Effects of Strain Rate and Temperature on Bending Point Stress in Tangent Modulus Method

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Abstract: Precise measurement of in-situ stress is important in design of underground excavations. Tangent Modulus Method (TMM) is an oriented core based method for measurement of rock stress. Two cycles of uniaxial compressive loading are carried out for rock specimen. The stress-tangent modulus curve, based on the local slope of stress-axial strain curve in the first cycle, shows a bending point. Stress value at the bending point is regarded as the normal stress component of in-situ rock stress in the direction of rock specimen. Experiments were done to clarify the strain rate to be used in TMM and the effects of in-situ rock temperature on TMM. Kimachi sandstone specimens of length 60 mm were preloaded for one hour, simulating in-situ stress. The preloaded stress was then estimated by TMM. This experiment was repeated over a range of strain rates in both dry and saturated specimens. It was clarified that any strain rate between 0.0036 mm/min and 3.6 mm/min can be used. For investigating the effects of temperature, preloading was done in temperature controlled pure water for one hour, followed by TMM in air at room temperature. Between 40^{o}C and 80^{o}C, temperature at preloading had no significant effect on the TMM stress.
Keywords: Tangent Modulus Method, Bending point, Strain rate, Temperature

Introduction

The measurement of in-situ rock stress state is a critical aspect in the design of underground excavations. In mining, initial stress condition data are essential for design of openings and determining the mining method as well as for monitoring stability during the life of the mine. This is so because post-excavation stress state is directly related to the redistribution of initial stresses. The evaluation of initial stress data is thus essential for understanding excavation behaviour as well as in numerical modelling of the excavation. Measurement of initial stress is done using the following methods:

(a) In-situ stress measurement.
This is done through borehole techniques such as hydraulic fracturing, stress relief, borehole breakouts, etc, and interpretation of drilling induced fractures by methods such as core discing.

(b) Methods using oriented cores in the laboratory.
Examples include Deformation Rate Analysis, Differential Strain Curve Analysis, Tangent Modulus Method and Acoustic Emission. Oriented core methods use a rock's ability to accumulate, retain and reproduce information on the stresses experienced in the past. Lavrov (2003) stated that this ability is essentially due to irreversible damage accumulated in rock when it is subjected to load [1].

(c) Back analysis.
Stress and mechanical properties are determined by comparing monitoring with calculated results. Displacement measurement data from site is used to back-calculate the initial stresses [2].

d) Using geophysical data analysis tools such as focal plane mechanism and others.
Although in-situ measurements would give more accurate measurements, they are not so often used because they are very expensive, time consuming and require highly skilled labour. Laboratory tests based on oriented core specimens are cheap and have the advantages of being usable for rough estimations of stress state at great depths and are expected to become more popular [3].

In the Tangent Modulus Method (TMM) of rock stress measurement, two cycles of uniaxial compressive loading are carried out for rock specimen (Fig. 1a). The stress-tangent modulus curve, based on the local slope of stress-axial strain relationship, shows a bending point. The stress value at the bending point is regarded as the normal stress component of in-situ rock stress in the direction of rock specimen [4].

Fujii (2008) explained the physical phenomenon that is utilized to detect stress memory in TMM to be based on a model, which consists of two springs and a slider. In the model, one spring represents the elasticity of rock, while another spring, which is connected in parallel to the slider, represents inelasticity. The inelasticity is due to the irreversible closure of voids. The model clearly simulates decrease of the tangent modulus at the preloaded stress [5].

This paper seeks to address the question of how rock temperatures at preloading, and the loading rate during cyclic loading, affect the bending point stress in the Tangent Modulus Method.

Principle of TMM

Assume that a very inelastic rock specimen is subjected to a preloading (A–D) and cyclic loading (D–J) in (Fig. 1a). The stress-strain curve would be like Fig. 1b. In the first cycle (D–F), tangent modulus is large when the stress is below preloaded value (D–E). However, it becomes small when the stress is beyond the preloaded value (E–

F). Tangent modulus is large during the entire second cycle (G–I) and shows no marked change. Therefore, the preloaded original stress is estimated as the stress value at the bending point in the first cycle (Fig. 1c). The inelasticity with respect to applied axial stress is mainly due to irreversible closure of voids and other pre-existing cracks in the rock specimen.

