Subcritical crack growth in rocks in an aqueous environment*

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Abstract. Subcritical crack growth is one of the main causes of time-dependent fracturing in rock. In the present study, we investigated subcritical crack growth in rock in distilled water (pH = 5–7) and in an aqueous solution of sodium hydroxide (NaOHaq, pH = 12), comparing the results to those in air. We also investigated the effect of the pH in an aqueous environment. We used andesite and granite for all our tests. We determined the relationship between the crack velocity and the stress intensity factor using the double-torsion test under conditions of controlled temperature. We showed that crack velocities in water were higher than those in air, in agreement with other research results indicating that crack velocity increases in water. When we compared our results for NaOHaq with those for water, however, we found that the crack velocity at the same stress intensity factor did not change even though the pH of the surrounding environment was different. This result does not agree with the accepted understanding that hydroxide ions accelerate subcritical crack growth in rocks. We concluded that the pH at the crack tip influences subcritical crack growth, and not the bulk pH, which has little effect.

Key words: aqueous environment, double-torsion test, rock, subcritical crack growth, temperature.

Introduction
Understanding the time-dependent fracturing behaviour of rock is essential to ensure the long-term stability of structures in a rock mass such as underground power plants or caverns for storing liquefied petroleum or natural gas. Cracks have been postulated to propagate dynamically when the stress intensity factor reaches the fracture toughness in classical fracture mechanics. However, a crack can propagate slowly even when the stress intensity factor is less than the fracture toughness. This phenomenon, called subcritical crack growth (Atkinson, 1984), is one of the main causes of time-dependent change in rocks. Because subcritical crack growth appears to be affected by the surrounding environment (Anderson and Grew, 1977), it is important to investigate the effects of environmental conditions.

The crack velocity in rocks, which clearly increases when the atmospheric water vapour pressure is high (Nara and Kaneko, 2005, 2006), is anisotropic due to the preferred orientation of pre-existing microcracks in granite (Nara and Kaneko, 2006; Nara et al., 2006). Based on the concept of subcritical crack growth, Jeong et al. (2007) reported that the strength of rock decreased when the water vapour pressure of the surrounding environment was high. In actual environments of rock engineering or underground excavation, the rock is often wet. Therefore, it is essential to investigate the subcritical crack growth in rocks in aqueous environments to have a better understanding of the time-dependent fracturing behaviour of rock.

In the present study, we investigated subcritical crack growth in rocks in an aqueous environment using distilled water (pH = 5–7) and NaOHaq (pH = 12). We focused on the effects of temperature, water, and pH on subcritical crack growth in andesite and granite.

Crack velocity for subcritical crack growth
The subcritical crack growth in silicate materials appears to be controlled by the chemical reaction between the siloxane bond and a corrosive agent at the crack tip under tension (Anderson and Grew, 1977; Atkinson, 1984). This reaction is called stress corrosion, and the corrosive agents that have been studied include water (Michalske and Freiman, 1982) and the hydroxide ion (Charles, 1958).

The crack velocity da/dt can be related to the stress intensity factor Ki by the following empirical equation (Wiederhorn and Bolz, 1970; Freiman, 1984):

\[
\frac{da}{dt} = v_0 a^b \exp \left( \frac{-E_a + \beta K_i}{RT} \right),
\]

where \( a \) is the activity of the corrosive agent, \( E_a \) is the stress-free activation energy, \( R \) is the gas constant, \( T \) is the absolute temperature and \( v_0 \) and \( \beta \) are constants (Freiman, 1984).

Methodology
Experimental method
In the current study, we used the double-torsion (DT) load-relaxation test (Williams and Evans, 1973; Sano and Kudo, 1992). Figure 1 shows a schematic illustration of the specimen and the loading configuration. As shown in this figure, the specimen is a rectangular plate that often includes a guide groove to control the path of the crack propagation in the central part of the specimen. In Figure 1, four thick arrows show the loading forces, which are applied at the end of the specimen. Because the stress intensity factor is independent of the crack length, the DT test is convenient for opaque materials such
as rocks in which the exact measurement of the crack length is difficult. For this reason, the DT test was used in this study.

