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Transition condition between memories of vibration and flow in the memory effect of paste

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Because of its plasticity, a densely packed colloidal suspension, called a paste, remembers directions of its motion, such as vibration and flow. When it dries, primary desiccation cracks propagate in a direction perpendicular to the direction of its vibrational motion and parallel to the direction of its flow motion, which are memory effects of paste. Application of an oscillatory shear strain to a paste using a rheometer reveals that the transition from memory of vibration to that of flow is induced when the amplitude of the oscillatory shear strain exceeds a threshold value. Findings also demonstrate that oscillatory motion is unnecessary, i.e., merely a large shear deformation is sufficient for the memory of flow. Therefore, only oscillatory shear strain with a small amplitude is necessary for memory of vibration; large shear deformation is sufficient for memory of flow.

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I. INTRODUCTION

Cracks formed by the drying of a paste made by mixing water and colloidal particles are familiar phenomena that are visible on dried lakes and ponds [1,2]. Although such desiccation crack patterns appear to be random at first glance, statistical analysis has revealed that they have some regularity. For example, in thin pastes consisting of coffee powders and water [3] or clay and water [4], the mean size of the size distribution of desiccation crack fragments is proportional to the sample thickness. The morphologies of desiccation crack patterns of thick starch paste, such as columnar joints, and those of thin alumina pastes are also known to be affected by the drying gradient [1,5]. As described above, the desiccation crack pattern can be partially controlled merely by adjusting the desiccation conditions.

One technique to control the desiccation crack pattern is by using the memory effect of paste This effect makes isotropic desiccation crack patterns anisotropic. When the paste is placed in a container and shaken horizontally in one direction for 1 min and then dried, the paste remembers the direction of its motion under shaking. Desiccation cracks appear in response to the direction of shaking. Depending on the direction in which the anisotropy of the cracks appears, the memory effects of paste are classifiable into two types: memory of vibration and memory of flow. In the case of memory of vibration, primary desiccation cracks propagate perpendicularly to the direction of shaking [6,7]. By contrast, in the case of memory of flow, primary desiccation cracks propagate in parallel to the direction in which the paste flowed during shaking [8]. A morphological phase diagram of desiccation crack patterns is expressed as a function of the solid volume fraction ϕ in paste and the strength of shaking. It shows the condition under which each crack pattern will appear. Reportedly, for magnesium carbonate hydroxide paste, the boundary between the memories of vibration and flow in the morphological phase diagram is expressed as the solid volume fraction of the paste $\phi = 10\%$, below which the memory of flow and above which the memory of vibration appear. Consequently, it has been considered that the conditions under which the memory of vibration and flow appear are determined mainly by the solid volume fraction of paste because a water-poor paste tends to be vibrated, whereas a water-rich paste flows under shaking of the container [9]. Some experimentally obtained results from studies suggest an effect of flow velocity on the transition between memories of vibration and flow [10]. From a study using x-ray computerized tomography to observe the internal microscopic particle arrangement in a vibrated lycopodium paste, findings indicated that a paste with the memory of the vibration had a density fluctuating structure of particles along the direction of the shaking [11].

Mainly, two theoretical models of memory of vibration have been presented based on residual tension theories [12–15]. One quasilinear model reproduces an experiment in which a container is shaken horizontally. Residual stresses are

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generated by partial compression and contraction of the paste as it hits the boundary wall because of shear deformation [12]. The other, a nonlinear model with a periodic boundary condition, shows that the natural metric of the paste is elongated along the vertical direction under horizontal shaking, during which tensile stresses are generated uniformly irrespective of the horizontal location [13,14]. The latter model predicted that the memory of vibration occurs when the paste is subjected to multiple oscillatory shear strain, and the model has been confirmed by memory-rewriting experiments [16]. However, to our knowledge, no theory of memory of flow has been presented to date, nor has a theory of the transition between memories of vibration and flow been proposed.

Therefore, the purpose of this paper is to clarify the condition of the transition between the memory of vibration and that of flow. We conducted desiccation experiments while precisely controlling the amplitude and frequency of the oscillatory shear strain applied to a paste using a rheometer.

