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Effects of relative humidity and temperature on subcritical crack growth in igneous rock

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Abstract

The effects of relative humidity and temperature on subcritical crack growth in igneous rock have been investigated experimentally on samples of Kumamoto andesite and Oshima granite. Stress intensity factors and crack velocities were measured using the double-torsion technique, and all experiments were conducted in moist air. Our results show that, in experiments conducted under the same relative humidity, crack velocity increased with increasing temperature, in agreement with previous studies. Our results also show that, in experiments conducted at the same temperature, crack velocity increased dramatically with increasing relative humidity. A three- to four-fold increase in relative humidity resulted in an increase in crack velocity of between one and four orders of magnitude. Such an increase is larger than that predicted by classical stress corrosion theory. It is suggested that capillary condensation of water vapour close to crack tips of small aperture influences the rate of crack growth. It is concluded that relative humidity needs to be controlled to avoid time-dependent weakening and extend the lifetime of structures in a rock mass.

Keywords: Subcritical Crack Growth, Double-Torsion Technique, Granite, Andesite, Temperature, Relative Humidity

1. Introduction

Understanding time-dependent brittle deformation due to subcritical crack growth is important in many geological applications. Time-dependent fracture propagation has been invoked as the key mechanism responsible for the increase in seismicity preceding earthquake ruptures and volcanic eruptions [1]. Furthermore, when designing sub-surface structures in the rock mass, such as repositories for radioactive waste, caverns to store liquified natural gas (LNG) or liquified petroleum gas (LPG), or underground power plants, it is essential to consider their long-term stability. In order to ensure long-term stability, it is necessary to evaluate the long-term strength of the rock in which such structures are constructed. In turn, this requires an understanding of time-dependent deformation and fracture propagation in the rock [2, 3].

Subcritical crack growth is considered to be one of the main mechanisms responsible for the time-dependent behaviour of rock in the brittle regime [4, 5]. It is known that the rate of subcritical crack growth in rock is dependent on both the rock fabric and the environmental conditions, as well as the level of stress. In particular, it has been shown that any preferred orientation in the pre-existing microcrack fabric can be responsible for significant anisotropy of the crack velocity [6]. Specifically, the crack velocity is higher in the direction parallel to the pre-existing microcrack fabric, especially where the crack density is high [7, 8]. According to the experimental results of Sano and Kudo [6], Waza et al. [9] and Nara et al. [10], the crack velocity in water is much higher than that in air. Nara et al. [10] reported that the crack velocity increased with temperature in water. Meredith and Atkinson [11] and Nara and Kaneko [7, 12] reported that the crack velocity increased when the water vapour pressure increased. However, the water vapour pressure is dependent on both the temperature and relative humidity. Therefore, in order to study the effect the water vapour pressure rigorously, it is necessary to

measure the crack velocity either under different relative humidities at the same temperature, or under different temperature at the same relative humidity.

In this study, we have therefore investigated the effects of temperature and relative humidity on subcritical crack growth independently, on samples of two igneous rocks. Specifically, the relation between the stress intensity factor and crack velocity in moist air was investigated under ambient and elevated temperature at the same relative humidity, and under different relative humidities at a fixed temperature.

2. Rock samples

All rock samples used in this study were manufactured from single blocks of Kumamoto andesite and Oshima granite.

Kumamoto andesite consists of plagioclase (about 50%), with hornblende and augite (2~3%) as phenocrysts in a fine-grained groundmass [13]. Some phenocrysts of about 1 ~ 2 mm in length were distributed in the groundmass in Kumamoto andesite. Oshima granite comprises quartz (36%), plagioclase (37%), K-feldspar (22%), biotite (4%) and hornblende (less than 1%) [14]. The mean grain size of Oshima granite was about 1 mm [15]. Neither rock contains any clay minerals.

For Kumamoto andesite, the porosity was about 7% [16]. P-wave velocities in three orthogonal directions were 4.80, 4.80 and 4.83 km/s. Thus Kumamoto andesite is essentially isotropic [12]. Uniaxial compressive strength, Young's modulus and Poisson's ratio measured in air were 151 MPa, 31.9 MPa and 0.27, respectively [17].

For Oshima granite, the porosity was about 0.8% [18]. According to the microscopic observation by Sano et al. [18], two sets of preferred orientation of pre-existing microcracks are found in Oshima granite. Sano et al. [18] reported that the most of the microcracks distributed within the rift plane, and secondary orientation of microcrack distribution was almost perpendicular to the rift plane, which is known as the grain plane. Additionally, Sano et al. [18] concluded that Oshima granite has orthorhombic elasticity due to the preferred orientation of microcracks. P-wave velocities measured in the direction normal to the rift plane, grain plane and hardway plane (the third plane within which the least microcracks distribute) were 4.91, 4.61 and 4.51 km/s, respectively [7]. In Table 1, the orthorhombic elastic compliance of Oshima granite is summarized [7].

Sano and Kudo [6] and Nara and Kaneko [7] reported that Oshima granite had

anisotropy of crack velocity. According to Nara and Kaneko [7], the velocity of a crack propagating parallel to the rift plane was higher by 3 ~ 5 orders of magnitude than the velocity of a crack propagating parallel to the hardway plane. Therefore, it is necessary to consider the crack propagation direction. We oriented our granite specimens so that cracks always propagated in a direction normal to the grain plane and parallel to the rift plane.

