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REVERSIBLE MOISTURE MOVEMENTS OF FIRED CLAY BRICKS USED IN HISTORIC MASONRY STRUCTURES

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ABSTRACT

Historic masonry structures, especially world heritage and cultural property buildings, need to be maintained to preserve their present appearance and avoid deterioration. The maintenance approach will vary depending on their usage. One of the most vital and fundamental characteristics for keeping buildings in good condition in the long-term is the control of moisture movements in the building materials.

The purpose of the present study is to confirm if there is any moisture movement in fired clay bricks and determine the potential magnitude of such movement. This is one of the essential properties that need to be determined in order to predict future performance. The brick specimens used in this study were obtained from old brick buildings, established in the Meiji and the Taisho eras, the period during the height of Japanese modernization (18th – 19th century). The reversible moisture movement and mass change in the brick specimens were examined by immersion in water and drying in air. The results show that movement was found in all the bricks. The movement in the Taisho bricks were smaller than the ones in the Meiji bricks, which is likely due to the improvement of manufacturing methods changing from cast to extrusion moulding. The amplitude of the movement was by and large related to the firing temperature of the brick.

KEYWORDS: historic masonry structures, world heritage, fired clay brick, moisture movement, control

INTRODUCTION

In the middle of the Meiji era, 1867-1911, the production technique for fired clay brick was improved leading to the start of full-scale production in Japan. After the Great Kanto earthquake in 1923, the brick production rate decreased and the new completion of the structure dropped sharply, but many masonry structures, including world heritage and cultural assets, still remain in Japan.

Movements of building materials under daily stress caused by wetting, drying, warming, and cooling may lead to damage of building materials, and even, in some cases, collapse of the structure. In order to establish a method to assess the preservation needs for masonry structures, the properties of the masonry units need to be identified. This paper investigates the potential movements in fired clay bricks used in older masonry structures so that its effect on these structures can be determined. In general, the moisture movements are much smaller than in cementitious building materials because they are produced by being fired in kilns. The moisture movements and weight changes during wetting and drying under a constant temperature and humidity were examined for different types of fired clay brick taken from historic structures, including the Japanese world heritage and cultural sites.

By the way, although the external walls of masonry structures sometimes have finishing, such as plastering and painting, not all structures are exposed to all weathers, such as, wind, rain, shine, snow, and so on.

METHOD

Table 1 lists the fifteen different types of fired clay bricks that were examined. Thirteen of these bricks were obtained from buildings built in the Meiji and Taisho eras; the other two were modern bricks. Brick 13, a refractory brick, is different from the rest. Test specimens, 10 mm wide, 10 mm high, and 20 mm long, were cut from each brick.

All experiments were carried out in the lab where the room temperature was twenty degrees centigrade with humidity sixty percent. As illustrated in figure1, each specimen was placed in the water for three days, and then was exposed to air for twenty-five days from the first to the third cycle, and during the fourth cycle the specimen stayed in the water for twenty-eight days without being exposed to the air. Based on the results obtained in the previous experiments [1], the cycle was limited also to four in this study.

Table 1 - List of the Specimens

Specimens	Moulding method	(Production year)
1 ONODA Bottle Kiln (An establishment)	Cast moulding	(1883)
2 ONODA Bottle Kiln (Upper side)	Cast moulding	(1889)
3 ONODA Bottle Kiln (Hunter brick)	Press moulding	(1889)
4 ONODA Bottle Kiln (Repaired)	Extrusion moulding	(1893)
5 Former ATSUTA Arms Manufactory	Extrusion moulding	(1904)
6 Former NAGOYA Higher Technical School 1	Extrusion moulding	(1907)
7 Former NAGOYA Higher Technical School 2	Extrusion moulding	(1907)
8 Chimney (ASO Cement Factory)	Extrusion moulding	(1910) (Imported from Germany)
9 Former YASUDA Nail Manufactory	Extrusion moulding	(1912)
10 Former Commercial Exhibition Hall 2	Extrusion moulding	(1915) (South face)
11 Warehouse (TOHO Gas Company)	Extrusion moulding	(1923)
12 Bottle Kiln 1 (Former MIKAWA Cement Company)	Press moulding	Unknown (White colour) (Fireproof brick)
13 Bottle Kiln 2 (Former MIKAWA Cement Company)	Not confirmed	Unknown (Brown colour)
14 Brick 1 (Present commercial for comparison)	Extrusion moulding	(Orange colour)
15 Brick 2 (Present commercial for comparison)	Extrusion moulding	(Red colour)

