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Abstract

It is important to understand time-dependent deformation and fracturing in rock to evaluate its long-term strength (LTS); subcritical crack growth (SCG) provides insight into the weathering of a rock mass over the long term. The LTS of rock is commonly evaluated under the same environmental conditions. However, in practice, the environment is constantly changing and must be accounted for in evaluating the LTS of rock. In this study, we developed a method to evaluate LTS under changing environmental conditions, with a focus on the influence of water on the LTS of rock. LTS decreased rapidly when the environmental conditions changed from air to water. In a case where the environmental conditions changed repeatedly from air to water at various duration intervals, the value of the LTS was similar to that in a continuous water environment. Because a dramatic decrease in the LTS occurred when the environmental conditions changed from air to water, we conclude that the effect of water on the acceleration of SCG in rock should be considered in the long-term use of rock structures.

Keywords long-term strength; rock; subcritical crack growth; time-to-failure; water

Taxonomy Materials Property, Materials Science Engineering, Materials Characterization

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Evaluating long-term strength of rock under changing environments from air to water

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Summary

It is important to understand time-dependent deformation and fracturing in rock to evaluate its long-term strength (LTS); subcritical crack growth (SCG) provides insight into the weathering of a rock mass over the long term. The LTS of rock is commonly evaluated under the same environmental conditions. However, in practice, the environment is constantly changing and must be accounted for in evaluating the LTS of rock. In this study, we developed a method to evaluate LTS under changing environmental conditions, with a focus on the influence of water on the LTS of rock. LTS decreased rapidly when the environmental conditions changed from air to water. In a case where the environmental conditions changed repeatedly from air to water at various duration intervals, the value of the LTS was similar to that in a continuous water environment. Because a dramatic decrease in the LTS occurred when the environmental conditions changed from air to water, we conclude that the effect of water on the acceleration of SCG in rock should be considered in the long-term use of rock structures.

Key words: Long-term Strength, Rock, Subcritical crack growth, Time-to-failure, Water

1. Introduction

The design and construction of subsurface structures within a rock mass, such as repositories for radioactive waste, caverns to store liquefied natural gas or liquefied petroleum gas, or underground power plants, should account for the long-term stability of the rock mass surrounding these structures. For this purpose, it is necessary to understand time-dependent fracturing in rock and its influence on the strength (Jeong et al., 2007; Li & Konietzky, 2014). Additionally, time-dependent fracturing has been invoked as an important mechanism responsible for the increase in seismicity preceding earthquake ruptures and volcanic eruptions (Main & Meredith 1991; Kilburn & Voight 1998; Heap et al. 2011; Brantut et al., 2013). Thus, a study of time-dependent fracturing is important to both engineering design and natural hazard risk mitigation.

Evaluating the long-term strength (LTS) of rock is important in ensuring the long-term stability of a rock mass, considering the design and construction of various structures within it. It is possible to evaluate the LTS of rocks based on subcritical crack growth (SCG), which is a major cause of time-dependent fracturing (Anderson & Grew, 1977; Atkinson, 1984; Atkinson & Meredith, 1987). Nara et al. (2010a) showed how to evaluate LTS based on SCG information. Nara et al. (2013) reported that the LTS of rock was affected by the surrounding environment; specifically, they reported that the LTS of rock in water was much lower than in air.

The LTS of rock has been evaluated under constant environmental conditions in previous works; however, in practice, the environmental conditions in nature are constantly evolving from wet to dry and vice-versa, meaning that experiments in which the conditions are maintained "dry" or "wet" do not necessarily represent the natural case. Thus, there is a need to consider changes in environmental conditions when evaluating the LTS of rock. In particular, water significantly affects the increase of the crack velocity (e.g., Waza et al., 1980; Meredith & Atkinson, 1983; Lajtai & Bielus, 1986; Nara et al., 2009), the fracture toughness (e.g., Lajtai et al., 1987; Wilkins, 1987), and the strength (e.g., Baud et al., 2000; Masuda, 2001; Okubo et al., 2010, 2013). It has been reported that the fracturing is accelerated if the temperature increases for igneous rocks (Kranz et al., 1982; Nara et al., 2010b) and sandstones in water (Heap et al., 2009a; Nara et al., 2011). On the other hand, Nara et al. (2011) showed that the temperature has few influences on fracturing in sandstone in air. Therefore, it is important to understand the influence of the change in the environment from air to water.

In this study, we developed a method to evaluate LTS under changing environmental conditions, in an attempt to clarify the influence of water on the LTS of rock and the long-term integrity of a rock mass surrounding various structures.

2. Method for evaluating LTS under changing environmental conditions

2.1 Method based on power law of SCG

The relationship between the crack velocity, da/dt, and the stress intensity factor, K_I, for SCG can be expressed empirically as follows (Charles, 1958):

$$\frac{\mathrm{d}a}{\mathrm{d}t} = AK_I^{\ n} , \tag{1}$$

where n is the SCG index (Atkinson, 1984), and A is an experimentally determined constant.

In a situation where a plate containing a single crack of length 2a is subjected to a uniform tensile stress σ, K_I is expressed as

$$K_I = \sigma(\pi a)^{1/2} . \tag{2}$$

Assuming that the value of the crack length diverges due to crack growth over x years and that the material fails at that time under a constant stress, LTS can be estimated from the following equation (Nara et al. 2010a):

$$S_t(x) = \left\{ \frac{1}{3.15\times10^7 x} \frac{2}{(n-2)\pi A} \right\}^{1/n} \left(\frac{K_{IC}}{S_t} \right)^{(2-n)/n} , \tag{3}$$

where K_{IC} is the fracture toughness, S_t is the tensile strength, and $S_t(x)$ is the long-term strength (LTS). We assume the following relationship between K_{IC} and S_t:

$$K_{IC} = S_t(\pi a_0)^{1/2} . \tag{4}$$

Here, we consider a situation where the environmental condition changes. We assume k is a natural number. In a time section k where $t_{k-1} \le t \le t_k$, assuming that no change in the environmental conditions occurs except at $t = t_{k-1}$ and t_k, then the following equation is obtained:

$$\frac{\mathrm{d}a}{\mathrm{d}\tau} = A_k {K_\mathrm{I}}^{n_k} , \quad (1')$$

where τ is the time ($\tau = t - t_{k-1}$), and A_k and n_k are determined according to the environmental condition in time section k. Using Eq. (2), the following equation can be obtained:

$$\frac{\mathrm{d}a}{\mathrm{d}\tau} = \pi^{n_k/2} A_k \sigma^{n_k} a^{n_k/2} \ . \quad (5)$$

The general solution of this equation is expressed as follows:

$$\frac{1}{1 - n_k/2} a^{1-n_k/2} = \pi^{n_k/2} A_k \sigma^{n_k} \tau + c_k \ , \quad (6)$$

where c_k is a constant of integration. The initial condition of this equation ($\tau = 0$) is as follows:

$$a = a(t_{k-1}) \ , \quad (7)$$

where $a(t_{k-1})$ corresponds to the crack length at $t = t_{k-1}$. From Eqs. (6) and (7), the following equation can be obtained:

$$a^{(2-n_k)/2} = \frac{2 - n_k}{2} \pi^{n_k/2} A_k \sigma^{n_k} \tau + (a(t_{k-1}))^{(2-n_k)/2} \quad (8)$$

Using the condition $\tau = t - t_{k-1}$, Eq. (8) can be rearranged as

$$t = t_{k-1} + \frac{2}{(n_k - 2)\pi^{n_k/2} A_k} \frac{(a(t_{k-1}))^{(2-n_k)/2}}{\sigma^{n_k}} \left\{ 1 - \left(\frac{a}{a(t_{k-1})} \right)^{(2-n_k)/2} \right\} . \quad (9)$$

From this equation, the time when the crack length diverges, $t_{k\infty}$, is expressed as

$$t_{k\infty} = t_{k-1} + \frac{2}{(n_k - 2)\pi^{n_k/2} A_k} \frac{(a(t_{k-1}))^{(2-n_k)/2}}{\sigma^{n_k}} . \quad (10)$$

Equations (8) and (9) show the relationship between crack length and time at $t = t_{k-1}$ when the environmental conditions change. In time section k, just after the environmental conditions change, two cases of crack propagation can be considered. In one, crack propagation accelerates and then the crack length diverges. In the other, the crack propagates in a stable manner, and the crack length does not diverge. In the former case, if $t_{k\infty}$ is within time section k ($t_{k-1} \leq t_{k\infty} \leq t_k$), then the time-to-failure t_f is equal to $t_{k\infty}$. Assuming that the environmental condition changes at x_{k-1} years ($3.15 \times 10^7 \times x_{k-1}$ seconds) and that failure occurs in x years, the following equation can be obtained from Eq. (10):

$$x = x_{k-1} + \frac{1}{3.15\times10^7}\frac{2}{(n_k-2)\pi^{n_k/2}A_k}\frac{(a(x_{k-1}))^{(2-n_k)/2}}{(S_t(x))^{n_k}} \quad . \tag{11}$$

In the latter case, in which $x_k \leq x_{k\infty}$, the following equation can be obtained from Eq. (8):

$$a(x_k) = \left\{3.15\times10^7 \times \frac{2-n_k}{2}\pi^{n_k/2} \times A_k\sigma^{n_k}(x_k - x_{k-1}) + (a(x_{k-1}))^{(2-n_k)/2}\right\}^{2/(2-n_k)} \quad . \tag{12}$$

The calculation for the next time section is conducted using this crack length $a(x_k)$. LTS considering the change in environmental conditions can be estimated with Eqs. (11) or (12), according to the crack propagation condition.