3. Methodology

3.1 Specimen

Stress intensity factors and crack velocities were measured using the double-torsion (DT) technique [6, 19, 20]. In Fig. 1, a schematic illustration of the specimen and the loading configuration of DT technique are shown. Specifically, we used the load-relaxation (RLX) method [19, 20]. In this method, the displacement of the loading point is kept constant during the experiment and the load relaxation due to crack propagation is measured. The stress intensity factor is a function of the load and the crack velocity is a function of the temporal load and decreasing rate of the load. This allows us to measure a wide range of stress intensity factors and crack velocities in a single experiment. This is the main reason why the RLX method was adopted to measure subcritical crack growth in this study.

Since Kumamoto andesite is isotropic, we used equations introduced by Williams and Evans [20] in order to evaluate the stress intensity factor and crack velocity. These equations are as follows [20]:

$$K_I = Pw_m \sqrt{\frac{3(1+\nu)}{Wd^3d_n}} \quad (1)$$

$$\frac{da}{dt} = -\varphi_c \times \frac{Wd^3G}{3w_m^2} \frac{S_i P_i}{P^2} \frac{dP}{dt} \quad (2)$$

where K_I is the stress intensity factor, da/dt is the crack velocity, P is the applied load, w_m is the moment arm (18 mm in this study), ν is Poisson's ratio, W is the width of the specimen, d is the thickness of the specimen, d_n is the reduced thickness of the specimen, P_i is the initial value of the applied load, S_i is the compliance of the specimen at the initial crack length a_i , dP/dt is the load relaxation rate, and G is the shear modulus. φ_c is

a constant that is dependent on the shape of the crack front. Experiments using glass [20] and quartz [21] suggested that $\varphi_c = 0.2$.

Considering the orthorhombic elasticity of Oshima granite, we used the equations introduced by Sano and Kudo [6] for orthorhombic materials in order to evaluate the stress intensity factor and crack velocity for Oshima granite. In this study, crack propagation occurs normal to the grain plane and parallel to the rift plane (see Section 2). Therefore, we used the following equations [6]:

$$K_I^2 = \frac{3P^2 w_m s_{44}}{2d^3 d_n (2s_{33} ((s_{33}s_{22})^{1/2} + s_{23} + s_{44}/2))^{1/2}} \quad (3)$$

$$\frac{da}{dt} = \varphi_c \times \frac{-2S_i P_i (dP/dt) d^3}{3P^2 s_{44} w_m} \quad (4)$$

where s_{22} , s_{33} , s_{44} and s_{23} are the elastic compliance of the sample.

Because these are approximate solutions based on a thin-plate assumption [20], the size of the DT specimen has to satisfy the condition as follows [22-24]:

$$12d \leq W \leq L/2 \quad (5)$$

where L is the length of the specimen.

According to the finite element analysis by Trantina [25], the stress intensity factor is independent of the crack length over the following range:

$$0.55W < a < L - 0.65W \quad (6).$$

Ciccoti and his co-workers have conducted analytical studies of DT RLX method using finite element methods [26-29]. They expressed the corrective factor of the specimen compliance for the DT technique to consider the non-linear terms of the dependence of the compliance on the crack length in a DT specimen [26, 27].

Additionally, they used thicker specimens ($W : d = 8 : 1$) than those recommended by Evans et al. [22] or Atkinson [23] based on the results of finite element analysis [28, 29]. By experiments with soda-lime glass, Madjoubi et al. [30] reported that the applicability

of equations for DT RLX method was satisfactory when the length of the specimen reached three times the width. Sano [31] reported that the stress intensity factor is independent of the crack length by showing the proportional relation between the compliance and the crack length in DT specimen of soda-lime glass, basalt and quartz andesite. Taking these restrictions into account, the size of the specimens in this study was set to the width $W = 45$ [mm], the thickness $d = 3$ [mm], the reduced thickness $d_n = 2$ [mm], and the length $L = 150$ [mm] for andesite and $150 \sim 170$ [mm] for granite.

It is necessary to make a guide groove in a DT specimen in order to control the crack path. Nara and Kaneko [12] suggested that the shape of the guide groove should be rectangular for rock, because the crack often propagated away from the guide groove in the cases of semi-circular or triangular guide grooves. According to the measurement for granite by Nara [32], the crack often propagated away from the guide groove when the width of the guide groove was smaller than the grain size. In this study, the width of the guide groove for Kumamoto andesite was set to 2 mm, because the size of some phenocrysts reaches 2 mm. For Oshima granite, the width of the guide groove was set to 1 mm, because the grain size was around 1 mm.

3.2 Apparatus

A schematic illustration of the experimental apparatus is given in Fig. 2. Experiments were performed in a temperature and humidity controlled room. The controllable ranges of the temperature and relative humidity are 283 to 353 K (10°C to 80°C) and 40 to 90 %, respectively. One exception to this is that experiments at very low relative humidity (22 to 26%) were conducted under ambient conditions during the winter (low humidity season) because this is outside the normal range of humidity control.

