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PORE DISTRIBUTION NEAR THE SURFACE OF WELDED TUFF BUILDING STONE BY WEATHERING AND ITS IMPACTS ON STRENGTH DETERIORATION

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Abstract

The authors have comprehensively evaluated the weathering condition near the surface of an arch stone from a 150-year-old welded tuff stone bridge (Takeno Bridge) in Kagoshima. In this paper, mercury penetration and Dorry attrition test are carried out in detail from the surface to inside of the arch stone. It turns out that, the pore size in the arch stone can be grossly classified into two groups, with radii of $750 < R \leqq 75000$ Å and $38 \leqq R \leqq 750$ Å respectively. The weathering in the 150 years bought about the increasing and magnifying of the pores with radii of $750 < R \leqq 75000$ Å, within about 5cm from the surface. The total pore volume increased about 0.025 cm^3/g near the surface, which caused about 500 m/sec of P wave velocity reduction, about 10MPa reduction of the wall strength of joint, and about 0.5g/m increase of wear down ratio. The good correlations between the pore distribution and wear down ratio, elastic wave velocity and the wall strength of joint, show that the mercury penetration can reflect clearly the changes of the physical and mechanical properties, and it is an effective method for evaluating the weathering of rock material in the engineering time scale.

Key words: historic stone bridge, weathering, pore distribution, strength reduction

1. Introduction

So far, in designing rock mass structures, the strength deterioration of the rock or rock mass caused by weathering during the service period has not been considered. However, in recent years, the long life design and management of the rock structures like the underground institution used in radioactive waste disposal, the preservation of historic and cultural lithic heritage, etc., necessitate considering weathering problem. It becomes very important subject to understand mechanism of weathering and to establish quantitative evaluation methods. Furthermore, it is expected to develop the experimental methods that can correctly examine the strength reduction in the incipient stage of weathering, and to clarify the distribution of the weathering degree from the rock surface along with proceeding of the weathering front.

Considering the above status, the authors have been studying a weathering problem of a 150-year-old welded tuff stone bridge (Takeno Bridge) in Kagoshima that was flooded in 1993. From the time scale, the weathering should be considered in the incipient stage. The study is carried out respectively from the points of view of mechanical, physical and chemical aspects[1),2),3)] to evaluate the weathering condition near the surface of arch stone from that stone bridge. Then, based on these evaluations, the following problems are being considered. 1) The effective experimental methods and evaluation index for the incipient stage of weathering. 2) Mechanism of the weathering. 3) The strength deterioration near the surface of the arch stone. 4) Quantitative evaluation on stability changes of the stone bridge by weathering[4),5)].

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In this paper, the distribution characteristics of pore volume and pore size near the surface of the arch stone caused by weathering is tested with mercury penetration method. Dorry attrition test is also carried out to know the wear resistance variation from the surface to the depth. Finally how the pore distribution affect the strength deterioration (elastic wave velocity, wear down ratio, Schmidt hammer rebound number) is discussed.

2. Outline of the experiments

2.1 Specimen

The specimens used in this study are from one block of arch stone from the Takeno Bridge. The arch stone, belonging to the "Ono stone" (welded tuff) in local area, is considered to have been collected from upper part of the Kakutou pyroclastic flow deposits formed about 0.3 Ma ago[6].

Before preparing the specimen, prismatic test bars (10cm * 12cm * 25cm) were cut out rectangularly from the central surface to about the center of the arch stone (Fig.1). Then, from the test bar, the specimen of mercury penetration, each with size of about 1cm*1cm*1cm, and the Dorry attrition specimen, a core with a diameter of 25 mm and with an axis perpendicular to the surface of the arch stone, were prepared in the way shown in Fig.1, to examine the changes of pore distribution and wear resistance from the surface to deep inside. Before the tests, the specimens were dried two days under 105 °C. In addition, other tests show that the specimens possess the effective porosity of 21~ 26%, and dry density of 1.8 ~ 1.9 g/cm^3.