2.2 Method based on exponential law of SCG

Wiederhorn & Bolz (1970) showed the relationship between the crack velocity, da/dt, and the stress intensity factor, K_I, for SCG empirically as follows:

$$\frac{\mathrm{d}a}{\mathrm{d}t} = v_0 \exp\left(\frac{-E^{\ddagger} + \beta K_I}{RT}\right), \tag{13}$$

where $E^{\ddagger}$ is the stress-free activation energy, R is the gas constant, T is the absolute temperature, and v_0 and β are constants, determined experimentally. Equation (13) can be rewritten as follows:

$$\left.\begin{aligned} \ln\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right) &= \alpha + \frac{\beta}{RT}K_{\mathrm{I}} \\ \alpha &= \ln v_0 - \frac{E^{\ddagger}}{RT} \end{aligned}\right\}. \tag{14}$$

As described in Section 2.1, we consider a situation where a plate containing a single crack of length $2a$ is subjected to a uniform tensile stress σ. Additionally, we assume that the value of the crack length diverges due to crack growth over x years and that the material fails at that time under a constant stress. In this case, LTS can be estimated with the following equation (Nara et al. 2013):

$$3.15\times 10^{7}x = \frac{2}{(\exp\alpha)\pi(\beta/RT)^2(S_{\mathrm{t}}(x))^2}\left(\frac{\beta}{RT}S(x)\frac{K_{\mathrm{IC}}}{S_{\mathrm{t}}}+1\right)\exp\left(-\frac{\beta}{RT}S_{\mathrm{t}}(x)\frac{K_{\mathrm{IC}}}{S_{\mathrm{t}}}\right). \tag{15}$$

As considered in Section 2.1, in a time section k where $t_{k-1} \le t \le t_k$, assuming that no change in the environmental conditions occurs except at $t = t_{k-1}$ and t_k, the following equation is obtained:

$$\left.\begin{aligned} &\frac{\mathrm{d}a}{\mathrm{d}\tau} = v_k \exp\left(\beta_k'\sqrt{a}\right) \qquad (\tau = t - t_{k-1}) \\ &v_k = \exp\alpha_k,\ \beta_k' = \frac{\beta_k}{RT}\sigma\sqrt{\pi} \end{aligned}\right\}, \tag{14′}$$

where α_k and β_k are decided according to the environmental conditions in time section k. The general solution of Eq. (14′) is expressed as follows:

$$-\frac{2}{\beta_k'^2}\left(\beta_k'\sqrt{a}+1\right)\exp\left(-\beta_k'\sqrt{a}\right) = v_k\tau + c_k, \tag{16}$$

where c_k is a constant of integration. The initial condition of this equation ($\tau = 0$) is as follows:

$$a = a(t_{k-1}) \tag{17}$$

where $a(t_{k-1})$ corresponds to the crack length at $t = t_{k-1}$. From Eqs. (16) and (17), the following equation can be obtained:

$$\frac{2}{\beta_k'^2}\left(\beta_k'\sqrt{a(t_{k-1})}+1\right)\exp\left(-\beta_k'\sqrt{a(t_{k-1})}\right)-\frac{2}{\beta_k'^2}\left(\beta_k'\sqrt{a}+1\right)\exp\left(-\beta_k'\sqrt{a}\right)=v_k\tau \tag{18}$$

Here, the first term on the left side is a constant. The second term on the left side converges to 0 if the crack length a diverges. From Eqs. (14′) and (18), the following equation can be obtained:

$$t_{k\infty} = t_{k-1} + \frac{2}{(\exp\alpha_k)\pi(\beta_k/RT)^2\sigma^2}\left(\frac{\beta_k}{RT}\sigma\sqrt{\pi a(t_{k-1})}+1\right)\exp\left(-\frac{\beta_k}{RT}\sigma\sqrt{\pi a(t_{k-1})}\right) \tag{19}$$

where $t_{k\infty}$ is the time when the crack length diverges. In time section k, it is possible to consider two cases of crack propagation. In one, crack propagation accelerates and then the crack length diverges. In this case, if $t_{k\infty}$ is within time section k ($t_{k-1} \le t_{k\infty} \le t_k$), then the time-to-failure t_f is equal to $t_{k\infty}$. Assuming that the environmental conditions change at x_{k-1} years ($3.15 \times 10^7 \times x_{k-1}$ seconds) and that failure occurs in x years, the following equation is obtained from Eq. (19):

$$x = x_{k-1} + \frac{1}{3.15\times10^7}\frac{2}{(\exp\alpha_k)\pi(\beta_k/RT)^2(S(x))^2}\left(\frac{\beta_k}{RT}S(x)\sqrt{\pi a(x_{k-1})}+1\right)\exp\left(-\frac{\beta_k}{RT}S(x)\sqrt{\pi a(x_{k-1})}\right) \tag{20}$$

In the other case, the crack propagates in a stable manner and the crack length does not diverge. In this case, in which $x_k \leq x_{k\infty}$, the following equation can be obtained from Eq. (18):

$$\frac{1}{3.15\times10^7}\frac{2}{(\exp\alpha_k)\pi(\beta_k/RT)^2\sigma^2}\left\{\begin{aligned}&\left(\frac{\beta_k}{RT}\sigma\sqrt{\pi a(x_{k-1})}+1\right)\exp\left(-\frac{\beta_k}{RT}\sigma\sqrt{\pi a(x_{k-1})}\right)\\&-\left(\frac{\beta_k}{RT}\sigma\sqrt{\pi a(x_k)}+1\right)\exp\left(-\frac{\beta_k}{RT}\sigma\sqrt{\pi a(x_k)}\right)\end{aligned}\right\}=x_k-x_{k-1} \tag{21}$$

Using this crack length $a(x_k)$, the calculation for the next time section is conducted. LTS considering changes in the environmental conditions can be estimated using Eq. (20) or (21), according to the crack propagation condition.

3. Rock samples

In this study, both igneous and sedimentary rocks were used. A gabbro obtained in Harare, Zimbabwe (Harare gabbro) was selected as an igneous rock sample. Berea sandstone was selected as a sedimentary rock sample. In Figure 1, photomicrographs of these rocks are shown, which were taken from thin sections at a thickness of 30 μm using a polarizing microscope.

The main rock-forming minerals in Harare gabbro are plagioclase, potash feldspar, pyroxene, and olivine. The mean grain size of Harare gabbro is 0.6 mm. The porosity obtained from the difference in weight between saturated and dry conditions was 0.65%. The P-wave velocities in the three orthogonal directions were 5.60, 5.55, and 5.50 km/s for a dry sample. In this study, we refer to these directions as axes-1, -2, and -3, respectively, in the order of P-wave velocity. We also refer to the planes normal to these three axes as planes-1, -2, and -3, respectively.

Berea sandstone consists primarily of quartz and includes small amounts of plagioclase and potash feldspar. Few clay minerals are included in this sandstone (Nara et al., 2011). The mean grainsize of Berea sandstone is 0.2 mm. The porosity obtained from the difference in weight between saturated and dry conditions was 20.4%. The P-wave velocities in three orthogonal directions for a dry sample were 2.33 km/s along axis-1, 2.33 km/s along axis-2, and 2.24 km/s along axis-3. Plane-3 in Berea sandstone corresponds to the bedding plane.

In Table 1, the values of the uniaxial compressive strength, Young's modulus, Poisson's ratio, Brazilian tensile strength, and the fracture toughness are summarised. These values have been obtained from dry samples. The uniaxial compressive strength, Young's modulus and Poisson's ratio were measured by the uniaxial compression test using three cylindrical specimen with 30 mm diameter and 60 mm length. Brazilian tensile strength was obtained using three cylindrical specimen with 30 mm diameter and 20 mm length. The strain rate of the uniaxial compression test and Brazilian tension test was both 10^{-5} s^{-1}. The fracture toughness was obtained with the constant displacement rate method of the double torsion test with a displacement rate at 0.23 mm/s, following the method reported by Nara et al. (2012).

In Figure 2, the relationships between the crack velocity and the stress intensity factor for SCG in Harare gabbro and Berea sandstone are shown, in air and in distilled water. The results in Figure 2 were obtained using the load-relaxation method of the double torsion test (Williams & Evans, 1973). We used the same experimental apparatus as Nara & Kaneko (2005) in air and that of Nara et al. (2009) for water. The measurement of pH in water were conducted just before and after the measurement of SCG. The relationships between the crack velocity and the stress intensity factor for Berea sandstone have been shown previously in Nara et al. (2011).

It can be seen from Figure 2 that the crack velocity in water is much higher than that in air for both rocks. The values of pH differs between the gabbro and the sandstone in water. This will be due to the difference of mineral grains contained in these rocks, because we used only distilled water to achieve the water environment. In Table 2, a summary of SCG measurements is provided. Using these values, we can evaluate the LTS.

4. Results

Figures 3 and 4 show the relationships between the LTS and the time-to-failure for Harare gabbro and Berea sandstone, respectively. In these figures, (a) and (b) show the relationships obtained from the power law and the exponential law of SCG, respectively. The relationships obtained under constant environmental conditions (in air or in water) and under changing environmental conditions are shown in Figures 3 and 4. The relationships under changing environmental conditions were determined by considering that the rocks have been exposed to air for 1 year, 2 years, 5 years, 10 years, or 100 years, and then immersed in water. It can be seen that the LTS in water is higher than that in air for both rocks. Additionally, the LTS decreased rapidly when the environmental conditions changed from air to water.

Figures 5 and 6 show the relationship between the LTS and the time-to-failure for Harare gabbro and Berea sandstone, respectively, evaluated considering that the environmental conditions changed repeatedly from air to water at various duration intervals (1 year, 2 years, 5 years, 10 years, and 100 years). In these figures, (a) and (b) show the relationships obtained from the power law and the exponential law of SCG, respectively. It can be seen that the values for LTS under changing environmental conditions are similar to those under water.

5. Discussion

This study reveals the marked importance of the influence of a change in the environment from air to water on LTS reduction. The influence of the change in environment from air to water on the mechanical properties of rock has been investigated in different ways. For example, Dhakal et al. (2002) investigated the slake durability of sedimentary rocks, and showed that the size of the rock sample decreased as the number of wetting and drying cycle increases. Hua et al. (2015) reported the decrease in fracture toughness of sandstone during cyclic wetting and drying processes. These reports suggest the importance of water exposure on the weakening of rock.

The evaluation of LTS in this study was based on the relationship between the crack velocity and the stress intensity factor, as shown in Eqs. (1) (Charles, 1958) and (13) or (14) (Wiederhorn & Bolz, 1970). The relationship between the LTS and the time-to-failure for other materials in which the crack velocity in water is much higher than that in air should be similar to that for rock.

It can be seen that when the environmental conditions change from an air environment to a water environment, the values of the LTS of gabbro and sandstone converged to those evaluated considering a continuous water environment, even though the air condition had been maintained over a long time. Thus, the influence of water on the LTS is significant and the information on the LTS in water is important for constructing structures within a rock mass that are intended for long-term use.

