A NEW DIRECT SHEAR TESTING APPARATUS FOR THE EXAMINATION OF THE VELOCITY- AND TIME-DEPENDENT FRICTION

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Abstract

There are contacting surfaces in all mechanisms moving on each other. Between these surfaces friction occurs, because of this we have to take the friction in all cases into consideration during design. Nevertheless in certain cases the description of the friction process is very difficult; because it depends on multiple number of parameters. In case of polymers, granular materials or in geology the velocity- and time dependent friction have great importance. In this paper, development of a direct shear testing apparatus to examine the velocity- and time-dependent friction is proposed. This shear apparatus is attached to the INSTRON 5581 type universal material testing machine and suitable for shearing with different (very low) velocities and on different loads. With our new apparatus creep and relaxation tests can be made, so the velocity- and time- dependent friction can be better understood.

Keywords

direct shear test, friction, time-dependent friction, velocity-dependence,

Introduction

Description of the friction process is very difficult in certain cases, because this phenomenon depends on a lot of parameters (materials, roughness, temperature, shear velocity). In geology, mining- and earthquake science, in case of polymers, granular materials or other special materials the time- and velocity-dependent friction (creep and relaxation) have great importance and just few researchers deal with this time dependence of friction [6], [7]. The aim of our work is to develop a new direct shear testing apparatus, which is attached to the INSTRON 5581 universal material testing machine to examine the velocity- and time-dependent friction process. By using our new machine, the normal load and the shear velocity can be changed in a wide range (and the velocity can have a very low value).

Direct shear test

The knowledge on the shear strength is very important in description of a friction process. This parameter means the relationship between the displacement and the shear force and a lot of parameters have influence on this [1]. The shear strength can be evaluated by using direct shear test; in course of this the surfaces are pressed together with constant normal load meanwhile these moving on each other. During the shear process, the shear force as function of displacement is measured. The material properties, the roughness and the shear velocity have great influence on shear strength [1].

During the direct shear test of two smooth surfaces (under constant normal load and constant shear velocity) the shear strength increases to an initial peak, which is followed by slowly displacement weakening and then stabilization at a residual shear strength, which does not change or increases very slowly with additional displacement [1].

Based on shear tests with different normal loads, the shear strength is in linear correlation with normal strength. The slope of this line is the friction coefficient concerning to the materials, the designate constant of this line is the cohesion between the surfaces. The shear strength based on the Mohr-Coulomb equation:

$$\tau(\phi) = c + \sigma_n \cdot tg\phi \qquad 1$$

where c is the cohesion, ϕ_r is the friction angle between the surfaces.

The residual strength is:

$$\tau(\phi) = \sigma_n \cdot tg\phi_r \qquad 2$$

where ϕ_r is the residual friction angle between the surfaces.

Time- and velocity-dependent experiments

The time- and velocity-dependent friction have great importance in geology: faults may undergo decelerating postseismic slip (afterslip), long term stable slip (fault creep) in the absence of earthquake instability, and perhaps slow postseismic slip [2]. For this reason Dietrich et al. made laboratory shear experiments with clean surfaces of granite [3, 4] and with a layer of simulated fault gouge consisting of crushed and sieved granite [2]. The crushed granite fractions were *<250 μm* in all cases. These experiments were made with different shear parameters (normal load, shear velocity). The sample assembly consists of a three blocks, sandwich type direct shear configuration (Fig. 1.). In this layout there are two contact surfaces, which have dimensions *50x50 mm*. The purpose of this vertical arrangement is to reduce differences in the vertical elastic displacements within the blocks induced by the vertical load [2]. With this type of direct shear arrangement the vertical and horizontal hydraulic rams independently control the shear and normal stresses, respectively, on the contacting surfaces. Motion of the vertical ram (so the displacement) was generally servo-controlled on displacement using a high-speed servo control valve. Owing to these servo control valves the minimal shear velocity was *0.1 μm/s* [2].

