate the creep phenomenon of the interface. To the author's knowledge, no shearing device exists for assessing the long-term behaviour of interfaces, thus an original apparatus is proposed. Long-duration tests require a continuous and sustainable loading system. Taking this into account, the adaptation of existing shear devices is not obvious, as they include electronic control systems that can create errors during a large time scale (power cuts, electronic drift, electronic noise, etc.). This paper deals with a new experimental device for the study of interfaces under long-duration load in two directions; normal and shear. The main features of the SInC box are described in details, some first results are presented.

2. Main features of SInC box

The characterisation of the mechanical behaviour of a geomaterial's interface in time required the design of a new experimental device. For the purpose of this work and based on the existing creep devices in traction for intact samples ([18]), SInC box has been developed, a sophisticated device that allows the study of an interface under long-duration load. This new experimental apparatus allows the application of a controlled normal load and introduces a second loading axis to the traditional uniaxial creep tests, permitting the study of the interface's delayed deformations due to shear.

2.1. General concept

The 2D sketch of the SInC box is presented in Fig. 1, involving the normal force centred on the active part of the interface and the shear force applied with the aid of a dead load (F_1) according to the Roman principle of balance [19]. The SInC box is attached to the entire system through two kneecaps (upper and lower as shown in Fig. 2), allowing the application of the shear force through the mean plane of the interfacial zone. The sample is moulded in two half shear boxes with a free distance of 10 mm at most between them (defined by the dimensions of the SInC box), defining the interface (as shown later in Fig. 6). The normal load is applied through a jack with a hydraulic pump, on a metallic plate which is screwed at one half shear box. This allows a homogeneous load application directly at the free outer interface. The sample is fixed to the system through the other half shear box.

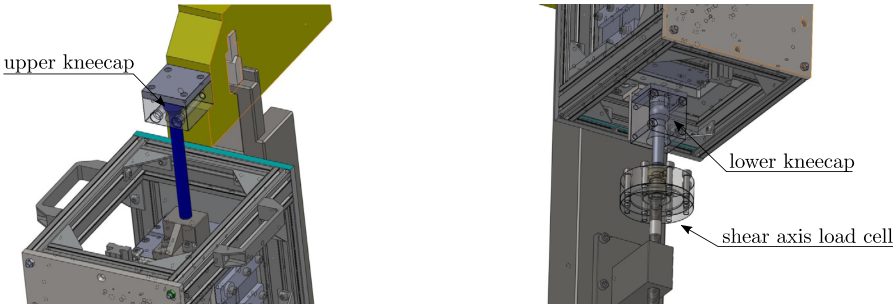

Fig. 2. Upper and lower kneecaps at the end of each rod, allowing the transfer of the shear load through the mean plane of the interface.

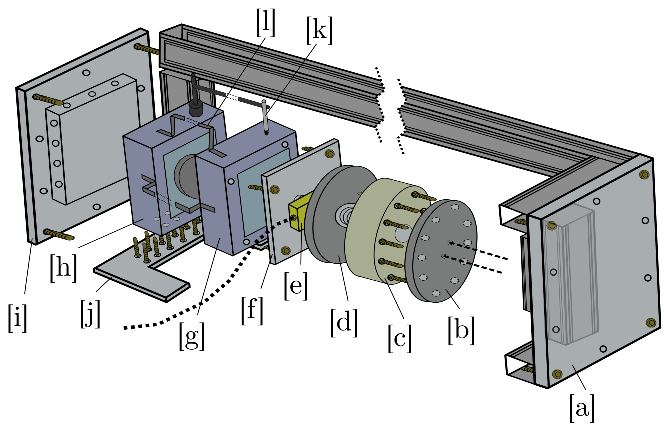

Fig. 3. Schematic of the components of the testing apparatus.