Strain difference used in Deformation Rate Analysis (DRA) is also shown in Fig. 1b and 1d. It is clear that the strain difference-stress plot is expected to show a bending point at preloaded stress. The stress value at the bending point can be simply observed in stress-strain curve if the inelasticity is large. However, the inelasticity is usually not so large. This is why TMM or DRA techniques are usually used to detect bending point.

The Effects of Strain Rate on Dry Specimens

Specimen Preparation

Kimachi sandstone cylindrical cores 60 mm long and of diameter 30 mm were cored off the main block that was a 250 mm cube. Drilling was done in a direction perpendicular to the sedimentary plane (Fig. 2). The specimen ends were smoothened to ± 0.02 mm, so as to prevent stress gradients being induced on the specimen as a result of end unevenness. Drying in an oven at 80°C for 24 hours followed this. Before use, the specimens were kept under room temperature condition for 3 years.

Experimental Procedure

Rock specimens were attached to end pieces at both sides and then placed on a spherical seat. Loading was done using an Instron 5586 loading frame with a maximum load of 300 kN (Fig. 3).

The dry Kimachi sandstone used had a uniaxial compressive strength (UCS) of 40.8 MPa. The preload stress was 30% UCS, equivalent to a load of 8.5 kN, and the sample was left for one hour under the load. After one hour the specimen was unloaded and the end pieces and spherical seat were detached so as to delete stress memory. An axial extensometer was attached to the specimen. End pieces were attached again. The specimen was cyclic loaded at 50% UCS for 2 cycles. The data recording was per every 0.2 μm of platen displacement. Rock stress estimation using Tangent Modulus Method is regarded as precise when the stress value at the bending point lies within ± 20% of the preload stress value.

Results

Examples of strain variation versus time at preloading, stress-strain curve as well as stress-tangent modulus curves during cyclic loading at 0.0036 mm/min are shown in Fig. 4. For the strain rates in the range from 0.001 mm/min to 3.6 mm/min, the stress values at bending point were within the ± 20% allowable error margins for TMM (Fig. 5). There seems to be a positive correlation between bending point stress value and strain rate. However, this correlation would be within error and has to be investigated further (Fig. 5b). The cyclic loading of specimens at 0.00036 mm/min lasted on average 52 hours and the stress at the bending point is only approximately 42% of the preload stress (Fig. 6). At 36 mm/min, all specimens failed as soon as cyclic loading began because of the limit of control of the loading frame.

Effects of Strain Rate on Saturated Specimens

Specimen Preparation and Experimental Procedure

Rock specimens were prepared in the same way as for the first experiments, but were not oven-dried. The specimens were kept under pure water after grinding. They were then vacuum-saturated overnight (Fig. 7a). End pieces were attached at both ends of the specimen. A 210 mm x 150 mm stainless steel tank, and of 5 mm thickness, was filled with pure water at room temperature and then placed under the loading frame (Fig. 7b). The UCS for saturated specimens was measured and found to be 23.1MPa. The rock specimen was then immersed into the pure water and a preload of 30% UCS was applied at a constant displacing rate of 0.36 mm/min and kept for a period of one hour. After this preloading, the end pieces were detached from the rock specimen so as to delete rock stress memory. The specimen was re-attached to the end pieces. An extensometer was also attached onto the test specimen. Uniaxial cyclic loading of two cycles to a maximum of 50% UCS was applied under a set strain rate. The experiment was repeated with a variety of strain rates ranging between 0.0001 mm/min and 36 mm/min.