A marked decrease in the LTS occurred when the environmental conditions changed from air to water; under these circumstances, the acceleration of SCG in rock has a significant influence. As also shown in this study (Figure 2), it has been reported that the crack velocity in water-immersed rock was much higher than that in air (Waza et al. 1980; Nara et al. 2009, 2011). According to several researchers, stress corrosion controls the crack velocity for SCG in silicate rocks (Anderson & Grew, 1977; Atkinson, 1982, 1984; Heap et al., 2009b). Nara et al. (2010b) reported that a large decrease in the suction at the crack tip occurred in water, which affected the increase in the crack velocity. The decrease of LTS in water was caused by the significant increase in the crack velocity.

Various researchers have reported experimentally the decrease of the strength of rocks in water. Here, we call the strength obtained by the laboratory measurement as "short-term strength (STS)". Baud et al. (2000) reported that the decrease of STS (the compressive strength) in water was observed for Berea sandstone and Darley Dale sandstone. According to the results of Berea sandstone, the decrease of STS from air to water ranged from 5 % (under 40 MPa confining pressure) to 11 % (under 10 MPa confining pressure). Masuda et al. (2001) reported the decrease of STS (the compressive strength) of igneous rocks (granite and andesite) from air to water under various confining pressure. According to their results, the decrease of STS ranged from 2 % (in granite under 200 MPa confining pressure) to 16 % (in granite under uniaxial compression). In the case of LTS at the time-to-failure of 10^5 years, the decreases were around 15 % and 40 % for Berea sandstone and Harare gabbro, respectively (see Figure 3). It is recognized that the decrease of LTS was more remarkable. As mentioned before, the evaluation of LTS is based on SCG, where the crack velocity increases by the effect of water. It is considered that the significant effect of SCG on LTS causes the marked decrease in the LTS.

Dry conditions should be maintained to ensure long-term stability of a rock mass. For example, if water migration into the rock can be prevented, a higher LTS will be achieved. However, if the rock is immersed in water, it is necessary to consider the LTS of rock in water in assessing the long-term use of the rock mass. Even if a dry condition is maintained, a rapid decrease in the LTS occurs readily and failure of the rock mass may occur soon after the rock is immersed in water.

6. Conclusions

In this report, we show a methodology to evaluate the LTS of solid materials under changing environmental conditions. In particular, considering SCG in gabbro and sandstone in air and water, we investigated the effects of water on the LTS of the rocks. It was shown that the LTS of rock decreased rapidly when the environmental conditions changed from air to water. Additionally, when the environmental conditions changed repeatedly from air to water, it was shown that the LTS was similar to that obtained in a continuous water environment. Thus, we conclude that the water environment has the most significant effect on LTS reduction in rock.

It is known that SCG in rock accelerates most under water environments. The marked decrease in the LTS in a water environment indicates a significant acceleration of crack propagation in the rock. To ensure the long-term stability of a rock mass surrounding various structures, it is essential to understand the effects of water in which the crack propagation is accelerated for LTS estimation in water.

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Figure legends

Figure 1. Photomicrographs of Harare gabbro under (a) open nicol and (b) crossed nicols and Berea sandstone under (c) open nicol and (d) crossed nicols.

Figure 2. Relationships between crack velocity and stress intensity factor for subcritical crack growth (SCG) in (a) Harare gabbro and (b) Berea sandstone.

Figure 3. Relationships between long-term strength (LTS) and time-to-failure for Harare gabbro when environmental conditions change from air to water, based on (a) a power law and (b) an exponential law of SCG.

Figure 4. Relationships between LTS and time-to-failure for Berea sandstone when environmental conditions change from air to water, based on (a) a power law and (b) an exponential law of SCG.

Figure 5. Relationships between LTS and time-to-failure for Harare gabbro when environmental conditions change repeatedly from air to water at various duration intervals, based on (a) a power law and (b) an exponential law of SCG.

Figure 6. Relationships between LTS and time-to-failure for Berea sandstone where environmental conditions change repeatedly from air to water at various duration intervals, based on (a) a power law and (b) an exponential law of SCG.

Tables

Table 1. Summary of uniaxial compressive strength, Young's modulus, Poisson's ratio, Brazilian tensile strength, and fracture toughness of Harare gabbro and Berea sandstone in dry condition.

	Harare gabbro	Berea sandstone
Uniaxial compressive strength [MPa]	395 ± 12	42.5 ± 2.5
Young's modulus [GPa]	95.3 ± 8.4	8.20 ± 0.81
Poisson's ratio	0.32 ± 0.00	0.25 ± 0.05
Brazilian tensile strength [MPa]	15.7 ± 0.7	2.80 ± 0.15
Fracture toughness [MN/$m^{3/2}$]	3.37 ± 0.13	0.33 ± 0.01

Table 2. Summary of subcritical crack growth measurement results for Harare gabbro and Berea sandstone.

	Temperature [K]	Condition	Humidity or pH	n	log A	β [$m^{5/2}$/mol]	α
Harare gabbro	323	air	50%	54±15	−28.1±6.0	0.0533±0.0150	−65.1±14.0
		water	pH = 7.5	39±12	−18.5±3.5	0.0471±0.0154	−50.9±11.4
Berea sandstone	290–293	air	54-56%	61±2	29.2±1.8	0.534±0.028	−71.9±2.3
		water	pH = 6	67±9	39.1±5.9	0.731±0.010	−78.0±9.7