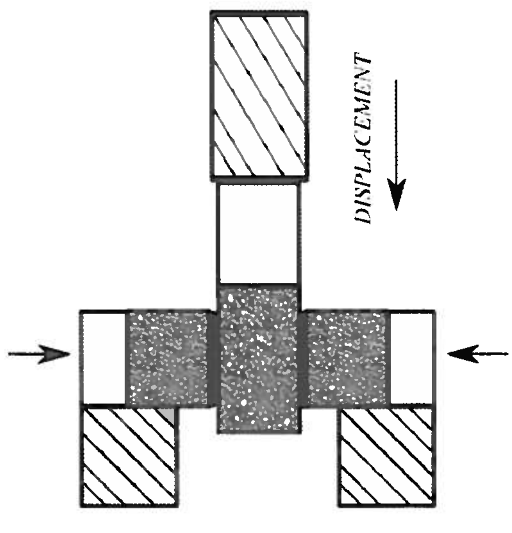

Figure 1. The sample assembly by Dietrich [2]

Three different types of tests were made: constant velocity, multiple velocity and time dependence shear tests. The constant velocity tests were made at *2.5 μm/s* (Fig. 2/a). In the multiply-velocity tests the shear velocity was constant for a predeterminated displacement, then suddenly changed by a factor of 10, held constant for another displacement then changed again and so on (Fig. 2/b). The third group of shear test was the time-dependence tests, in which constant velocity shear was interrupted at a specified displacement where the control displacement is held at zero for a specified time interval (Fig. 2/c) [2].

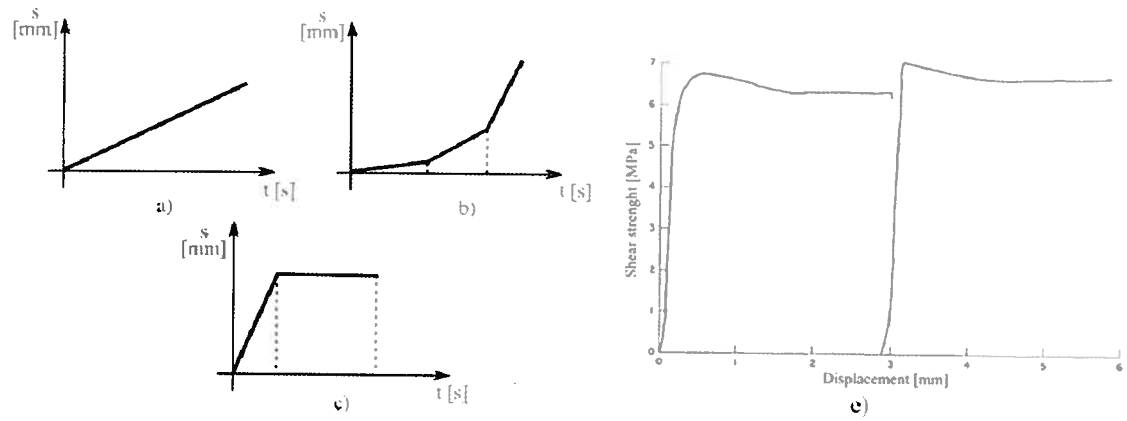

Figure 2. a) Constant velocity test; b) Multiply velocity-test; c) Time dependence test;
d) Shear diagram with constant velocity and normal stress [2]

The aim of the constant velocity tests were to examine the overall from stress-displacement curves (Fig. 2/d) to permit reasonably direct comparison to be made for the control of strength by the fault parameters. Based on these curves the shear strength increases to an initial peak, which is followed by a slow displacement weakening and then stabilization at residual shear strength (Fig. 2/d). If the shear stress cycling to zero after reaching residual strength, acts to restore the peak in the stress-displacement curves. This cycling increases the total displacement and also the peak and residual strength [2].

The purpose of the multiply-velocity tests was to look for variations of strength as a function of velocity. A step increase of shear velocity results an immediate jump in frictional coefficient followed by displacement dependent decay and stabilization at a new steady-state friction. The reverse is seen if the shear speed is decreased (Fig. 3.) [3].