II. EXPERIMENTAL METHOD

For this paper, we used a rheometer (Physica MCR-301; Anton Paar, Graz, Austria) for precise control of the oscillatory shear strain applied to a paste. A rheometer is an instrument that measures the rheological properties of a sample by application of stress or strain to the sample, measuring its response to the applied stress or strain, and allowing us to ascertain how much force we have applied. The sample used here is a paste of magnesium carbonate hydroxide (Kanto Chemical Co., Inc., Tokyo, Japan) mixed with distilled water. This sample shows both the memory of vibration and memory of flow. The magnesium carbonate hydroxide density is $2.0\ \mathrm{g/cm^3}$. The median diameter of the colloidal particles is $3.0\ \mu\mathrm{m}$.

A 25-mm-diameter aluminum plate is used for the measurement upper parallel plate jig of two parallel plates which sandwich a sample. A transparent circular plastic plate (DUS-120; Mitsubishi Pencil Co., Ltd.) with 67.2-mm diameter and 0.7-mm thickness is fixed at the bottom of the upper parallel plate jig using double-sided tape (667-1-19D; 3M Japan Ltd.) (Fig. 1). First, the sample is placed on the temperature-controlled bottom plate (100 mm diameter) of the measurement section. A measurement upper parallel plate jig with a transparent circular plastic plate at its bottom is then lowered vertically downward from above to sandwich the sample between two parallel plates and to set the sandwiched sample thickness as 3 mm. Second, the oscillatory shear strain is applied to a sample at the set amplitude and frequency of oscillatory shear strain. The bottom plate temperature can be controlled using a Peltier element. The temperature is set as 25 °C during oscillatory shear strain motion. It is then raised to 50 °C to promote uniform drying of the paste throughout the entire area. The sample shrinks vertically as well because of drying, causing the double-sided tape which adheres the jig to the plastic plate to peel off and causing the circular plastic plate and parallel plate jig to separate. At 2.0–2.5 h after the oscillatory shear strain was applied to a paste, formation of new desiccation cracks ended, at which time the desiccation crack pattern was imaged from the top.

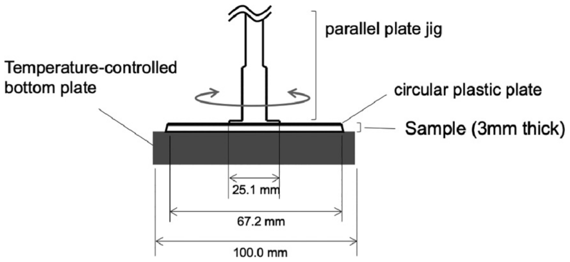

FIG. 1. Diagram of the experiment setup: A side view of the measuring section of the rheometer. After paste is placed on the bottom plate, the upper parallel plate jig, which is fixed with a circular plastic plate, is lowered vertically to sandwich a sample with a temperature-controlled bottom plate. After applying oscillatory shear strain, the temperature of the temperature-controlled bottom plate is raised from room temperature (25 °C) to 50 °C to promote uniform drying throughout the paste. The paste shrinks as it dries. After the double-sided tape which had fixed the parallel plate jig to the circular plastic plate is peeled off, we can observe the crack pattern through the transparent circular plastic disk by removing only the parallel plate jig.

We performed two experiments with different conditions of oscillatory shear strain. First, experiments were conducted to investigate the effects of amplitude and frequency of oscillatory shear strain on the memory effect of paste. We used pastes of solid volume fractions ϕ of 7.7% (which shows memory of flow in Ref. [8]), 10.0% (which is located at a boundary between the memory of flow and that of vibration in the morphological phase diagram of desiccation crack patterns reported in Ref. [8]), and 12.5% (which shows memory of vibration in Ref. [8]). For each solid volume fraction condition, the amplitude of oscillatory shear strain applied to a sample was varied from 100% to 3300%; the frequency was varied from 1.0 Hz to 18.0 Hz. In both cases, oscillatory shear strain was applied for 1 minute. The amplitude of the oscillatory shear strain was estimated on the circumference of the transparent circular plastic plate fixed at the bottom of the upper parallel plate jig and was expressed as a value relative to the sample thickness. For example, when the amplitude is 100%, the circumference of the plastic plate is subjected to the motion of oscillatory shear strain with the same amplitude of the circular arc as the sample thickness. Second, experiments were conducted to investigate the effect of the duration of oscillatory shear strain on each memory effect of paste, i.e., memory of vibration and that of flow. The cycle of oscillations given to a paste was controlled from 0.25 (shear deformation in one direction) to 20 cycles. In all experiments, three experiments were performed under the same experiment conditions.