3.3 Procedure

All experiments were conducted following the same procedure and loading conditions as that described in Nara and Kanko [7, 12] and Nara et al. [10, 33]. At first, precracking was conducted. Then, the temperature and relative humidity in the testing room were set and kept constant, and the apparatus and the DT specimen were exposed to the testing environment for more than 20 hours. Finally, the measurement of subcritical crack growth was conducted with DT RLX method. In this measurement, we slowly applied a preload of 14 ~ 16 N, which corresponded to 15 ~ 25 % of the maximum load (initial load P_i in Eqs. (2) and (4)). Then we applied a large displacement rapidly to the loading points of the specimen and held it constant throughout the measurement. This large displacement has to be decided so that the initial value of the applied load approaches the value corresponding to the fracture toughness [7, 12]. This displacement was 0.27 mm for Kumamoto andesite and 0.24 mm for Oshima granite in all conditions as specified by Nara and Kaneko [7, 12]. In Fig. 3, the temporal change of the applied load is shown. Although this figure shows the change of the load from 0 to 200 seconds, the measurement with RLX method has been conducted for 1.5 ~ 2 hours.

4. Results

Experimental results were fit to a relation between the mode I (tensile) stress intensity factor K_I and the crack velocity da/dt (K_I - da/dt relation) of the following form [34]:

$$\frac{da}{dt} = AK_I^n \exp\left(\frac{-E^\ddagger}{RT}\right) \quad (7)$$

where E^\ddagger is the activation energy, R is the gas constant, T is the absolute temperature, and A and n are constants determined experimentally. In particular, n is known as the subcritical crack growth index, and is a measure of the susceptibility of the rock to subcritical crack growth under the particular environmental conditions of the test.

Fig. 4 illustrates the K_I - da/dt relations for Kumamoto andesite (Fig. 4(a)) and Oshima granite (Fig. 4(b)) under different relative humidities at the same test temperature. The results clearly demonstrate that the crack velocity increases dramatically when the relative humidity is increased. For example, at a constant stress intensity factor of 1.5 $\text{MN}\cdot\text{m}^{-3/2}$, the crack velocity in Kumamoto andesite increases by about 3 orders of magnitude as the relative humidity is increased from 25% to 90% (Fig. 4(a)). The increase in crack velocity is even more dramatic for Oshima granite (Fig. 4(b)). Fig. 5 illustrates the K_I - da/dt relation for Kumamoto andesite for different test temperatures at the same relative humidity. At the same stress intensity factor, the crack velocity increases by about 1 order of magnitude as temperature is increased by 55 K.

Tables 2, 3 and 4 provide summaries of the main experimental results. Tables 2 and 3 summarize the results for andesite and granite, respectively, for different relative humidities. Table 4 summarizes the results for crack propagation in andesite at the different temperatures. In each table, the mean and standard deviation from several experiments are shown. The stress intensity factor at a crack velocity of $10^{-5} \text{ m}\cdot\text{s}^{-1}$ is listed as $K_I(10^{-5})$ in each table to provide a quantitative point of comparison, since the

range of crack velocities was very wide (10^{-2} - 10^{-8} m.s⁻¹). Also, since the stress intensity factor range for Kumamoto andesite shown in Fig. 4(a) was approximately 1.2 - 1.9 MN.m^{-3/2}, the crack velocity at $K_I = 1.5$ MN.m^{-3/2} is listed in Table 2 as $da/dt(1.5)$ to provide a quantitative point of comparison for the crack velocities. Similarly, $da/dt(1.6)$ is listed in Table 3 to provide a quantitative comparison, because the stress intensity factor range for Oshima granite shown in Fig. 4(b) was approximately 1.3 – 2.0 MN.m^{-3/2}. Finally, $da/dt(1.4)$ is listed in Table 4 to provide a quantitative point of comparison, because the stress intensity factor range for Kumamoto andesite shown in Fig. 5 was approximately 1.2 – 1.7 MN.m^{-3/2}. It is clear from the data in the tables that crack velocity increases as both relative humidity and temperature increase. Tables 2 and 3, and Fig. 4 show that a threefold to fourfold increase in relative humidity produces an increase of up to 4 orders of magnitude in the crack velocity. This increase is, however, too large to be explained by classical stress corrosion theory which predicts that crack velocity is proportional to relative humidity when the temperature is constant [35]. By contrast, the increases in crack velocity with increasing temperature reported in Table 4 and Fig. 5 are consistent with stress corrosion theory [36].

The trend in the values of the subcritical crack growth index n suggests lower values when the temperature or relative humidity is higher. This is consistent with the studies of Lajtai and Bielus [37] and Holder et al. [38] who suggested that n was also dependent on environmental conditions. However, the change of n shown in Tables 2, 3 and 4 is small. Additional studies will be necessary in order to clarify the dependence of n on environmental conditions.

5. Discussion

Stress corrosion in the quartz-water system is a stress-enhanced chemical reaction which involves the preferential weakening of strained siloxane bonds near the crack tip. This process is described by the following bond-weakening chemical reaction [39]:



Since stress corrosion is a thermally-activated chemical reaction, the data shown in Fig. 5 and Table 4 are entirely consistent with stress corrosion being the mechanisms allowing subcritical crack growth in our experiments on igneous rocks.

