Shear Strength of Ice-Filled Rock Joints

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Abstract

Ice-filled rock joints are a common feature of high mountain permafrost areas. Warming of these joints in rock can lead to instabilities and rockfall events. In the following study, a series of direct shear tests was performed with artificial samples simulating ice-filled rock joints. The direct shear tests were carried out in two testing modes: constant strain and constant stress. In constant stress tests, the ice-filled joints show a parabolic relationship between normal stress and shear stress unlike the linear relationship usually found in mineral filled rock joints (Barton 1974). Constant stress tests were also conducted in which the samples were allowed to warm up until failure occurred while a constant normal stress and a constant shear stress were applied. Different failure modes could be identified, either driven by breaking the connection of ice and concrete or ductile deformation of the ice or a combination of both.

Keywords: direct shear; ice strength; rock joints; rock slopes; shear strength.

Introduction

In recent years, increased numbers of landslide and rockfall events have been reported in high mountain areas (Gruber et al. 2004). A connection between the landslide events and the warming of permafrost due to increasing mean annual air temperatures was observed in landslide events, such as the Val Pola Landslide in 1987 (Dramis et al. 1995).

Earlier laboratory experiments, carried out on a geotechnical centrifuge (Davies et al. 2003 and Günzel & Davies 2006) showed that ice-filled joints in rock are stable as long as the temperature of the ice is low (below about 2°C); however, both the strength and stiffness of ice in the joint reduce if the temperature rises closer to melting point. This leads to a reduction in strength of the rock joint which, if it is critical to maintaining slope stability, can result in slope failure or rockfall. However, the stability increases again when the ice from the joint melts and the rock surfaces come into contact with each other. That means that slope failure can occur at a joint during warming of the permafrost ice, even if a slope is stable both when the rock joints contain "cold" ice and when no ice is present. Slope failure might be avoided if these critical joints can be identified and stabilised temporarily during the period when the ice is warming and when the shear capacity of the joint is below that required for stability.

The current study systematically uses direct shear testing to investigate the shear strength of an ice-filled rock joint during warming of permafrost.

Laboratory Methods

Preparation of samples

In the study, artificial samples made of high-strength concrete (Densit Ducorit D4) were used. To simulate the roughness of the rock joint surfaces, a regular saw-tooth surface was used with the dimensions as shown in Figure 1. Regular, saw-toothed surfaces are a commonly used idealisation of rough rock surfaces in the literature (de Toledo & de Freitas 1993). The dimensions of the samples were 59mm x 59mm to fit inside a 60mm square shear box.

A thermocouple was cast into the concrete samples with the sensitive tip in a small cavity at the centre of the sample surface (Fig. 2). This allowed the temperature of the ice to be measured during the shear tests.

Initial tests were carried out without ice to establish the friction of the concrete surface. Then two different types of ice-filled samples were prepared: concrete-ice samples (Fig. 3) and sandwich samples (Fig. 4).

The concrete-ice samples consist of a concrete block with saw-toothed surface overlaid by an equally thick ice block (Fig. 3). This sample type simulates an ice-filled joint, with

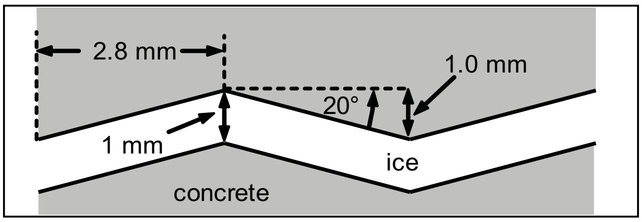

Figure 1. Dimensions of the saw-tooth surface.

Figure 2. Concrete block with cast saw-tooth surface; the small cavity in the center holds the tip of the thermocouple.

Figure 3. Concrete-ice sample after a constant strain test with normal stress = 207 kPa.

Figure 4. Sandwich sample after a constant stress test with normal stress = 207 kPa.