Meiji era Taisho era Present

Polyester foil strain gages, 10 millimetres long and 0.9 millimetres wide with adhesion and waterproof coating on the surface of each specimen were set, as shown in Figure 2. The static warp measurement instrument was used in order to measure the strains automatically. When the specimens were immersed in water, the measurement interval was thirty minutes only for the first day of each cycle, and thereafter it was changed to the one hour interval at every cycle. The interval where the specimens were exposed to the air was the same as when they were placed in the water. Here, the point from three days after the specimens were placed in the water was called "surface dry" and the strain at this point was called the "expansion strain." The point that the specimens were exposed to the air after twenty-five days was called "air dry," and the strain at this point was called the "shrinkage strain". Furthermore, the strain at the end of the fourth cycle was called the "last strain", and the difference between the expansion strain and the shrinkage was called the "amplitude".

At the same time, the mass change ratio was measured. The ratio was measured once an hour for the first eight hours where the specimens were placed in the water. Then, the measurement was carried out once a day up to the last day of every cycle. The mass change ratio was obtained through the value of the mass at any time divided by the weight at the first surface dry point.

RESULTS

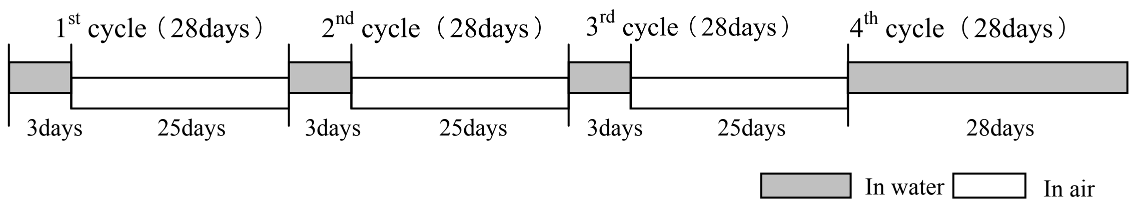

Figure 1 - Procedure of Experiment

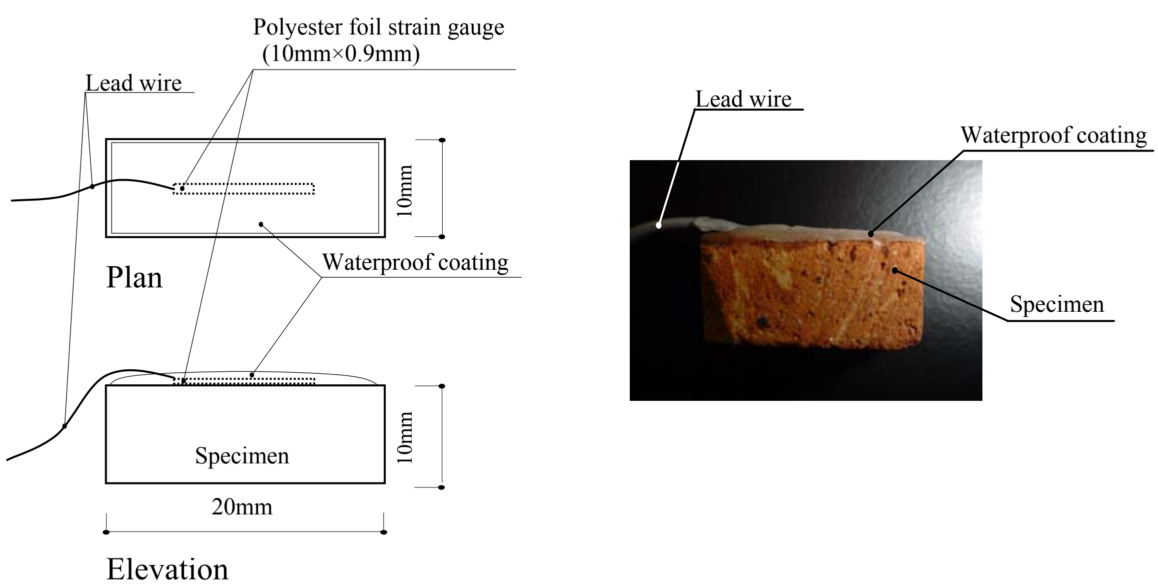

Figure 2 - Specimen

Figure 3 shows the moisture movements with all specimens sorted by the era of production. All specimens expanded in water and contracted when exposed to air.