2.2. Mechanical aspects

A graphical rendering of the main part of the apparatus is shown in Fig. 3. On the rectangular 3D frame (290 mm × 350 mm × 360 mm), a front [a] and a back [i] steel plate (290 mm × 350 mm × 12 mm) are fixed, each one with ten M10 socket head screws. The normal force transducer [c] is screwed on a round metallic plate [b] of ⌀ 160 mm, with ten M8 socket screws. The jack [e], which is connected to a hydraulic pump with a tube (dashed curved line), is fixed to another round metallic plate [d] (⌀ 160 mm), which is bolted to the force transducer.

The pressure from the jack is applied in the middle of a square metallic plate [f], which is screwed with four M8 socket screws on one half shear box. The surface of the plate is the same with the one of the shear box (160 mm × 160 mm) and it is 15 mm in thickness. The first half shear box [g] is held by the rod of the upper kneecap (Fig. 2 left) with two M12 socket screws. The second half shear box is positioned on a metallic piece [j] through which it is screwed on the external frame with twelve M10 socket screws. On the back metallic plate [i], a thicker one, 170 mm × 210 mm × 30 mm in size, is laterally screwed to the external frame with fourteen M10 socket screws, as a reinforcement to the structure.

Three Pi-shaped displacement transducers [l] are placed along three sides around the sample; each foot of the transducer is fixed on one half shear box, allowing the measurement of the relative normal displacement between the two half boxes. An LVDT [k] measures the shear displacement positioned on a magnetic base. The base is fixed on the top of one half box and the edge of the LVDT touches the top of the other half box, allowing the measure of the relative shear displacement of the two half boxes.

2.3. Metrology and data acquisition system

Two load cells (max. capacity 100 kN) indicate the normal and shear forces. The normal load is applied using a hydraulic pump of maximum pressure 700 bar and an oil capacity of 770 cm^3. The pump is connected to a jack with capacity of 100 kN, which distributes the force to the sample. The shear load is applied using a dead weight fixed at position F_1 in Fig. 1. The three Pi-shaped displacement transducers that measure the normal relative rotation of the walls of the interface have a range of ±5 mm. The relative shear displacement is measured using an LVDT (±5 mm). Their exact arrangement is presented in Fig. 4.

The data acquisition system (DAQ) is composed of two major modules accommodated in a chassis (both National Instrument), as shown in Fig. 5. Module A allows the direct recording of the temperature (±1 °C). Module B (range ±10 V) reads

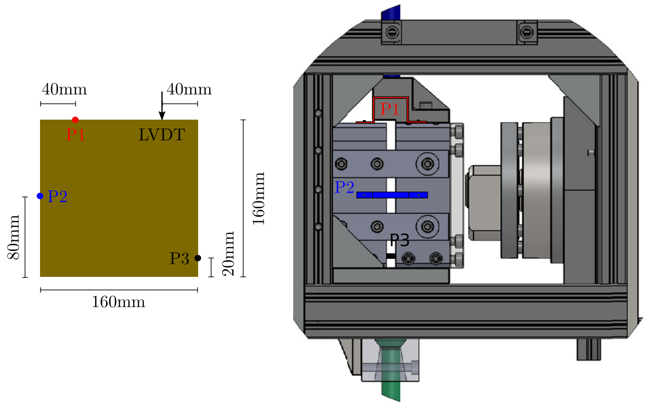

Fig. 4. Arrangement of the displacement transducers around the interface.

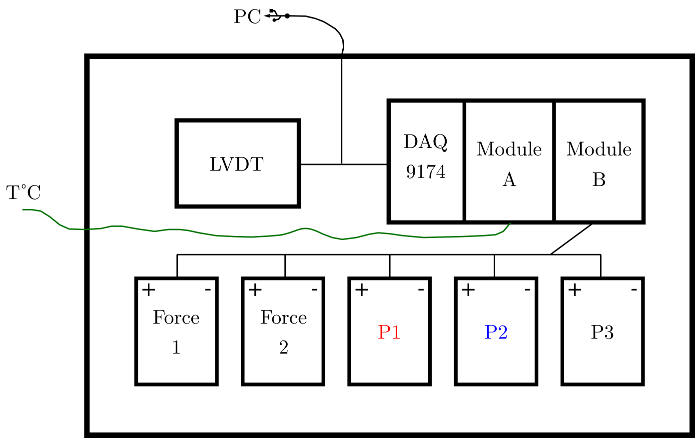

Fig. 5. Schematic of the data acquisition system.

the data from the force and displacement transducers, which are powered each one by a separate source. The power supply for the two force transducers is up to 10 V, for the LVDT displacement transducer ±15 V and for the Pi-shaped ones up to 2 V. Both modules take measurements at a frequency of 1 Hz.