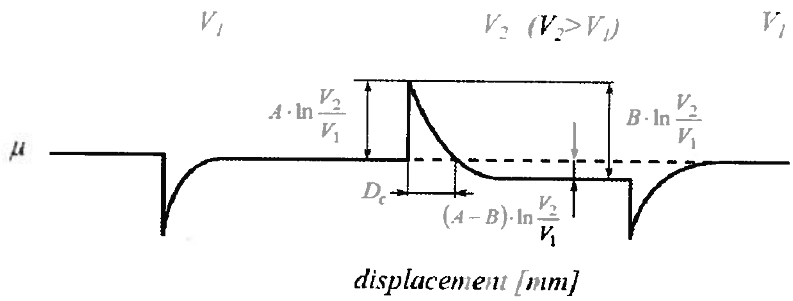

Figure 3. Effect of steps in shear speed on a friction coefficient [3]

Dietrich and Kilgore [3] made a shear rate- and state-dependent constitutive formulation for fault tests. This formulation provides a descriptive framework for the interpretation of the transient shearing phenomenon. The coefficient of friction can be represented [3]:

$$\mu = \frac{\tau}{\sigma} = \mu_0 + A \cdot \ln\left(\frac{V}{V^*} + 1\right) + B \cdot \ln\left(\frac{\Theta}{\Theta^*} + 1\right) \qquad 3$$

where τ and σ are shear and normal stress V is a shear speed and Θ is a state variable. Parameters μ_0, A and B are experimentally determined constants and V^* and Θ^* are normalizing constants [3].

Developing of a shear testing apparatus

The design was made on the basis of Dietrich's vertical shear apparatus [2]. In case of Dietrich's arrangement the displacement was vertical and the normal force was horizontal, while in our case the normal force is provided by an INSTRON 5581 type universal material testing machine, so it should be vertical thus the displacement must be horizontal. In order to avoid the change in contact surface during the shear process, one of the probes must be a longer one. We decided on a box type layout because this apparatus must be suitable for shearing also granular materials, for this reason this must contain a fixed, loaded part and a moving part. These parts are suitable for fixing the probes. The shear force was measured by a load cell which is at the holding point of the fixed part; the displacement was measured by an inductive displacement transducer at the moving part. The displacement was provided by a stepper motor (Fig. 4.).

To reduce the friction force between the moving part and the base-plate linear bearings were used. Owing to the stepper motor and the control electronics very low shear velocity can be set. The rotation of the stepper motor is transformed to linear displacement by a screw shaft, this connects to the stepper motor with a cased coupling.

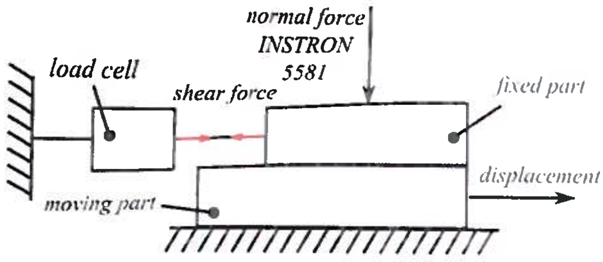

Figure 4. The sample assembly

The parts were designed based on Dietrich's experiments [2]: During his tests with granite the largest shear strength was 10 MPa, we supposed this value like maximum stress. Before designing of the geometry we had to choose the suitable stepper motor based on the torque demand of shearing. For this we need to know the parameters of the screw shaft and the maximum shear force, because the maximum torque is:

$$M_{\max} = F_{\max} \cdot \frac{d_2}{2} \cdot tg(\alpha + \rho'), \qquad 4$$

where $F_{\max}$ is the maximum load on the shaft during shearing, d_2 is the effective diameter of the screw thread, α is the profile angle of the metric thread and ρ' is the modified friction angle. In case of 350 mm^2 shear surface and 10 MPa maximum stress during shearing, the maximum shear force is:

$$F_{\max} = 10\ MPa \cdot 350\ mm^2 = 3500\ N \qquad 5$$

M8x0.75 metric fine thread was chosen to the screw shaft. With this according to Eq. 5 the torque demand of shearing is $M_{\max}$=5.2 *Nm*. Based on the torque demand a XINJE 86BYGH3125 3-phase stepper motor with a torque of *6 Nm* was chosen, because of its very low speed and small size. With the knowledge of dimensions of the stepper motor the geometry of the apparatus can be designed (Fig. 5.).