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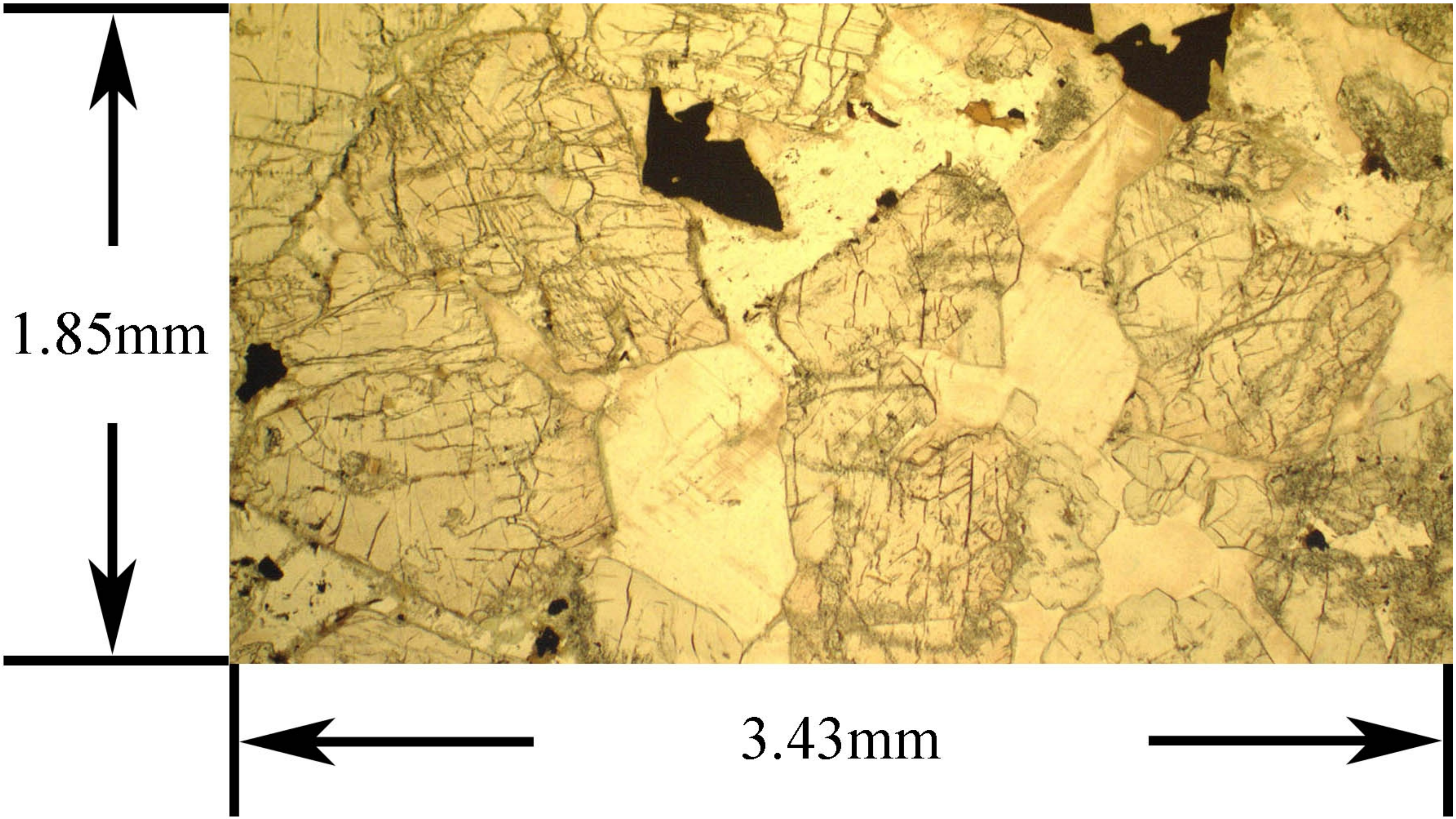
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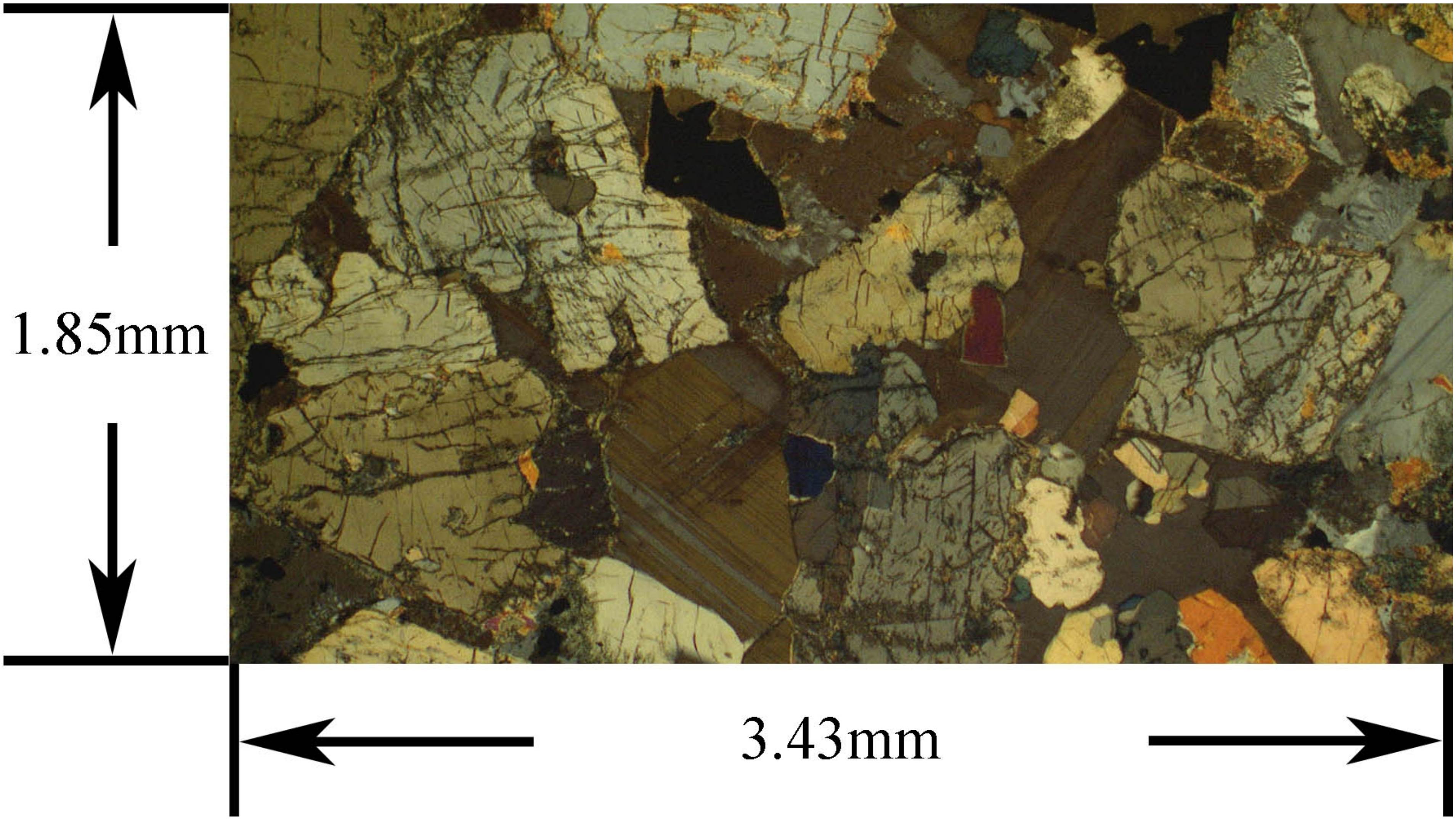
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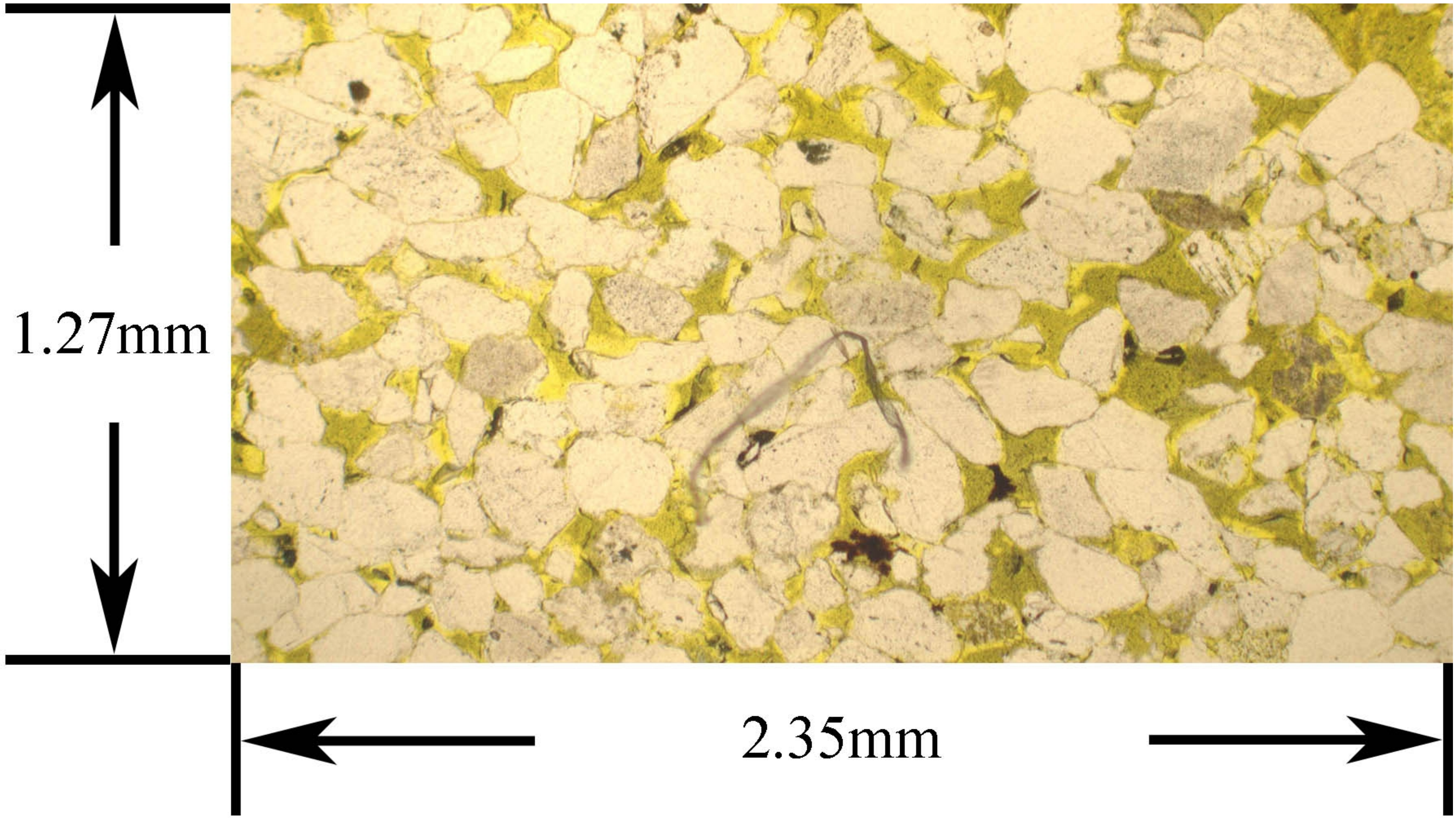
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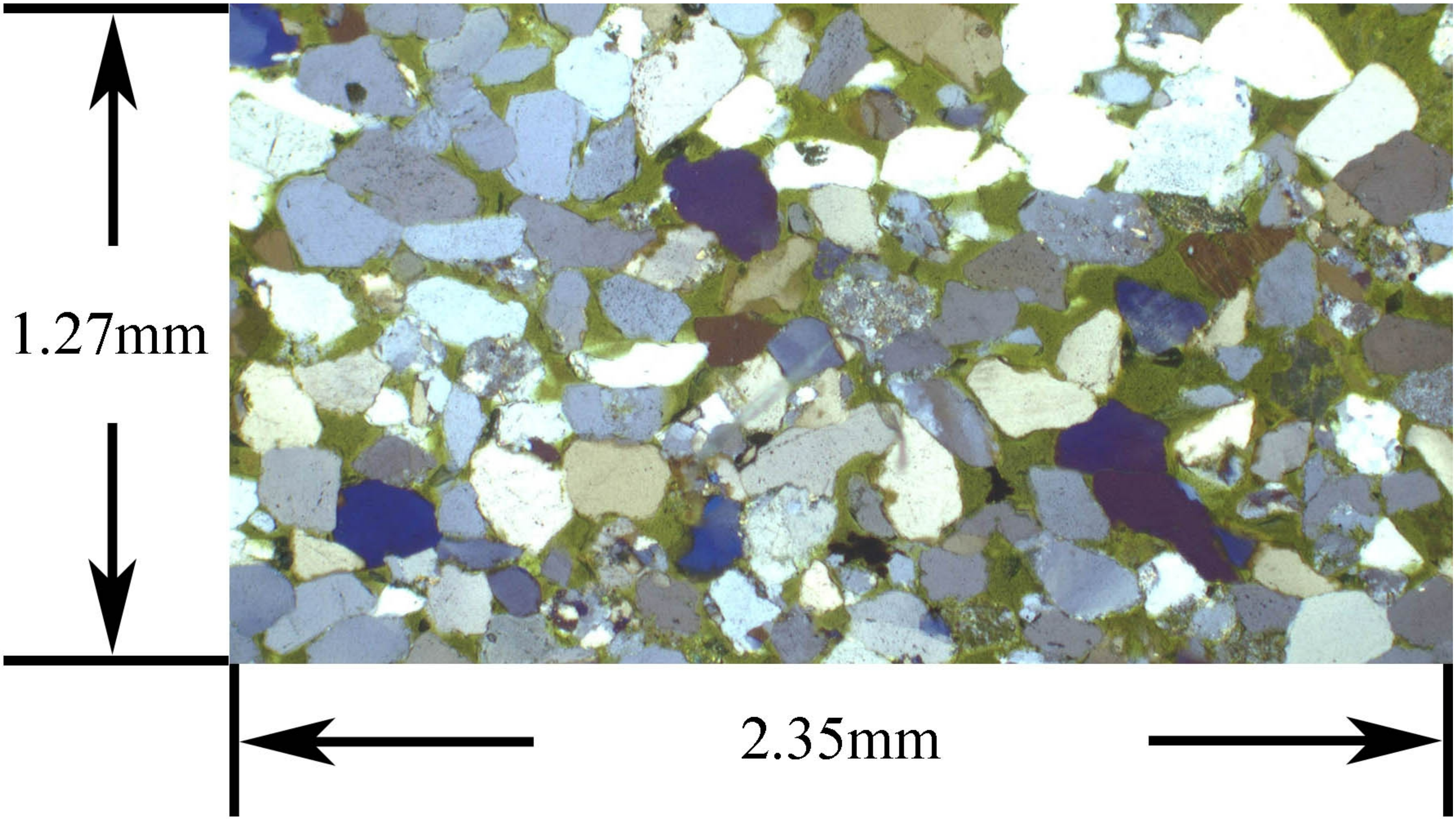
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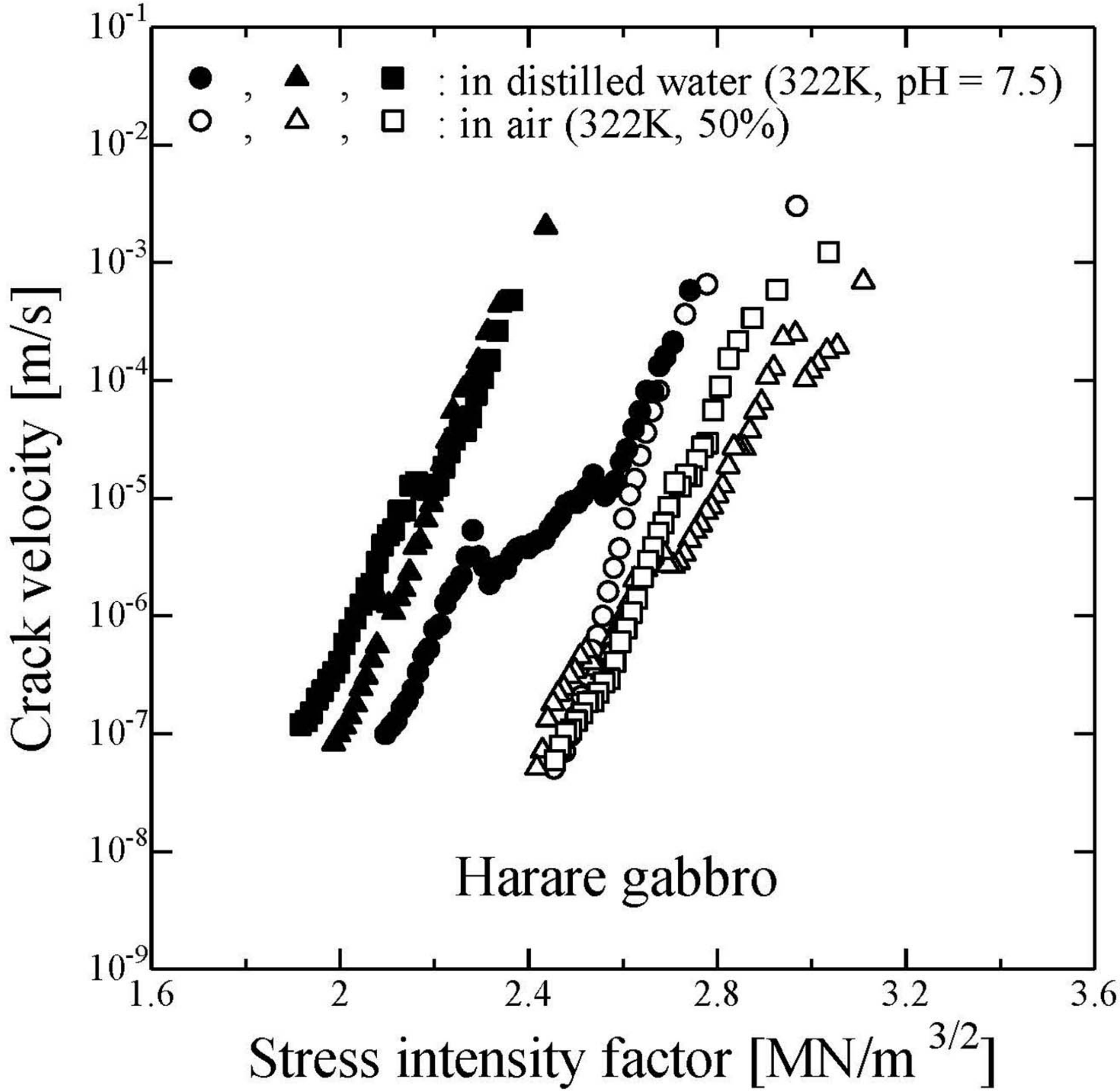
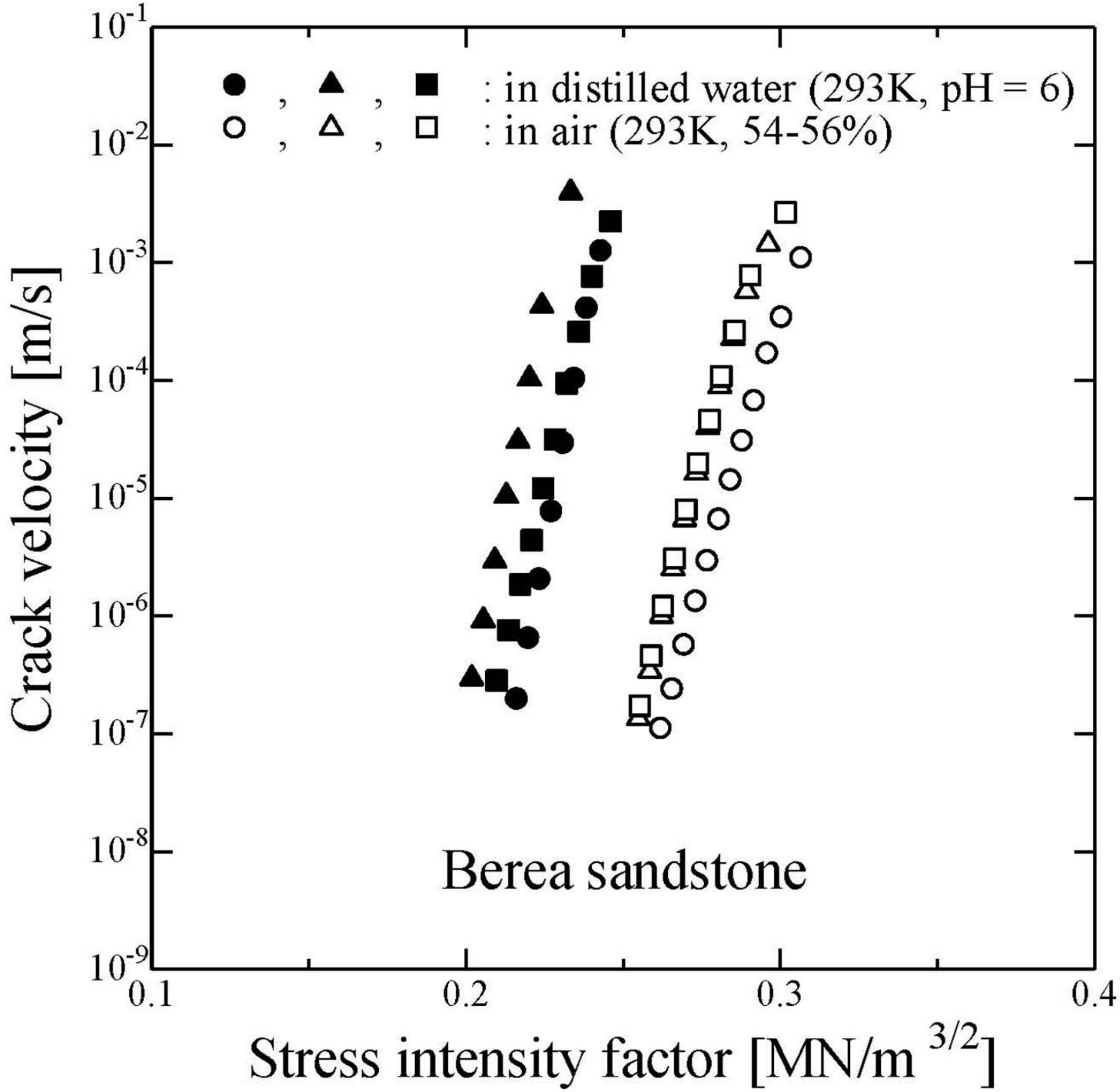
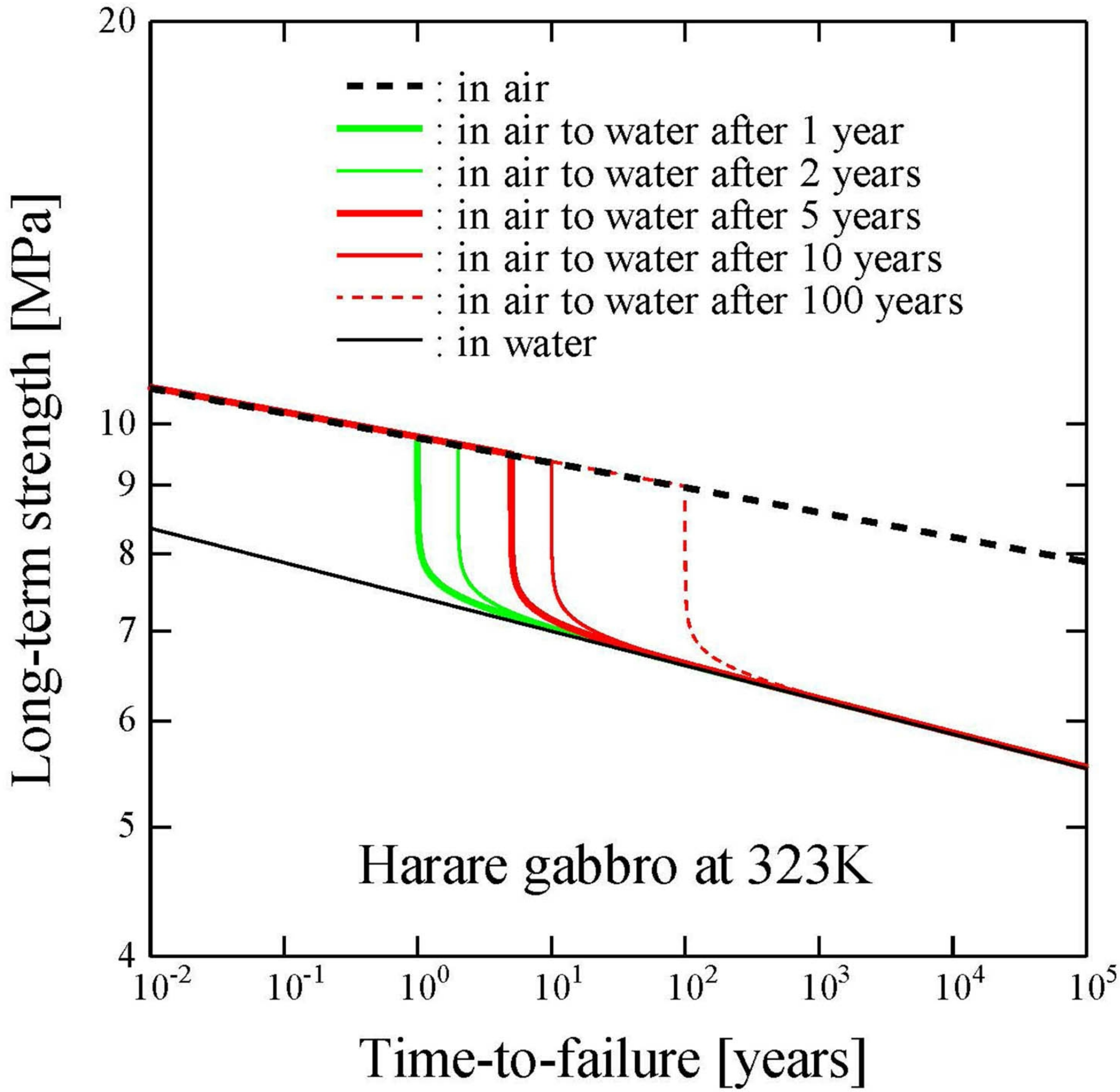