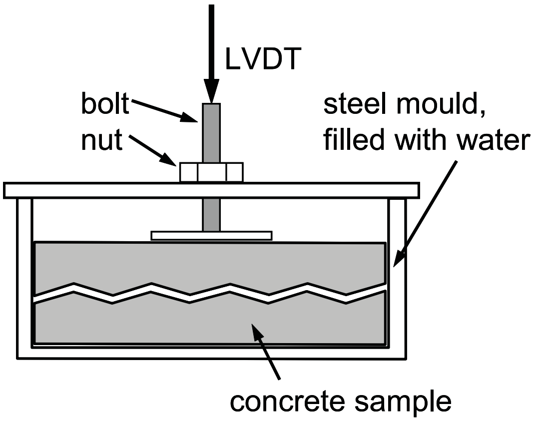

Figure 5. Preparation of sandwich sample.

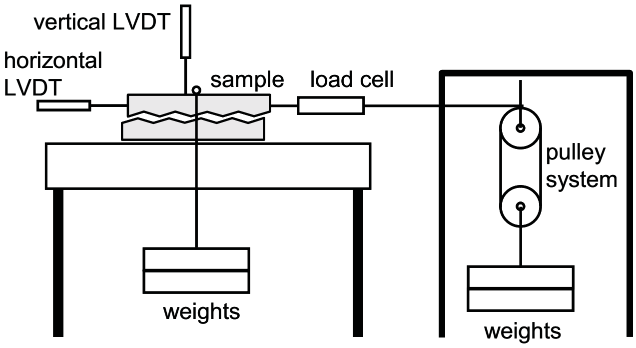

Figure 6. Schematic overview over experimental set-up of the constant strain test.

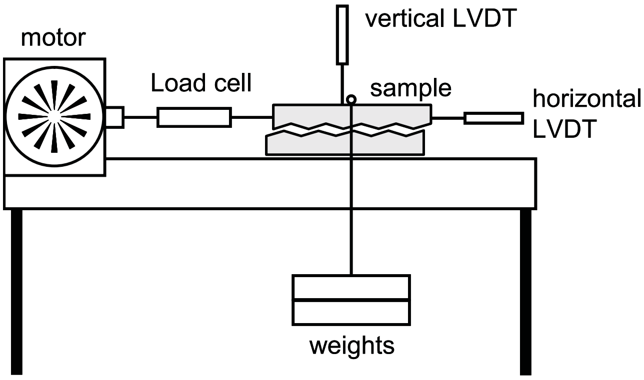

Figure 7. Schematic overview over experimental set-up of the constant stress tests.

the ice thickness being much larger than the amplitude of the surface roughness. The concrete-ice samples are prepared by placing concrete blocks into moulds filled with water and allowing them to freeze.

The sandwich samples consist of two saw-toothed concrete blocks with a 1mm thick layer of ice in-between (Fig. 4). This sample type simulates an ice thickness equal to the amplitude of the surface roughness. These samples are prepared as illustrated in Figure 5. The two concrete blocks are immersed in water in a mould. A bolt is glued to the top block. The top block is then lifted by turning the nut against the lid of the mould while the movement is measured with an LVDT (Linear Variable Displacement Transducer). After that, the surplus water on top of the sample is drained, and the sample is frozen.

Direct shear tests

Two different modes of direct shear tests were carried out in this study: constant strain tests and constant stress tests. Schematic overviews of both testing modes are shown in Figures 6 and 7. Normal stress is provided by hanging weights. Horizontal and vertical displacements are measured with LVDTs.

In the constant strain tests, shear stress is applied by an electric motor pushing the upper part of the sample while the lower part remains stationary. The shear stress is measured with a load cell. These tests were carried out at -2°C and -4°C, with normal stresses ranging between 135 kPa and 620 kPa. This is equivalent to a depth of 5–25 m below ground. This depth is above the range of the annual freeze-thaw depth of 5±2 m in the Alpine periglacial belt reported by Matsuoka et al. (1998). However, with increasing air temperatures, the freeze-thaw depth can be

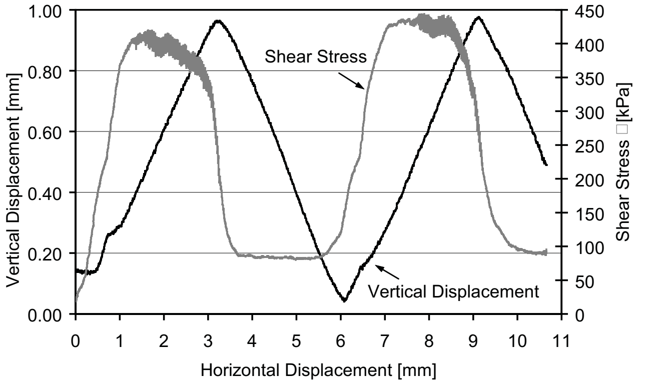

Figure 8. Vertical displacement and shear stress vs. horizontal displacement of a shear experiment without ice (normal stress = 207 kPa).

