Evaluation of Physical Properties of Rocks in Forced Deterioration Experiments

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To investigate deterioration rate of rocks, the authors conducted measurements of the physical properties of naturally weathered Kimachi sandstone and forcedly deteriorated Kimachi sandstone. The naturally weathered Kimachi sandstone was obtained by boring from a surface after excavation which had not been touched for approximately 100 years. From the Measurement results of the physical properties of the naturally weathered Kimachi sandstone, the relationship between these properties, depth and time was obtained. The forced deterioration experiments were carried out by repeated drying-wetting and drying-wetting-freezing-thawing cycles. The experiment results revealed that the decrease in ultrasonic wave speed with each cycle approximated well with the logarithmic function.

Key words: rock, weathering, forced deterioration

1. Introduction

In order to prevent disasters such as rockfalls and collapsing of rock slopes, countermeasures are taken on slopes along railways by extracting unstable slopes in advance by inspection. On the other hand, it is currently difficult to predict all disasters in advance solely by inspection, and consequently, slope disasters still occur along railways every year in Japan. One of the reasons why it is difficult to predict the occurrence of a disaster is that these inspections are based on predictions of location such as extraction of current unstable slopes, whereas methods for predicting the timing of disasters have not yet been established. Accordingly, to predict the timing of these disasters, it is necessary to clarify the rate of decrease in rock strength due to weathering. However, since weathering progresses in the geological term, it is difficult to measure the progress of weathering in the natural state with time.

Previous studies have reported the results of experiments with forced deterioration of rocks through repeated cycles of drying-wetting and freezing-thawing, to simulate weathering [1]. However, the relationship between the number of cycles and the changes in values of physical properties has not been clarified. To apply the results of forced deterioration to an actual slope and utilize it for predicting the timing of a disaster, it is necessary to convert the number of cycles into time to obtain the rate of change of the physical properties.

Hence, to evaluate changes in the values of physical properties, we conducted two series of forced deterioration experiments: one with drying-wetting cycles and the other with drying-wetting-freezing-thawing cycles. Considering that bedrock is composed of cracks and intact rocks, we examined the deterioration of the intact rocks. In this study, at first, we collected samples of Kimachi sandstone whose exposure period to the atmosphere is known and measured its physical properties. We investigated changes in the values of these physical properties due to natural weathering with the results. Next, we conducted the forced deterioration experiments using specimens of Kimachi sandstone and examined the changes in values of physical properties due to deterioration by measurement at predetermined numbers of cycles. Furthermore, in order to evaluate changes in physical properties in relation to time, we attempted to examine the rate of decrease in strength by comparing experiment results with measurements at the site.

2. General properties of Kimachi sandstone

We performed destructive tests, such as unconfined compression tests, in each cycle of the forced deterioration experiment and evaluated the changes in physical property values over the repeated cycles. For these tests, ideally the characteristics and values of physical properties of the specimens in their initial state have to be uniform. In particular, when specimens have mechanical discontinuities such as cracks, there is a possibility that these will determine their physical properties. Therefore, it was considered that homogeneous and massive rocks without mechanical discontinuities would be suitable as specimens for the forced deterioration experiment. In this study, we used Kimachi sandstone as a type of rock that matches this condition (Fig. 1). Since Kimachi sandstone has the above properties, it has been used in rock mechanics studies such as fatigue experiments and triaxial compression tests [2, 3].