Figure 3 (a) shows the four types of ONODA bottle kiln of the Meiji era. For Specimen 1, the maximum shrinkage strain when exposed to the air was 0.23mm/m and the expansion strain was 0.11mm/m in the water from the first to the third cycle. After that, the expansion strain reached up to 0.27 mm/m at the end of the fourth cycle. All kinds of strain of Specimen1, namely the amplitude, the expansion strain at the point of surface dry, and the shrinkage strain at the point of air dry, were larger than those found in other ONODA specimens. Both the expansion and shrinkage strains of Specimen 1 moved up as the cycle times progressed, and their movements became unstable, as illustrated in Figure 3. For Specimen 2, the shrinkage strain was 0.12 mm/m and the expansion one, 45. At the end of the fourth cycle, the last strain was 0.13 mm/m, which was smaller than that found in Specimen 1. This suggests that the movement slightly crossed over the horizontal axis in the direction of expansion. Specimen 3 shows the air-dry strain, 0.07mm/m, and the surface-dry strain, 0.04 mm/m. At the end of the fourth cycle, the surface

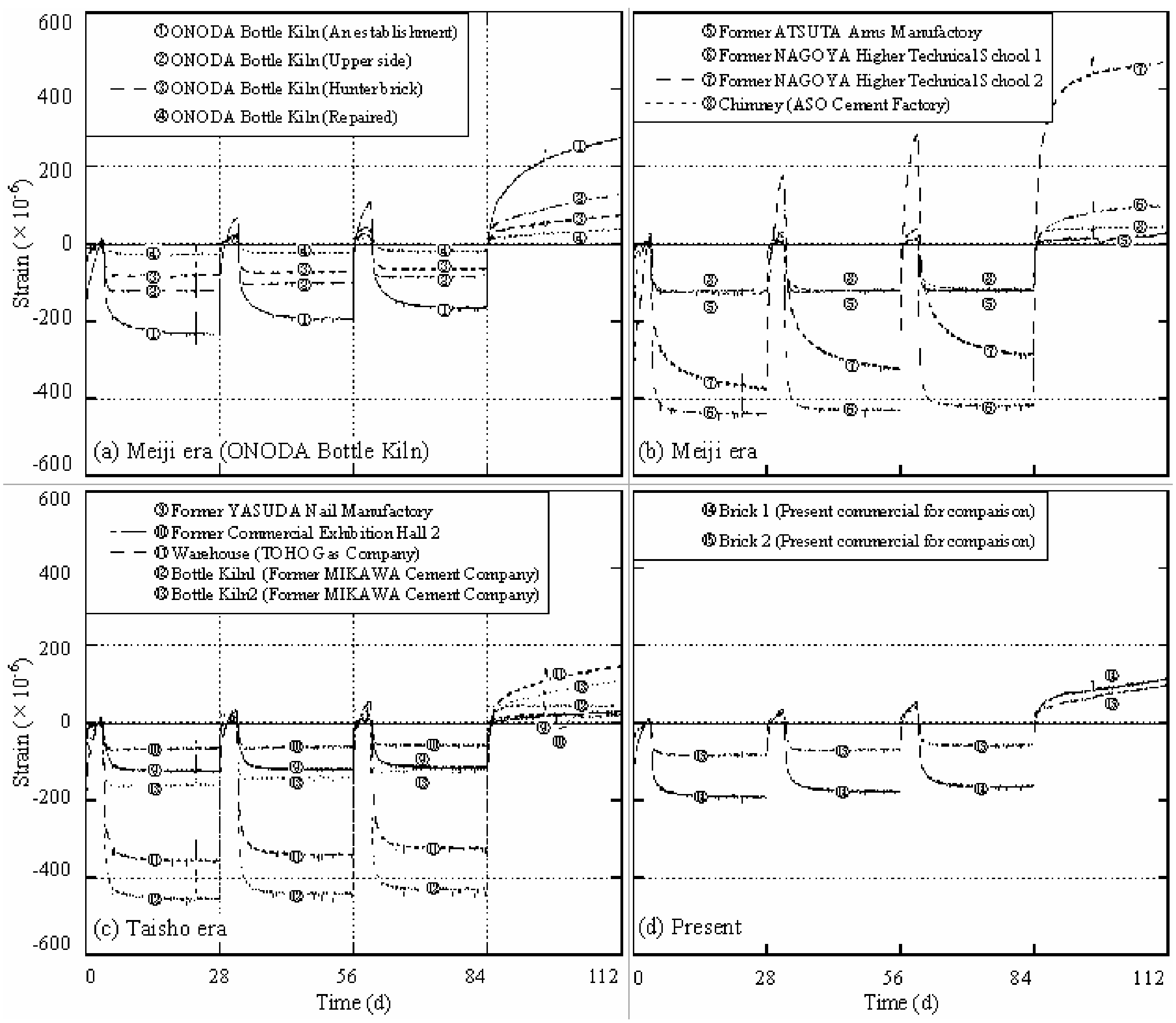

Figure 3 - Moisture Movements

strain was 0.07 mm/m, which is clearly smaller than in Specimen 1. Specimen 4 demonstrates the smallest strains: Shrinkage strain was 0.03 mm/m, expansion strain, 0.022 mm/m, and the amplitude, 0.52 mm/m, at the end of the fourth cycle. The movements along with moistening and drying repetition were stable in Specimens 2 and 4.

Figure 3 (b) displays the moisture movements of four other kinds of bricks produced in the Meiji era. The shrinkage strains of Specimens 5 and 8 were almost the same; approximately 0.13 mm/m correspondingly. However, the expansion strains in Specimens 5 and 8 were different, 0.041 mm/m and 0.014 mm/m respectively, which were smaller than those found in Specimens 6 and 7. The values of expansion at the end of the third and fourth cycles for Specimens 5 and 8 were also about the same, and the movements did not depend on moistening and drying repetition. For Specimen 6, the expansion strain was 0.039 mm/m, the shrinkage strain, 0.44 mm/m, the last strain, 0.1 mm/m, and the amplitude, 0.48 mm/m. For Specimen 7, the expansion strain was 0.29 mm/m, the shrinkage strain, 0.37 mm/m, the last strain, 0.47 mm/m, and the amplitude 0.4 mm/m. The movements of these two bricks did not change according to moistening and drying repetition but the amplitudes did.

