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DENSITY DISTRIBUTIONS WITHIN CERAMIC MATERIALS SATURATED FOR USE IN SUCTION MEASUREMENT

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ABSTRACT: Unsaturated soil contains air and water within the voids of the skeleton formed by soil particles. To investigate the complicated behavior of these materials through unsaturated soil testing, pore air and water pressure must be measured and controlled independently. For this purpose, a microporous ceramic material is used. The ceramic, which is installed in tensiometers and other experimental apparatus used for testing unsaturated soil, must be saturated using degassed water. The degree of saturation of the ceramic influences the accuracy of measuring and controlling suction. However, microporous ceramic is difficult to saturate. Currently, the ceramic material is saturated using empirical methods, the applicability of which have not been confirmed up until now. In this study, the effects of ceramic saturation methods were investigated. Three kinds of saturation methods, the vacuum method, the pressurization method, and the Berthelot method, were utilized. In each method, saturation time and the number of saturation cycles was varied. The saturated ceramic was also exposed to air drying to check the saturation effect, and X-ray computed tomography was used to visualize the degree of saturation of the ceramic. These efforts determined that trends in the distribution of saturation within the ceramic are dependent on saturation method.

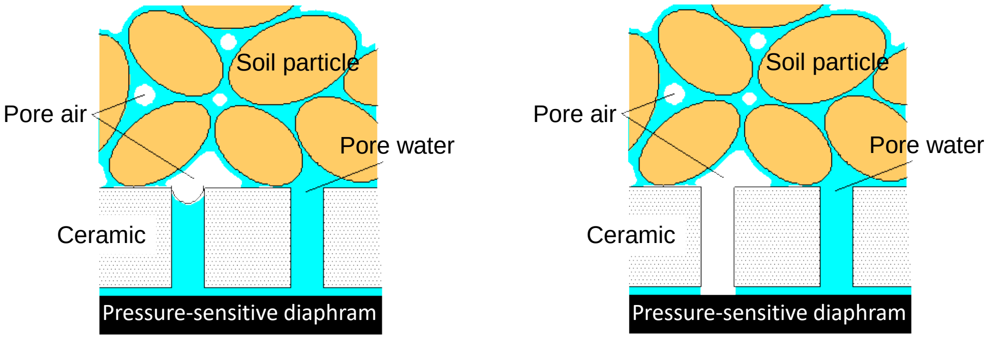
Keywords: Tensiometer, Ceramic, X-ray computed tomography

1. INTRODUCTION

Recently, landslide disasters due to rainfall occur frequently. Natural slopes remain stable under unsaturated conditions, while the decrease in suction due to rainfall infiltration leads to a loss of slope stability. Therefore, the suction-dependent behavior of unsaturated soil is investigated through lab-tests and in-situ monitoring. Suction is the pressure difference between pore air and water, as demonstrated by the following equation;

$$s = p_a - p_w \tag{1}$$

Here, s is suction; p_a is pore air pressure, and p_w is pore water pressure. Pore water pressure must be measured or controlled independently of pore air pressure. For this unsaturated soil testing, a microporous ceramic is used to isolate pore water pressure from pore air pressure. Figure 1 shows the principle of pore water pressure measurement using the ceramic material. Pore water pressure within the unsaturated soil is smaller than pore air pressure. In most cases, since pore air pressure corresponds to atmospheric pressure, pore water pressure indicates a negative value for gauge pressure. If the pressure measurement is directly applied to unsaturated soil, the measurable pressure is pore air pressure. For this, the saturated ceramic material is used. Ceramic is a microporous material. Once this microporous structure is saturated with water, air cannot pass through due to the resistance induced by water surface tension (as Fig.1 (a)). Under these