Kimachi sandstone is a tuffaceous sandstone of the Miocene period distributed in the Kimachi district of Shishido-cho, Matsue City, Shimane Prefecture, located in western Japan facing the Sea of Japan. Although some Kimachi sandstones generally show bedding, the bedding of the Kimachi sandstone block used in the experiment was unclear. So, it can be regarded as homogeneous and isotropic. It is soft and tends to be weathered easily, and it shows blue-gray color right after quarrying, but gradually becomes brown [4]. Regarding the physical properties of Kimachi sandstone, previous studies reported that the specific gravity was about 2.54, the unconfined compression strength was about 60-70 MPa, the porosity was about 20%, and the water absorption rate was about 11% when sufficiently immersed [5, 6]. Prior to conducting the forced deterioration experiment shown below, specimens with a diameter of 25 mm and a height of 50 mm were prepared from the blocks of Kimachi sandstone, and the average values from the three specimens of each physical property were examined. According to the result of examination, the average density was 1.98 g/cm³, the average P-wave velocity was 2.8 km/s, the average S-wave velocity was 1.9 km/s, and the average unconfined compression strength was 54 MPa (Table 1).

Fig. 1 The appearance of Kimachi sandstone

Table 1 Physical properties and mineral composition of Kimachi sandstone used in the experiments

Physical property	Density [g/cm ³]	P-wave velocity [km/s]	S-wave velocity [km/s]	Unconfined compression strength [MPa]
	1.98	2.83	1.86	54
Mineral composition	Quartz, Plagioclase, Pyroxene, Zeolite, Smectite			

3. Measurement of naturally weathered samples

3.1 Method of collecting samples and measurement of physical properties of samples

In order to investigate changes in physical properties due to natural weathering, samples were collected by boring on slopes whose exposure period to the atmosphere is known. The boring was carried out at the quarry in Higashikimachi, Shinji-cho, Matsue City, Shimane Prefecture. In this study, a surface after excavation which had been untouched for about 100 years since the last digging was selected and boring was carried out in the direction perpendicular to the surface after excavation. The elapsed years could be interpreted as the number of years that the surface after excavation had been weathered. This is based on the assumption that the surface after excavation of the quarry always exposed its fresh surface to the atmosphere at that time when the quarry was in operation.

The 40 mm diameter, 1560 mm long boring core was cut into 50 mm long specimens for measurement. After natural drying of the specimens, we measured the ultrasonic wave velocity of the specimens. Ultrasonic wave velocity was measured in accordance with “Method for laboratory measurement of ultrasonic wave velocity of rock by pulse test” (JGS 2110), and the density was measured in accordance with “Test method for bulk density of rock” (JGS 2123).

3.2 Result of measurement

Figure 2 shows the boring core obtained from the surface after excavation exposed about 100 years ago. The depth represents the depth of the center of the specimens from the surface. No cracks or remarkable bedding were found in the boring core. The color of the boring core was brown from 0 to 330 mm near the surface, while it was blue-gray from 330 mm. The boundary between the brown part and the blue-gray part was clear.

Figures 3 and 4 show the relationship between the depth and the ultrasonic wave velocity measured for the specimen prepared from the boring core. From the value of the P-wave velocity with the

Fig. 2 Photo of boring core

Fig. 3 P-wave velocity with depth

Fig. 4 S-wave velocity with depth

depth shown in Fig. 3, it is within the range of 2.7 to 3.0 km/s between 0 and 850 mm in depth, and it tends to decrease slightly with the depth. The P-wave velocity in the depth below 900 mm was within the range of 3.0 to 3.3 km/s, and there was a gap in value between depths of about 850 to 900 mm. However, the dependence of the S-wave velocity on depth cannot be seen from Fig. 4.

4. Forced deterioration experiments

4.1 Method of forced deterioration experiments

We carried out the forced deterioration experiments using a specimen with a diameter of 50 mm and a height of 100 mm, which was made from a purchased block of Kimachi sandstone. We carried out two kinds of the experiment: a repetition of drying-wetting, and a repetition of drying-wetting-freezing-thawing, which are defined in below. Table 2 shows the conditions of each experiment. One cycle of the repetition experiment of drying-wetting was drying at 110°C for 24 hours in the furnace after immersion for 24 hours. One cycle of the repetition experiment of drying-wetting-freezing-thawing was drying at 110°C for 24 hours in the furnace after freezing-thawing in addition to immersion for 24 hours. Freezing-thawing was carried out on the basis of the “Method of test for resistance of concrete to freezing and thawing” (JIS A 1148). However, since the specimen for thermal control was not prepared, we controlled