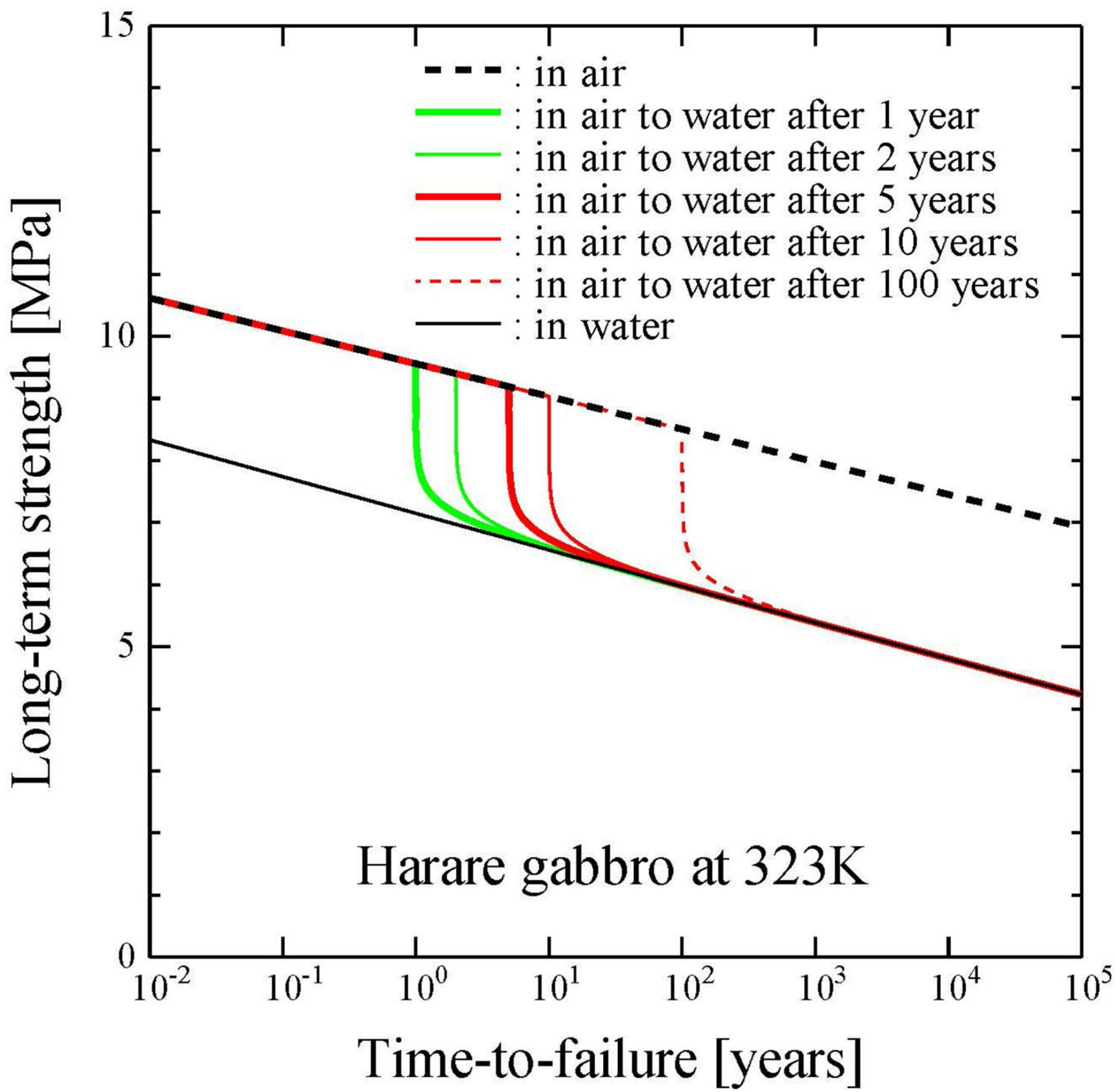
●, ▲, ■ : in distilled water (322K, pH = 7.5)
○, △, □ : in air (322K, 50%)
Harare gabbro
Crack velocity [m/s]
Stress intensity factor [MN/m 3/2]
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
1.6
2
2.4
2.8
3.2
3.6