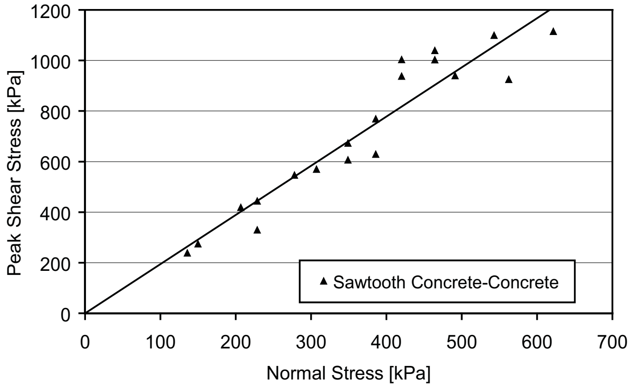

Figure 9. Overview of peak shear test results of concrete samples.

expected to increase.

A constant horizontal displacement rate of 0.47 mm/hour was used for all tests. However, earlier studies (Barnes et al. 1971) found that not only the temperature, but also the strain rate, has a significant effect on the shear strength of an ice-granite interface. Also, failure of a rock slope is not controlled by constant strain, but rather by constant stress.

Therefore the shear box was modified to be able to apply a constant shear stress rather than a constant strain onto the concrete ice samples and the sandwich samples. Here, the motor was replaced by a pulley system and weights to apply a constant shear stress to the samples. The sample temperature was then increased slowly until the sample failed.

Cold room

The experiments were carried out in a cold room. To ensure a constant temperature of the sample during the defrosting cycles of the cooling element, the shear box was encased inside a Styrofoam box with 100 mm wall thickness. However, the electric motor of the shear box apparatus caused the temperature inside the Styrofoam box to increase during the constant strain tests. Therefore it was very difficult to control the temperature of the sample and subsequently the temperatures at failure varied by about 0.5 C.

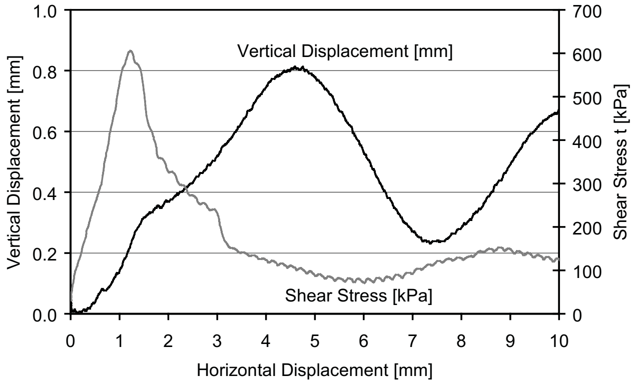

Figure 10. Results of a constant strain shear experiment with a concrete-ice sample at -2°C (normal stress = 207 kPa).

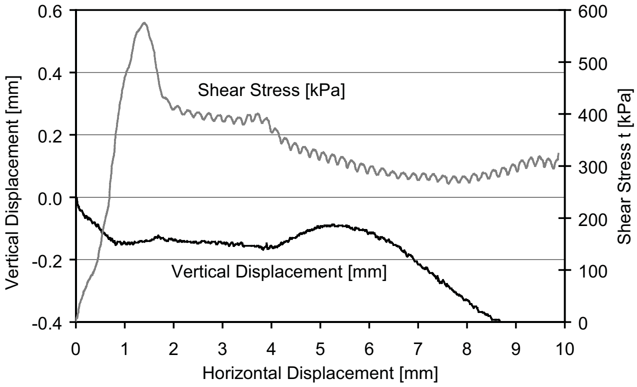

Figure 11. Results of a shear experiment at constant strain with a concrete-ice sample. Temperature = -4°C, normal stress = 562 kPa.