(a) Perfectly saturated ceramic (b) Imperfectly saturated ceramic

Fig. 1 Measuring pore water pressure using ceramic material

(a) Exterior (b) Interior

Fig. 2 X-ray CT scanner system

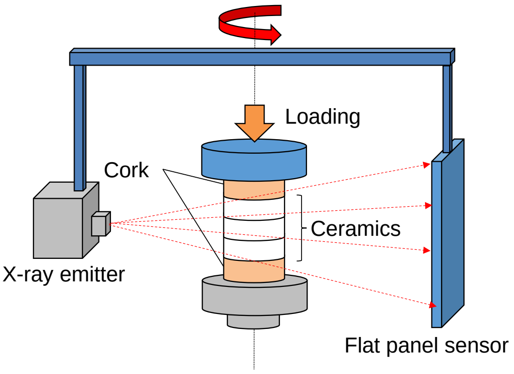
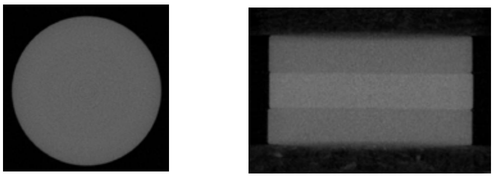


Fig. 3 X-ray CT scan



(a) X-Y cordinate (b) X-Z cordinate

Fig. 4 Example of a CT image

Table 1 Average density obtained from the supplier’s catalog

Ceramic (A.E.V)	Perfectly dried (g/cm^3)	Perfectly saturated (g/cm^3)
1bar	1.92	2.46
3bar	1.74	2.27
5bar	1.73	2.14

conditions, continuous water can pass through the ceramic, and a pressure-sensitive diaphragm can measure pore water pressure within the unsaturated soil. However, when the ceramic is imperfectly saturated, as in Fig. 1 (b), the pressure-sensitive diaphragm measures pore air pressure. The degree of saturation of the ceramic strongly influences the accuracy of the suction measurement. When suction is controlled in lab tests, air pressure is applied to the specimen under drained condition. In this circumstance, water pressure can be regarded as zero, and suction corresponds to applied air pressure, according to equation (1). When applied air pressure exceeds a certain value, or when pore water pressure falls below a certain negative value that corresponds to the surface tension induced by the water within ceramic micropores, then air can pass through ceramic micropores and make the ceramic become unsaturated. This value is called the air entry value (A.E.V), and commercial ceramics each have their own A.E.V. This introduces difficulty into the process measuring and controlling relatively high suctions and long-term testing on the unsaturated soil. Though the degree of saturation for a ceramic material is very important, a robust ceramic saturation method has not been established up to this point. In this study, the effects of the ceramic saturation method are investigated.

2. EXPERIMENTAL PROCEDURE

In this study, three kinds of ceramic plates (41mm diameter and 7mm thickness), having 1, 3 and 5 bar A.E.V., were employed. The average specifications of these commercial ceramic plates were available from the supplier’s catalog. Table 1 summarizes each ceramic plate’s completely dried and completely saturated density, as calculated from the weight, volume and porosity specifications in the catalog. The ceramic plates were first oven-dried at 110°C for 24 hours and then saturated by either the vacuum method, the pressurization method or the Berthelot method. The saturated ceramic was then air dried. The degree of saturation of the ceramic was estimated using an X-ray computed tomography (CT) scanner. The X-ray CT scan is a non-destructive monitoring instrument used for visualizing inner density distributions. When ceramic micropores are saturated by water, they exhibit a higher density on a CT image. Figure 2 shows the X-ray CT scanner system used for this study. This system was developed by Fumoto [1]. In this system, loading is possible by turning both the X-ray emitter and the flat panel sensor (seen in Figure 3). Figure 4 shows an example of a CT image. A saturated ceramic plate was sandwiched between unsaturated ceramic plates on an X-ray scanner to clarify the outline of the target ceramic (seen in Figure 4 (b)). The sandwiched, saturated ceramic showed a whiter image than the unsaturated outer ceramics. This whiter color indicates a greater density. X-ray CT scans were conducted four times, at 15min, 30min, 1hour and 2 hours after saturation of the air-dried ceramic.