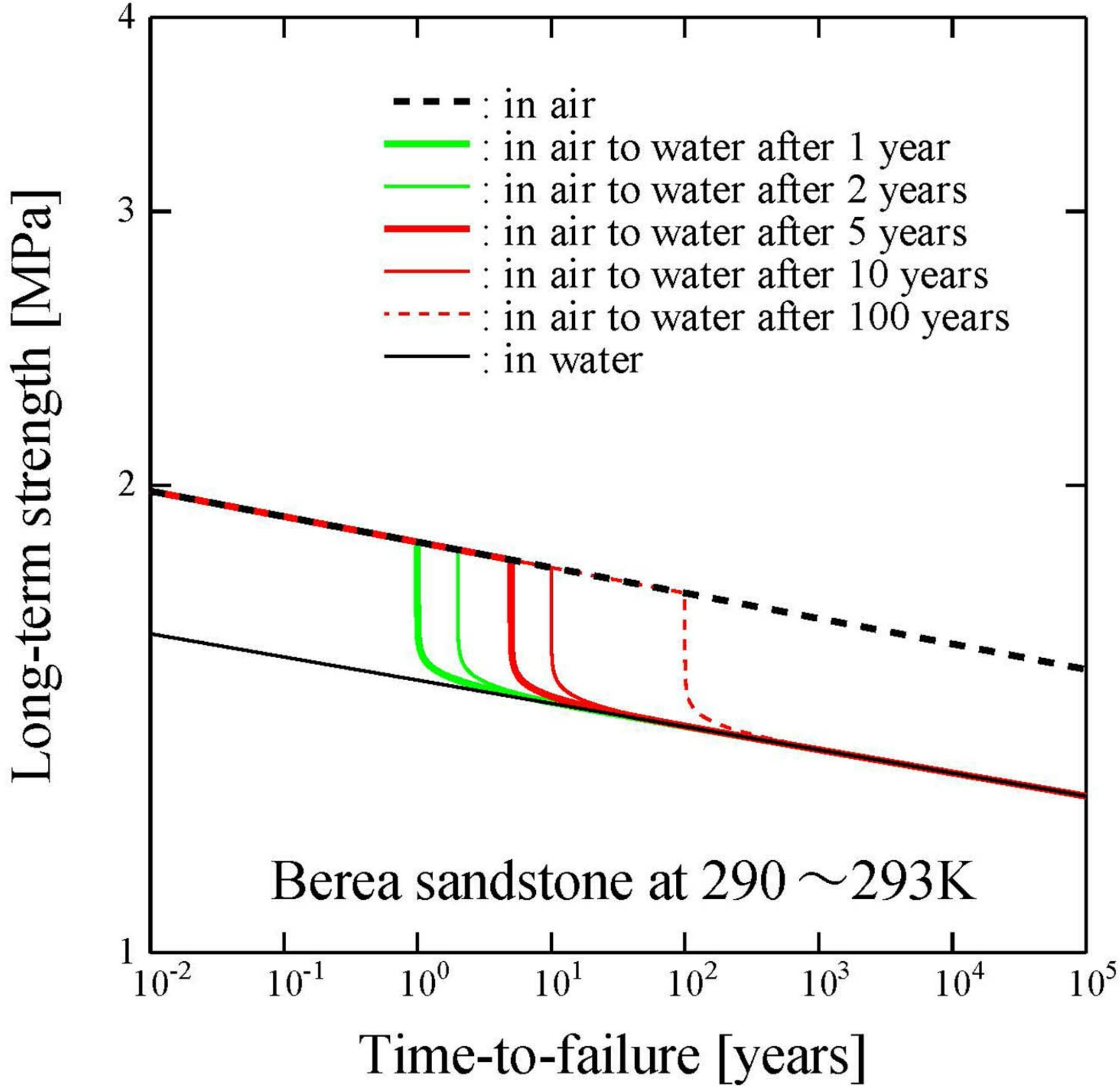
●, ▲, ■ : in distilled water (293K, pH = 6)
○, △, □ : in air (293K, 54-56%)
Berea sandstone
Crack velocity [m/s]
Stress intensity factor [MN/m 3/2]
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
0.1
0.2
0.3
0.4