III. ANALYSIS METHOD

We quantified the crack direction for all experimentally obtained data to discriminate between memories of vibration and flow. An earlier study proposed a method to calculate Shannon's information entropy S, expressed by Eq. (3.1), for experimentally obtained images to quantify cracks propagating in a particular direction [17]. Here, the input image is an m [pixel]$\times m$ [pixel] square image. n_i represents the number of pixels representing cracks in the ith row from the top when the image is regarded as a matrix. $N = \sum_i n_i$ denotes the total number of pixels representing cracks in the entire image. We introduce Shannon's information entropy S to evaluate the amount of information of a rare event in which many long cracks propagate in a particular direction, such as in a right and left direction along the ith row. If many long cracks propagate in the right and left directions, then the value of S defined by the following equation takes a small value, indicating that the right and left direction corresponds the direction of the anisotropic crack pattern:

$$S = -\sum_{i=1}^{m} \frac{n_i}{N} \log_2 \frac{n_i}{N}. \tag{3.1}$$

For an earlier study [17], a square experiment image is rotated to investigate along which direction cracks tend to propagate. Then, information entropy S is derived for each rotation angle. If there is anisotropy in the direction of the crack patterns, then S corresponding to that angle becomes smallest because a rare event is realized, which makes the cracks propagate more easily at the particular angle.

For this paper, the analytical method of Shannon's information entropy S used for an earlier study was optimized to be applicable to circular samples because the experiments were conducted on circular samples. First, we perform adaptive threshold binarization on numerically or experimentally obtained images [Fig. 2(a)]. Here is an example of an image analysis of a computer-generated random pattern, a Voronoi diagram. Next, a logarithmic polar coordinate transformation is performed to convert the circular image of Fig. 2(a) into a rectangular image of Fig. 2(b). For a circular experimentally obtained image of radius r, the analysis area for calculating S in the rectangular image after coordinate transformation is the white area from $0.5r$ to $0.95r$ [except for the gray shaded area in Fig. 2(a)]. Regions corresponding to the area from $0.95r$ to r are excluded because of the influence of boundary conditions. Regions between 0 and $0.5r$ are excluded because the amplitude of the oscillatory shear strain becomes smaller at regions close to the center of the circular sample (the amplitude of oscillatory shear strain is set to be proportional to the radius) and because the deformation of the image due to coordinate transformation is larger at the center. For the rectangular image of the analysis area, nine square images are cut out as shown in Figs. 2(b) and 2(c). For each image, the thinning and calculation of S are performed as in an earlier study. The derived S is normalized by the average of the S values for all angles. By analyzing a Voronoi diagram containing isotropic lines and plotting the information entropy as a function of angle [Fig. 2(d)], it was confirmed that the isotropic Voronoi pattern produces a flat graph in which no angle dependence appears. The angles shown in Fig. 2(c) correspond to the angles in the graph [Fig. 2(d)].

IV. RESULT

In this section, we present results of our experiments, in which we investigate the effects of amplitude and frequency of oscillatory shear strain on memory effects of paste in Sec. IV A and the effect of the duration of oscillatory shear strain in Sec. IV B.