2.1 Vacuum Method

The vacuum method, standardized by the Japanese Geotechnical Society [2], is generally used for saturating ceramic materials. Figure 5 shows the vacuum method procedure. Two desiccators are utilized, into which dried ceramic material and degassed water are placed, respectively. A vacuum of -98kPa is applied for 24 hours (Figure 5(a)). Next, the water from one desiccator is poured into the desiccator that contains the ceramic material under vacuum and left to soak under vacuum for 24 hours (Figure 5(b)). Figure 6 shows the relationship between the CT number obtained from the X-ray CT scan of the ceramic material dried and saturated by the vacuum method and its density as provided in Table 1. The broken line in the figure represents the following equation.

$$\rho = 1.0 + \frac{CT}{1000} \tag{2}$$

Here, ρ is density and CT is the CT number obtained from an X-ray CT scan. CT number is generally considered dependent on density, as well as other factors. However, we assume that the other factors are negligible under the conditions in this study and use equation (2) in the following section. Equation (2) is based on the concept that the CT number is a comparative value between -1000, seen in air density, and 0, seen in water density. All data are plotted on the line expressed by equation (2). This infers that the qualities of the commercial ceramic, such as porosity, density and so on, are consistent to some degree and that we can use equation (2) to estimate density from CT number.

In this study, three different soaking vacuum periods, 3, 12 and 24 hours, were used to investigate the effect of vacuum period on the degree of saturation of the ceramic.

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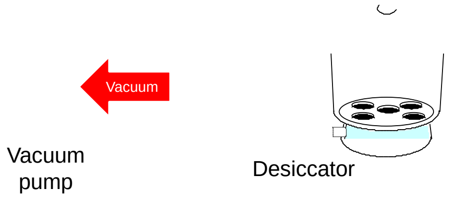
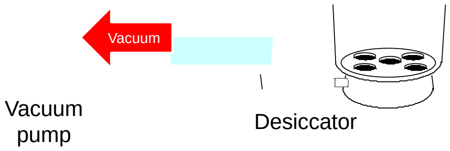
2.2 Pressurization Method

Ridley and Burland [3] indicated that careful saturation of ceramic by degassed water under vacuum and subsequent pressurization at a pressure higher than A.E.V. could provide a satisfactory suction measurement. In this study, the saturation effect of the pressurization method was investigated. The dried ceramic was set, together with degassed water, in a box made of duralumin, to which 0.8MPa pressure was applied (seen in Figure 7). Three pressurization periods, 3, 12 and 24 hours, were investigated. An X-ray CT scan of the ceramic saturated by this method was conducted after pressurization.



(a) Preliminary vacuum



(b) Soaking vacuum

Fig. 5 Vacuum method

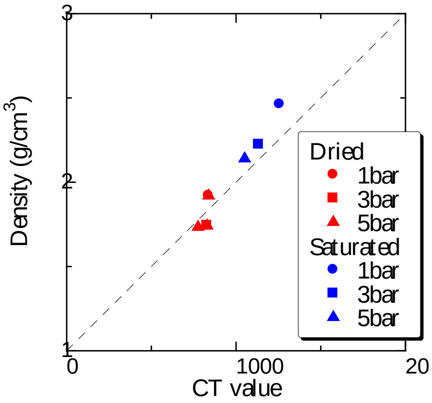


Fig. 6 CT value of dried and saturated ceramic material

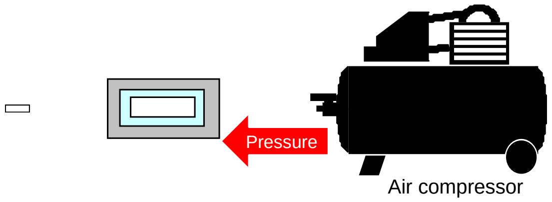


Fig. 7 Pressurization method

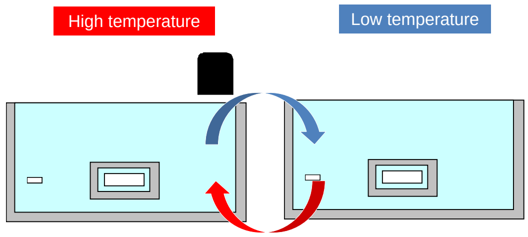


Fig. 8 Berthelot method

2.3 Berthelot Method

The cavitation of water that typically occurs at high negative gauge pressures has been generally explained by the inability of water to sustain tensile stress. Liquids under negative pressures are thermodynamically metastable and easily make the transition to a stable state after cavitation occurs. Berthelot [4] proposed a method to create high negative liquid pressures without cavitation. In this method, application of a high and low temperature cycle to a sealed metal case containing liquid can change liquid pressures at a constant volume due to the difference in thermal expansion rate between the metal and the liquid. Moreover, Hiro et al. [5] determined that the main factor preventing liquid from achieving high negative pressures is the bubbles in micro crevasses on the surface of the solid contact with the liquid. These bubbles do not originate from the liquid. The Berthelot method can decrease these bubbles and diminish the occurrence of cavitation. Tarantino and Mongiovi [6] indicated that the repeated application of pre-pressurization to ceramic is effective in saturating the material. This effect can be considered equivalent to the Berthelot method. In this study, the Berthelot method was used for saturating the ceramic. A duralumin box that contained dried ceramic material and degassed water was soaked in high temperature water of 80°C and low temperature water of 10°C, repeatedly. The number of temperature cycles was set to 20n, 30 and 40.