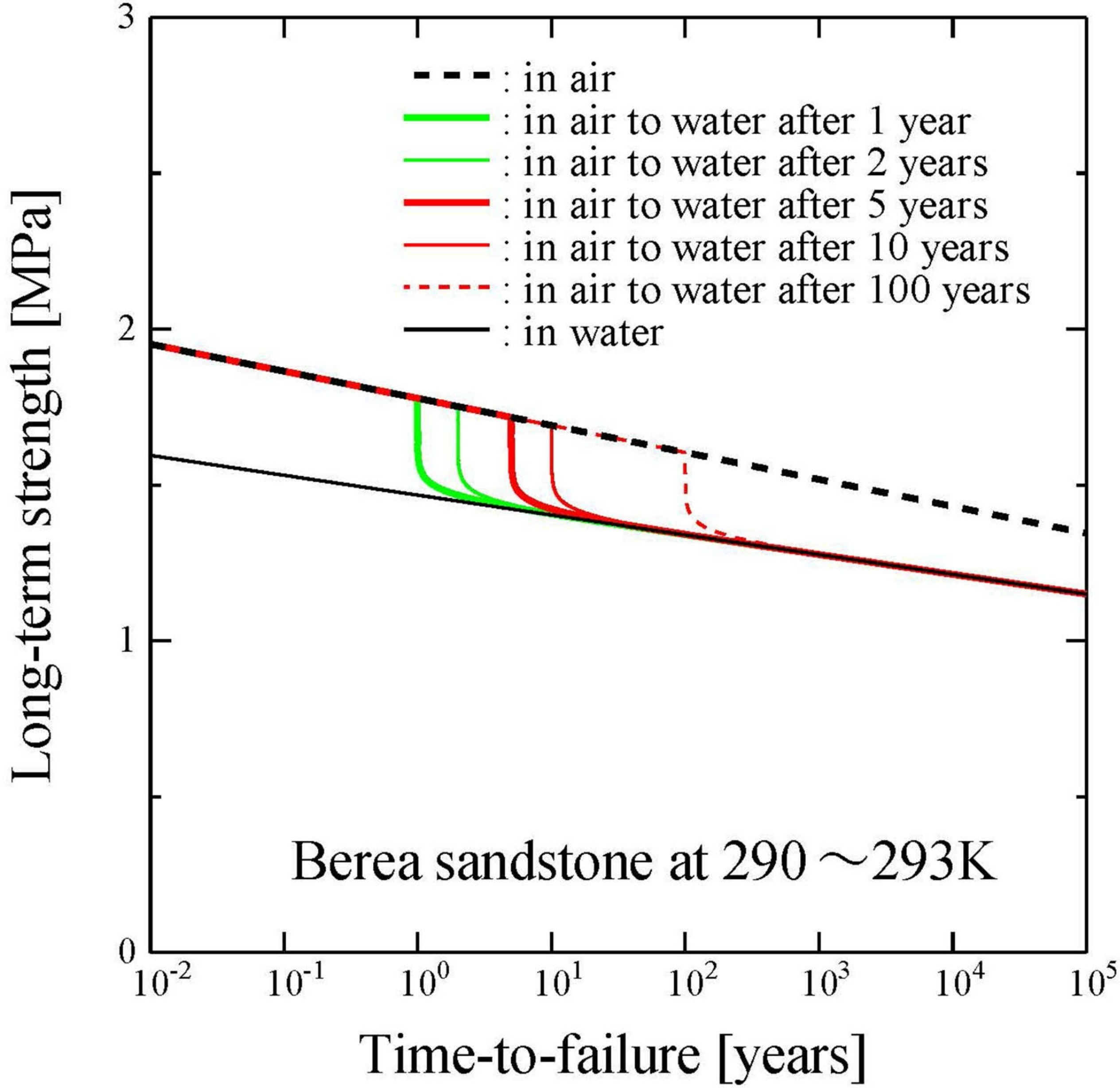
: in air
: in air to water after 1 year
: in air to water after 2 years
: in air to water after 5 years
: in air to water after 10 years
: in air to water after 100 years
: in water
Harare gabbro at 323K
Long-term strength [MPa]
Time-to-failure [years]
20
10
9
8
7
6
5
4
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}



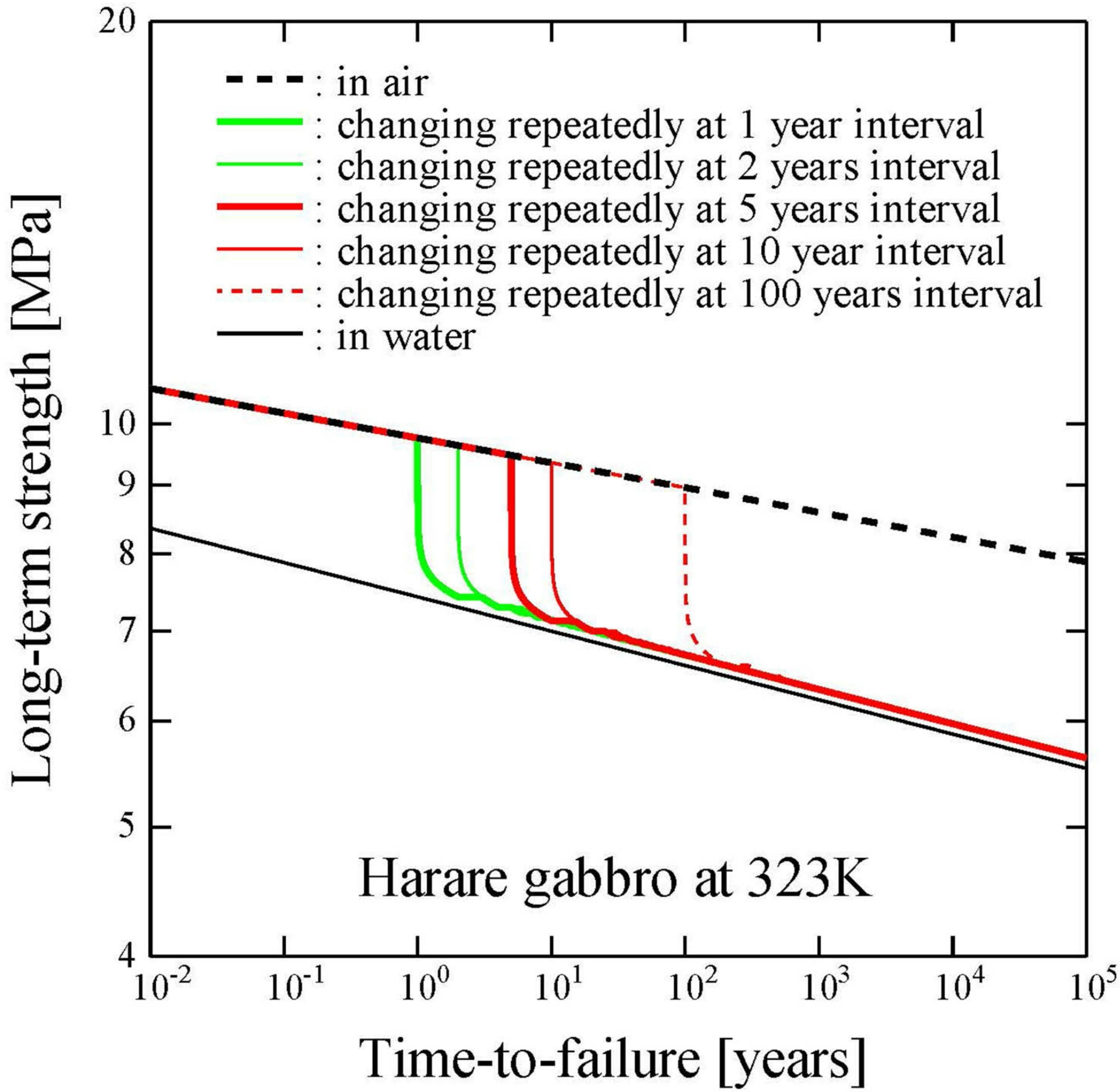
15
10
5
0
Long-term strength [MPa]
: in air
: in air to water after 1 year
: in air to water after 2 years
: in air to water after 5 years
: in air to water after 10 years
: in air to water after 100 years
: in water
Harare gabbro at 323K
10-2
10-1
100
101
102
103
104
105
Time-to-failure [years]



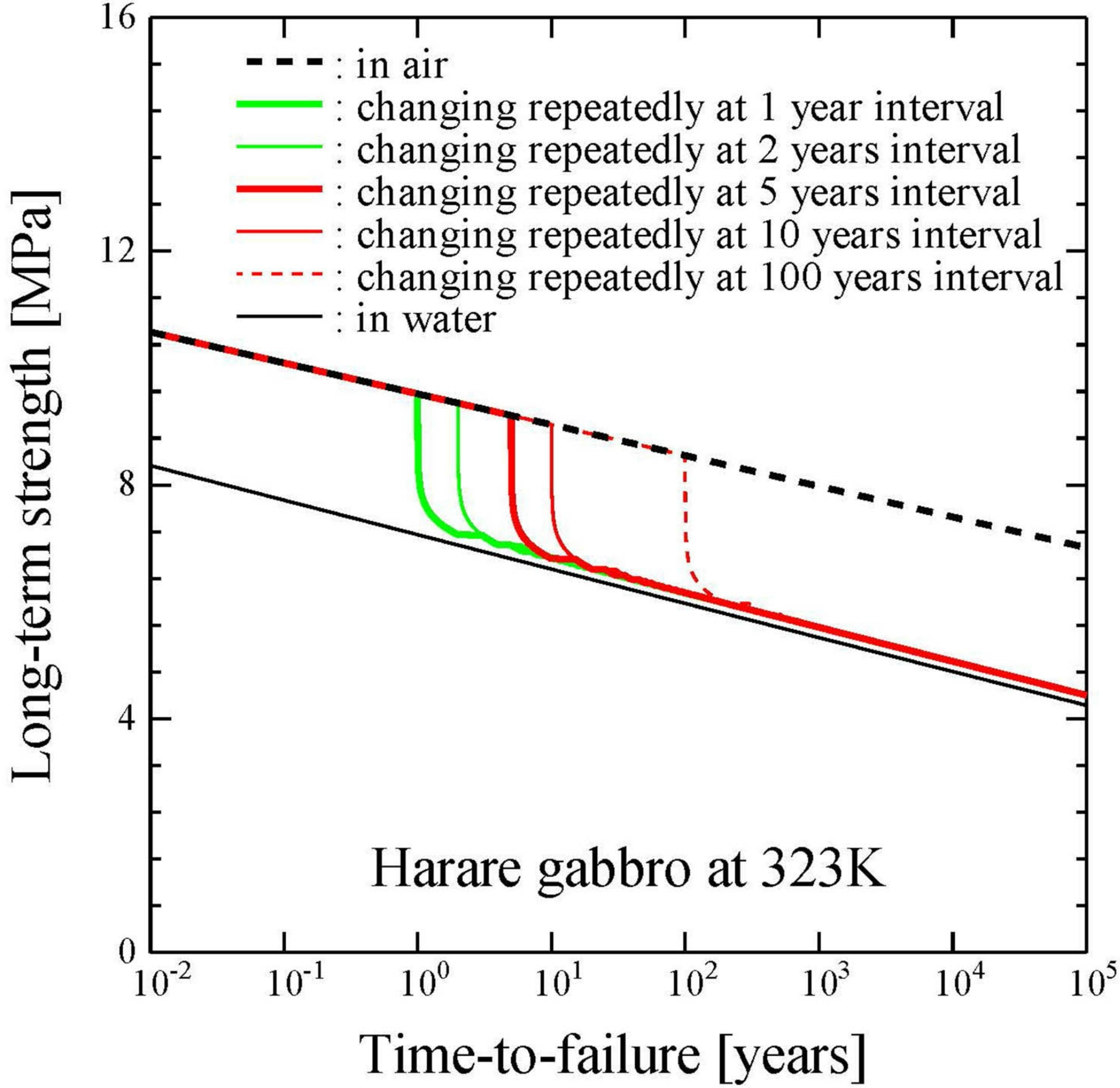
: in air
: in air to water after 1 year
: in air to water after 2 years
: in air to water after 5 years
: in air to water after 10 years
: in air to water after 100 years
: in water
Berea sandstone at 290～293K
Long-term strength [MPa]
Time-to-failure [years]
1
2
3
4
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}