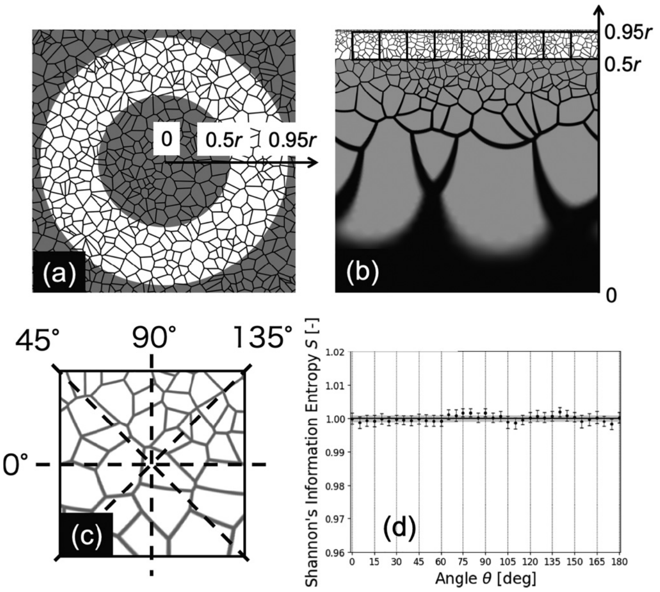

FIG. 2. Analysis results of the Voronoi diagram, which is an isotropic pattern. A computer-generated Voronoi diagram was used to simulate the isotropic crack pattern for analysis. (a) Binarized image of the Voronoi diagram. We applied image analysis to white areas; the shaded area is outside the analysis area. The range of the analysis was from $0.5r$ to $0.95r$, where r represents the radius of the circular image, i.e., the radius of an inscribed circle of the whole square image. (b) Rectangular images of (a) transformed into logarithmic polar coordinates. Arrows in the figure correspond to the radial direction indicated by the arrows in (a). For each of the three independent computer-generated data sets, nine squares which correspond to regions from $0.5r$ to $0.95r$ were cut from the analysis area to calculate Shannon's information entropy S, which represents the anisotropy of the crack propagation direction. (c) Enlarged view of one of the square areas in (b). (d) Results of Shannon's information entropy S presented as a function of the angle of rotation. The angles in (d) correspond to the angles along which we calculate Shannon's information entropy S, shown in (c). The value of S is derived for each angle with its standard deviation shown as an error bar for each angle. Shaded area plots the averaged S, plus or minus its standard deviation, calculated using data for all angles. In this figure, values of S with their error bars overlap the shaded area at all angles. Therefore, we can confirm that Voronoi diagram is classified as an isotropic pattern by the image analysis based on Shannon's information entropy S.

A. Effects of amplitude and frequency of oscillatory shear strain on the memory effect of paste

As a result of the experiments, we succeeded in obtaining desiccation crack patterns that reflect the memories of vibration and flow in the same solid volume fraction conditions. Here, we found that even a paste with a solid volume fraction of 7.7%, which was regarded as showing only memory of flow in Ref. [8], shows the memory of vibration when the amplitude of oscillatory shear strain is small. Furthermore, we found that even a paste with a solid volume fraction of 12.5%, which was regarded as showing only memory of vibration, exhibits memory of flow when the amplitude of the oscillatory shear strain is large.