Assuming that the crack velocity is proportional to the chemical reaction rate, then it will also be proportional to the water vapour pressure in air, since crack velocity is proportional to the activity of water [40]. Furthermore, Freiman [35] proposed that the crack velocity should be proportional to the relative humidity when the temperature is constant. This proposal is supported by the results of experiments on soda-lime glass by Wiederhorn [41] and Soga et al. [42]. However, the increases in crack velocities due to increasing the relative humidity measured in this study were larger than expected from simple stress corrosion theory. As suggested by Freiman [35] theoretically, if the crack velocity is proportional to the relative humidity, the values of the crack velocity under the conditions of intermediate humidity and high humidity should be around 2 times higher and 3 times or 4 times higher than that under the condition of low humidity, respectively. However, Tables 2 and 3 show that a threefold to fourfold increase in relative humidity produces an increase of up to 4 orders of magnitude in the crack velocity. Considering the effect of the temperature on the crack velocity, it is considered that stress corrosion is one important mechanism of subcritical crack growth in igneous rocks. However, it is obviously impossible to explain this increase only by the stress corrosion theory. We therefore need to consider what additional mechanisms may be

contributing to the rate of subcritical crack growth in our experiments.

Since the aperture of the crack close to the crack tip is very small, it is possible that the water vapour turns to liquid water by capillary condensation in this zone, and that the crack path close to the crack tip is therefore immersed in liquid water. Further, if the crack is immersed in a liquid, suction occurs between the crack planes by liquid bridging [43]. Therefore, compressive stress acts around the crack tip. This suction will decrease with increasing radius of curvature of the condensed liquid. Also, any increase in relative humidity will lead to an increase in the volume of condensed water present. In this case, the radius of curvature of the liquid water will increase as the aperture of the crack increases. By using the Young-Laplace equation which describes the capillary pressure difference sustained across the interface between two static fluids, such as water and air, it is possible to approximate the compressive stress around the crack tip. If the aperture of the crack is $2r$, the Young-Laplace equation is expressed as follows [44]:

$$P_c = \frac{\gamma_s}{r} \quad (9)$$

where P_c is the pressure due to the capillary condensation, that is, the compressive stress around the crack tip, and γ_s is the surface tension of water, which is $73 \times 10^{-3} \text{N/m}$. In the image of the crack path in granite obtained with the Electron Probe Micro Analyzer by Nara et al. [8], the least aperture of the crack is less than 10 nm. For example, assuming that $r = 5$ or 10 [nm], the compressive stress around the crack tip is 14.6 MPa or 7.3 MPa, respectively. These values are similar to the tensile strength of igneous rocks. It is considered that the effect of the compressive stress around the crack tip due to the capillary condensation can be significant.

Hence, suction around the crack tip will decrease as the volume of condensed water increases. We therefore suggest that the compressive stress around the crack tip will decrease with increasing relative humidity. It is therefore possible that the change in the

compressive stress acting around the crack tip induces a change in the activation energy in Eq. (7), and this induces a concomitant change in the crack velocity.

It is also possible that an electric double layer is formed in the condensed water around the crack tip and that a repulsive force therefore acts between the crack planes. In this case, increasing the relative humidity would result in the electric double layer being formed over a wider range due to the increase in the quantity of condensed water present. In turn, this would result in larger repulsive forces acting between the crack planes. This effect can therefore also change the activation energy in Eq. (7), and consequently also change the crack velocity.

The above effects can occur in glass but, in that case, capillary condensation acts only at the tip of the single macrocrack [45]. By contrast, most rocks contain many pre-existing defects such as microcracks and microcavities. Furthermore, crack propagation in rock generally also involves multiple crack branching [8]. It is therefore possible that the effects of capillary condensation act not only at the tip of the macrocrack, but also at pre-existing microcracks and microcavities, and at the tips of branching cracks. The effect will be especially significant at defects which have small apertures. Since we expect capillary condensation to occur at multiple locations in rock, the larger increase in crack velocity observed in rock with increasing relative humidity, with respect to glass, is easily explained.

The changes in crack velocity measured in igneous rocks as a result of changes in relative humidity, and reported here, provide new data that cannot be explained by classical stress corrosion theory alone. Nevertheless, we can conclude that relative humidity needs to be controlled in order to avoid time-dependent weakening and extend the lifetime of structures in the sub-surface rock mass.

6. Conclusions

In this study, the effects of relative humidity and temperature of moist air on subcritical crack growth in two igneous rocks were investigated. Increasing the temperature resulted in an increase in the crack velocity, and since stress corrosion is a thermally activated process, we consider it as the most likely mechanism for the subcritical crack growth in our igneous rock samples. The crack velocity also increased dramatically with increase in the relative humidity. Increasing the relative humidity by a factor of 3 to 4 resulted in an increase in the crack velocity of between 1 and 4 orders of magnitude. However, such increases are larger than can be explained by classical stress corrosion theory. We therefore suggest that capillary condensation of water vapour close to crack tips of small aperture can influence the rate of crack growth. The changes in crack velocity measured in igneous rocks as a result of changes in relative humidity, and reported here, provide new data on subcritical crack growth in igneous rocks. We conclude that relative humidity therefore needs to be controlled in order to avoid time-dependent weakening and extend the lifetime of structures in the sub-surface rock mass.

