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Relations between Fracture Process and Fracture Strength Observed by Means of Triboluminescence with High Resolution of Time

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Abstract

The fracture process of agate is examined experimentally by means of triboluminescence (TL) with time resolution of 0.1 msec under uni-axial compression. The load drops to zero within 0.1 msec at the sample failure without any precursory decrease. TL activity begins at this time, rapidly grows, then attenuates. Comparisons are made between agate and other rocks, granite and marble, of which characters are already reported. It is found relations between the fracture strength and the speed of the process or the pattern of TL activity; the higher the strength is, the faster the process is and the more the time of peak TL intensity is delayed. The attenuation rate of TL intensity increases as the fracture strength increases. These relations are explained with a concept of the local strength distribution.

1. Introduction

The activity of triboluminescence (TL) during the process of sample failure of rocks is very similar to the activity of earthquakes before and after a large earthquake. The similarity is especially remarkable for granite (Maeda, 1986). TL intensity after reaching its maximum decreases with time according to an inverse power law (linear variation in a log-log scale) as the number of aftershocks does. The powers indicating the decreasing rate are different between granite and marble in the case of uniaxial compression, and depend on whether the experiments are uni-axial compression or bi-axial one (Maeda, 1991). It is suggested that the decreasing rate seems to depend on the fracture strength (stress at the time of sample failure) of rock samples (Maeda, 1991).

The fracture strength is not the stable quantity which can vary from sample to sample even when these samples are produced from one rock mass. It can also depend on the stiffness of the testing machine and stress rate. To compare results obtained from different kind of rocks, we must take into account of many factors discriminating between rocks: mineral composition, grain size, porosity, shape- and size-distribution of cracks, etc. These factors along with the way stress applied will affect the fracture strength. A series of experiments in which only one factor is changed while the others are fixed are desirable but it is impossible.

It is considered that, if a sufficiently tough rock is examined, the ambiguity in measured fracture strength would not prevent to see the relation between the fracture strength and the attenuation rate of TL intensity. To reduce effects by the other factors, we examine in this study agate which is extremely tough and mineralogically uniform but of which grain size is quite small comparing granite and marble already examined.

In this study we also make a comparison of overall feature of TL activities for three kinds of rocks.

2. Experiment

The testing machine is a hand-made bi-axial press controlled manually, only one loading axis of which is used. This press is considered to be rather soft for testing extremely tough rock samples. The load applied to samples is detected by a small load-cell inserted between a sample and the head of the ram. This way of measuring load is different from other experiments already reported. We would not claim absolute accuracy of measured values obtained using different measuring systems. We measured fracture strengths of granite and marble, each sample of which was obtained from the same rock masses used for the studies already reported, as well as agate by the present system.

Sample size is $4 \times 4 \times 8$ mm^3. Samples were dried for more than 6 hours at 50°C but the experiments are carried out in a room condition. TL was measured with the same system as before with the same time resolution of 100 μs. The time resolution of load is the same.

3. Resutls and discussion

A record of TL and load variations is shown in Fig. 1. Within the present time resolution, no precursory reduction of load can be recognized. This means that the process time of fracture is less than 100 μs which is extremely shorter than those of marble and granite. Crashed samples are complete dust or