2.2 Mercury penetration

The principle of this test is based on an assumption that the small pores in the specimen take the shape of cylinder. Thereby, the radius of the pore R, the applied pressure of mercury P, and the surfacial tension σ and the contact angle θ of mercury will have the following relation.

$$P R = -2 \sigma \cos\theta \qquad (1)$$

If we use 4.8*10^{-3} N/cm and 140° as the surfacial tension and contact angle of mercury respectively, the following equation of R(Å) and P(MPa) can be obtained.

$$R = \frac{750000}{P} \qquad (2)$$

That is, a given pressure value corresponds to certain radius of small pore in the specimen. Therefore, if the reduced volume of the mercury at a given pressure is measured, the volume of the pores with the corresponding radius can be calculated. In this study, The pressure extent of the measurement is 0.1 ~ 200 MPa, the corresponding radius extent of pores that can be measured is from 38 to 75000 Å .

2.3 Dorry attrition test

The Dorry attrition test is in accordance with ASTM C 779-76. Firstly, the specimen is set under a normal load of 12.5 N on a round table with circumference of 2 meters. Then, one set of test is to let the table rotate 500 circuits at a speed of 28 rpm (revolutions per minute). At the same time, the standard sand is used as an abrasive, evenly dropped down right at the trial along which the specimen is attrited. In 100 circuits, 40 grams of the standard sand was used. After each set of test, the weight of the specimen is weighted with electronic balance (with precision of 10 mg); the length is measured at three fixed places on the specimen.

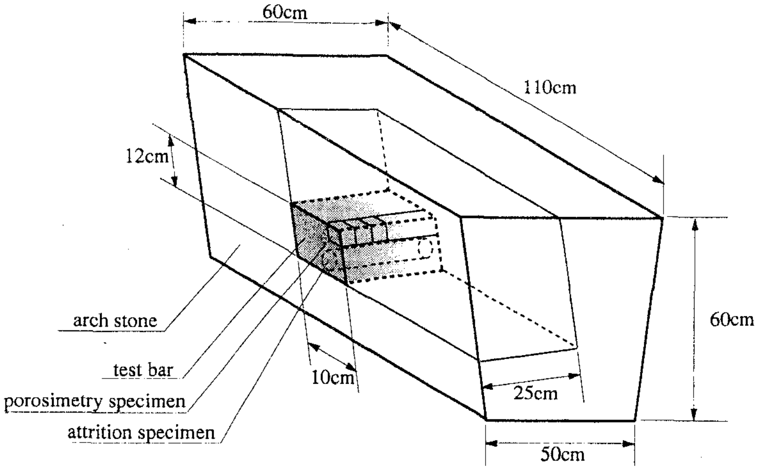

Fig.1 Schetch of sampling method

3. Experimental results and discussions

3.1 Characteristics of pore distribution

In this measurement, the compression correction of both mercury and specimen must be considered. Here, the compression correction of mercury was processed by the equation:

$$Shg\,(P) = \frac{4.2}{19990} \times (P - 10) \times \alpha \tag{3}$$

Shg(P)(mm) is the compression value of mercury at the pressure P(MPa); α is correction value corresponding to the mercury filling in the specimen holder. Here, unity is used as the α value, because the specimen are rather smaller than the holder.

The compression correction for the specimen was conducted with three pieces of specimen according to Uchino and Ichinose[7]. It turns out that the compression correction for the specimen in this study is not necessary. Therefore, the pore volume (n_m, cm^3/g) is calculated by the following equation:

$$n_m = \frac{\{\,Scd(P) - Shg(P)\,\} \times S}{W} \tag{4}$$

Scd (P): experimental value for the reduction of mercury at the pressure P (MPa);

W: weight of the specimen(g);

S: cross section area of the specimen holder (0.0707 cm^2).

The calculated total pore volume of the specimens from different depth is showed in Fig.2. It is clear that the total volume of pores increased about 0.025 cm^3/g within about 5cm depth from the surface of the arch stone. Beyond that depth the total volume of the pores remains about a constant value. This reflects the depth and the degree of the weathering in the 150 years.