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in oxide glasses. *J Am Ceram Soc*, 2006; 89: 746-749.

Figure captions

Fig. 1 Double-Torsion specimen and loading configuration. The loading forces are shown by four thick arrows.

Fig. 2 A schematic illustration of the Double-Torsion testing apparatus.

Fig. 3 Temporal change of the applied load.

Fig. 4 K_I - da/dt relations for Kumamoto andesite in air under different relative humidities at the same temperature.

(a): for Kumamoto andesite

(b): for Oshima granite in which the crack propagates normal to the grain plane and parallel to the rift plane.

Fig. 5 K_I - da/dt relations for Kumamoto andesite in air for different temperatures at the same relative humidity.

Tables

Table 1 Elastic compliance of Oshima granite (after Nara and Kaneko [7]).

		Effective compliance s_{ij} [$\times 10^{-12} \text{Pa}^{-1}$]					
		j					
		1	2	3	4	5	6
i	1	16.7	-3.28	-3.28	0	0	0
	2	-3.28	18.9	-3.28	0	0	0
	3	-3.28	-3.28	19.7	0	0	0
	4	0	0	0	46.0	0	0
	5	0	0	0	0	43.4	0
	6	0	0	0	0	0	42.4

Table 2 Summary of the results for Kumamoto andesite under different relative

humidities at the same temperature. SD means the standard deviation.

Condition	n	$K_I(10^{-5})$ [$\text{MN}/\text{m}^{3/2}$]	$da/dt(1.5)$ [m/s]
Low humidity (290K, 25%)	58±9	1.62±0.03	1.1×10^{-7} (SD = 4.8×10^0 in log)
Intermediate humidity (293K, 55%)	61±10	1.50±0.00	8.9×10^{-6} (SD = 1.0×10^0 in log)
High humidity (293K, 90%)	45±4	1.44±0.04	6.0×10^{-5} (SD = 2.8×10^0 in log)

Table 3 Summary of the results for Oshima granite under different relative humidities

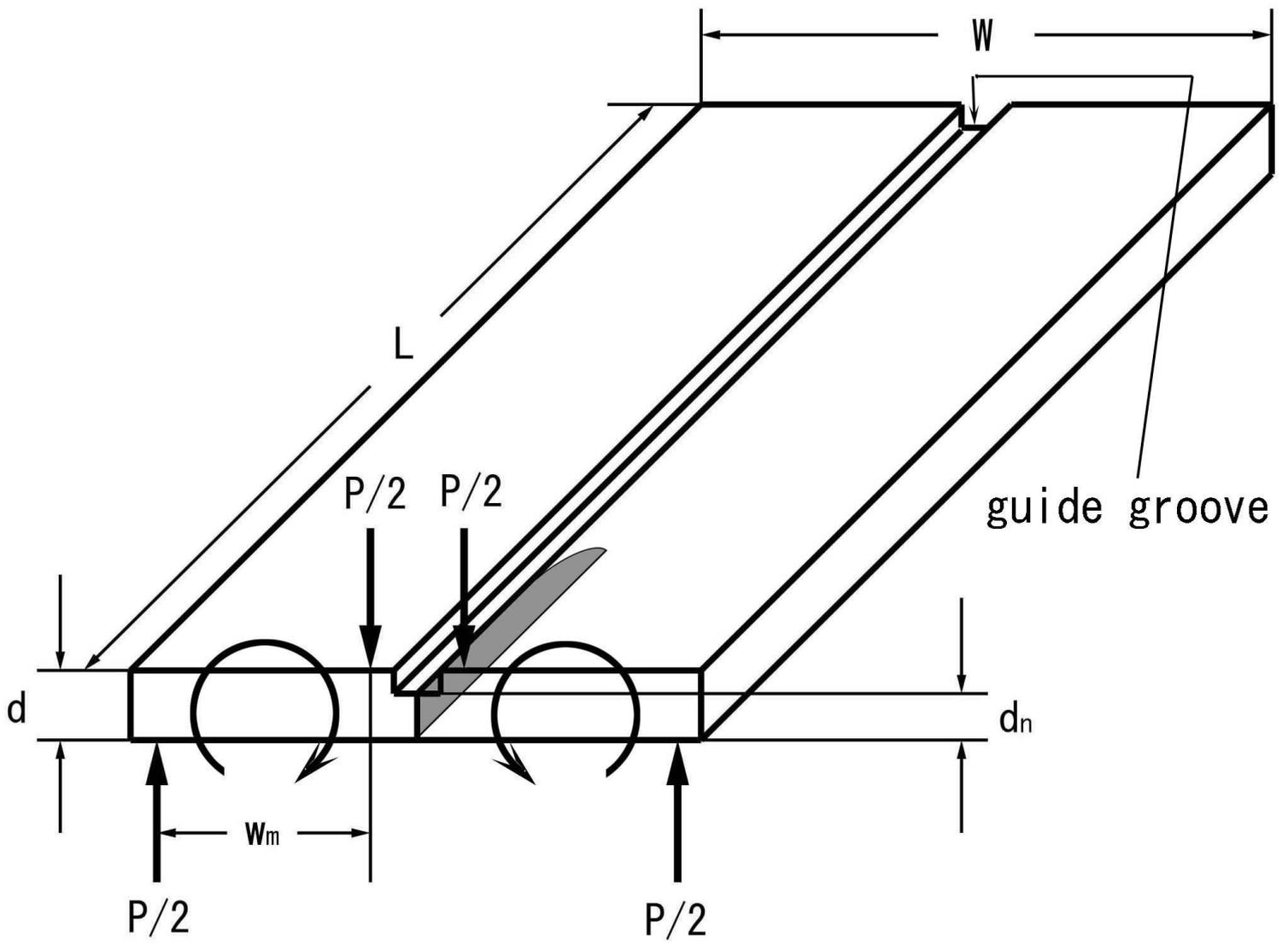
at the same temperature. SD means the standard deviation.