Results

At a platen displacing rate of 0.00036 mm/min and 0.0001 mm/min bending points were observed on the stress-tangent modulus curve at 3 MPa and 2 MPa, equivalent to 33% and 29% of the preload stress for both extensometer and stroke based readings respectively (Fig. 8). This is because the cyclic loading took very long periods of time, with the maximum duration being 4499 minutes. And also the specimens were dry by the time of completion of cyclic loading. Clear TMM stress values, which lie within ± 20% of the preload stress, were obtained for platen displacing rates lying between 0.0036 mm/min and 10 mm/min (Fig. 9).
There was only one exception for the extensometer based TMM bending point stress value at a cyclic loading rate of 0.1 mm/min. TMM stress results based on stroke were more constant compared to those based on the extensometer, which showed a higher degree of variability. However, the variation for both extensometer and stroke based results is within error. At 36 mm/min, the specimen failed

instantaneously when the cyclic load was introduced. This is due to the limit of control of the loading frame itself.

The Effects of Temperature

Experimental Procedure

Rock specimens were vacuum saturated in pure water. They were then attached to end pieces and placed in the stainless steel tank. A controller heater, (Nippon Heater Company, THC-15 High Controller model) was placed in the tank. The rock specimen was fully immersed in pure water. A 150 mm long extension rod was used. The rock specimen had a 41 μV/^{o}C sensitive K-type thermocouple attached to it (Fig. 10). The water was heated to a preset temperature for a period of 4 hours. It took approximately 5 minutes to achieve temperatures of up to 40^{o}C from room temperature, and approximately 20 minutes to reach the higher temperatures. Preloading of the specimen under a constant load of 53% UCS for one hour followed this. Then, for one hour, the rock was allowed to cool in pure water at room temperature. Cyclic loading was done in air at room temperature. A load of 87% UCS for 2 cycles at a strain rate of 0.36 mm/min was then used on the cooled specimen, with an axial extensometer attached to measure the axial strain corresponding to the increase in load. The duration of cyclic loading was ranging between 2–3 minutes for all temperatures. The experiments were then repeated at changing temperatures.

Results

The stress values at bending points were within ± 20% preloading stress except for one datum in the stress-temperature results curve (Fig. 11). It was observed that the rock specimen temperature condition at preloading had no significant effect on the stress value at bending point. Results based on platen displacement and extensometer showed a similar trend.

Conclusion

Kimachi sandstone core specimens were preloaded and cyclic loaded under different conditions to investigate the effects of strain rate and temperature on the bending point stress in TMM.

The results are as follows:

1. For dry specimens, the stress values by TMM lie within ± 20% preloaded stress value for strain rates in the range between 0.001 mm/min and 3.6 mm/min.
2. For saturated specimens, the stress values lie within ± 20% except for one datum, for strain rates in the range between 0.0036 mm/min and 10 mm/min.
3. Very low bending points were observed in both saturated and dry specimens at a loading rate of 0.00036 mm/min.
4. The upper threshold strain rate was not clarified because of the limit of loading frame control
5. The rock temperature at preloading in the range between 40°C and 80°C has no significant effect on the bending point stress value in TMM.

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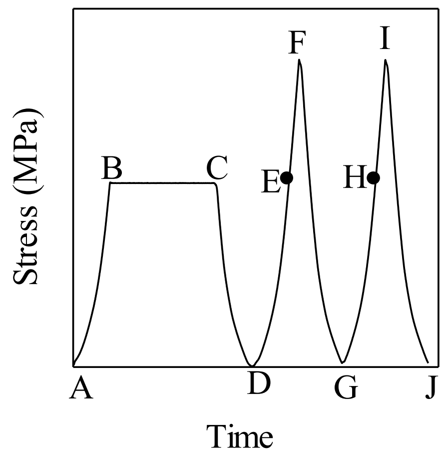