Furthermore, the pore size in the specimen can be grossly classified into two groups, $750 < R \leqq 75000$ Å and $38 \leqq$

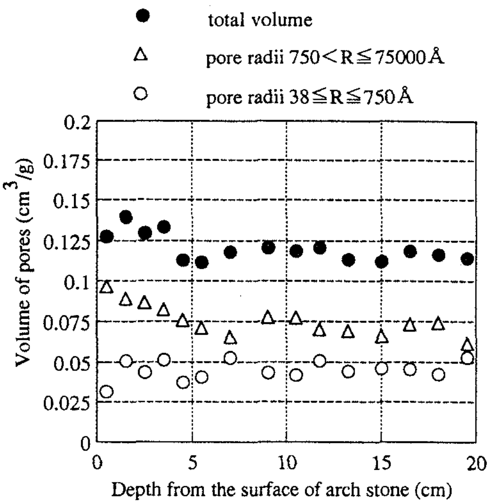

Fig. 2 Distribution of pore volumes at different depth

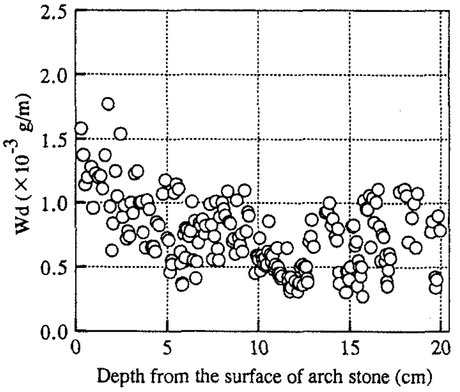

Fig.4 Wear down ratio (Wd) at different depth

$R \leqq 750$ Å(Fig.3). The volumes of the pores with $750 < R \leqq 75000$ Å radii are generally greater than that of the pores with smaller radii(Fig.2). The volume of the pores with radii of $38 \leqq R \leqq 750$ Å generally do not change with the depth from the surface, especially the peak radius 150 Å almost do not change in all specimen. But the volumes of the pores with radii of $750 < R \leqq 75000$ Å increase within about 5cm from the surface, especially interesting thing is that the peak radius 1500Å in the specimen of more than 5 ~ 6cm depth (those are considered fresh specimen) expanded from 5 ~ 6cm to the surface. That is, the pore increase by the weathering is reflected by not only the increase of the pore volume with radii of about $750 < R \leqq 75000$ Å , but also the expanding of the pore size.

As for the distribution type of the pores in rocks, there should be one peak radius for one kind of rock, if the rock is relatively uniform. Reversely, the existing multi-peak radii of pores may reflect the heterogeneity of the rock. The two peak radii existing in the specimen of this study may be attributed to the two major types of materials constituting the specimen welded tuff. That is, lithoclasts and volcanic ashes[3]. The latter is relatively easier to be weathered than the former. The peak radius 1500 Å may reflect the pores in volcanic ash that was weathered near the contact surface.

3.2 Wear resistance of the material

The result of the Dorry attrition test is reflected by the wear down ratio Wd (g/m), meaning the weight of the specimen worn down in one meter of attrition. Though because of the unhomogeneity of the specimen, the results are in a wide range (Fig.4), it reflects that the Wd values near the surface are high, but rapidly decrease along with increase of the depth, and tend to converge to a constant grossly. Concerning that the Wd value is related to weathering, it is obvious that the apparently weathered extent reached about 5 cm in depth, where is just the extent with increasing pore volume and pore size. Wd value at the surface increased about 0.5 g/m.

3.3 Strength deterioration by the changes of pore volumes

Physical weathering is usually the dominant form in the incipient stage of weathering. The ultimate result of physical weathering is reflected by one basic phenomenon, i.e. the increase of porosity in the weathered rocks. The total volume and size of pores increase with the degree of weathering[8]. This increase in turn changes the other physical and mechanical properties at the same time. The following will discuss how the pore volume affects the wear resistance, elastic wave velocity and the wall strength of joint.