Figure 3 (c) illustrates the strain values of five kinds of brick manufactured in the Taisho era. Specimen 10 was a part of a brick which came from the wall of the world heritage, Genbaku Dome (Hiroshima Peace Memorial Hall) in Hiroshima, Japan, established in 1915 and later atomic bombed. Its expansion strain was 0.012 mm/m, the shrinkage strain, 0.013 mm/m, and the last strain, only 0.003 mm/m. The expansion strain of Specimen 11 was 0.025 mm/m, the shrinkage strain, 0.07 mm/m, and the last strain, 0.02 mm/m. Specimen 9 had the expansion strain of 0.053 mm/m, shrinkage strain, 0.07 mm/m, and the last strain, 0.15 mm/m. Likewise, the expansion strain of Specimen 12 was 0.032 mm/m, the shrinkage strain, 0.46 mm/m, and the last strain, 0.05 mm/m. The expansion strain of Specimen 13 was 0.043 mm/m, the shrinkage strain, 0.16 mm/m, and the last strain, 0.11 mm/m. The moisture movements of all these specimens in the Taisho era crossed over towards the direction of expansion a bit. The amplitudes of Specimens 10, 11, and 13 were a little smaller, but those of Specimens 12 and 13 were rather larger. At the end of the fourth cycle, the last strains of Specimens 9 and 13 continuously increased.

Figure 3 (d) presents each strain value of the bricks that were produced recently. Although Specimens 14 and 15 were expected to have the smallest movement, they had roughly the same strain characteristics as other specimens except for Specimen 4 which is manufactured in the Meiji era. The rationale for this is presumably that the main usage of these bricks is not for structures but for gardening.

Figure 4 indicates the results of mass change ratio. Figures 4 (a), (b), (c), and (d) comprise similar characteristics, as seen in Figure 3. The ratios at the air dry point for those specimens in the Meiji era were about 14% larger than those in the other eras except for those of ONODA bottle kiln. Especially the value of Specimen 4 was the smallest (7%) among all the specimens including the recent productions whose manufacturing method has been much improved. Over the course of time, the ratios of all specimens decreased: the values of the specimens in the Meiji era, excluding Specimen 4, were from 14 to 21%, those in the Taisho era, 8.6 to 14.6%, and those built recently, 9.4 to 11.6%. After the specimens were immersed in water, the values at the end of the fourth cycle hardly varied regardless of what era the specimens came from.