Table 2 Conditions of each forced deterioration experiment

Category of experiment	Contents in a cycle
Repetition of drying-wetting	Measurement of density and ultrasonic wave velocity→Water absorption (more than 24 h)→Measurement of water absorption→Furnace drying (110°C, 24 h)→Putting in room temperature
Repetition of drying-wetting-freezing-thawing	Measurement of density and ultrasonic wave velocity→Water absorption (more than 24 h)→Freezing-thawing→Measurement of water absorption→Furnace drying (110°C, 24 h)→Putting in room temperature

the temperature of the specimens by that of the chamber. Each experiment was performed up to 40 repetition cycles.

To investigate the physical properties as the number of cycles increased, ultrasonic wave velocity, dry mass, dry density, water absorption rate, unconfined compressive strength, and deformation modulus were measured for cycles 1, 2, 4, 10, 20, and 40 during the forced deterioration experiment. In this study, in order to focus mainly on mechanical weathering, we measured physical property values. The ultrasonic wave velocity, dry mass, and dry density were measured right before immersion, the water absorption rate was measured right after immersion, and the unconfined compressive strength and deformation modulus were measured after drying. The same specimens were used at each measurement cycle for the measurement of ultrasonic propagation velocity, dry mass, dry density, and water absorption rate. However, different specimens were used at each measurement cycle for unconfined compression tests to measure unconfined compression strength and deformation modulus, because they are destructive tests.

4.2 Result of forced deterioration experiments

Figures 5 to 11 summarize the relationship between the number of repetition cycles and the values of each physical property in the repetitions of drying-wetting and drying-wetting-freezing-thawing. The average value of each physical property in each measurement cycle was calculated from the values of 3 specimens. Figures 5 and 6 show that the P-wave velocity and the S-wave velocity tend to decrease in a curve with each repetition cycle. While the amount of the decrease in ultrasonic wave velocity is large in the early repetition cycles, it becomes smaller as the number of repetition cycles rises. The unconfined compression strength and the deformation modulus also tend to decrease with repetition cycles as shown in Fig. 7 and 8. However, the values vary widely compared with the results of the ultrasonic wave velocity. This reason for this is thought to be that different specimens were used for each measurement cycle for the measurement of unconfined compression strength and deformation modulus. As shown in Fig. 9, the dry mass tends to

increase with repetition cycles up to 20 repetition cycles, but then decreases from 20 to 40 repetition cycles. Figure 10 shows the dry density tends to decrease with repetition cycles. From Fig. 11, Although the water absorption rate basically tends to increase with repetition cycles, only the water absorption rate of the repetition of drying-wetting-freezing-thawing tends to decrease from 20 to 40

Fig. 6 Measurement result of S-wave velocity in forced deterioration experiments

Fig. 7 Measurement result of unconfined compression strength in forced deterioration experiments

Fig. 5 Measurement result of P-wave velocity in forced deterioration experiments

Fig. 8 Measurement result of deformation modulus in forced deterioration experiments

Fig. 9 Measurement result of dry mass in forced deterioration experiments

Fig. 10 Measurement result of dry density in forced deterioration experiments

Fig. 11 Measurement result of water absorption in forced deterioration experiments

repetition cycles.

Comparing the repetition experiment results of drying-wetting with the repetition experiment results of the drying-wetting-freezing-thawing, there is almost no difference in unconfined compressive strength, deformation modulus, dry mass, and dry density. Differences in P-wave velocity, S-wave velocity, and water absorption rate were observed after a relatively large number of repetition cycles such as 20 to 40 repetition cycles. In particular, the P-wave velocity and S-wave velocity showed a remarkable decrease after 20 repetition cycles in the repetition experiment of drying-wetting-freezing-thawing.

