Tensile test of natural microbiotic crust

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Abstract

The mechanical properties of microbiotic crust are important to stabilize sandy surfaces in arid and semi-arid regions. We developed a new experimental approach to perform the tensile test of natural microbiotic crust. The modulus of elasticity, ultimate stress and one-dimensional stress–strain relation was obtained. The microbiotic crust we measured exhibits linear elastic behavior firstly and then breaks. This mechanical character was applied to the study of the rupture of microbiotic crust under the impact of one saltating grain. A very simple dimensionless variable was suggested to quantitatively assess surface stability.

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1. Introduction

The microbiotic crust, a complex mosaic of sand, dust and biological components such as cyanobacteria, green algae, lichens, mosses, microfungi, and other bacteria, plays an essential role in reducing wind erosion and fixing sand in arid and semi-arid regions (see, for instance, West, 1990; Danin, 1996; Belnap et al., 2001, and references therein). To date, the mechanical properties, which are important to stabilize sandy surfaces, of microbiotic crust have not been well measured. Many previous experiments only focus on the strength of crust. Two commonly used methods are bending experiment and penetrometry. The bending experiment (Gillette et al., 1982; McKenna Neuman et al., 1996; McKenna Neuman and Maxwell, 1999) provides a means of comparing the strengths between different crusts. The penetrometry method (Rice et al., 1997, 1999; Rice and Mcewan, 2001; McKenna Neuman and Maxwell, 2002; Langston and McKenna Neuman, 2005; McKenna Neuman et al., 2005) was subsequently employed to simulate the rupture of crust under grain impact.

From the mechanical point of view, the stress–strain relation is a central mathematical formula describing the behavior of microbiotic crust. The most basic test in the study of constitutive laws is the one-dimensional tensile test (Shames, 1975). It was found that the ultimate strength of three type of microbiotic crusts growing in laboratory is in the scale of $10^3$–$10^4$ Pa (McKenna Neuman et al., 1996). As a comparison, the yield stress of aluminium we are familiar with is about $10^8$ Pa. So, the universal tensile test machine is not suitable for the fragile microbiotic crust. In this paper, a new experimental method was developed and then the mechanical property of natural microbiotic crust was investigated. Finally, the result of tensile test was applied to the study of the rupture of microbiotic crust under the impact of one saltating grain.

2. Material and method

The study site is located at Shapotou. The physical and biological features of this region have been reported in
many previous studies (for example, Li et al., 2002; Zhenghu et al., 2003). All samples were taken away from the stabilized surface near the bare sandy bed. The field condition is shown in Fig. 1(A). Once the local blowing sand is controlled, the light color microbiotic crusts with the mean thickness less than 0.4 cm will occur after 2–3 years (Zhenghu et al., 2003), see Fig. 1(B). Some $15 \times 10$ cm pieces of this kind of microbiotic crusts were carefully removed and transported to the laboratory.

Since our main concern is the macroscopical mechanical characters of microbiotic crust, a rough estimate of the main components was made. After heating and crushing tension specimens, it was found that the mass fractions of water and organic matter do not exceed 0.02% and 8%, respectively. Different from the surface of bare sandy bed, the microbiotic crust contains some fine particles, ranging from 10 to 50 μm, see Fig. 2.

To reduce destroying samples, microbiotic crusts were wet slowly, and then were cut into about $6.0 \times 1.5 \times 0.3$ cm pieces by hand with a razor blade and a stainless steel ruler. These slices were used as tension specimens after they were dried. The actions such as tapping, dragging and pressing which could introduce initial stress were avoided in this process.

We designed and constructed a special apparatus for the tensile test of microbiotic crust, see Fig. 3. One end of specimen was strengthened by glue before it was attached to grip. Meantime, some sands were fixed on the surface of specimen to prevent slipping and promote the uniform stress within the grip. The other end was stuck to the central section of a $10.6 \text{ cm long, } 0.25 \text{ cm wide, and } 0.5 \text{ cm high rigid bar made of aluminium alloy or steel. Two very smooth semicircular cuts at the symmetrical cross sections of the bar were produced to hang a light cone. The applied load was predominately determined by the mass of sand in the cone. To reduce the effect of impact, only several sand grains were added every time. An analytical balance with the linearity of $\pm 0.3 \text{ mg}$ was used to weigh the sand. The displacement of the specimen’s lower end was transmitted by the lower surface of the bar and was measured by an inferior Laser Displacement Sensor (LDS). The reference distance, linearity, and measuring range of the LDS are 80 mm, $\pm 0.1\%$ F.S., and $[−15 \text{ mm, 15 mm}]$, respectively. This test was carried out at room temperature ($\approx 18 \text{ °C}$).

3. Result and discussion

Different from the three-point bending test results of the microbiotic crusts growing in laboratory (McKenna Neuman et al., 1996), plastic deformation is insignificant, see Fig. 4(A). Most samples behave elastically until failure. The typical stress–strain curve, in which the stress and strain values were calculated from the original dimensions of the testing region, was plotted in Fig. 4(B). The modulus of elasticity (also known as Young’s modulus) and ultimate stress vary from $1.596 \times 10^7$ to $3.193 \times 10^7$ Pa and from 30.0 to 42.8 kPa, respectively. The mean values are $1.997 \times 10^7$ Pa and 36.4 kPa. Since some equations are not strictly valid, the three-point bending test cannot provide mechanical parameters accurately. For example, the elastic modulus of Lyngbya crust changes over a significant range from 400 to 48,000 kPa (McKenna Neuman et al., 1996).
although the average value is close to the $1.997 \times 10^7$ Pa we obtained.