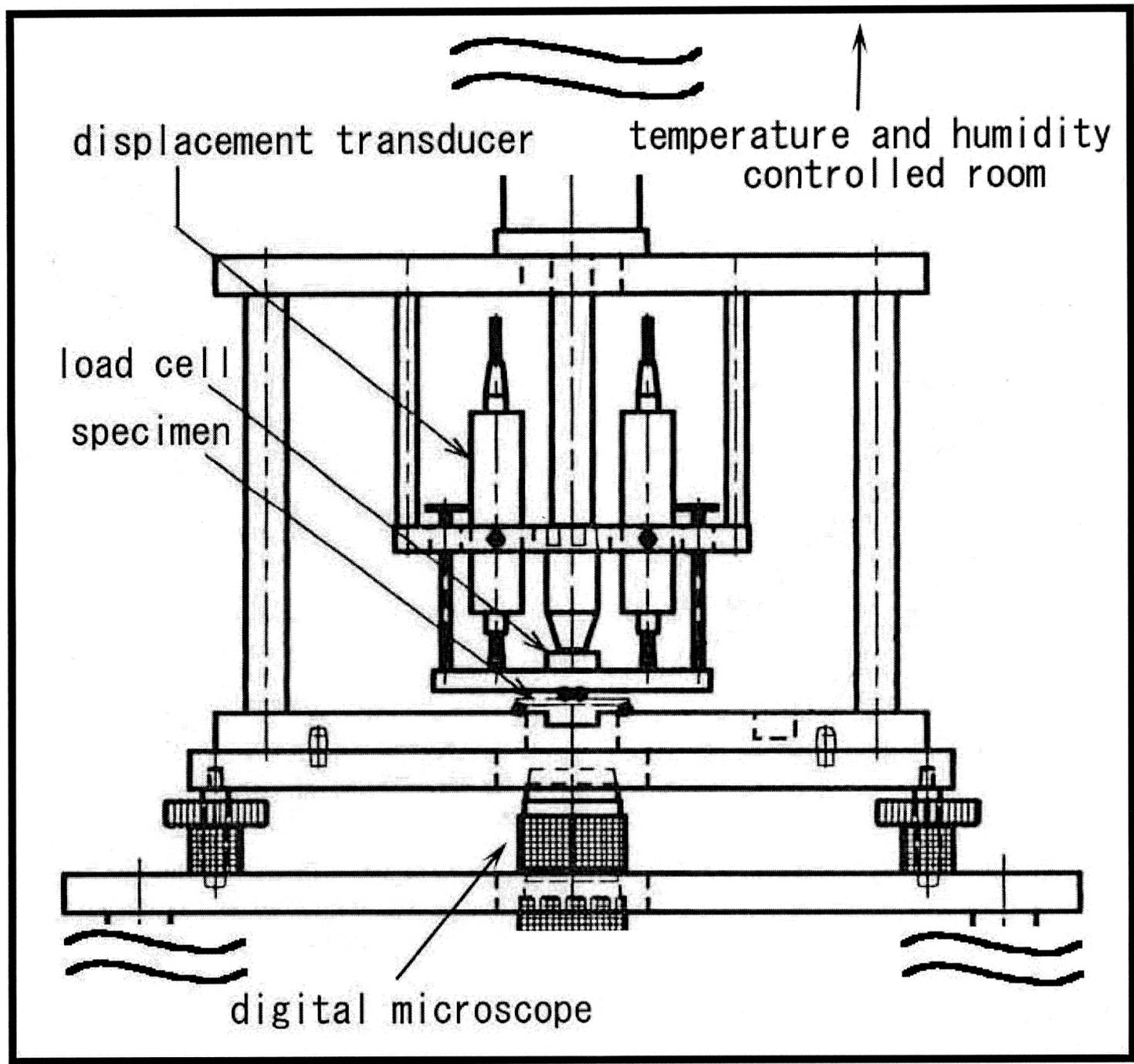
Condition	n	$K_1(10^{-5})$ [MN/m ^{3/2}]	$da/dt(1.6)$ [m/s]
Low humidity (295K, 22-26%)	75±20	1.76±0.10	7.8×10 ⁻⁹ (SD = 2.8×10 ¹ in log)
High humidity (293K, 88-91%)	65±8	1.53±0.06	2.3×10 ⁻⁴ (SD = 1.5×10 ¹ in log)