Experimental Results

Samples without ice

To establish the frictional resistance of the concrete samples without ice, direct shear tests were carried out with normal stresses between 135 kPa and 620 kPa. The typical response of a sample is shown in Figure 8. Here the shape of the saw tooth surface is clearly visible from the vertical displacement. The development of the shear stress follows the same pattern with the maximum shear stress during the uplift of the top sample.

Figure 9 shows the maximum measured shear stresses of all concrete samples plotted against the normal stress applied to the sample. As expected, there is a clear linear relationship between the normal stress and the shear stress. The scatter of data above a normal stress of 400 kPa is due to abrasion of the concrete samples during the test.

Constant strain tests with concrete-ice samples

A total number of 26 constant strain tests were carried out at two different temperatures: -2°C and -4°C. Depending on the normal stress, the vertical displacement during the test showed different behaviour (Figs 10,11): at low normal stresses, the vertical displacement clearly reproduces the shape of the saw-toothed surface, albeit with a slightly reduced amplitude (Fig. 10). This behaviour can be

Figure 12. Shear deformation of a concrete-ice sample after a constant strain test with normal stress = 490 kPa.

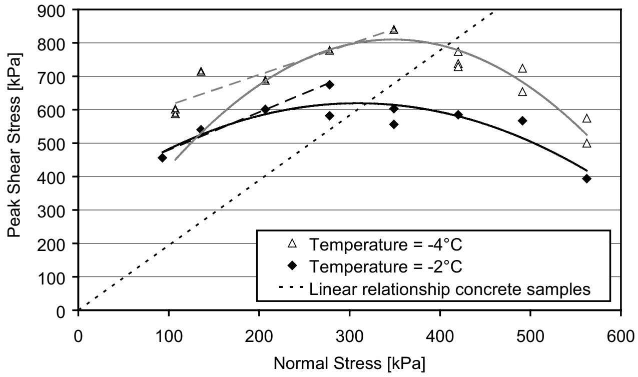

Figure 13. Peak shear test results from concrete-ice samples in constant strain tests.

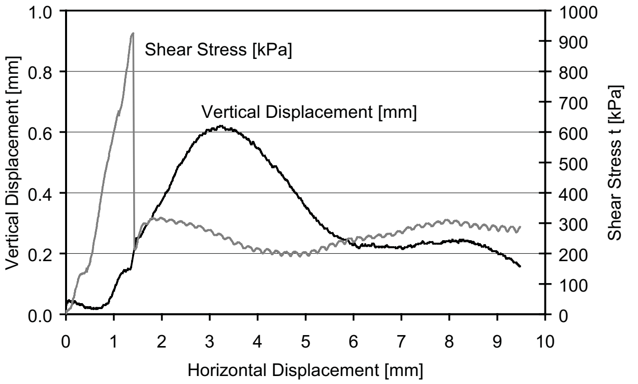

Figure 14. Results of a constant strain shear experiment with a sandwich sample at -5°C (normal stress = 490 kPa).

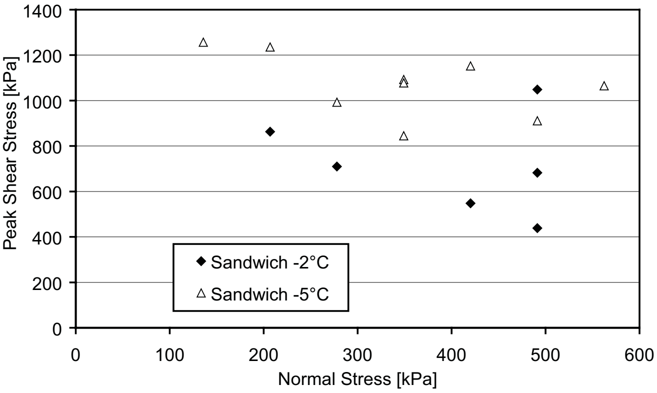

Figure 15. Overview of peak shear test results of sandwich samples in constant strain tests.

interpreted as the ice becoming detached from the concrete surface, and the behaviour of the sample is mainly defined by the friction between surfaces of the ice and the concrete (Fig. 3). However, at high normal stresses, no dilation of the sample was observed (Fig. 11). Here the deformation of the sample is mostly due to a shear deformation of the ice itself rather than the sliding of ice over concrete. At the end of these tests, the ice was still firmly attached to the concrete surface (Fig. 12). No granularisation of the ice comparable to the "rubblisation" reported by Yasufuku et al. (2003) was observed. It should be noted, that the initial stiffness of the samples is approximately the same, irrespective of the type of deformation.