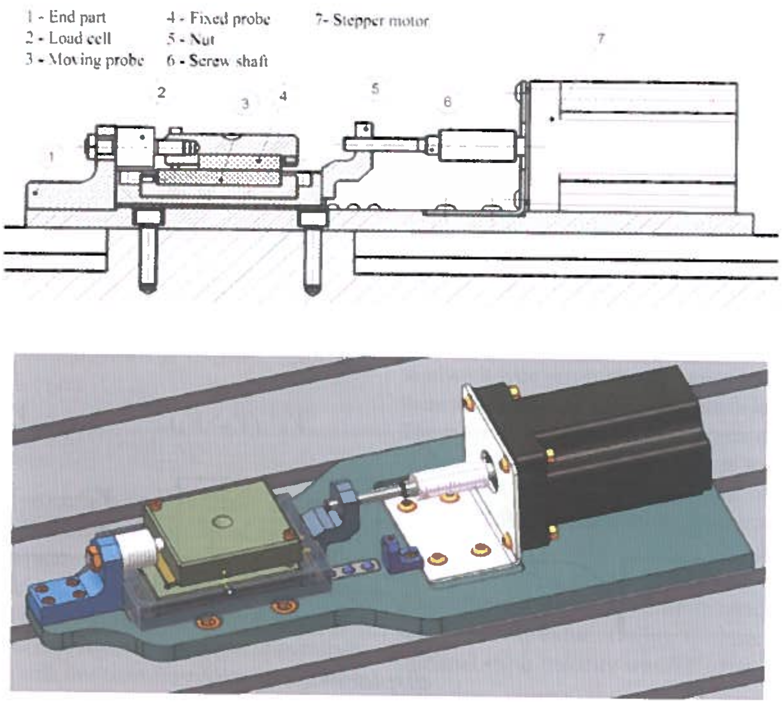

Figure 5. The test assembly and the 3D modell of the apparatus

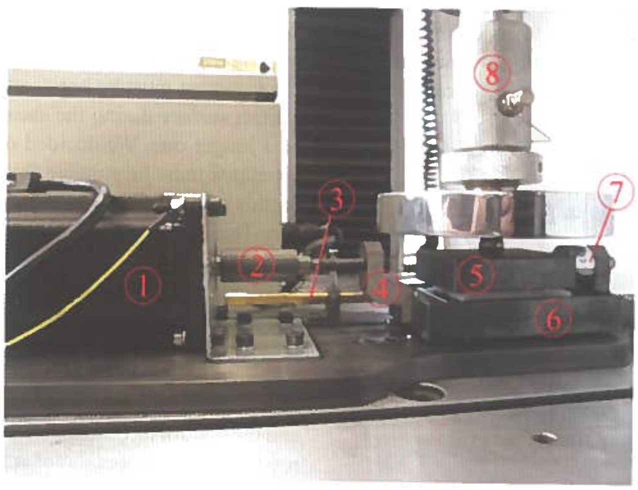

Figure 6. The finished apparatus

On Fig. 6 the finished shear apparatus can be seen: 1 – stepper motor; 2 – screw shaft and cased coupling; 3 – displacement transducer; 4 – nut; 5 – fixed part; 6 – moving part; 7 – load cell; 8 – INSTRON 5581. The normal load was provided by the INSTRON 5581 type universal material testing machine the load was transferred trough a steel ball, that ensures the punctual load to the fixed part.

The controlling electronics

The chosen motor is a three phase stepper motor that divides a full rotation into a number of equal steps, therefore in order to achieve the minimum speed a XINJE DP-7022 digital stepper drive was used. With its microstep function no more than *65535 step/rotation* can be set up which ensures the low and exact angular velocity of the stepper motor. Microstepping is a way of moving a stepper smoothly. Due to all square-impulse the stepper motor rotates with an angle which depends on the microsteps, therefore the number of the impulses determines the full rotation angle and their frequency determines the angular velocity of the rotation. The motor and the user interface are controlled by an own developed electronics which is based on an 8 bit PICF18F4550 microcontroller. The user interface consists of a 2x16 character LED display, 2 toggle switches, 5 press buttons and a potentiometer. The changing of the direction of rotation and the enabling or disabling of driving are possible with the help of toggle switches. The shearing velocity can be changed step by step between *0.075 μm/s* and *156.25 μm/s* and the displacement in a range of *0-25 mm* with a precision of *1 μm*. All parts of the controlling electronics are placed in a sheet cabinet and the user interface is on its face. The measurement system of the appliance is a separate module. The displacement is measured by an HBM WETA 1/10 inductive economic displacement transducer, the shear force by an HBM U9B *5 kN* force transducer. The Spider 8 and the Catman 4.5 software carry out the data acquisition.