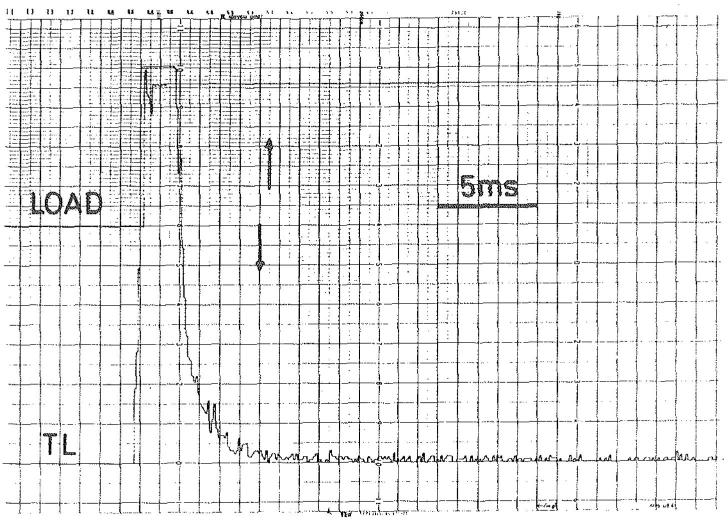

Fig. 1. An example of records of TL and load variations of agate. Upward and downward arrows indicate relative pen positions for the load and TL, respectively.

powder. The fracture strength is nearly 20 kb which is ten times higher than that of granite. Consistent with the variation of load, no TL activity is recognized before the time of sample failure. TL begins exactly at that time and the intensity rapidly increases to its maximum some time later the completion of the sample failure, at the time of the maximum, TL record being out of scale in Fig. 1. Then, the intensity decreases nearly linearly in a log-log scale, as shown in Fig. 2, with attenuation constant A being nearly 4. The constant A is defined as $I=1/t^A$ where I is the TL intensity and t is time.

In the following, we will compare the present results for agate with those of granite and marble. Patterns of TL activities along with those of load variations around the time of sample faifure of marble, granite, and agate can be illustrated as in Fig. 3, taking into account of the results reported (Maeda, 1986 ; 1991). Some trends can be recognized from left to right (ie. marble to agate) in the figure. We define the origin of time, $t=0$, as the time when the load has dropped to zero. Before this time ($t<0$)), TL activity changes from high to zero ; the duration of it from long to zero and the intensity from strong to zero. The time of peak intensity is delayed, that is, t_{max}(marble)$<t_{max}$(granite)$<t_{max}$ (agate). In the cases of granite and marble, the maximum TL intensity attains when the load decreases most rapidly. As for the load variation, it changes

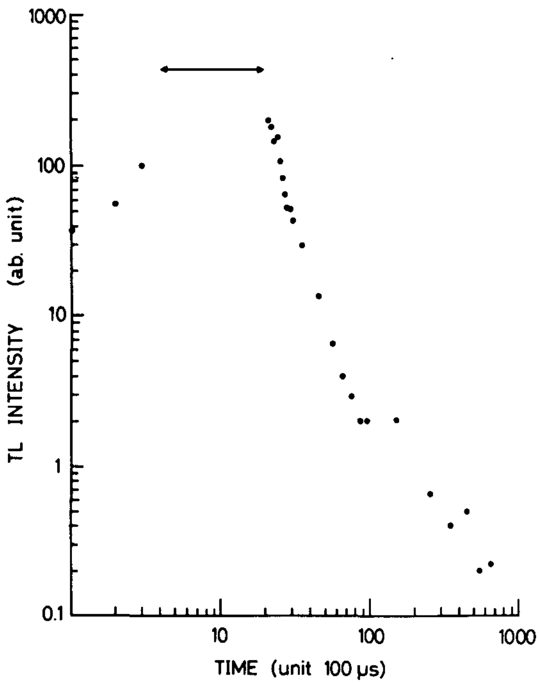

Fig. 2. Variation of TL intensity as a function of time. Data are out-of-scale during the time interval indicated by a horizontal arrow.

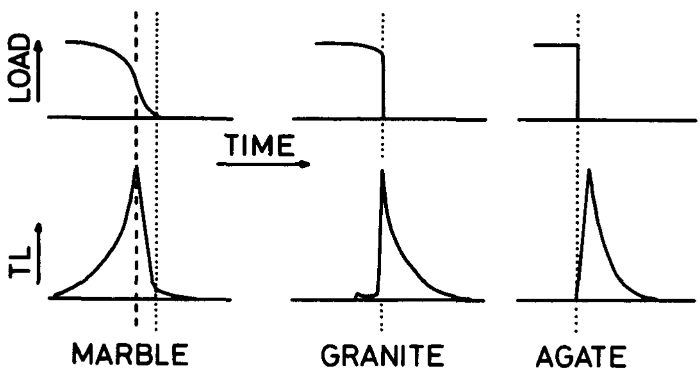

Fig. 3. Patterns of TL and load variations for marble, granite, and agate. Dotted lines indicate the time when the load has returned to zero. Variations of TL are exaggerated around this time.