The two different mechanisms of deformation also become apparent in the relationship of maximum shear stresses and normal stresses at failure (Fig. 13): at low normal stresses, the relationship between maximum shear stress and maximum normal stress appears to be linear (dashed lines in Fig. 13), which is in agreement with the behaviour of mineral-filled rock joints (Barton 1974). However, at normal stresses, above 220 kPa and 300 kPa for -2°C and -4°C, respectively, this relationship becomes parabolic. This result agrees with the parabolic strength envelopes of ice found by Fish & Zaretsky (1997).

Constant strain tests with sandwich samples

The constant strain tests with sandwich samples were carried out at -2°C and -5°C. Unlike the concrete-ice samples, the sandwich samples dilated even at high normal stresses (Fig. 14). It is also noticeable that the shear stress maximum forms a very sharp peak with a sudden drop when the ice becomes detached from the concrete surface. Again, the initial stiffness of the sample is very similar to the stiffness of the concrete-ice samples. Due to the sharp peak, a considerable scatter of the maximum strength at failure is to be expected (Fig. 15). It is unlikely that the scatter is enhanced to a large extent by the sampling rate: the shear stress increased with a rate of approximately 10 kPa per minute, so that with a one-minute sampling rate, the error would be not more than 10 kPa. Despite the large scatter, a decrease of the maximum shear stress with increasing normal stress can be observed.

Constant stress test

The tests were started at an ice temperature of approximately -5°C, and then the temperature was increased at a rate of about 0.3°C per hour until failure occurred. These shear tests were carried out at normal stresses between 136 kPa and 630 kPa. The typical result of a constant stress shear test with a concrete-ice sample is shown in Figure

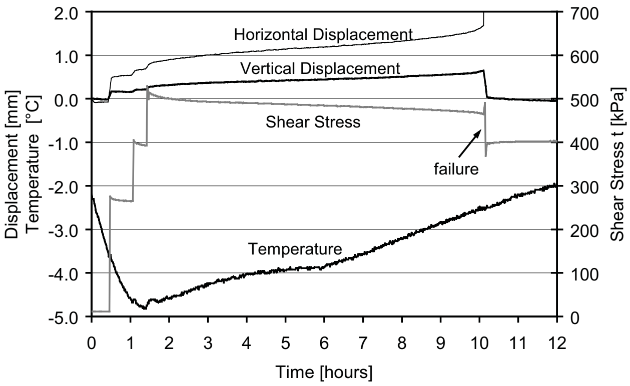

Figure 16. Results of a constant stress experiment (concrete-ice sample, normal stress = 207 kPa) plotted against time.

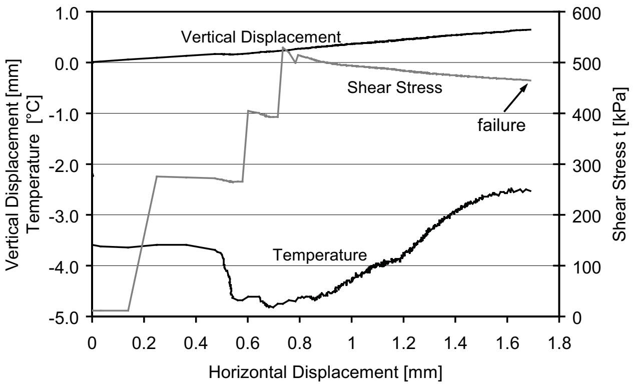

Figure 17. Results of a constant stress experiment (concrete-ice sample, normal stress = 207 kPa) plotted against horizontal displacement.

16 (plotted against time) and Figure 17 (plotted against horizontal displacement). The results for concrete-ice samples and sandwich samples are very similar. The steps of the shear stress at the beginning of the test correspond to adding weights to the pulley system. The decrease of stress during the test is due to friction in the pulley system: the tension in the nylon rope connecting the sample with the weight slackens slightly as the sample deforms, due to creep in the ice prior to failure. The apparent change of the rate of temperature increase is due to the increasing rate of horizontal deformation immediately before failure of the sample.