From the above results, it can be concluded that the P-wave velocity, S-wave velocity, unconfined compressive strength, deformation modulus, dry mass, dry density, and water absorption rate all varied with repetition cycles in the forced deterioration experiments. However, although the dry mass is expected to decrease due

to the outflow of particles and the dissolution of minerals as rocks deteriorate, the experiment results showed an increase. This could be due to the oxidation of minerals and the precipitation of water-soluble components in the water used during immersion. Therefore, it is necessary to consider the effects of factors other than rock deterioration in the forced deterioration experiment, when thinking about changes of dry mass. This can also be applied to the dry density and water absorption rate calculated using the dry mass.

5. Evaluation of physical properties with time

5.1 Change of P-Wave Velocity with repetition cycles

Using the results of the forced deterioration experiments, we estimated the rate of change in the value of physical properties with the number of repetition cycles. We discuss the P-wave velocity which shows a smooth change with the number of repetition cycles shown in the results described in Chapter 4.

First, we estimated the relationship between the number of repetition cycles and the P-wave velocity based on previous studies. Sunamura assumed that the decrease in strength ΔS of rock during infinitesimal time Δt under natural weathering can be expressed by (1) using the strength S at time $t = 0$ and the non-negative coefficient k [7].

$$\frac{\Delta S}{\Delta t} = -kS \quad (1)$$

Assuming that the initial value of the strength at $t = 0$ is $S = S_0$, the rate of decrease in strength can be expressed by (2).

$$S = S_0 \exp(-kt) \quad (2)$$

Furthermore, considering the rate of decrease in strength with the number of repetition cycles in the forced deterioration experiment, if the number of repetition cycles N in the forced deterioration experiment and time under natural weathering t have a linear relationship, (3) is obtained using the non-negative coefficient k_n .

$$S = S_0 \exp(-k_n N) \quad (3)$$

Here, interpreting the above strength as the unconfined compression strength, we consider the relationship between the unconfined compression strength and the ultrasonic wave velocity. Inoue and Omi have proposed (4) as an empirical formula between the unconfined compressive strength S (kg/cm²) and the P-wave velocity V_p (km/s) based on the measurement results of various rocks [8].

$$S = 43 V_p^{2.23} \quad (4)$$

From (3) and (4), the relationship between the number of repetition cycles and the ultrasonic wave velocity is expressed as the form of an exponential function as described in (5), using the coefficients α and β .

$$V_p = \alpha \exp(-\beta N) \quad (5)$$

Based on (5), the exponential approximation curve shown in Fig. 12 is obtained by the least-squares method for the measurement result of the P-wave velocity in the repetition of drying-wetting. However, this exponential approximation curve does not sufficiently represent the tendency of the P-wave velocity, since the amount of decrease becomes larger with the decrease of the number of repetition cycles and becomes smaller with increase of the number of repetition cycles. On the other hand, the curve shown in Fig. 13 is obtained by approximating based on the logarithmic function. This function is generally used to express the relationship between the number of repetition cycles until failure and the stress amplitude of repeated loading in the fatigue test by repeated loading. This logarithmic approximation curve has a high correlation with the measured value, so that it is considered to be suitable as a format for

Fig. 12 Exponential approximation curve for measurement result of P-wave velocity in repetition of drying-wetting

Fig. 13 Logarithmic approximation curve for measurement result of P-wave velocity in repetition of drying-wetting

expressing the relationship between the number of repetition cycles and the P-wave velocity in the forced deterioration experiment. Since the measured value of the P-wave velocity at $N = 1$ in the forced deterioration experiment in this study is the measured value of the specimen once dried in the furnace, we process it here as the initial value of the P-wave velocity. By its processing, the relationship between the number of repetition cycles and the P-wave velocity in the forced deterioration experiment is expressed by (6) using the initial value of the P-wave velocity V_0 and the non-negative coefficient A .

$$V_p = -A \ln(N + 1) + V_0 \quad (6)$$

Since the coefficient A in (6) is considered to be a value unique to the rock, the change in P-wave velocity in the forced deterioration experiment can be estimated by (6) if A can be obtained. Since the correlation between the P-wave velocity and the strength has been confirmed as shown in (4), it is possible to indirectly estimate the change in strength.