The DAQ is controlled by a LabVIEW program installed on a computer, placed in the same chamber with the device. The real time readings of displacements and forces are shown on the LabVIEW interface and monitored remotely to assure that the tests are running without disturbances.

2.4. Sample preparation and installation

For the fabrication of the interface sample, a metallic square shear box (outer length, 160 mm, inner length, 140 mm, height, 60 mm) composed of two half shear boxes is used as mould. Based on the sample's configuration presented in Fig. 6, the rock sample (⌀ 80 mm, $h = 50$ mm) is placed in the first half shear box and positioned in such a way that its surface is higher by 5 mm than the box (Fig. 6-2), with the help of an adjusting table. The prominent surface of the rock is laterally sealed by a plexiglas plate of 10 mm in thickness, on top of which the second half shear box is centred, with two screws M10 and two rods (⌀ 10), as shown in Fig. 6-2a. Concrete is poured on top of the rock's surface, filling up the top half box. Finally the rock is sealed with cement and left to cure for 28 days before being tested.

The removal of the plexiglas plate leaves a free rock/concrete interface 10 mm in height and 80 mm in diameter, with the joint being in the middle (Fig. 6-3). Interface samples of different diameters or shapes can be tested, although in this study, interface samples of this single configuration (Fig. 6) have been used. The two screws and the rods hold the two half shear boxes together reassuring no relative movement of the interface. The positioning of the sample in the SInC box requires a 90° rotation; the interface is not anymore horizontal, but rather vertical (Fig. 6-4). Four metallic stems (two at each horizontal side) are screwed on the shear box, as a replacement for the two M10 screws and the rods which must be removed, stay fixed until the beginning of the test. With the beginning of the test, the single screws of each stem (top screws in Fig. 6-1 and -3) are unscrewed, allowing the relative displacement of the two half boxes in the shearing direction.

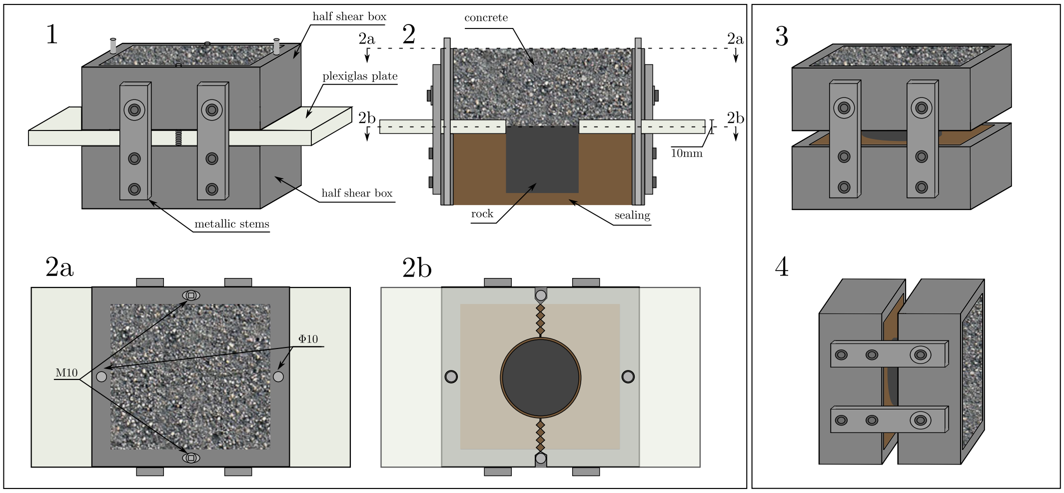

Fig. 6. Sample illustration, (1) 3D concept of the sample, (2) vertical section illustrating the interface of the two geomaterials, (2a) top of the sample showing the position of the two screws and two rods, (2b) horizontal section of the sample at the level of the interface, (3) sample after removal of the plexiglas plates, the two screws and the two rods, (4) sample rotated of 90° to be positioned in the SInC box.