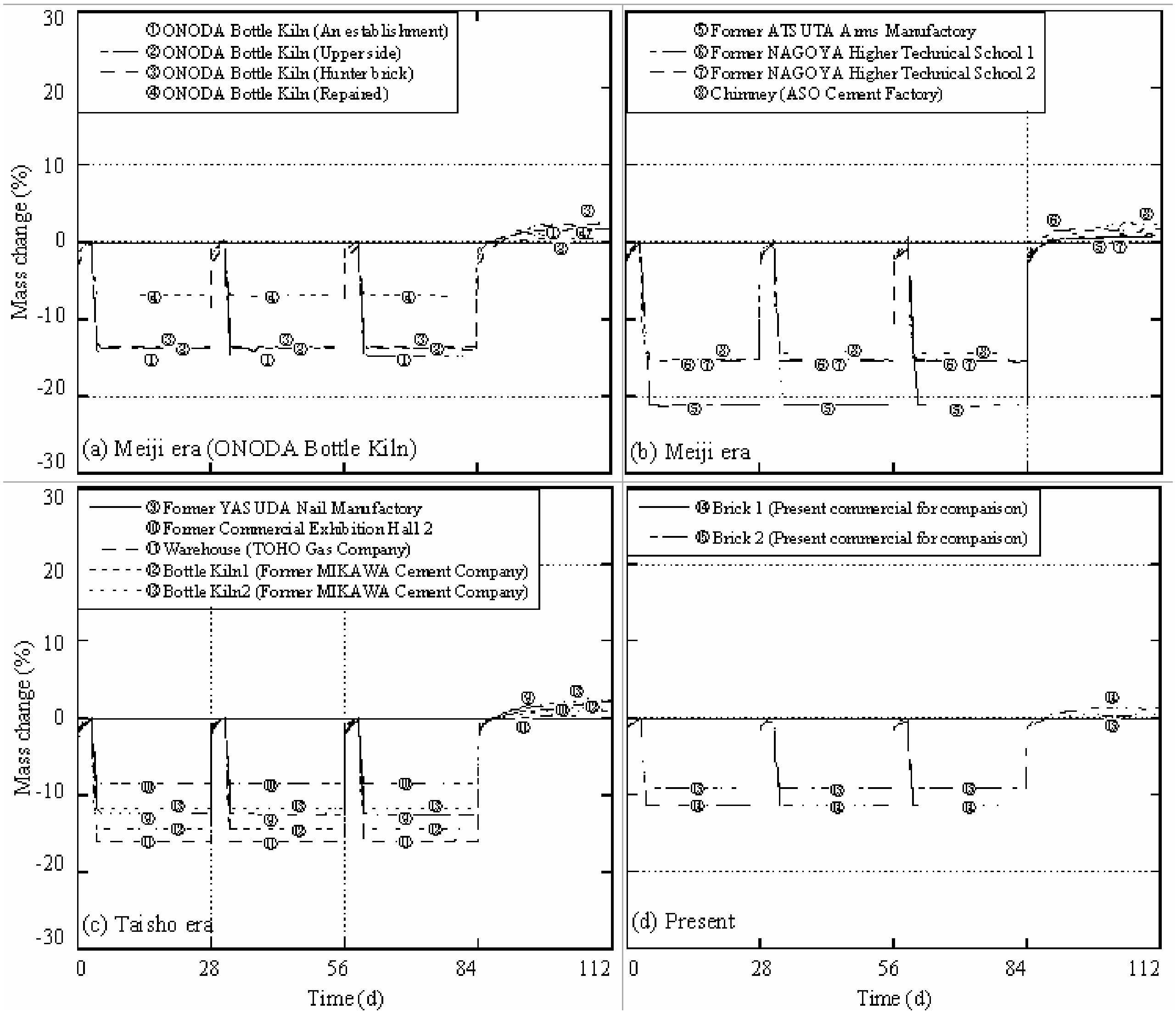

Figure 4. Mass Change Ratio

DISCUSSION

It was well recognized that the bricks which came from slag, cement, and so forth generally undergo moisture movement. The more the movement of cementitious building materials is, the less the life span of the structures composed of these materials due to frost damage. Furthermore, it is said that based on the simulation, in light of controlling crack occurrence in the body of the structure, the desirable amplitude is under 0.2 mm/m.

On the other hand, the advanced production technique for fired clay roofing tile built in Japan had avoided structural problems due to the weather. Using the method was crucial for buildings to maintain high durability against the long-term exposure to weather.