5.2 Change of P-Wave Velocity with time

To determine the rate of decrease in the P-wave velocity in real time from the relationship between the number of repetition cycles and the P-wave velocity obtained from the experiments, it is necessary to clarify the relationship between the number of repetition cycles and the real time. We examined the relationship between the number of repetition cycles and real time by the application of the measurement results in the field to the approximation curve in Fig. 13.

From Fig. 3, we assume that the weathering front on the actual slope is located at a depth of 850 to 900 mm where a gap in P-wave velocity exists. The part shallower than 850 mm is assumed as the range that has been weathered for about 100 years, and the part

Fig. 14 Rate of decrease in P-wave velocity based on the results of forced deterioration experiments

deeper than 900 mm is assumed as the range that has not been weathered. According to Fig. 3, the average value of the P-wave velocity in the slope shallower than 850 mm is 2.85 km/s, and the average value of the P-wave velocity at a depth over 900 mm is 3.15 km/s. Substituting these P-wave velocities into the logarithmic function shown in Fig. 13, the number of repetition cycles N required to reduce the P-wave velocity from 3.15 km/s to 2.85 km/s in the forced deterioration experiment is about 1.53. This is estimated to be equivalent to about 100 years, when it is converted to real time. Therefore, based on the assumption that the number of repetition cycles and the real time have a linear relationship, the relationship between the number of repetition cycles N and the real time t can be expressed by (7).

$$N = t/65 \quad (7)$$

From (6) and (7), the rate of decrease in P-wave velocity can be expressed as (8) from the results of the forced deterioration experiment.

$$V_p = -A \ln\{(t/65) + 1\} + V_0 \quad (8)$$

The rate of decrease in P-wave velocity can be represented by the curve shown in Fig. 14 based on the results of the forced deterioration experiments in this study. Furthermore, the rate of decrease in strength can be obtained indirectly by converting this result into strength. However, since the rate of decrease in strength obtained from this result is a logarithmic function, there is a defect such as the strength becoming 0 or less with the increase of time. Therefore, it should be noted that the rate of decrease in strength obtained in this study is limited to within the time range corresponding to the number of repetition cycles of the forced deterioration experiments conducted in this study.

6. Conclusions

In this study, in order to evaluate changes in the physical properties of rocks due to weathering, we measured the values of physical properties of naturally weathered rocks and rocks deteriorated in forced deterioration experiments. The obtained results led to the following conclusions:

- Examination of boring cores collected from a slope of Kimachi sandstone whose weathering period was estimated for about 100 years, showed that there was a difference in P-wave velocity between the weathered and fresh parts of the rock.
- Forced deterioration experiments with specimens of Kimachi sandstone showed that physical property values of P-wave velocity, S-wave velocity, unconfined compressive

strength, deformation modulus, dry mass, dry density, and water absorption rate, tended to change with the number of drying-wetting cycles.

- The change in P-wave velocity in the forced deterioration experiments can be estimated with the approximation formula expressed by the logarithmic function, which is obtained by examining its relationship with the number of drying-wetting cycles.
- The rate of decrease in strength can be estimated from the results of the on-site measurement and the forced deterioration experiments.

We will examine the more general equation of rate of decrease in strength by conducting experiments and measurements on multiple series of rock as a future work. In addition, we are going to clarify the relationship between real time and values of physical properties from the measurement of actual weathered samples. After clarifying the rate of decrease in strength of rock, it is necessary to extend the discussion to the rate of decrease in strength of rock mass, considering the decrease in strength due to cracks in the rock mass.

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