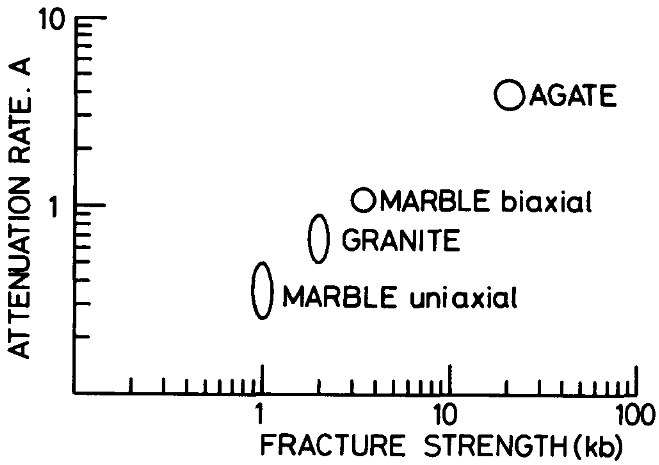

Fig. 4. A log-log plot of attenuation rates, A, of TL versus fracture strengths. The rate, A, is defined by the equation $I=1/t^A$, where I is TL intensity and t is time.

from gradual reduction to sudden drop.

These trends seem to relate to the fracture strength of rocks. Marble is the weakest, agate is the strongest, and granite is in between. The fracture strength also relates to the way of attenuation of TL after the load having dropped to zero. The TL intensity reduces linearly in a log-log scale, which is common to three kind of rocks examined and is the most remarkable feature of TL. The rate of the attenuation, A, defined above against to the fracture strength is given in Fig. 4. The data for marble obtained in the bi-axial experiments are added to the figure. For uniaxial marble and granite, the ellipsoids express the range of data, but for bi-axial marble and agate, the circle's size is given as a degree of inaccuracy or ambiguity of the measurements because the number of data are sparse for these cases. The attenuation rate, A, increases linearly in a log-log scale as the strength increases, though the linearity is not definitely claimed because of the reason given above.

The fact that these relations given are obtained for completely different kind of rocks suggests some universarity on the TL activity and, as a result, on the whole process of fracture of rock. The whole process of course includes the process after the load having dropped to zero, which simply means a fault has propagated completely through a sample rock resulting in complete loss of strength but is usually regarded as the end of fracture process. Because this after-process is difficult to study by means of methods other than TL, it has been ignored.

We will begin with some general remarks on what we have seen by means of TL. It should be noted that the data were recorded only for 0.1 second around the sample failure, the duration of which is much shorter than that of loading, and the events occurring in such short time are usually not analysed or simply ignored. In this study, the word fracture process has, therefore, somewhat different meaning from what usually used. Let's consider in what situation in the loading history the present data were obtained. Under stress, microcracks are generated in rock, the number of which increases gradually at low stress then exponentially as the stress approachs to the fracture strength as observed by means of acoustic emissions. Such cracks do not directly lead the rock to ultimate failure in the sense that if applied stress is reduced the rock will not meet its end. In this type of experiments, the most important factor is the response times of the rock sample and the testing machine. When applied stress has nearly reached to the fracture strength, it would be impossible to stop the sample from being broken down. What we observe by means of TL are the events occurring during this final stage in which the stress change is out of control.

We now reconstruct what is happening during this stage of fracture and consider the strength of rocks. Destruction of a rock sample is the result not of a single crack propagation but of accumulation of micro-cracks. When the accumulation rate is low, the load will gradually decrease. In order the cracks to accumulate gradually, generation of a crack should not cause instantly to produce a large number of other cracks. This condition implies that the stress increased around the crack does not exceed the local strength. If the variance of the local strength distribution is large, only small portion of the rock will be affected and a few crack generation will follow.