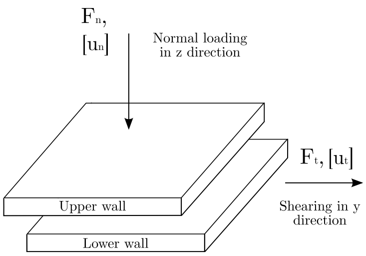

Fig. 7. Conceptual representation of an interface creep test in shearing.

Table 1
Measured variables during a creep test in shearing.

Type of variable	Number	Variables to be recorded versus time
Physical	1	Temperature (T)
Mechanical	4	Force vector acting on the axes of the interface (2 components: F_n, F_t) Relative displacement vector of the interface (2 components: u_n, u_t)

3. Performance of the device – first test results

Some first results of the creep tests performed with the SInC box on clay rock/concrete interfaces are presented, in the context of the experimental campaign of ANDRA (French National Radioactive Waste Management Agency) in Bure, France. During a creep shear test, five scalar variables have to be recorded in real time, as shown in Fig. 7 and Table 1.

The following three tests were performed in a temperature-controlled environment (20 °C), under a different normal stress (6 MPa, 8 MPa, 10 MPa, respectively), which was tried to be maintained constant as shown in Fig. 8a. This variation of the normal load is due to the continuous normal deformation of the sample after compression (axial creep), *i.e.* the sample is moving away from the jack, which applies a constant load in volume. Thus, the sample was manually reloaded in short time periods. Each sample was initially submitted for a few days in compression only, so that the rate of delayed axial deformation decreases before the application of the shear load. Fig. 8b shows the applied shear stress for each test, including increasing loading steps and loading–unloading paths.

If the interface is not perfectly orthogonal to the normal force and smooth, the application of the normal load might cause some initial relative rotation between the two walls of the interface. This relative rotation evolves with creep or any variation in load, such as the application of the shear load (Fig. 9a). The tested samples present a certain variability in the geometry of the interface, as can be noticed from the initial relative rotation with the application of compression. In later-performed tests, not presented here, improvements in the sample's preparation have limited the initial rotation lower than 1°.

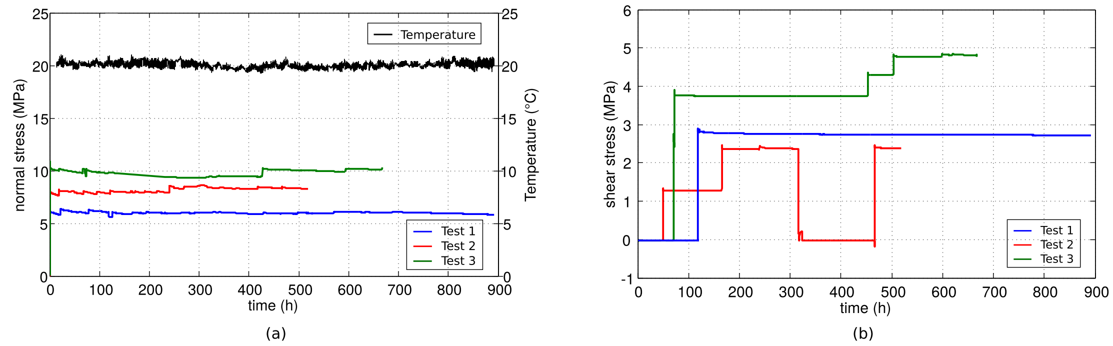

Fig. 8. (a) Normal stress and temperature, (b) applied shear stress.