Now, let us discuss the relationship between the mechanical property of the crust and wind erosion. Despite being very thin, the cyanobacteria crust, a relative weaker kind, can increase threshold friction velocity considerably (Belnap and Gillette, 1998). This means that the grain entrainment via aerodynamical forces rarely occurs for sandy surface covered with microbiotic crusts. The grain-bed impact is a vital process during the aeolian sand transport. If it can undergo the collisions of streamwise airborne grains, the local surface will be stable. Rice and coworkers (Rice et al., 1997) suggested that surface erodibility may be characterized by a modulus of elasticity and then gave a local surface failure rule. Recently, this theoretical model was further developed by using the classical theories of elastic thin plate and plastic mechanics (Wang and Zheng, 2005). The following relation between the critical impact velocity of saltating grain and the mechanical characteristics of microbiotic crust was obtained.

$$v^* = \frac{a\sigma_Y}{\sin\theta} \sqrt{\frac{3\pi(1 - \mu^2)h}{2mE}}$$  (1)

where $m$ and $\theta$ are the mass and impact angle of saltating grain, $a$, $\sigma_Y$, $E$, $\mu$ and $h$ are the length scale of rupture area, yield stress, Young’s modulus, Poisson’s ratio and thickness of microbiotic crust.

The yield stress and Young’s modulus in the expression of critical impact velocity (Eq. (1)) have been measured via tensile test in the present research. The values of Poisson’s ratio are within the range of 0 and 0.5. The length scale of rupture area, $a$, should be experimentally determined. Since it is very difficult to control the velocity of a sand grain in

![Apparatus designed for the tensile test of microbiotic crust.](image)

![Stress–strain curves. (A) Mechanical property with plastic deformation. (B) Typical stress-strain diagram for microbiotic crust.](image)
practice, an impact experiment between a steel ball, ranging from 0.40 to 1.83 cm in diameter, and the natural microbiotic crust was performed in the field. Although a detailed analogy may be limited, we expect such an experiment will be helpful to get some useful information about $a$. The device has been described in detail previously (Zheng et al., 2004). In the experiment, a steel ball was released with zero speed from a site of an inclined stainless steel groove whose inclination angle can be changed. The steel ball collided with the microbiotic crust after rolling a distance along the groove. The largest length scale of rupture area was measured by a vernier calipers. The resultant rupture area (see Fig. 5) of microbiotic crust depends on many factors including the release site, the ball diameter, the impact angle, etc. It seems that the ball diameter plays a dominating role. After some dimensional arguments, it is found that a possible or the simplest relationship is that the length scale of rupture area is proportional to the projectile diameter. Therefore, Eq. (1) can be written as

$$v^* = \frac{3\xi \sigma_Y}{\sin \theta} \sqrt{\frac{(1 - \mu^2)h}{\rho_s dE}}$$  (2)

where $\xi$ ($\approx 1.0-3.0$) is an empirical parameter, $\rho_s$ and $d$ are the density and diameter of saltating grain, respectively.

Here, we suggest a dimensionless variable $\lambda$ to assess surface stability under grain impact

$$\lambda = \frac{v}{v^*} = \frac{v \sin \theta}{3\xi \sigma_Y} \sqrt{\frac{\rho_s dE}{h(1 - \mu^2)}}$$  (3)

where $v$ is the impact velocity of saltating grain. If $\lambda < 1$, then an impacting grain will not result in the rupture of microbiotic crust; otherwise, the surface will be unstable. Substituting typical values of impact velocity, impact angle (Shao, 2000) and yield stress, Young’s modulus, etc. into Eq. (3), the values of $\lambda$ can be obtained (see Table 1). We always have $\lambda < 1$ under the impacts of very coarse, coarse, medium or fine grain. So, the surface we studied is stable. This conclusion is correct obviously. The value of $\lambda$ can also be used to compare the erodibilities of surface covered with different crusts. The expression (3) indicates that a rigid and weak microbiotic crust is more easily broken down by saltating grains than a soft and strong one, because $E$ and $\sigma_Y$ represent stiffness and strength, respectively.

In the above discussion, we neglect the influence of human activities. For instance, vehicles and trampling exert compressional and shear forces on the microbiotic crust (Belnap et al., 2001). The proper model and feasible experiment is needed to establish while quantitatively researching these complicated mechanical processes. As a very fundamental measurement, the tensile test can give one-dimensional stress–strain relation and two mechanical parameters. We affirm that this experiment will be helpful to future research.

4. Summary

In summary, the mechanical properties of natural microbiotic crust were studied via a tensile test designed especially. The microbiotic crust exhibits linear elastic behavior until failure. The modulus of elasticity, ultimate stress and one-dimensional stress–strain relation was obtained. As an application of the tensile test result, we attempted to suggest a simple dimensionless variable to assess surface stability under the impact of one saltating sand grain in the Result and discussion section. It should be pointed out that other mechanical experiments such as bending and vibration, the influence of species on the tensile test and the interaction between aeolian sand flow and microbiotic crust need be stressed hereafter.

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