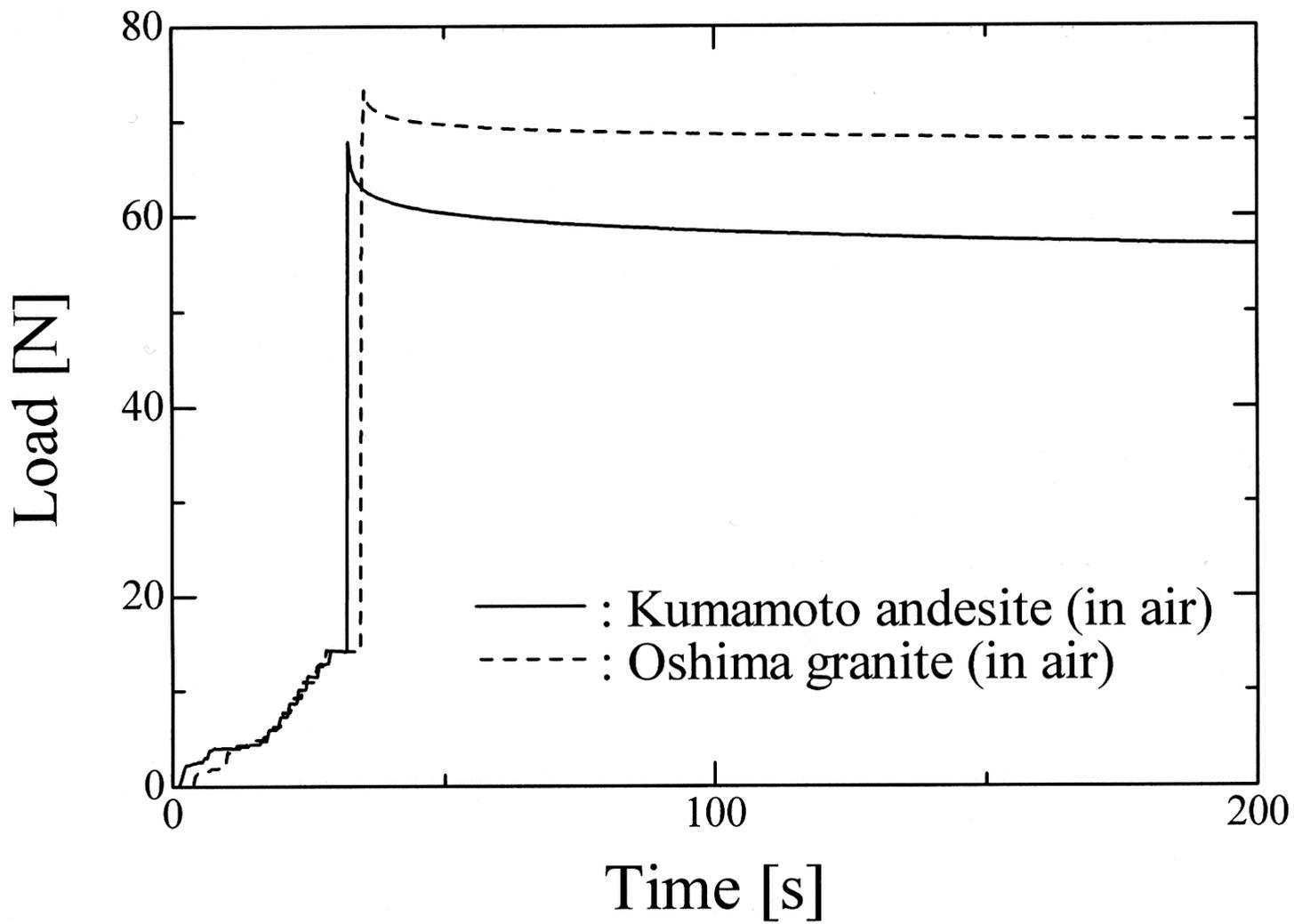
Table 4 Summary of the results for Kumamoto andesite for different temperatures at