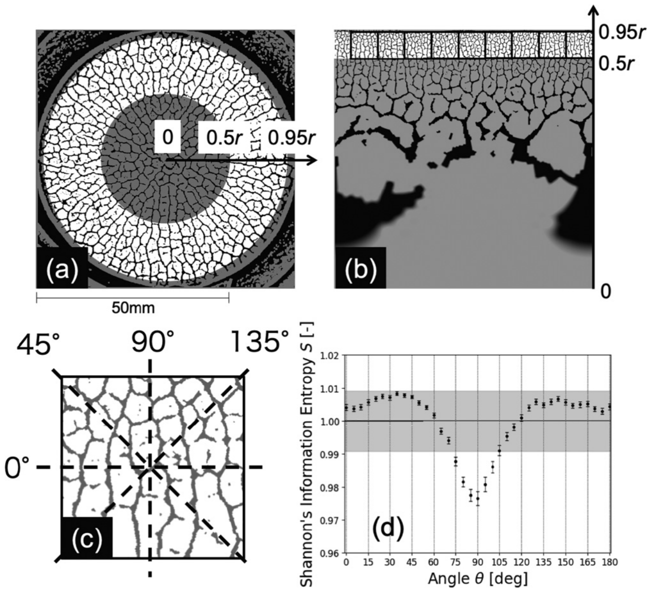

FIG. 3. Experimentally obtained images and analytical results for crack patterns of memory of vibration. The solid volume fraction of the paste was 7.7%. The amplitude of the oscillatory shear strain was 100% and its frequency was 5.0 Hz. (a) Binarized image of the experimentally obtained result. The paste was affected by oscillatory shear strain in the rotational direction. We applied image analysis to white areas; the shaded area is outside the analysis area, as in Fig. 2. (b) Rectangular image of (a) transformed into logarithmic polar coordinates, as in Fig. 2. For each of the three independent experimentally obtained data sets, nine squares were cut from the analysis area to calculate Shannon's information entropy S, which represents the anisotropy of the crack propagation direction. (c) Enlarged view of one of the square areas in (b). (d) Results of Shannon's information entropy S presented as a function of the angle of rotation. The angles in (d) correspond to the angles along which we calculate Shannon's information entropy S, shown in (c). The value of S is derived for each angle with its standard deviation shown as an error bar for each angle. Shaded area plots the averaged S, plus or minus its standard deviation, calculated using data for all angles. In this graph, the value of S is below the shaded area at the range of 90 ± 15°. Therefore, it is classified as a radial crack pattern corresponding to the memory of vibration.

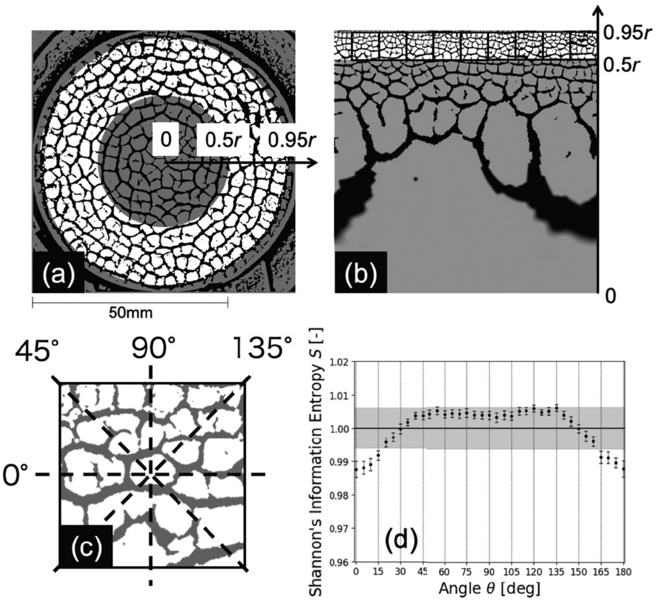

FIG. 4. Experimentally obtained image and analytical results for crack patterns of memory of flow. The solid volume fraction was 12.5%. The amplitude of the oscillatory shear strain was 1700% and its frequency was 1.0 Hz. (a) Binarized image of the experimentally obtained result. (b) Rectangular image of (a), transformed into logarithmic polar coordinates. (c) Enlarged view of one of the square areas in (b). (d) Result of Shannon's information entropy S presented as a function of the angle. In this graph, the values of S are below the shaded area at the ranges of 0(180) ± 15°. Thus, it is classified as a circular crack pattern corresponding to the memory of flow.

Based on the calculation of Shannon's information entropy S, we classified desiccation crack patterns into those induced by memory of vibration [radial desiccation crack pattern presented in Fig. 3(a)] and those by memory of flow [circular desiccation crack pattern presented in Fig. 4(a)]. Using the analytical method explained in Sec. III, nine images were prepared from three data obtained independently by experimentation, each cropped as shown in Figs. 3(b) and 4(b), and analyzed. These values of information entropy S were derived for each angle. Its mean square error is shown as an error bar [Figs. 3(d) and 4(d)]. The solid horizontal line denotes the mean value of information entropy S averaged over all angles. The shaded area represents a region around the averaged value of S over all angles within its standard deviation. If the graph is convex downward and has a minimum value around 90° corresponding to the radial direction, i.e., the vertical direction of the rectangular image in Fig. 3(b) after coordinate transformation, it is classifiable as a radial crack pattern (memory of vibration). If it is convex downward and has minimum values at 0° and 180° corresponding to the angular direction, i.e., the horizontal direction of the rectangular image in Fig. 4(b) after coordinate transformation, then it is classifiable as a circular crack pattern along a circular flow direction (memory of flow). For this paper, if the plot point of the average of information entropy S at a certain rotation angle was below the shaded area around the mean value of S within its standard deviation, then the value of information entropy was inferred as minimal at that angle. Because the rotation angle at which the minimum value is taken corresponds to the direction in which cracks tend to propagate, we can estimate which type of memory effect is realized.