Testing of the apparatus

The first tests were made with polyamide probes. The aim of these was checking of the constant velocity and making of constant velocity shear tests. In case of velocity checking shear test was made in unloaded state, and the displacement was measured in function of time:

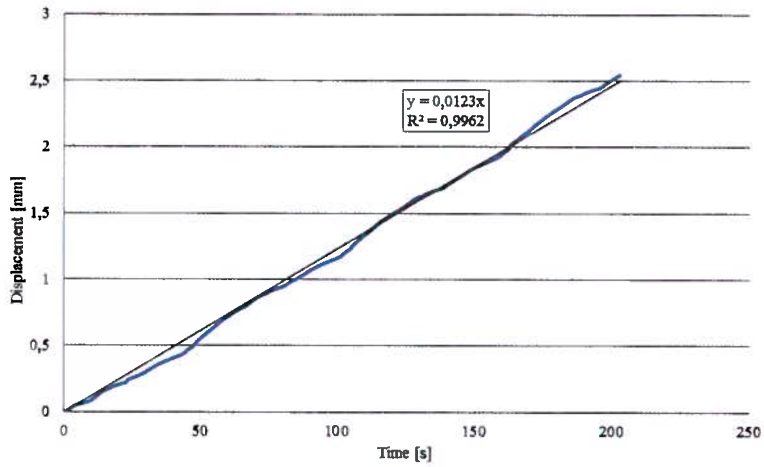

Figure 7. The displacement in function of time in unloaded state

During this test a velocity of *12.5 μm/s* was set. Based on the results of the linear regression the real velocity of the moving part was *12.3 μm/s* that means the difference between the set and the real velocity is 1,6%. Because the measured data and the theoretical values are in good relation the shear velocity is constant in an unloaded case.

After this shear tests were made with two different normal stresses. In first case the normal stress was $\sigma_1 = 40$ *kPa*, in second case $\sigma_2 = 80$ *kPa*. The shear velocity was *100 μm/s* and the sampling rate 10 Hz in both cases:

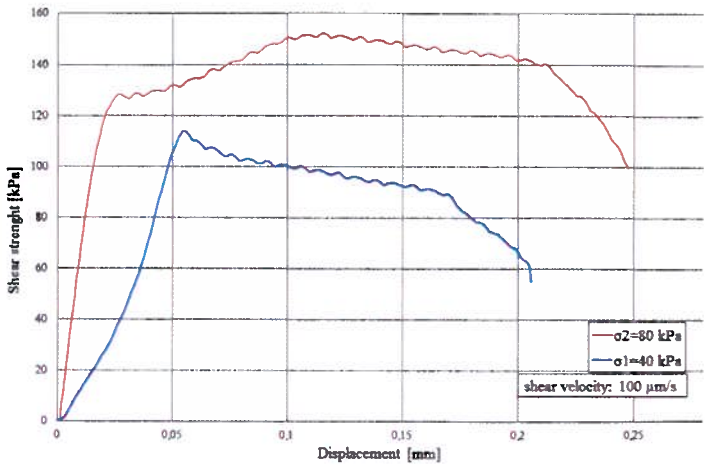

Figure 8. The shear diagrams

Results and conclusion

Based on the above the new direct shear apparatus is suitable for making direct shear test with very low velocity. This velocity is constant during a test, and its value is same as the set. During measuring the shear force and the displacement were acquired by a data acquisition system, thus the shear diagrams can be taken. The characteristic of these diagrams is same as described in a literature, based on this the apparatus is suitable for examine the velocity-dependent of friction. Following our further aim is a development a software with which the shear velocity can be changed during a test according to a predetermined program.

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