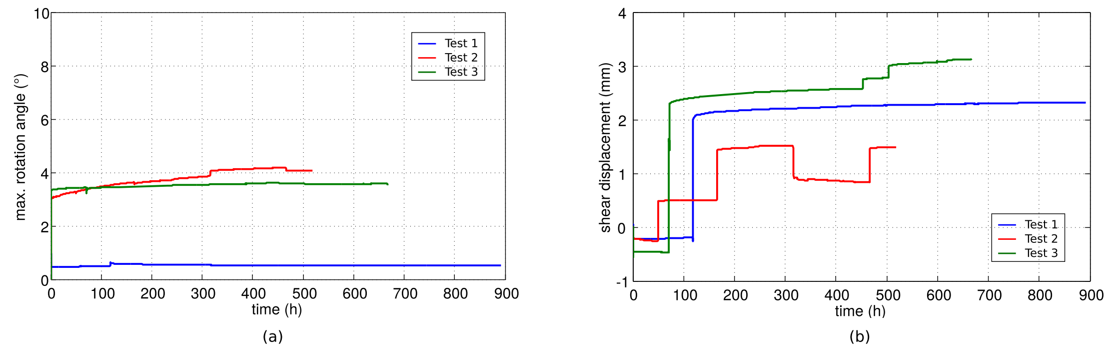

Fig. 9. (a) Maximum relative rotation angle of the two half shear boxes, (b) shear displacement.

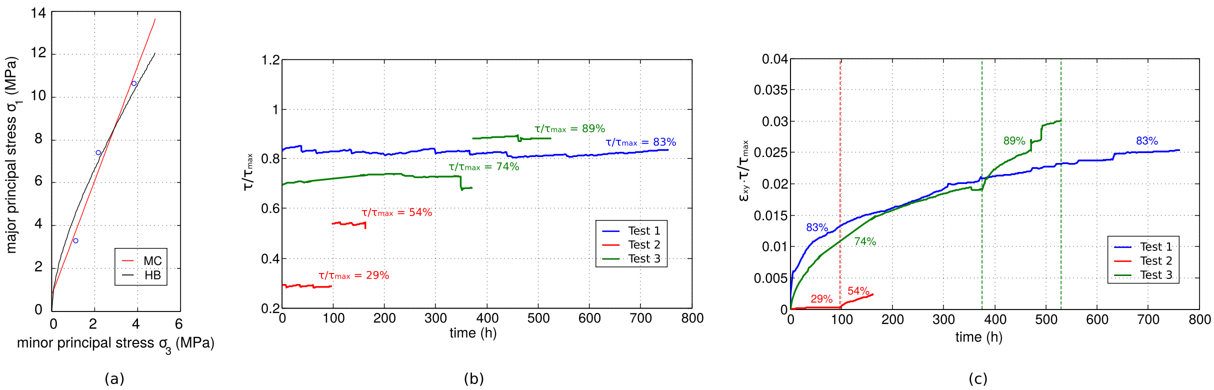

Fig. 10. (a) Calibration of the short-term experimental results of shear tests on the COx/concrete interface with Mohr Coulomb (MC) and Hoek–Brown (HB) failure criteria, (b) applied shear stress over shear strength, (c) measured compliance for each percentage of applied shear strength.

Fig. 9b shows the different shear displacement paths that were measured, with the application of shear stress. For the analysis of these results, the maximum shear strength of the interface is taken into account, which was previously calculated with short-term shear tests under constant volume. Fig. 10a shows the fitting of the short-term experimental results of the COx/concrete interface using two different failure criteria; Mohr Coulomb and Hoek–Brown. For the calculation of the maximum shear strength of the interface in this study, the Mohr Coulomb criterion is used, with calculated friction angle $\phi = 27°$ and initial cohesion $C = 0.24$ MPa.