For isotropic materials, the stress intensity factor and the crack velocity can be estimated by the following equations (Williams and Evans, 1973):

$$K_1 = \frac{Pw_m}{2d^3d_n},$$  \hspace{1cm} (2)

$$\frac{da}{dt} = -0.2 \times \frac{S_0P_0dP}{BP^2\frac{dP}{dt}},$$  \hspace{1cm} (3)

where $P$ is the applied load, $w_m$ is the moment arm, $v$ 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, $P_0$ is the initial value of the applied load, $S_0$ is the compliance of the specimen at the initial crack length $a_0$, $dP/dt$ is the load relaxation rate, and $G$ is the shear modulus.

For orthorhombic materials, assuming that the directions of the coordinate axes and loading are defined as shown in Figure 1, the stress intensity factor and the crack velocity can be estimated by the following equations (Sano and Kudo, 1992):

$$K_1 = \left(\frac{3P^2w_m^3a_{44}}{2d^3d_n(2s_{22}(s_{32}^2s_{22})^{1/2} + s_{32} + s_{44}/2)^{1/2}}\right)^{1/2},$$  \hspace{1cm} (4)

$$\frac{da}{dt} = -0.2 \times \frac{2s_{ij}P_0(dP/dt)/d^3}{3P^2s_{44}w_m^3},$$  \hspace{1cm} (5)

where $s_{ij}$ (i, j = 1–6) is the compliance constant of the material. If the loading direction is different from that shown in Figure 1, the subscripts of $s_{ij}$ in equations (4) and (5) must be switched.

For our experiments, the width ($W$) was 45 mm, the length ($L$) was 140–200 mm, the thickness ($d$) was 3 mm and the reduced thickness ($d_n$) was 2 mm. For a DT specimen, a guide groove is often cut in the specimen to make the crack propagate in the central part of the specimen as shown in Figure 1. Nara (2004) reported that crack propagation was not controlled by the guide groove if the width of the groove was less than the mean grain size of the rock. Therefore, the width of the guide groove in these experiments was 1 mm for granite, because the mean grain size of granite used in the present study was ~1 mm. The width of the guide groove for andesite was 2 mm, because the size of some phenocrysts was larger than 1 mm. The guide groove was set upward according to the method of Pletka et al. (1979) as shown in Figure 1.

**Rock samples**

The rock samples used for our DT tests were Kumamoto andesite and Oshima granite, quarrried in Japan.

We measured the P-wave velocities in three orthogonal directions using the ultrasonic transmission method. The P-wave velocities of the Kumamoto andesite were 4.80, 4.80, and 4.83 km/s. Therefore, this rock was considered isotropic, and we used equations (2) and (3) to estimate its stress intensity factor and crack velocity.

Young’s Modulus and the Poisson’s Ratio were determined with a uniaxial compression test on cylindrical specimens using a strain rate of $10^{-6}$ s$^{-1}$. The diameter and length of the specimens were 35 mm and 70 mm, respectively. We determined the uniaxial strength to be 151 MPa. Young’s Modulus and the Poisson’s Ratio determined from the tangential line of the stress–strain curve at the 50% uniaxial strength point were 31.9 GPa and 0.27, respectively. Therefore, the shear modulus was 12.6 GPa.

Granite, however, has been described as being anisotropic, and Sano et al. (1992) and Peacock et al. (1994) both reported that Oshima granite exhibited P-wave velocity anisotropy. Additionally, Sano et al. (1992) stated that the granite had orthorhombic elasticity due to the preferred orientation of pre-existing microcracks. For this study, we measured the P-wave velocities of Oshima granite in three orthogonal directions, and the results of 4.91, 4.61, and 4.51 km/s confirmed that Oshima granite is indeed anisotropic. We defined the orthogonal directions we used as axis-1, axis-2, and axis-3 in the order of the measured P-wave velocities. The planes normal to these three axes are plane-1, plane-2, and plane-3, and are consistent with the Hardway, Grain, and Rift planes, respectively (Kudo et al., 1987).

In the preparation of our DT granite specimens, it was necessary to consider the crack opening direction and crack propagation direction, because of the orthorhombic elasticity generally observed in granite. Figure 2 shows the possible orientation of our granite specimens. In the current study we used the 32-specimen, in which the crack propagates parallel to axis-3 and opens parallel to axis-2.

We used equations (4) and (5) to estimate the stress intensity factor and the crack velocity in granite. The values of the compliance constants $s_{ij}$ were determined by Nara and Kaneko (2006). Parameters $s_{22}$, $s_{33}$, $s_{44}$ and $s_{12}$ in equations (4) and (5) were 18.9, 19.7, 46.0, and $-3.28 \times 10^{-12}$ Pa$^{-1}$, respectively.