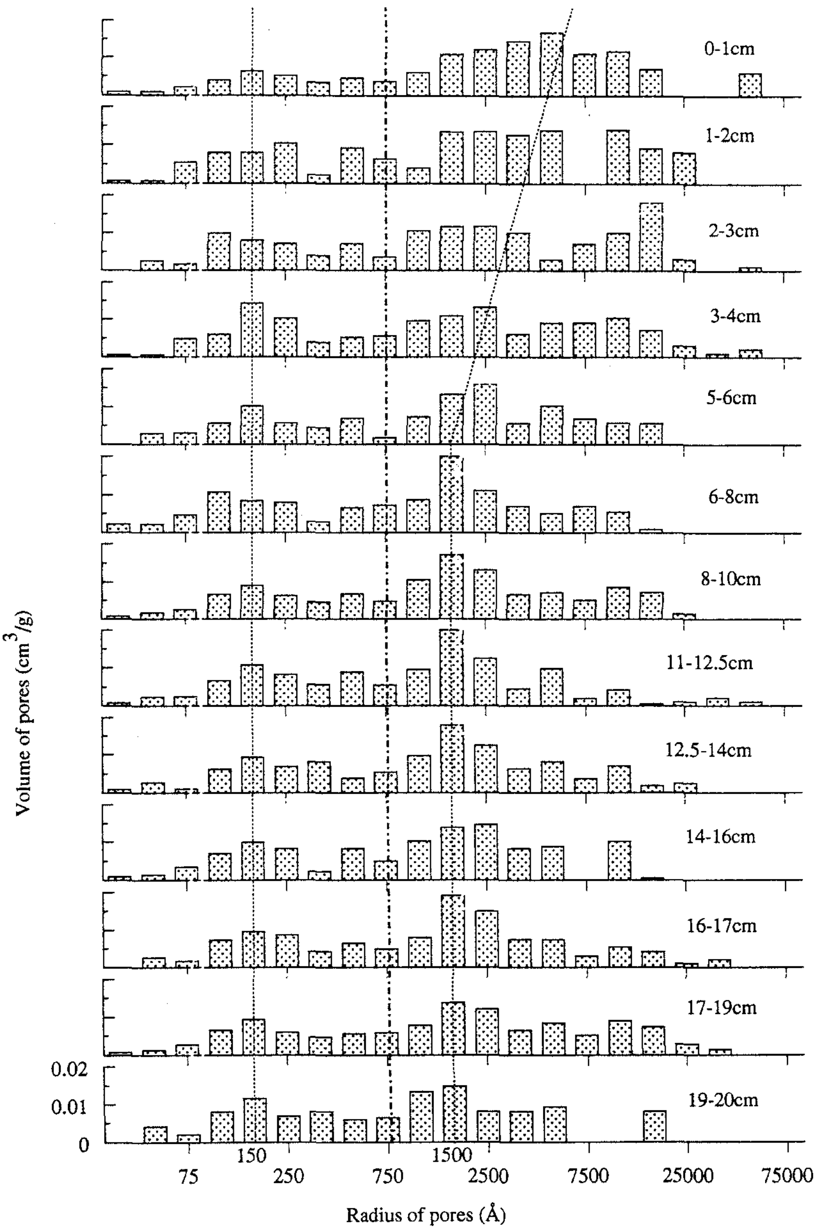

Fig.3 Volumes of pores with different radii in the specimen and their spatial distribution. The data in figure are the depth from the surface

(a) Wear down ratio and pore volume

Fig.5 shows the relation of wear down ratio and volume of pores with radii of $750 < R \leqq 75000$ Å . It can be seen that within about 5cm depth from the surface the wear down ratio increase with the volume of the pores. It means that the increase of the pore in the specimen makes the material easy to be attrited. The wear down ratio increased about 0.5g/m.

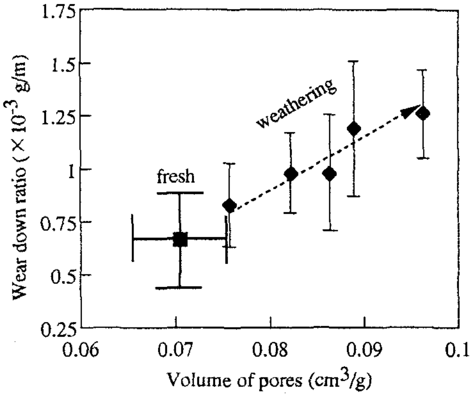

Fig.5 Relation of wear down ratio(Wd) to volume of pores with radii of 750 < R ≦ 75000 Å. Range of the data in figure is ± 1 σ (standard deviation)

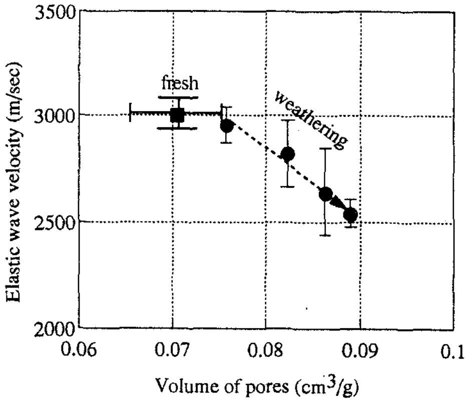

Fig.6 Relation of elastic wave velocity(Vp) to volume of pores with radii of 750 < R ≦ 75000 Å. Range of the data in figure is ± 1 σ (standard deviation)