3. EXPERIMENTAL RESULTS AND DISCUSSION

To investigate the distribution of density within the ceramic, CT numbers obtained from X-ray CT scans were divided into 6mm layers by thickness. Figure 9 shows an example of a CT number distribution obtained from a scanned image of one layer. Trends in density distribution can be compared by statistical coefficients, such as mode, median, average, and standard deviation, as illustrated in Figure 9.

Figure 10 shows the difference in density distributions among different A.E.V. ceramics saturated by the vacuum method for 12 hours. Densities were obtained by substituting the mode of the CT number distribution in equation (2). A period of 24 hours is generally considered necessary to saturate the ceramic by the vacuum method. Density decreases with elapsed time in all figures. This means that the ceramic kept drying with exposure to air. The drying tendency was more obvious in ceramic with a higher A.E.V. As a

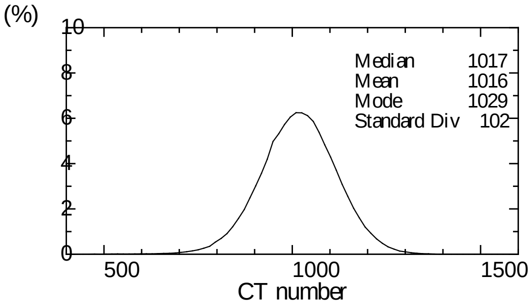
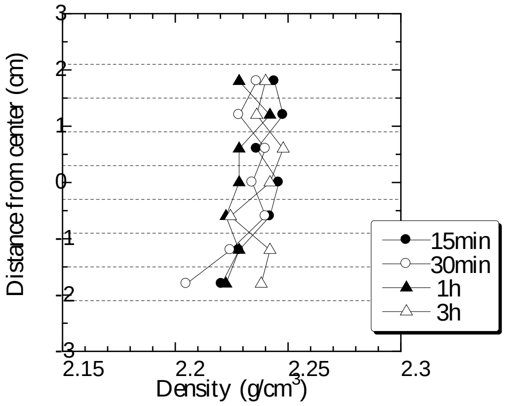
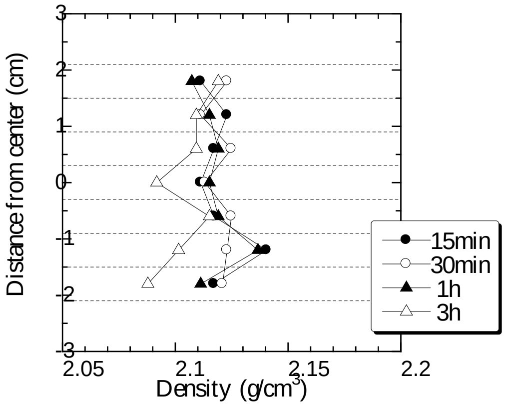


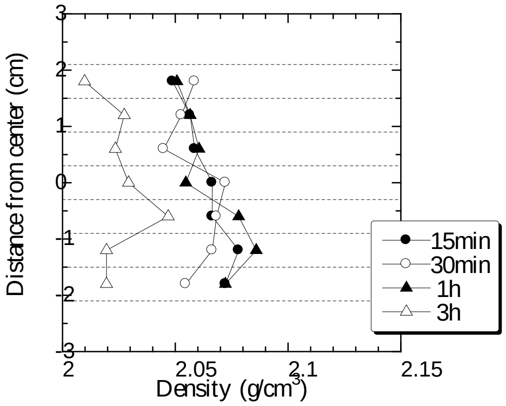
Fig. 9 Example of CT number distribution