We kept our rock specimens in distilled water or NaOHaq for more than 2 weeks before conducting our DT tests.

**Experimental apparatus**

Figures 3a and 3b show the DT testing apparatus used for our experiments with water and NaOHaq, respectively. The apparatus was located in a room in which the temperature and the relative humidity could be controlled in the ranges 278–353 K and 40–90%, respectively. The apparatus was the same as that used by Nara and Kaneko (2005) except for the stainless steel tank in Figure 3a and the stainless steel plate at the bottom of the polymethyl methacrylate tank in Figure 3b. In all experiments, the
Subcritical crack growth in rocks

First, we performed specimen precracking with the apparatus used by Nara and Kaneko (2005), because it was possible to observe the crack introduced by this procedure with a digital microscope mounted under the DT specimen as shown in Figure 4. We used the technique described by Pletka et al. (1979). The load was applied slowly to the specimen, occasionally adjusting the displacement of the loading points, while observing the crack introduced in this procedure. We rapidly decreased the load when we recognised that the crack length reached 25 mm, to satisfy the condition shown by Trantina (1977). According to Trantina (1977), $K_I$ is independent of the crack length when the crack length satisfies the condition:

$$0.55W < a < L - 0.65.$$  \hspace{1cm} (6)

Because the width $W$ in this study is 45 mm, the above condition is satisfied when the crack length exceeds 25 mm.

After precracking, we held the temperature of the testing room constant. The rock specimens were exposed to the testing environment for 20 h before we conducted the DT load-relaxation tests.

We conducted our DT tests under the same loading conditions for each rock type. First, we slowly applied a preload of 12–15 N, which corresponded to 15–25% of the maximum load. Then we applied a large displacement rapidly to the loading points of the specimen and held it constant throughout the measurement. This large displacement was 0.27 mm for Kumamoto andesite and 0.24 mm for Oshima granite, as specified by Nara and Kaneko (2005, 2006). In the DT load-relaxation test, the temporal change of the applied load is measured to evaluate the crack velocity and the stress intensity factor. The temporal changes of the applied load obtained by the above procedure are shown in Figure 5. Although the data of 0–300 s is shown in this figure, each DT load-relaxation test was carried out for 1.5–2 h.

### Results

Before actually testing rocks, we conducted DT tests on soda-lime glass in distilled water to investigate the reproducibility of the results. Figure 6 shows the relationship between the stress intensity factor and the crack velocity ($K_I$–$da/dt$ relationship) for soda-lime glass. Open and solid symbols indicate the $K_I$–$da/dt$ relationships obtained from the apparatus shown in Figures 3a and 3b, respectively. The mean value of the measured bulk pH was 6. Figure 6 shows that the reproducibility of the results was high. Additionally, the $K_I$–$da/dt$ relationships agreed closely with each other even when the testing apparatus was different. Therefore, we concluded that the DT test setups worked well, and that the experimental procedure in this study was appropriate.

After the preliminary tests on soda-lime glass, we performed the DT tests on rock. To investigate the effect of the temperature, we conducted these tests in distilled water at different temperatures for Kumamoto andesite. The mean value of the measured bulk pH was 5 for high temperature (328 K) DT tests and 7 for low temperature (285 K) tests. Figure 7 shows the $K_I$–$da/dt$ relationships for Kumamoto andesite, and illustrates that the crack velocity at the same stress intensity factor is higher when the temperature is higher. The same tendency was observed for Inada granite and Shirahama sandstone by Kodama et al. (2003). Thus, the temperature appears to affect the subcritical crack growth of rock in water.

Figure 8 shows the $K_I$–$da/dt$ relationships in water to compare the results in air for Kumamoto andesite reported by Nara and Kaneko (2005); the crack velocity at the same stress intensity factor is clearly much higher in water. The same tendency exists for Oshima granite as shown in Figure 9. Water undoubtedly has a strong effect on the subcritical crack growth in rocks.