Marble is considered to belong to this category of rocks, though it is made only of calcite and is considered to be uniform in certain senses. The ostensible discrepancy between the large variance of local strength and the mineralogical uniformity can be resolved by the fact that calcite can easily cleaved and the cleavage can be created only in certain crystallographic directions resulting in a strong directional dependence on stress, only specific components of stress tensor being involved in creating a cleavage at a local point. Only when the stress concentration at certain point has the directional character preferred at the point, a cleavage will be created. This means that creation of a crack or cleavage only selectively affects to the surrounding area, resulting in a relatively slow accumulation of cracks.

If the experiment is bi-axial, the normal stress acting on a potential cleavage plane will be large and it will suppress the creation of a cleavage and prevents also the expansion of pre-existing cracks and cracking of weak crystal boundaries. Because the cleavages and pre-existing cracks are the most weak point in a rock body, if they are prevented from being active, the fracture strength of the rock becomes high. The other types of defects, from which cracks start, will not be severely affected by the applied stress at the level we are discussing. If it is true, the distribution of the local strength becomes narrow, ie., the variance of the distribution becomes small. From the argument given above, we can expect the rapid accumulation of cracks resulting in the rapid fall of the stress and quick rising of TL activity. We think that the differnce in the data obtained by uni-axial and bi-axial experiments for marble has thus been explained.

If the distribution of local strength in a rock is very narrow (the variance of the distribution is very small), at certain stress state, everywhere in the rock has nearly the equal possibility to bear a crack or cracks. Once a crack is created at certain point in the rock, the stress disturbance will almost certainly and instantly create cracks in the surrounding area, then an avalanche of cracks spreads over the rock body. This process will be very rapid and will reach its end within short time. We can infer, therefore, that the applied stress drops almost suddenly and Tl actitvity rapidly grows then rapidly attenuates.

In addition to the speed of the process, the small variance of the strength distribution implies low concentration of weak points such as pre-existing cracks, weak cleavage planes, or weak crystal boundaries in the rock and, therefore, high strength of the rock. The variations of the load and the TL activity of agate show that agate belongs to this category of rock. High intrinsic strength of constituent mineral, quartz, doubles the strength of agate.

The case of granite is easily explained by the above arguments. Voluminally, granite are made of quartz and felsper which are much stronger than calcite. The distribution of the local strength in granite will be as wide as marble because of the existence of weak biotite. We cannot definitely say only through reasoning which rock, granite or marble, is stronger. Experiments show that granite is stronger than marble. From this we can readily conclude qualitatively that the variations of TL and load are just in between marble and agate. This conclusion is in agreement with experiental observations.

4. Implication to the occurrence of earthquakes

We can see the resemblance between TL activity of rock samples and the occurrence of earthquakes before and after a large earthquake. It seems to be justifiable to make correspondence between these activities if we consider space-time scale ratios between two phenomena. The space-time scale for TL experiments is several milimeters for the fault length and one second for the duration of TL activity. As for an earthquake accompanying smaller ones, the fault length may be several ten kilometers and its aftershocks may be observed over months, though the durations of aftershocks and also of TL are largely depend on the observation systems. The ratio for the time-scales will be of the order of 10^7 which is comparable to that of the length-scales. This scale ratio can be expected if these phenomena are mainly controlled elastically as usually thought to be.

At present, no one knows what conditions do make large earthquakes to accompany precursory earthquakes. No report seems to exist on the subject of the attenuation rate of aftershocks and its relation to other quantities. If the arguments given in the preceding section can be applied to the earthquake phenomena, we can expect that the attenuation rate of an aftershock sequence has some relation with the probability that the main shock is preceded by a precursory activity of earthquakes. Whether this inferance is true or not is up to seismologists.

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