This suggests that there was no regulation and criterion on moisture movements of fired clay tile and bricks in the Japanese Industrial Standard. Therefore, it is uncertain whether the movements in the fired clay bricks existed or not.

Given these results, this study confirmed that the bricks of masonry structures, including Japanese cultural assets, had moisture movements and that some movement was to keep expanding in water.

Hereafter, the brick manufacturing methods in the Meiji and the Taisho era are discussed based on the findings of moisture movement in this study.

The quality and kind of clay minerals have a significant influence on the quality of fired clay bricks. Additionally, great attention should be paid to many technical issues in the process of manufacturing bricks in order to reduce strains, since the durability of buildings is strongly affected by the manufacturing method of the bricks. For example, pores in bricks benefits the durability of the building of the bricks but capillaries do not, due to the potential of causing frost damage to the bricks. Sintering of minerals in clay, which is generated by firing, helps reduce the water absorption and moisture movement [2]. Moreover, bricks that are continuously immersed in water or the clay that is not firmly fired causes water to intercalate in the layers of the clay, leading to the expansion of the clay, which may end up with the brick having strains. Thus, it is important that the water content in clay and an adequate firing temperature in accordance with the fireproof degree caused by the clay mineral are the essentials to produce bricks with great durability as well as to reduce strains in them.

Owing to the usage of Specimens 1, 2, 3, and 4 that were the kiln of cement manufacturing, its endurance against high temperature was emphasized. Since Specimen 1 contained much kaolin, which made the standing temperature high, mullite should have been found when it was fired over 1350 degrees centigrade. However, the presence of the mineral could not be confirmed. It is assumed that the maximum temperature, over 1350 degrees centigrade, in a rising kiln could not be generated at the adequate temperature level for sintering [3]. That is probably why Specimen 1 had the largest moisture movement and mass change ratio which kept expanding in the water, compared to other specimens taken from the same kiln.

This tendency was not found in Specimens 2 and 3, although the firing temperature was low due to the different clay mineral contained in each specimen. However, mullite was found in Specimen 4. It was fired at over 1350 degrees centigrade, and this gave the specimen the smallest shrinkage strain among all units of this experiment. This finding implies the improvement of brick manufacturing method including moulding and firing.

Furthermore, the tendency of reduced expansion strain in the water was similar to that of shrinkage strain. The large shrinkage strain and expansion strain gave the brick many damages and this points out the inadequate firing temperature of the brick. If this were true, Specimens 5, 8, 10, 11, 14, and 15 would have been fired at the adequate temperature fitting for the raw clay material and those of 6, 7, 9, and 12 would not.

In considering the mass change ratio carefully, there were two kinds of bricks that had considerable mass change ratio among other specimens. One had a large mass change ratio although it was fired at an adequate temperature. Another also had that, but was fired at an inadequate temperature.

Additionally, if the amplitude was less than 0.2 mm/m, the stress and strain caused between building materials or components should have been small and problems in the structures should also have been likely to be avoided in the case of concrete [4]. As the amplitudes of some units used in this experiment were 0.3 mm/m or 0.4 mm/m, the destruction of the masonry structures might be conceived by moistening and/or drying.

Nevertheless, because joints of mortar lie in every brick of masonry structures, this study may not have provided enough data to discuss the propriety of the standards for the long-term building preservation. Thus, it is necessary to gather more data regarding the characteristics of prisms in order to establish standards for evaluating the long-term performance of historic masonry structures.

CONCLUSIONS

In order to establish standards for evaluating the long-term performance of historic masonry structures made with fired clay brick, the brick properties need to be known. An important property is movement due to changes in moisture content. In this study, short-term moisture movement was evaluated for fifteen different bricks, thirteen taken from older structures dating back to 1883, and two from modern brick production.
The following findings were obtained:

1. There was expansion when the fired clay bricks were placed in water and shrinkage when they were subsequently dried in air. This occurred for all the bricks including those fired at high temperatures. The maximum strain of amplitude was about 0.5 mm/m and minimum strain was 0.052 mm/m. These data were obtained in the specimen in the Meiji era.
2. Appropriate firing temperatures corresponding to the mineral composition of the clay should be taken into account to reduce the moisture movement.
3. The durability of a building as well as the moisture movements in the bricks were based on its manufacturing method rather than the manufacturing period, such as the Meiji and Taisho eras or the contemporary period.

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