In both experiments, the desiccation crack patterns which appeared when the paste was applied to oscillatory shear strain by a rheometer and then allowed to dry were classified as either memory of vibration or as memory of flow. From the crack pattern classification results, we show the morphological phase diagram of the desiccation crack pattern in Fig. 5 as a function of amplitude A and frequency f of oscillatory shear strain. The morphological phase diagram shows the same results for all three solid volume fractions of 7.7%, 10.0%, and 12.5% with which we conducted experiments, indicating a small effect of the solid volume fraction on the transition between memories of vibration and flow, contrary to earlier studies [8]. In all three solid volume fractions, a radial crack pattern appears corresponding to the memory of vibration

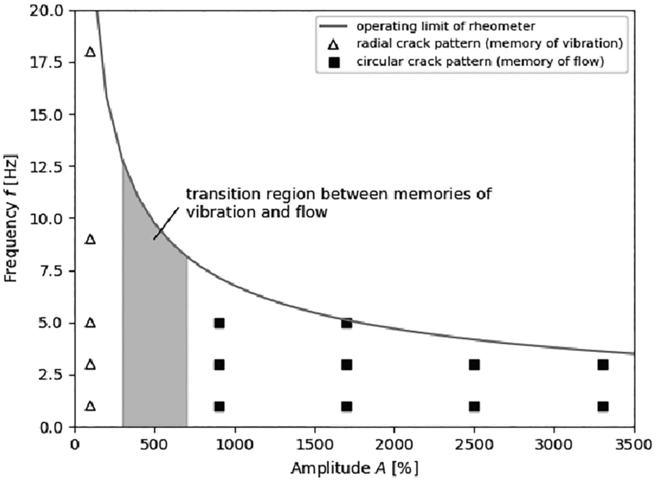

FIG. 5. Morphological phase diagram of desiccation crack patterns, which reflect the types of memory effects of paste, presented as a function of amplitude A and frequency f of oscillatory shear strain. The same phase diagram is obtained for all solid volume fractions of 7.7%, 10.0%, and 12.5%, indicating that there is no effect of solid volume fraction on the condition of transition between memories of vibration and flow under the experimental conditions in this paper.

under conditions of 100% amplitude. A circular crack pattern corresponding to the flow memory appears under conditions of 900% amplitude and higher of oscillatory shear strain. The boundary at which the transition from memory of vibration to memory of flow occurs is regarded as existing from 300% to 700% oscillatory shear strain. Future desiccation fracture experiments using a rheometer will enable us to define the boundary more precisely.

B. Effect of the duration of oscillatory shear strain on the memory effect of paste

An experiment was conducted using a rheometer to vary the duration of oscillatory shear strain applied to the paste. Thereby, we verified the number of oscillation cycles above which the memory effect appears. In the case of memory of flow, the experiment was conducted with a solid volume fraction of 12.5%, an oscillatory shear strain amplitude of 2500%, and a frequency of 1.0 Hz. In the case of memory of vibration, the experiment was conducted with a solid volume fraction of 12.5%, an oscillatory shear strain amplitude of 100%, and a frequency of 5.0 Hz. The duration of oscillatory shear strain that starts from the center position applied to the paste was varied from 0.25 to 20 cycles. Here we change only the value of the duration of oscillatory shear strain while the values of frequency and amplitude are fixed as described above, depending on which type of memory effects is investigated. Analysis was performed using information entropy S on experimental data with the different duration of oscillatory shear strain (Fig. 6). For each analysis result, the values of information entropy at 90º for memory of vibration and 0º for memory of flow were extracted and plotted for each duration of oscillatory shear strain. Smaller values of entropy S indicate stronger anisotropy in the crack direction at each angle. In the case of memory of flow, the value of S becomes smaller and memory appeared even when the paste was subjected to a