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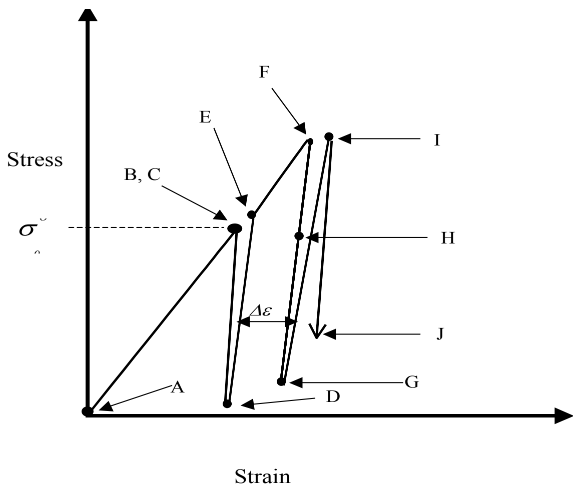

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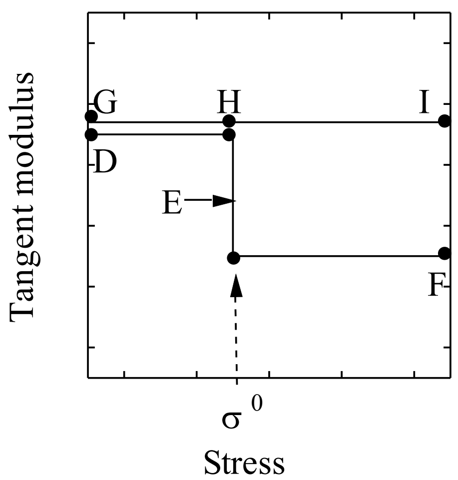

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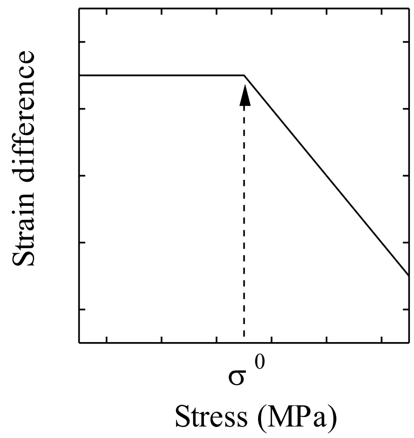

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Fig. 1. Illustration of TMM method. (a) Stress-time graph of TMM. A-D is preloading, which is followed by two cycles of loading namely D-F and G-I respectively. The unloading cycles are FG and IJ for the first and second cycles respectively. (b) Stress- strain curve during preloading and cyclic loading. (c) Tangent modulus-stress curve in TMM, and (d) Strain difference-stress curve for DRA. Preload stress, σ^0, is observed at the bending point.

(a)

(b)

Fig. 2. Preparation of Kimachi sandstone specimens (a) Specimen drilling, and (b) Cutting and grinding of the drill cores to specification.

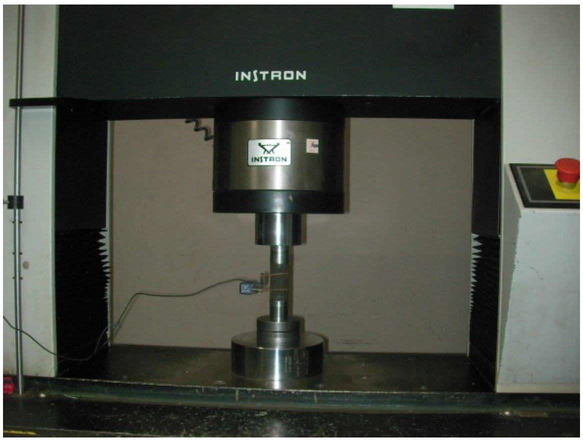
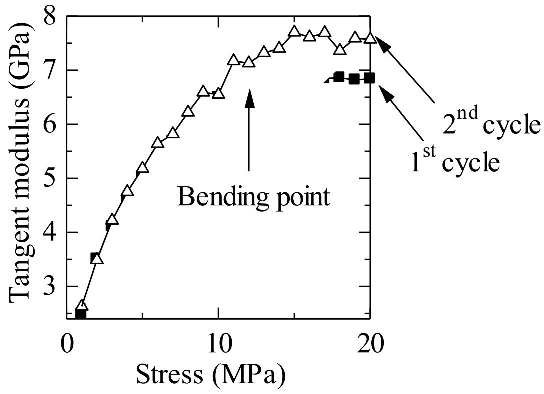


Fig. 3. Experimental setup during cyclic loading. An axial extensometer is attached to the rock specimen.