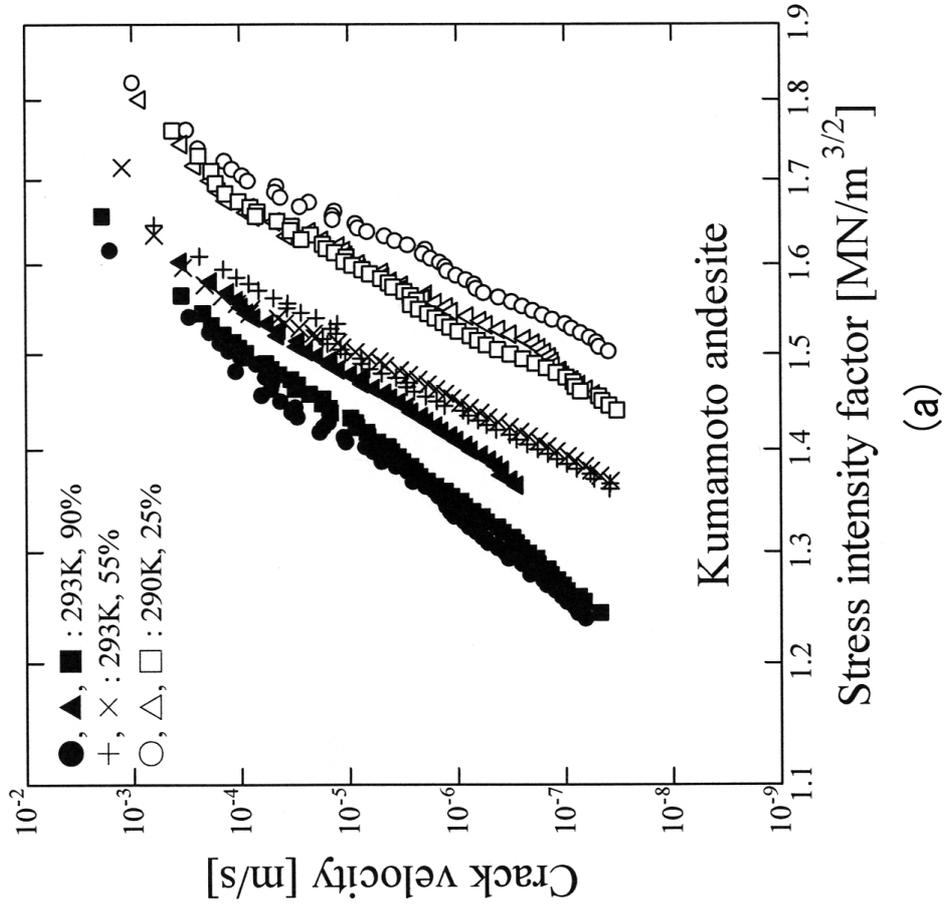
the same relative humidity. SD means the standard deviation.

Condition	n	$K_1(10^{-5})$ [MN/m ^{3/2}]	$da/dt(1.4)$ [m/s]
Low temperature (293K, 55%)	61±10	1.50±0.00	1.3×10 ⁻⁷ (SD = 2.1×10 ⁰ in log)
Intermediate temperature (329K, 50%)	49±5	1.48±0.04	7.9×10 ⁻⁷ (SD = 2.9×10 ⁰ in log)
High temperature (348K, 50%)	43±1	1.43±0.00	3.6×10 ⁻⁶ (SD = 1.0×10 ⁰ in log)

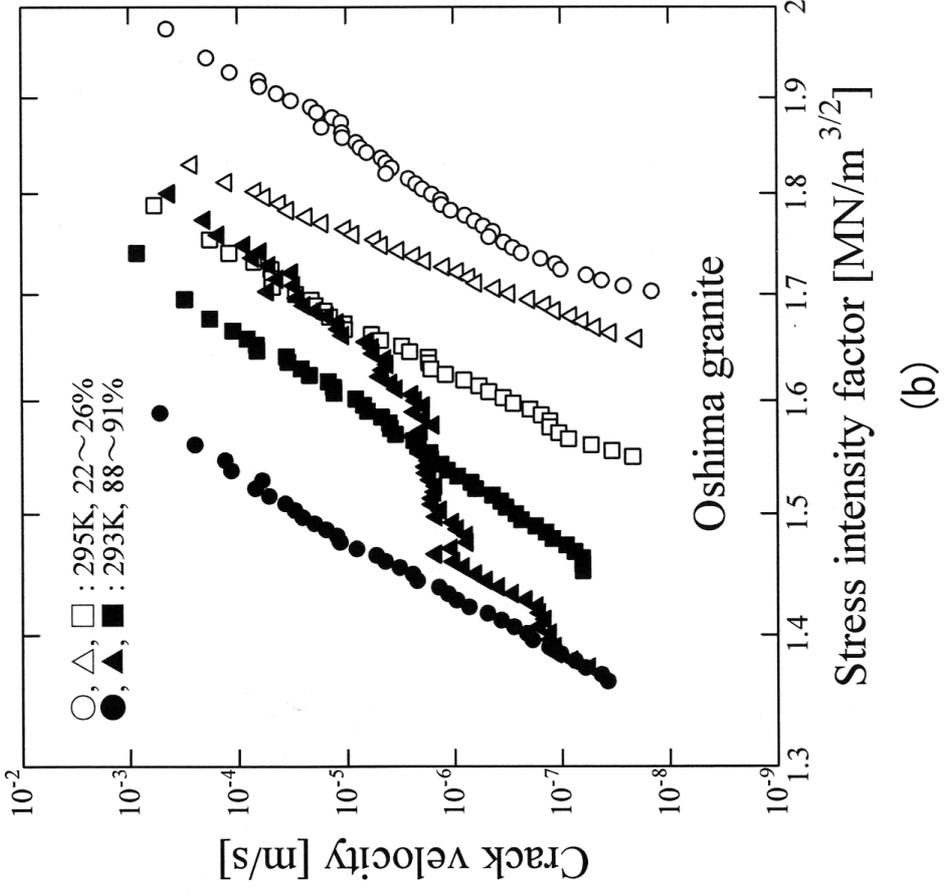








(a)



(b)