(b) Elastic wave velocity and pore volume

Esaki, et al.[2] tested elastic wave velocity of the test bars from the surface to the depth in one centimeter interval with pulse transmission method. From the elastic wave velocity data, it was recognized that the velocity reduction reaches about 5 cm depth where is just the extent with increasing pore volume, after that depth, the velocity do not change so much, that basically represent the fresh rock.

Fig.6 shows the relation of elastic wave velocity and volume of pores with radii of 750 < R ≦ 75000 Å. The elastic wave velocity within about 5cm from the surface decrease with increasing of the pore volume. The reason can be considered that the pore would bring about consumption of the wave energy and the scatter phenomenon. From Fig.6, it is known that about 500 m/sec reduced by the increase of the pore volume.

(c) Wall strength of joint and pore volume

Esaki, et al.[1] carried out the stiffness tests on the surface (0cm) and the artificial joints parallel with the surface at depth of 4cm, 8cm and 12cm from the surface of the arch stone. At 0cm, the specimen was set by a well-fitted pair of the surfaces from two test bars. With these joints (including the surface) used in the stiffness tests, the Schmidt hammer rebound numbers were measured, and the result showed that the Schmidt hammer rebound test is an effective method for evaluating the incipient stage of weathering. With the obtained Schmidt hammer rebound numbers, the wall strength of joint is calculated according to Deere and Miller[9], and showed in Fig.7 with function of volume of pores with radii of 750 < R ≦ 75000 Å. It can be seen that with the increase of the pore volume, the wall strength of joints decreases, especially within 4cm depth from the surface. At the surface the wall strength of joint decreased about 10 MPa.

From the above, the pore volumes have good correlations with wear down ratio, elastic wave velocity and the wall strength of joint, that is, the pore volumes can reflect clearly the changes of the physical and mechanical properties. Therefore, the mercury penetration is an effective method for evaluating the incipient stage of weathering.

4. Conclusion

In this paper, mercury penetration and Dorry attrition test were carried out in detail from the surface to inside of the arch stone. According to the spatial distribution and correlation of different parameters, the following conclusions are obtained.

1) The pore size in the arch stone can be grossly classified into two groups, with radii of 750 < R ≦ 75000 Å and 38

≦ R ≦ 750 Å respectively. The volumes of the pores with 750 < R ≦ 75000 Å radii are generally greater than those of the pores with smaller radii. The volume of the pores with radii of 38 ≦ R ≦ 750 Å generally do not change with the depth from the surface, especially the peak radius 150 Å almost do not change in all specimen.

But, during the 150 years, the weathering bought about the increasing and magnifying of the pores with radii of 750 < R ≦ 75000 Å , within about 5cm from the surface of the arch stone. The total pore volume increased about 0.025 cm^3/g near the surface.

2) The increasing and magnifying of the pores caused about 500 m/sec of P wave velocity reduction, about 10MPa reduction of the wall strength of joint, and about 0.5g/m increase of wear down ratio.

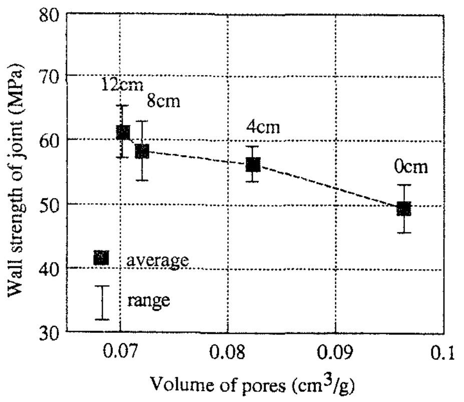

Fig.7 Relation of wall strength of joint to volume of pores with radii of 750 < R ≦ 75000 Å , data in the figure are depth from the surface

3) Mercury penetration is proved to be an efficient method for evaluating the degree and mechanism of the incipient stage of weathering of rock material.

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