In Test 1, a normal stress of 6 MPa is followed by the application of a shear stress of 2.7 MPa, which corresponds to $\tau/\tau_{\max} = 83\%$ of shear resistance. This relatively low shear load leads to a deformation rate that tends to zero (primary creep). Test 2 takes place under a normal stress of 8 MPa. An initial shear stress of 1.3 MPa ($\tau/\tau_{\max} = 29\%$) results in a quick stabilisation of the shear displacement only in a couple of days. The creep mechanism is then accelerated, with an increase of the shear stress to 2.5 MPa ($\tau/\tau_{\max} = 54\%$), always within the frame of the primary state, *i.e.* a decreasing displacement rate with time. A certain reversibility of the deformation is observed with the unload of the shear force. The reapplication of the same shear load brings the shear displacement to the same level as it was before unloading. It can already be noticed that while the applied shear stress is lower than the shear strength of the interface and, for the given test duration, only primary creep is observed. An increase in the applied stress leads to a higher evolution of displacement in time.

Finally, Test 3 was performed under a normal stress of 10 MPa, while four increasing steps of stress in the shear direction were applied as follows: an initial low shear stress with $\tau/\tau_{max} = 74\%$ up to a value where $\tau/\tau_{max} = 89\%$. At all steps, only primary creep is observed, meaning that the shear delayed displacement decreases more slowly with time.

The exact evolution of the ratio of the applied shear stress over the shear strength for each given normal stress is plotted in Fig. 10b. The value of τ/τ_{max} is not constant during the application of each shear load, since the normal stress is taken into account for the calculation of τ_{max}. Fig. 10c shows the compliance with time for all three tests. The compliance is usually expressed in Pa^{-1}, as it is defined as the ratio of the delayed deformation over the applied constant stress. This definition is widely used for uniaxial creep tests [20,21]. However, the analysis of results of creep tests including a second loading axis requires the consideration of the influence of both applied stresses. Thus, what is called compliance in Fig. 10c is the product of the delayed shear strain with the percentage of applied shear strength. The shear strain is calculated as $\epsilon_{xy} = \frac{dL_x}{L}$, where dL_x is the relative shear displacement of the interface and $L = 10$ mm is the height of the interface, taken as the part of the specimen free to shear.

Observing the initial evolution of the compliance between the three tests ($t = 0 \rightarrow t = 100$ h), one can notice that the measured compliance increases faster for higher applied shear strength levels. This is also the case within the same test for increasing steps of shear level; in test 2 an increase of τ/τ_{max} from 29% to 54% leads to a clear acceleration of the compliance, as well as in test 3 passing from $\tau/\tau_{max} = 74\%$ to 89%. In all three tests, the measured compliance increases non-linearly with time with a decreasing rate. This reveals the existence of delayed deformations within the primary phase.

4. Conclusions and perspectives

The long-term behaviour of a structure or a rock mass is greatly affected by the delayed response of the existing interfaces. For this purpose, a new experimental apparatus for the study of interfaces in time was designed. The development of a creep device equipped with a new shear box (SInC box) allowing long-duration tests on interfaces has been presented.

The tested samples, containing the interface within the same material or two different ones, are moulded in two half shear boxes (max. 140 mm × 140 mm). SInC box allows the application of a controlled load (max. 100 kN), normal to the plane of the interface and a tangential one (max. 100 kN) along the mean plane of the interface. The normal relative displacement of the two half shear boxes is measured in three different points around the interface, allowing also the calculation of the orientation of the mean plane of the interface during the test. The relative shear displacement of the walls of the interface is also measured with time.

The results of three preliminary creep tests in shear on clay rock/concrete joints under constant normal stress, show the reproducibility in the performance of SInC box. In all three tests, creep due to shear has been observed, always within the primary phase for the given applied stress and duration.

Finally, it's worth it to be mentioned that even though SInC box was developed in order to allow the study of shear creep of interfaces, in practice its design introduces a second loading axis to the uniaxial creep device. This means that different kinds of samples can be tested (including intact samples) both in compression and shear, exploring completely the 2D stress state.

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