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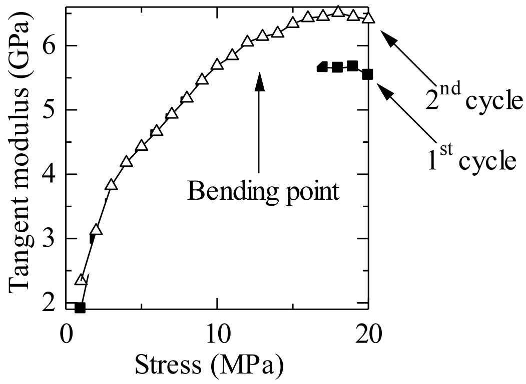

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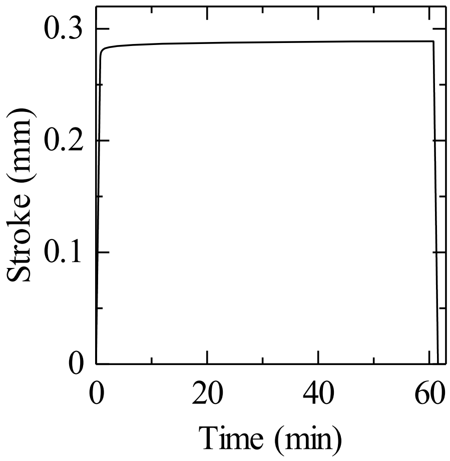

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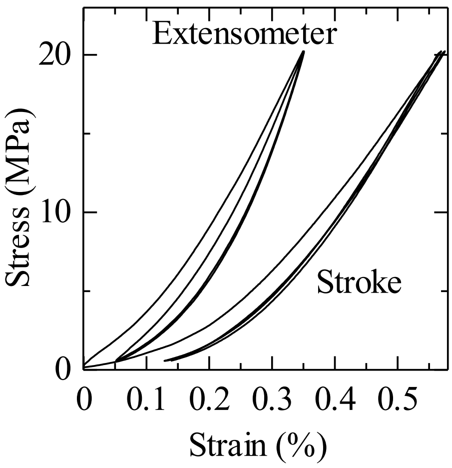
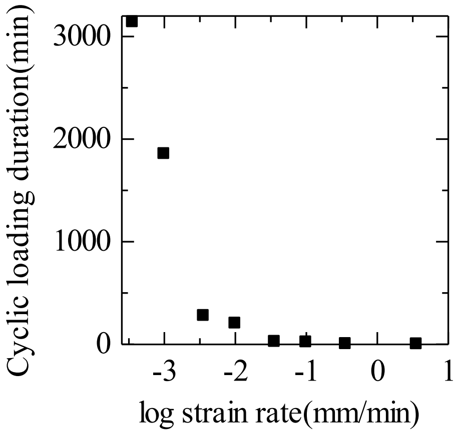


(b)

Fig. 4. Examples of the experimental results at strain rate of 0.0036 mm/min. (a) Stroke variation with time in the preloading. (b) Stress-strain curves during cyclic loading (c) Tangent modulus- stress curve during the cyclic loading based on extensometer readings, and (d) Tangent modulus-stress curve during cyclic loading based on stroke readings.



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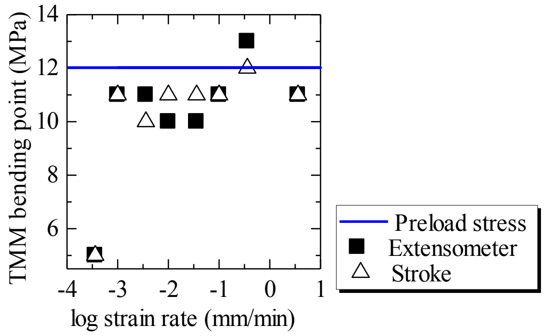

(b)

Fig. 5. Results of cyclic loading of dry Kimachi sandstone specimens (a) Variation of length of time taken to complete two cycles of uniaxial loading at a load of 50% UCS, and (b) TMM bending point stress values based on stroke and extensometer readings.