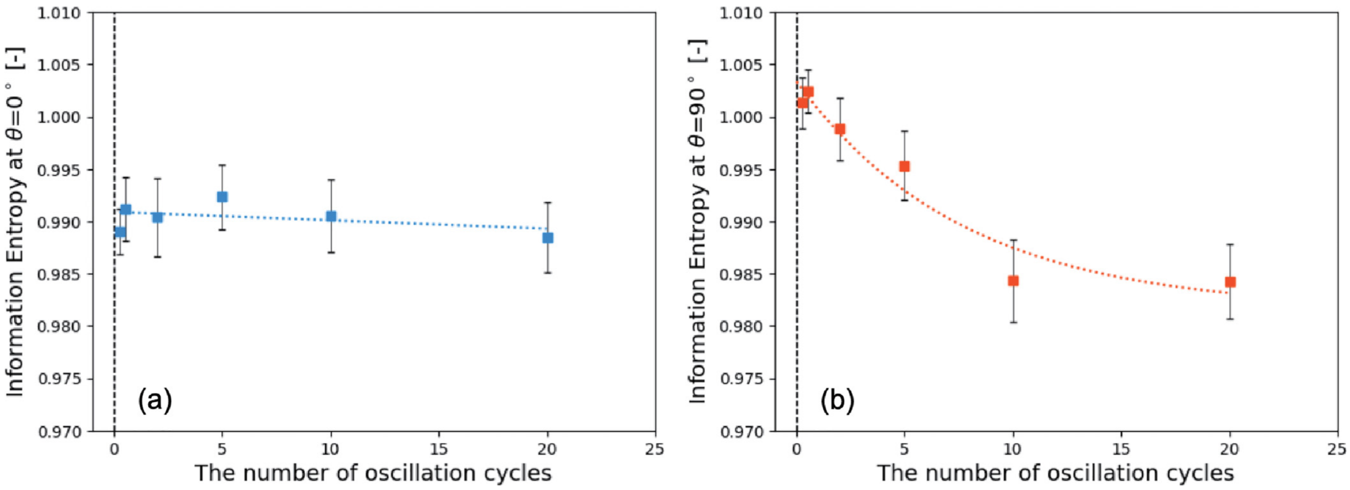

FIG. 6. Dependence of the strength of the anisotropy of the desiccation crack pattern on the number of oscillations. (a) Results for the case of memory of flow. The experiment was conducted with a solid volume fraction of 12.5%, an oscillatory shear strain amplitude of 2500%, and a frequency of 1.0 Hz. The dependence of the number of oscillations on the value of S at 0º, where S becomes small when the memory of flow appears, is plotted. Plots are approximated as linear functions using the least squares method. (b) Results for the case of memory of vibration. The experiment was conducted with a solid volume fraction of 12.5%, an oscillatory shear strain amplitude of 100%, and a frequency of 5.0 Hz. The dependence of the number of oscillations on the value of information entropy S at 90º, where S becomes small when the memory of vibration appears, is plotted. Plots are approximated as a sum of a constant value and an attenuating exponential function that converges to the constant value using the least squares method. In the case of memory of flow, S is small and anisotropy in the crack direction is observed even when the number of oscillations is 0.25 (shear deformation in one direction). On the other hand, in the case of memory of vibration, the value of S is larger than 1 for a small number of oscillations and no anisotropy in the direction of crack pattern is observed. As the number of oscillations increases, the value of S becomes smaller than 1 and the anisotropy in the crack direction becomes stronger. This indicates that multiple oscillations are required for memory of vibration, whereas no oscillations are required for memory of flow.

duration of 0.25 cycle oscillatory shear strain that starts from the center position (shear deformation in one direction, i.e., only in the counterclockwise direction). Thus, for the memory of flow, we need not apply an oscillatory shear strain to a paste: large shear deformation is sufficient for memory of flow. On the other hand, in the case of the memory of vibration, an oscillatory shear strain must be applied to a paste. No memory appears and the value of S remains to be larger than 1, when the paste was subjected to a duration of 0.25 cycle oscillatory shear strain. Furthermore, when the pastes were oscillated for durations of 2 to 5 cycles, weak memory of vibration appeared. When they were oscillated for durations of 10 cycles and more, a clear memory of vibration is apparent, which indicates that oscillatory shear strain with small amplitude is necessary for memory of vibration, whereas large shear deformation is sufficient for memory of flow.