To investigate the effect of the pH in an aqueous environment, we measured the crack velocity and the stress intensity factor in
NaOHaq. The mean value of the measured bulk pH was 12. The $K_I$-da/dt relationships in NaOHaq for Kumamoto andesite and Oshima granite are shown in Figures 10 and 11, respectively. These figures also indicate the $K_I$-da/dt relationships in distilled water for the sake of comparison. Distinct differences cannot be observed in the $K_I$-da/dt relationships even for the different values of bulk pH. This result does not agree with the accepted understanding that hydroxide ions accelerate subcritical crack growth in silicate materials (Atkinson and Meredith, 1981). No accounts of this tendency have been reported in rocks.

Tables 1 and 2 show the results obtained by applying equation (1) to the experimental data for Kumamoto andesite and Oshima granite, respectively. In these tables, $\alpha$ can be expressed by the following equation, which was obtained by rearranging equation (1):

$$\ln \left( \frac{da}{dt} \right) = \alpha + \frac{B}{RT} K_I$$

where $\alpha = \ln v_0 + \ln a_c - \frac{E_a}{RT}$.

The value of $\alpha$ corresponds to the crack velocity at $K_I=0$. The experimental scattering of this value is large. The stress intensity factor at $da/dt=10^{-5}$ [m/s], $K_I(10^{-5})$, is listed in Tables 1 and 2 to provide a quantitative comparison of the stress intensity factor because the range of the crack velocity was $10^{-2}$–$10^{-8}$ m/s. Because the range of the stress intensity factor for Kumamoto andesite was $0.8$–$1.4$ MN/m$^{3/2}$, the crack velocity at $K_I=1.1$ [MN/m$^{3/2}$], $da/dt(1.1)$, was listed in Table 1 to provide a quantitative comparison of the crack velocity. In the same way, $da/dt(1.45)$ is listed in Table 2 to provide a quantitative comparison because the range of the stress intensity factor for Oshima granite was $1.2$–$1.7$ MN/m$^{3/2}$. The numbers given in these tables are the mean values and standard deviations of three specimens. The logarithmic average and standard deviation are provided for the crack velocity in Tables 1 and 2.
As shown in Table 1, $K_I(10^{-5}/C_0^{5})$ clearly decreased and $d\alpha/dt$ increased when the temperature was high. This indicates that the thermal activation process controls subcritical crack growth in rock in water. The values of the stress intensity factor and the crack velocity are recognised to be similar even though the bulk pH is different. It appears that the bulk pH has little effect on subcritical crack growth in rocks within the range of pH in this study.

The differences in the values of $\beta$ between Tables 1 and 2 are small. We considered $\beta$ to be a material constant.

**Discussion**

Some research has been conducted on the effect of water on subcritical crack growth in rocks. For example, Waza et al. (1980) reported that the crack velocities for andesite and basalt in water were higher than those in air when tested with the DT constant load test (Kies and Clark, 1969). Although our experimental method was different, we observed the same tendency. These results are consistent with the observation that the subcritical crack growth in rocks is controlled by stress corrosion, and water is likely to be the corrosive agent (Atkinson, 1984).

Sano and Kudo (1992) investigated the $K_I$–$d\alpha/dt$ relationship in NaOHaq (pH = 11) for Oshima granite and reported that the crack velocity in NaOHaq was higher than that in distilled water by 1 or 2 orders of magnitude. Those results are shown in Figure 12, which was drawn by authors using the data of Sano.
and Kudo (1992), and do not agree with the results of our study. We must thus consider the possible reasons for the difference between our results and those of Sano and Kudo (1992).

In general, experimental results are subject to scattering due to the experimental apparatus and procedure, among other possible causes, which can be avoided by taking care to use the appropriate equipment and test procedures. We demonstrated that the reproducibility of our results for glass was quite high, as shown in Figure 6, indicating that our experimental apparatus was reliable and the procedure was appropriate.

The other source of result scattering is the heterogeneity of rock. In Oshima granite, the crack velocity data obtained using the DT test had some scattering even though the crack propagation direction and the crack opening direction were the same with each specimen. It thus seems wise to use multiple specimens when multiple specimens and considered the scattering of the data, the results in this study are most likely more reliable.