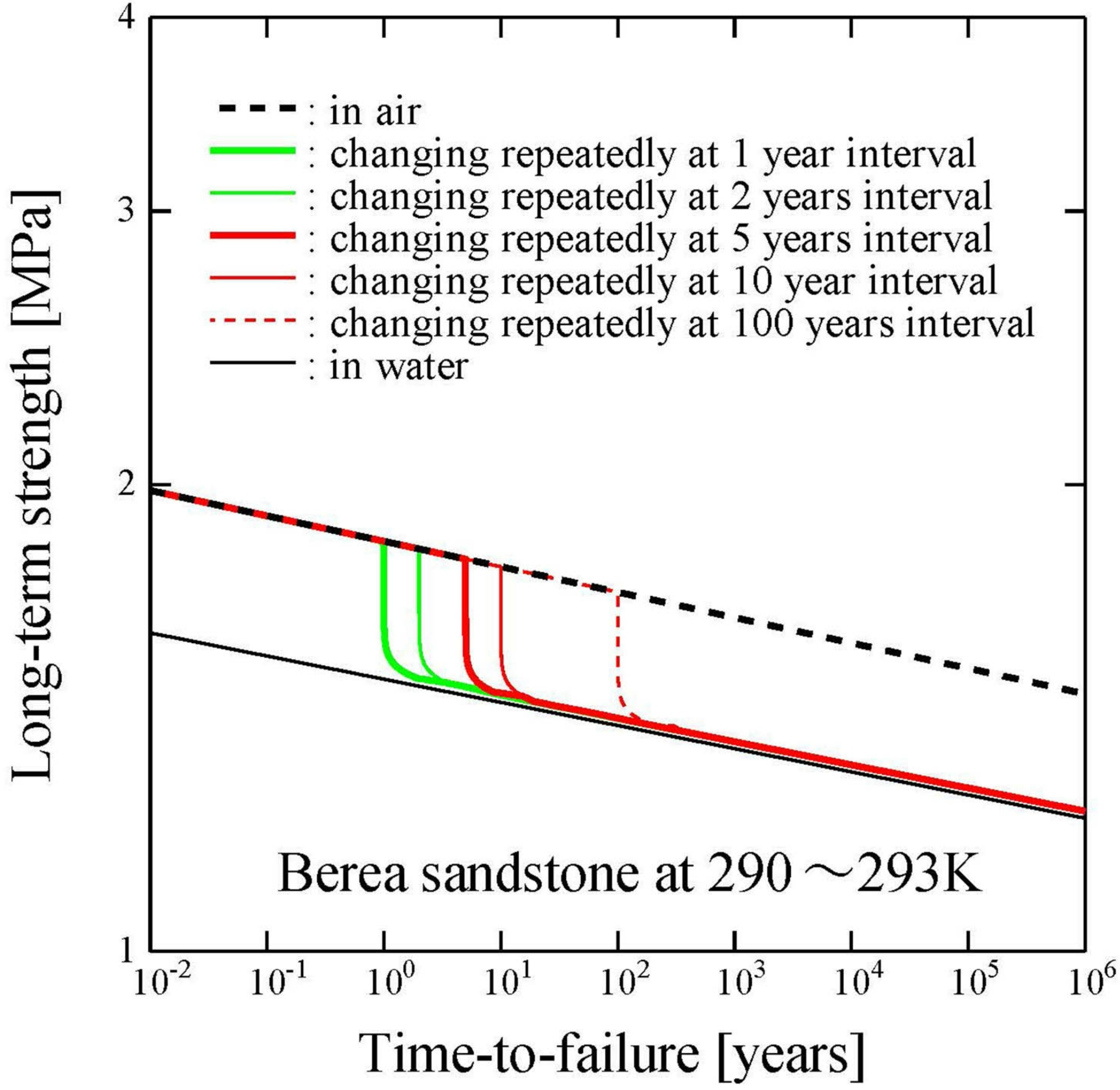
: in air
: in air to water after 1 year
: in air to water after 2 years
: in air to water after 5 years
: in air to water after 10 years
: in air to water after 100 years
: in water
Berea sandstone at 290～293K
Long-term strength [MPa]
Time-to-failure [years]
0
1
2
3
10-2
10-1
100
101
102
103
104
105



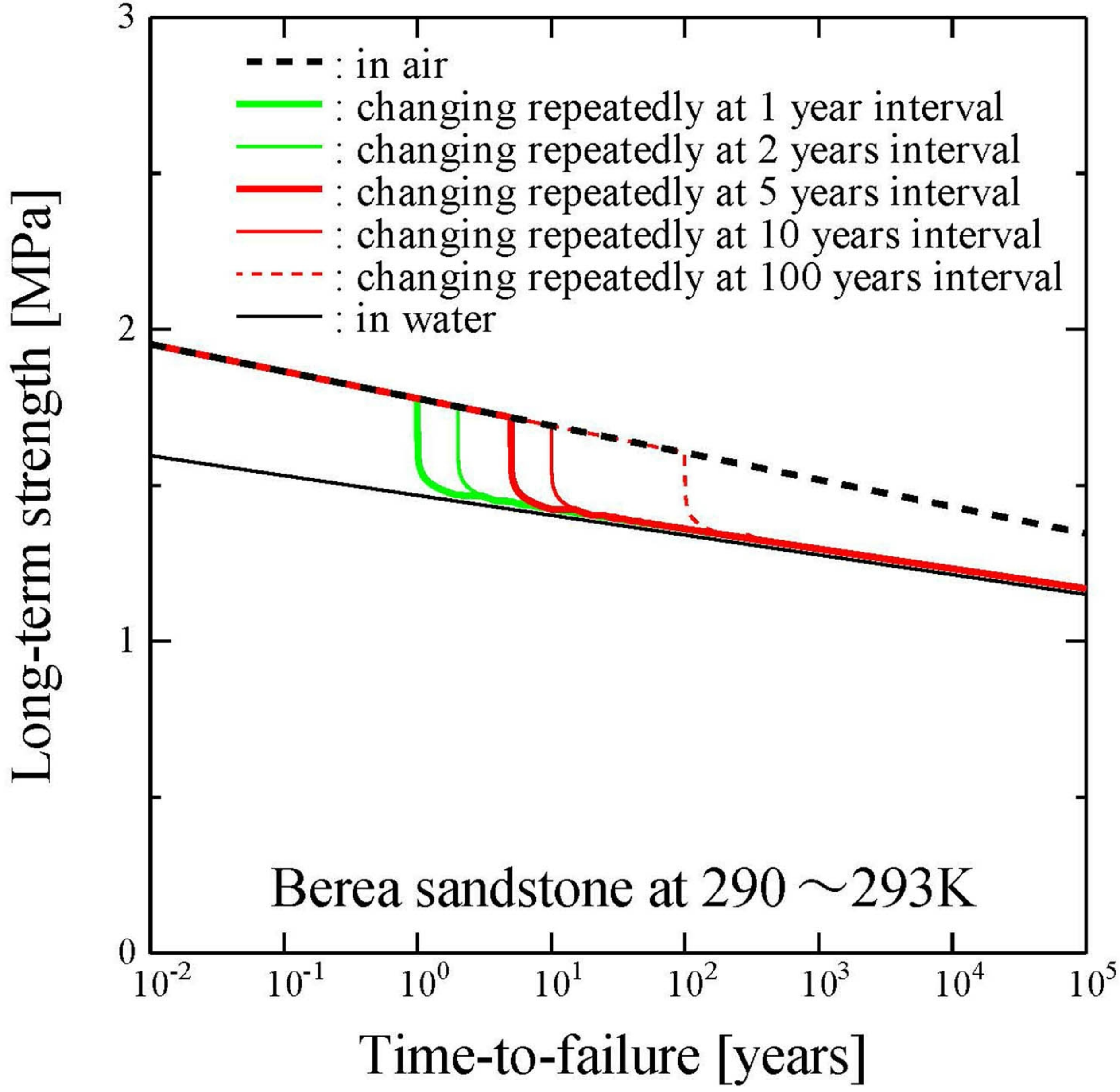
Long-term strength [MPa]
Time-to-failure [years]
: in air
: changing repeatedly at 1 year interval
: changing repeatedly at 2 years interval
: changing repeatedly at 5 years interval
: changing repeatedly at 10 year interval
: changing repeatedly at 100 years interval
: in water
Harare gabbro at 323K
20
10
9
8
7
6
5
4
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5



16
12
8
4
0
: in air
: changing repeatedly at 1 year interval
: changing repeatedly at 2 years interval
: changing repeatedly at 5 years interval
: changing repeatedly at 10 years interval
: changing repeatedly at 100 years interval
: in water
Long-term strength [MPa]
Harare gabbro at 323K
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
Time-to-failure [years]



4
3
2
1
: in air
: changing repeatedly at 1 year interval
: changing repeatedly at 2 years interval
: changing repeatedly at 5 years interval
: changing repeatedly at 10 year interval
: changing repeatedly at 100 years interval
: in water
Long-term strength [MPa]
Berea sandstone at 290 ～293K
10-2 10-1 10^0 10^1 10^2 10^3 10^4 10^5 10^6
Time-to-failure [years]



3
2
1
0
: in air
: changing repeatedly at 1 year interval
: changing repeatedly at 2 years interval
: changing repeatedly at 5 years interval
: changing repeatedly at 10 years interval
: changing repeatedly at 100 years interval
: in water
Berea sandstone at 290 ～293K
Long-term strength [MPa]
10-2
10-1
100
101
102
103
104
105
Time-to-failure [years]

Highlights

- A method to evaluate long-term strength under changing environmental conditions is shown based on subcritical crack growth in rock.
- Long-term strength decreased significantly when the environment changed from air to water.
- Even when the environment changed repeatedly, long-term strength was similar to that in continuous water environment.
- Water has the significant influence on the reduction of long-term-strength.