V. DISCUSSION

In the earlier study's experimentation method of horizontally shaking a container of paste, the strain was induced spontaneously by the shaking condition, i.e., the solid volume fraction of the paste and the strength of the shaking applied to a container [8]. Next we can consider that the magnitude of this strain determined which memories would be realized. In other words, when the solid volume fraction is high, the deformation is small, even if the container is shaken at the same strength because of the strong plasticity and viscosity of water-poor paste. Even if the container is shaken at the same strength when the solid volume fraction is low, the deformation is large because of the weak plasticity and viscosity of water-rich paste. For this reason, an earlier study in Ref. [8] gave us the impression that a transition depends mainly on the change in the solid volume fraction. The proposed experimentation method, which includes control of the amplitude and the frequency of oscillatory shear strain using a rheometer, enables us to conduct experiments under controlled methods that have not been possible for earlier horizontal vibration experiments.

The setup used for experimentation in this paper is similar to the nonlinear theoretical model based on residual tension theories [13,14] in which tensile stresses occur uniformly in the paste under periodic boundary conditions. This theory suggests that oscillatory shear strain with small amplitude is necessary for memory of vibration. The experimentally obtained results of this paper are consistent with the nonlinear theoretical model. An earlier study suggested that memory of flow is formed microscopically as a loose network formed by short-range interparticle attraction that can be stretched under large shear deformation [18]. Although no theory explaining the mechanism of memory of flow has been proposed, the conditions for the transition were clarified by the present paper. Its elucidation by future studies is anticipated.

Comparing Figs. 3(a) and 4(a), the sizes of the fragments of desiccation crack patterns in the experimental images with a solid volume fraction of 12.5% of Fig. 4(a) tend to be larger than those with a solid volume fraction of 7.7% of Fig. 3(a). This is thought to reflect the relationship that the average cell area is proportional to the square of the thickness of the sample [3,4]. Even if the thicknesses of the pastes are set to be 3 mm when pastes suffer oscillatory shear strain, after drying, the thickness of the sample with a solid volume fraction of 12.5% is thicker than that with a solid volume fraction of 7.7%. This is the main reason why the cell sizes in Figs. 3(a) and 4(a) are different. There may be other influences such as amplitude and frequency of oscillatory shear strain, which will be discussed in the future.

An effect of frequency of oscillatory shear strain were not observed in the transition between memories of vibration and flow within our experimental results, but possibly affects the strength of memory. The memory of vibration at 100% amplitude shown in the morphological phase diagram (Fig. 5) tended to be weak at a lowest frequency of 1.0 Hz. As the frequency increases, the memory of vibration becomes stronger. In the case of memory of flow, there is no frequency dependence under the conditions of the phase diagram shown in Fig. 5. However, when shear deformation with shear rate D [1/s] and time t [s] in one direction was applied to a paste with a solid volume fraction of 12.5% for condition (1) of 25[1/s] and 1[s], condition (2) of 2.5[1/s] and 10[s], condition (3) of 0.25[1/s] and 100[s] and allowed to dry, memory of flow appeared for condition (1), while for the other conditions memory of flow did not clearly appear. This suggests that for both memory of vibration and flow, the strength of the memory depends on frequency and shear rate. Further experiments using a rheometer to control the oscillations applied to the paste will reveal more details in the future.

VI. CONCLUSIONS

To summarize, we proposed a method of experimentation for desiccation crack formation using a rheometer to investigate conditions of transitions between memories of vibration and flow. This method enabled us to conduct experiments while controlling the amplitude and frequency of the oscillatory shear strain on the paste, which had not been controlled for earlier studies. Using Shannon's information entropy to analyze the anisotropy of desiccation crack patterns, we found that the transition between memories of vibration and flow is determined by the amplitude of the oscillatory shear strain applied to the paste. Furthermore, results show that, although it is necessary to apply oscillatory shear strain for more than a certain time to memorize the vibration, it is not necessary to apply oscillatory motion to memorize the flow. In fact, only a large shear strain exceeding a certain value is sufficient for the memory of flow. Therefore, the findings revealed that oscillatory shear strain with a small amplitude is necessary for memory of vibration, whereas large shear deformation is sufficient for memory of flow. Our experimentally obtained results are expected to elucidate the essential mechanism of how pastes remember their respective motions.

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