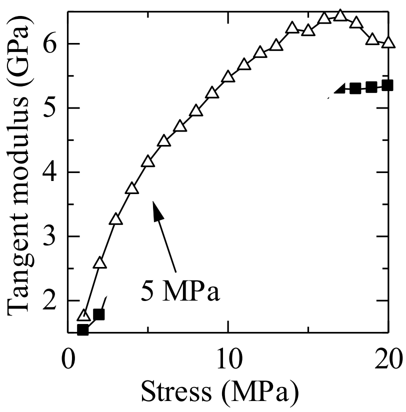

Fig. 6. Change in tangent modulus with increasing load for strain rate of 0.00036 mm/min. in dry Kimachi sandstone.

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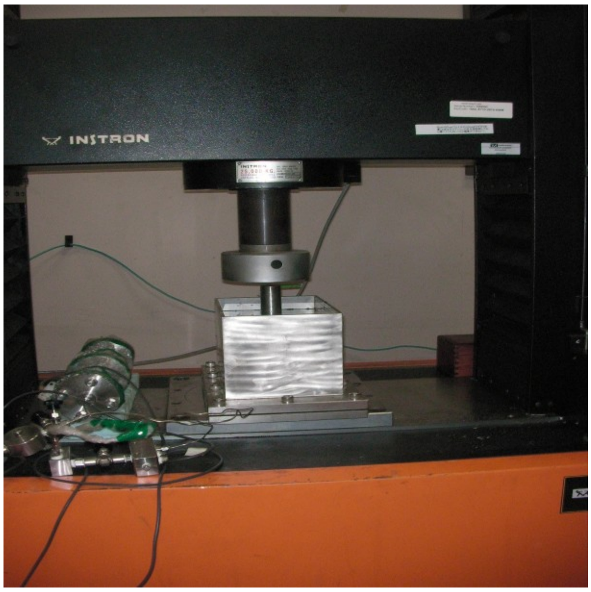

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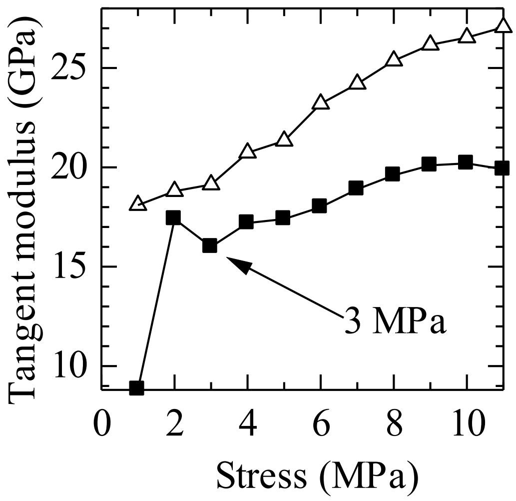
Fig. 7. (a) Vacuum saturation of specimens using a vacuum pump, and (b) Preloading of saturated specimen in pure water at room temperature.



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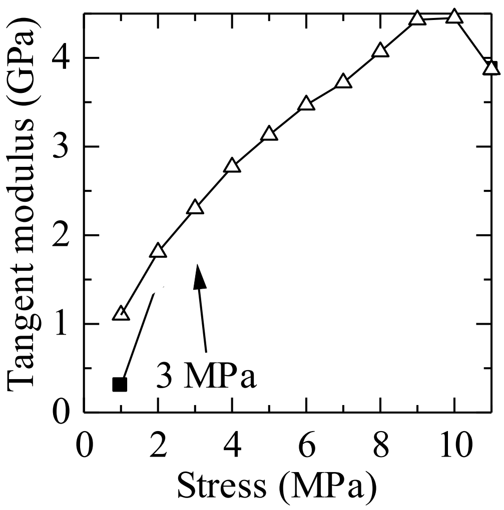