Based on our findings, we concluded that bulk pH has little effect on the crack growth in rock, which is consistent with the observations for soda-lime glass by Wiederhorn and Johnson (1973). Wiederhorn (1972) showed that the pH of a slurry made with water and finely ground soda-lime glass was around 12, even though the pH of water was neutral. From other studies of glass, Wiederhorn (1978) suggested that the pH of the crack tip solution is highly dependent on the chemistry of the solid phase. The basic solution at the crack tip is formed with glass containing alkali through the following ion-exchange reaction:

\[
\text{Na}^+ \text{(glass)} + \text{H}_2\text{O} \rightleftharpoons \text{H}^+ \text{(glass)} + \text{Na}^+\text{OH}^-.
\]  

Charles (1958) proposed the following chemical reaction between the hydroxide ion and a silicon-oxygen network to explain the effect of pH on the crack growth rate as:

\[
\equiv\text{Si-O-Si} + \text{OH}^- \rightarrow \equiv\text{Si-O}^- + \equiv\text{Si-OH}.
\]  

Assuming that the state of the solution at the crack tip was equal to the ground glass-water slurries, Wiederhorn and Johnson (1973) reported that the pH at the crack tip of soda-lime glass could be ~12, even though the surrounding environment was water, and they concluded that the pH at the crack tip, rather than the bulk pH, influenced the strain rate relationship.

However, the bulk pH does affect subcritical crack growth in silica glass (Wiederhorn and Johnson, 1973) and synthetic quartz (Atkinson and Meredith, 1981) when the crack velocities are low. The crack velocity increased when the bulk pH was higher in both cases. The reasoning is as follows. Using direct measurements, the pH of slurries of silica glass was 4–5 for silica glass (Wiederhorn, 1972) and 6.5 for quartz (Atkinson and Meredith, 1981), based on the pH measurement of deionized water passing through a column of ground quartz. In both cases, the amount of the ground solid was much higher than that of water. If these are consistent with the pH of the crack tip solutions, the differences in the pH are large when the surrounding environment is a basic solution such as NaOHaq. Diffusion of hydroxide ions from the bulk solution to the crack tip can occur in these cases, and the pH of the crack tip solutions could approach the bulk pH value when the crack velocity is low. Therefore, subcritical crack

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**Table 1. Summary of the results for Kumamoto andesite.**

<table>
<thead>
<tr>
<th>Condition</th>
<th>( \alpha ) ( (\text{m}^{5/2}/\text{mol}) )</th>
<th>( \beta ) ( (\text{MN/m}^{3/2}) )</th>
<th>( K_I ) ( (10^{-3}) ) ( (\text{MN/m}^{3/2}) )</th>
<th>( \text{da}/\text{dt} ) ( (1.1) ) ( (\text{m/s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>In distilled water 328 K, pH = 5</td>
<td>-43.9 ± 2.2</td>
<td>0.082 ± 0.008</td>
<td>1.08 ± 0.05</td>
<td>2.51 \times 10^{-3} (s.d.: 3.63 \times 10^{-6} in log)</td>
</tr>
<tr>
<td>In distilled water 285 K, pH = 7</td>
<td>-52.5 ± 2.3</td>
<td>0.083 ± 0.006</td>
<td>1.16 ± 0.03</td>
<td>1.07 \times 10^{-6} (s.d.: 2.45 \times 10^{-6} in log)</td>
</tr>
<tr>
<td>In NaOHaq 284 K, pH = 12</td>
<td>-45.0 ± 1.4</td>
<td>0.069 ± 0.002</td>
<td>1.14 ± 0.04</td>
<td>2.34 \times 10^{-6} (s.d.: 2.75 \times 10^{-6} in log)</td>
</tr>
</tbody>
</table>

**Table 2. Summary of the results for Oshima granite.**

<table>
<thead>
<tr>
<th>Condition</th>
<th>( \alpha ) ( (\text{m}^{5/2}/\text{mol}) )</th>
<th>( \beta ) ( (\text{MN/m}^{3/2}) )</th>
<th>( K_I ) ( (10^{-3}) ) ( (\text{MN/m}^{3/2}) )</th>
<th>( \text{da}/\text{dt} ) ( (1.45) ) ( (\text{m/s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>In distilled water 284 K, pH = 6</td>
<td>-58.4 ± 10.8</td>
<td>0.076 ± 0.016</td>
<td>1.46 ± 0.05</td>
<td>5.37 \times 10^{-6} (s.d.: 4.57 \times 10^{-6} in log)</td>
</tr>
<tr>
<td>In NaOHaq 284 K, pH = 12</td>
<td>-55.8 ± 8.4</td>
<td>0.072 ± 0.015</td>
<td>1.45 ± 0.07</td>
<td>9.27 \times 10^{-6} (s.d.: 9.77 \times 10^{-6} in log)</td>
</tr>
</tbody>
</table>
growth in silica glass and synthetic quartz is affected by the bulk pH.