(a) 1bar ceramic

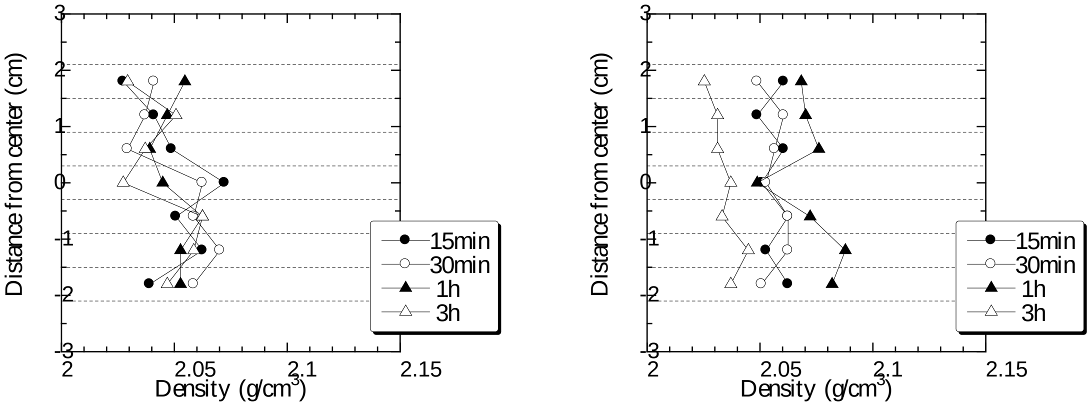


(b) 3bar ceramic



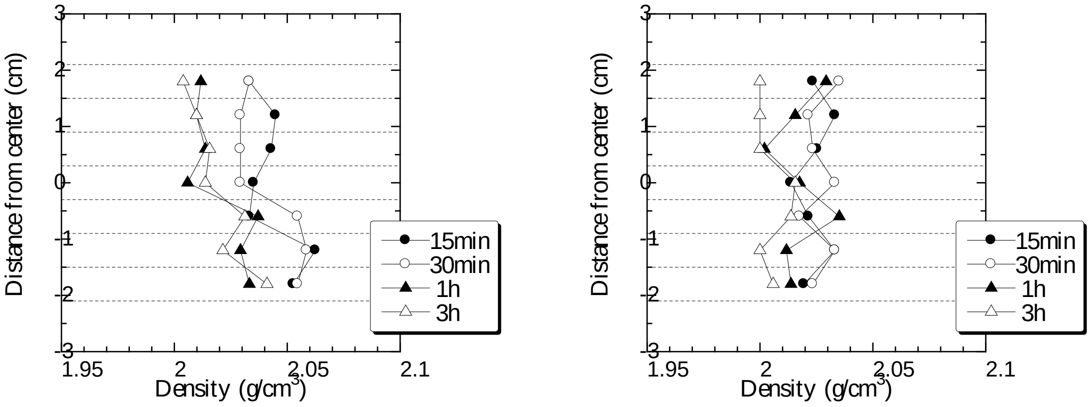
(c) 5bar ceramic

Fig. 10 Density distributions of ceramic saturated by the vacuum method (12hours)