The horizontal displacement during the constant stress tests was considerably slower than during the constant strain tests; it varied between 0.002 mm/hour and 0.06 mm/hour. The deformation rate increased with increasing shear stress, but no significant change could be observed for increasing normal stress or temperature. The horizontal displacement at failure was between 1.5 mm and 2.5 mm, similar to the displacement at failure of the constant strain tests. The vertical displacement decreased with increasing normal stress.

Figure 18 shows the variation of failure temperature depending on normal stress and shear stress for concrete-ice samples and sandwich samples. The data points represent the shear stress at failure versus the normal stress acting on the sample. The temperature distribution for both sample types is very similar, with the only difference being that the failure temperatures of the sandwich samples were about 0.5°C lower than the concrete-ice samples. The data show decreasing failure temperatures with increasing shear stresses. However, the failure temperatures increase with increasing normal stresses throughout the test series up to normal stresses of 630 kPa. This behaviour differs from the constant strain experiment where, at normal stresses above 300 kPa, a decrease of failing temperature with increasing normal stress was observed (Fig. 13).

Figure 18 also shows the failure envelope of the concrete samples. It can be seen that, at low temperatures and low normal stresses, the ice-filled joints have a higher shear strength than joints without ice-filling.

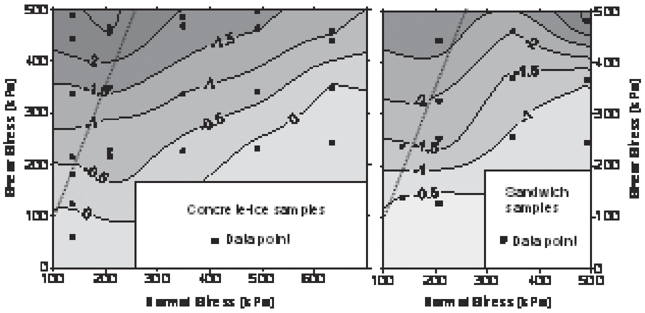

Figure 18. Temperatures at failure (measured by the sensor in the middle of the sample) during constant stress tests with concrete-ice samples (left) and sandwich samples (right). The dotted lines represent the linear relationship between shear stress and normal stress obtained for the concrete samples.

Discussion

Depending on sample type (concrete-ice or sandwich) and test type (constant stress or constant strain), three different types of deformation could be identified:

1. Deformation driven by breaking of the connection between the ice and the concrete surface;
2. Deformation driven by shear deformation of the ice itself; and
3. Combination of the deformation types 1 and 2.

In the constant strain tests with concrete-ice samples at low normal stresses, the first type of deformation is predominant. Indicators for this type of failure are the extent of the dilation of the samples during the test (Fig.10) and the visual examination of the sample after the test (Fig. 3) that clearly shows the ice being detached from the concrete surface. However, the same sample type shows ductile deformation of the ice at high normal stresses. Here the samples show no net dilation during the test (Fig. 11); any local dilation that may be present in the sample is counteracted by the ductile deformation of the ice, which is clearly visible in the sample after the test (Fig. 12).

In the constant-strain tests of the sandwich samples, a combination of the first two failure modes is observed. Visual examination of the samples showed the ice detached from one of the concrete surfaces. However, these samples show a reduced dilation of 0.4mm–0.6mm (Fig. 14) indicating that sliding of the ice over the concrete surface is not the only type of deformation in these samples. The other type of deformation may be shear deformation of the ice itself. The maximum shear strength reduces with increasing normal stress (Fig. 15), again indicating shear deformation of the ice.

Constant-stress experiments with both sample types show that here the predominant type of deformation is breaking the connection between the ice and the concrete. This observation is consistent with the data shown in Figure 18, where the shear stress at failure increases rather than decreases with normal stress for a constant temperature.

Conclusions and Outlook

In this study, three different failure modes of ice-filled joints could be distinguished. This adds to the understanding of the failure mechanisms of rock slopes in warming permafrost conditions.

Several issues that have not been considered to date will be addressed in the near future:

- The strength of ice depends on the strain rate; constant strain tests need to be carried out with the same strain rate as observed in the constant stress tests.
- Creep measurements of ice at constant temperatures, rather than increasing temperatures, need to be conducted.
- The strain rate measured in the laboratory needs to be compared with strain rates measured in full scale rock slopes rather than small-scale centrifuge model tests.

Acknowledgments

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