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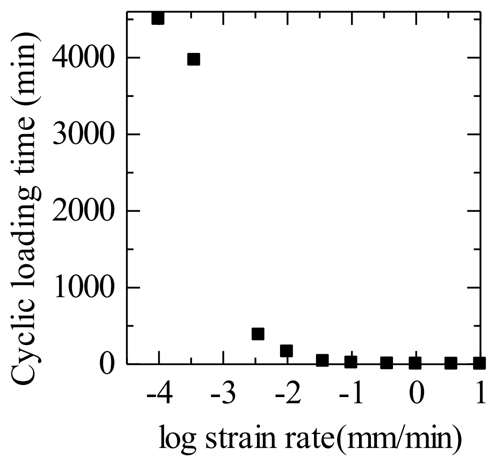
Fig. 8. Stress-tangent modulus curves at 0.00036 mm/min for saturated specimens showing bending point. (a) based on extensometer measurements, and (b) based on stroke measurements.



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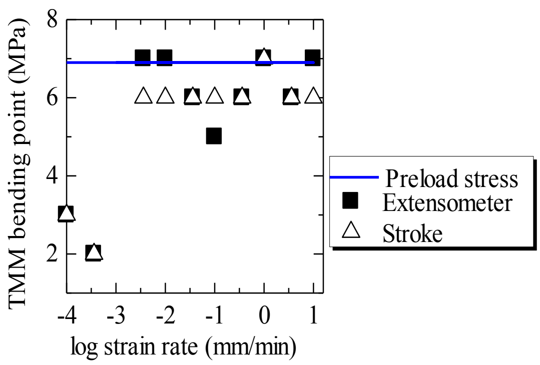

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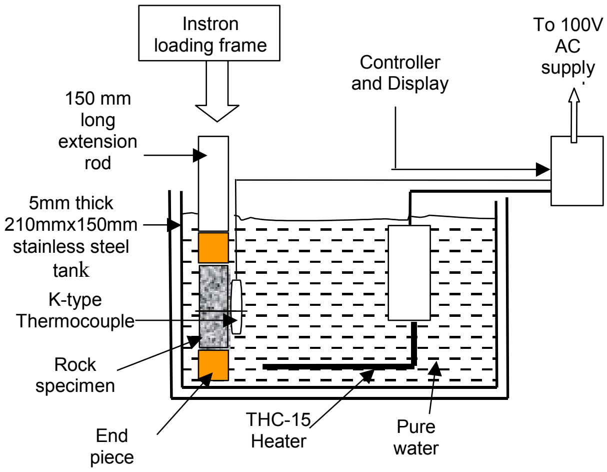
Fig. 9. (a) Duration of cyclic loading at different platen displacing rates, and (b) TMM stress bending points based on the extensometer readings and on stroke.

(a)



(b)

Fig. 10. Effects of temperature on TMM stress value experiment. (a) Rock specimen being preloaded at set temperature as indicated on the display, and (b) Schematic diagram of experimental setup at preloading.

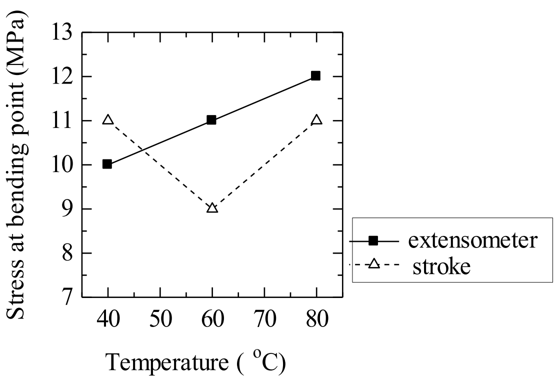


Fig. 11. TMM stress variation with temperature.