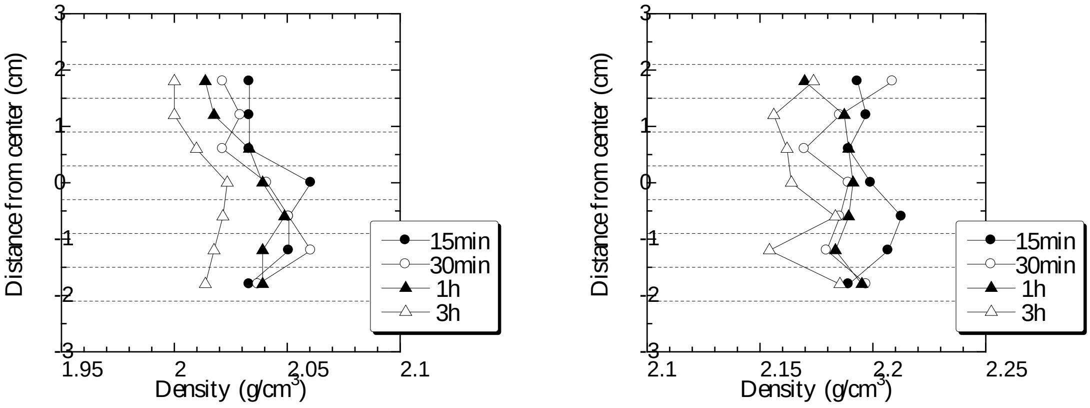
(a) 3hours (b) 24hours

Fig. 11 Density distributions of 5bar ceramic saturated by vacuum method



(a) 3hours (b) 24hours

Fig. 12 Density distributions of 5bar ceramic saturated by pressurization method



(a) 30cycles (b) 40cycles

Fig. 13 Density distributions of 5bar ceramic saturated by the Berthelot method

ceramic material with a higher A.E.V. has a smaller microporous structure, it can be more difficult to saturate. Because of this, 12 hours was not enough time to saturate the higher A.E.V. ceramic perfectly. The effects of vacuum period were investigated in Figure 11. Here, the density distributions for the 5bar ceramic showed saturation at a different vacuum period length than in Figure 10(c). With a longer vacuum period, the density distribution immediately following saturation (15min) was higher and the drying tendency was smaller.

Figure 12 investigates the effects of pressurization periods, illustrating the density distributions in the 5bar ceramic saturated by the pressurization method. Comparing Figure 12 with Figure 11 indicates that the vacuum method is more effective than the pressurization method. In the pressurization method, the ceramic was oven dried

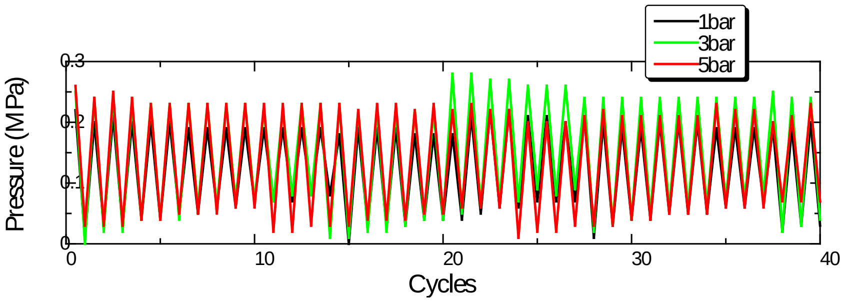


Fig. 14 Water pressure fluctuation observed during temperature cycles in the Berthelot method

prior to pressurization. In this condition, inner air within the ceramic tended to become entrapped by infiltrated water due to pressurization. The objective of the pressurization method is to dissolve this entrapped air into high pressure water. From this experiment, the pressurization period does not appear to be sufficient. Likely, pressurization can be effective as a supplement to the vacuum method, as employed by Ridley and Burland (1995).

Figure 13 shows the density distributions of the 5bar ceramic saturated by the Berthelot method. The density distribution is higher with a greater number of temperature cycles. From these data, the Berthelot method appears effective for saturating the ceramic, especially in Figure 12(b). However, the density decrease was not small, considering the initial density. Figure 14 shows fluctuations of water pressure during temperature cycles. The observed pressures were not so high, making it difficult to regard the effects of the Berthelot method as that of cyclic pressurization. Likely, these results derive from, not only saturation but also other factors. First, water viscosity is also dependent on temperature and it can facilitate water infiltration into ceramic micropores. Second, density distributions in the ceramic also changed due to damage to the ceramic as it was exposed to pressure changes and/or temperature cycles. Further investigation and an accumulation of experimental data is needed to fully assess the effects of the Berthelot method.

4. CONCLUSIONS

In this study, the method to saturate the ceramic material used for unsaturated soil testing was investigated. The ceramics saturated by each method were scanned by X-ray, and the degree of saturation of the interior structure was determined from the density distributions. From this, the following findings were obtained.

(1) An X-ray CT scan is applicable for detecting the effects of the method on ceramic saturation.
(2) Saturation method effects are dependent on a ceramic’s A.E.V. A longer saturation period is needed with a higher A.E.V. ceramic because of its smaller micropores.
(3) The pressurization method is not so effective for saturating ceramic material, and it is only applicable as a supplement to the vacuum method.
(4) The effect of the Berthelot method is not due to cyclic pressurization, and the saturation effect of this method is not confirmed.

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