In the present study, the pH of distilled water that included the powders of andesite or granite was measured. At first, rock was ground into powders less than 50 μm and mixed into distilled water. The distilled water with the rock powders was kept for 2 days at the temperature of 284 K, and then the pH was measured. The results of the pH measurements for distilled water with ground Kumamoto andesite and Oshima granite (less than 50 μm) are shown in Figure 14, along with the amounts of the ground rock and distilled water. This illustrates that the pH increased and converged to 7–8 for Kumamoto andesite and to 8–9 for Oshima granite, although the initial values of the pH were 5–6 in both cases. These pH increases might show that the pH at the crack tip in rock can also be greater than the pH of the bulk solution. Namely, Figure 14 indicates that the pH at the crack tip in these rocks can increase, even if the bulk environment is water. Because the surface area of the crack in rock is large and the amount of the crack tip solution is small, the actual ratio of the surface area to the crack tip solution should be much larger than those shown in Figure 14. Therefore, the pH of the crack tip solution can be higher than those shown in Figure 14. Therefore, the bulk pH might have little effect on subcritical crack growth in rock.

**Conclusion**

We investigated the subcritical crack growth in rocks in distilled water (pH = 5–7) and in NaOH solution (pH = 12) using the DT test. From measurements in distilled water, we showed that the crack velocity was higher when the temperature was higher, and much higher in water than in air. We demonstrated that the difference in the crack velocity and stress intensity factor were not significant even though the bulk pH changed. We concluded that the pH at the crack tip influences subcritical crack growth, and not the bulk pH, which has little effect.

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水溶液環境下における岩石のサブクリティカルき裂進展

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要旨：低速で起こるき裂進展現象であるサブクリティカルき裂進展は、岩石の時間依存性の破壊挙動の重要な要素プロセスである。本研究では、岩石のサブクリティカルき裂進展測定を、蒸留水中（pH=5–7）および水酸化ナトリウム水溶液中（pH=12）で行い、き裂進展に及ぼすpHの影響を調べた。さらに、水溶液環境下で得られた結果と大気中で得られた結果の比較を行った。岩石試料として、安山岩と花崗岩を用いた。試験法としてダブルトーション試験を用い、き裂進展速度と応力拡大係数の関係を求めた。また、全ての試験は、周辺環境の温度を制御した条件下を行った。試験により、水中におけるき裂進展速度は、大気中でのものよりも大きくなった。これは、他の研究における結果と一致する傾向である。一方、水酸化ナトリウム水溶液中で得られた結果を蒸留水中で得られた結果と比較したところ、周辺環境のpHが異なるにも係わらず、き裂進展速度に明確な変化は認められなかった。この結果は、従来推奨されてきた、周辺環境中の水酸化物イオンが岩石のサブクリティカルき裂進展を促進するという考え方とは異なるものである。本研究の結果より、き裂先端近傍におけるpHが岩石のサブクリティカルき裂進展に影響し、周辺環境のpHが及ぼす影響は小さいものと考えられる。

キーワード：サブクリティカルき裂進展、ダブルトーション試験、岩石、温度、水溶液環境

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水質浄化における分裂形気浮による汙泥分解

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要約：分裂形気浮(subcritical crack growth)は分裂形気浮が観察される均質系が破壊するための主な原因であり、その重要性は明らかである。本研究では、分離用（pH = 5–7）と水酸化ナトリウム（NaOH）（pH = 12）水溶液中において分裂形気浮の発生、および分裂形気浮に関与する破壊性を検討した。アクリロール、アクリル酸を基本体とした、分裂形気浮の破壊性を示す影響を計測した。水中における分裂形気浮の破壊性は、大気中でのものよりも大きかった。これは、他の研究における結果と一致する傾向である。一方、水酸化ナトリウム水溶液中で得られた結果を蒸留水中で得られた結果と比較したところ、周辺環境のpHが異なるにも係わらず、分裂形気浮の速度に明確な変化は認められなかった。この結果は、従来推奨されてきた、周辺環境中の水酸化物イオンが岩石の分裂形気浮進展を促進するという考え方とは異なるものである。本研究の結果より、分裂先端近傍におけるpHが岩石の分裂形気浮進展に影響し、周辺環境のpHが及ぼす影響は小さいものと考えられる。

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