JCS Journal of Conservation Science

Research Article

Clarification the Current Situation of Deterioration and Its Causes of Modernization Heritage Built with Bricks in Japan: A Case Study of Long-Term Monitoring Investigation at Sarushima Battery, Yokosuka, Japan

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Received July 16, 2022
Revised August 17, 2022
Accepted August 23, 2022

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Journal of Conservation Science
2022;38(4):265-276

https://doi.org/10.12654/JCS.2022.38.4.02

pISSN: 1225-5459, eISSN: 2287-9781

ABSTRACT A long-term monitoring investigation at Sarushima Battery (Kanagawa, Japan), which is one of the modernization heritages was conducted from 2017.06 to 2020.12. The investigation of the temperature and relative humidity (RH), measurement of the amount of brick decay, and X-ray diffraction analysis of the brick decay was conducted to understand in detail the environment in which the historical brick structure, the state of deterioration, identify the factors of deterioration. Furthermore, it was discussed whether the suitability of these investigation methods for assessing the status, identifying the level of deterioration and the factors that led to deterioration at the historical brick heritages.

It was found that the brick deterioration at the site progressed especially in two periods: in April, and from June to August. These periods coincided with the period when the RH inside the structure decreased, and the Toyo-gumi bricks were in the process of absorbing moisture. Several different types of salts were detected in brick decay, especially thenardite, which is considered highly hazardous and destructive during periods when the amount of brick decay increased.

Therefore, the RH in the structure and the salts present in the bricks were identified as one of the factors in the deterioration of the bricks at the site. The methods used in this study are appropriate as the initial survey methods for investigating the current conditions and identifying the causes of deterioration because it is possible to understand the environment within the modernization heritages, grasp the details of deterioration progression, and identify the characteristics of deterioration progression and its factors through long-term investigation using the simple methods.

Key Words Brick, Environmental survey, Modernization heritage, Salt weathering, XRD

1. INTRODUCTION

In recent years, Japan has been promoting the preservation and utilization of buildings called “Modernization Heritage” in the country. According to the Agency for Cultural Affairs, modernization heritages in Japan refer to buildings and facilities related to the industry, transportation, and civil engineering that played a major role in Japan’s modernization from the end of the Edo period (the 1850s ~ 1860s) to the World War II period and contributed to the modernization of Japan (Agency for Cultural Affairs, 2019). Therefore, modernization heritages are important cultural assets for understanding the history and culture of modernization in Japan. Since Wieliczka and Bochnia Royal Salt Mines in Poland was registered as a UNESCO World Heritage site in 1978, modernization and industrial heritage sites have been registered as world cultural heritages around the world. In Japan, the Tomioka Silk Mill and Related Sites was registered as a world heritage site in 2014, and Sites of Japan’s Meiji Industrial Revolution: Iron and Steel, Shipbuilding and Coal Mining which consisting of 23 components across several areas were registered as a world cultural heritage in 2015 (Jodai *et al*., 2020). Thus, interest in modernization heritage is growing with the inscription of several modernization heritage sites on the UNESCO World Heritage list in Japan. Most of those are brick or concrete buildings and structures. However, a survey on modernization heritage conducted by the Tokyo National Research Institute for Cultural Properties in 2017 reported that brick structures account for approximately 30.9% of the total non-timber modernization heritage and have the highest number of registered buildings (Tokyo National Research Institute for Cultural Properties, 2017).

However, brick modernization heritages are often exposed to outdoor conditions, and those sites in Japan are located in diverse or unique environments, such as urban areas and coastal areas. Therefore, deterioration of bricks due to salt weathering caused by the surrounding environment has been observed in various parts of Japan (Figure 1). Studies have been conducted on the phenomenon of salt weathering, and the mechanism of occurrence of the phenomenon. Also, the characteristics of salt and the degree of danger have already been elucidated. It is essential to understand the deterioration of brick heritage sites in detail through investigation of the current conditions and to clarify the deterioration factors to consider conservation treatment methods for deterioration of bricks caused by salt weathering. Long-term field investigation over several years is necessary to elucidate these deterioration factors. However, it is currently unclear what investigation methods are appropriate for this purpose.

In this study, a long-term monitoring investigation for three years and six months at Sarushima battery (Kanagawa, Japan) was conducted. Sarushima battery is one of the modernization heritage sites exposed to a unique environment. In the monitoring investigation, temperature and relative humidity (RH) in the brick structure were investigated, the amount of brick decay from a brick wall was measured, and X-ray diffraction analysis (XRD) of the brick decay was conducted. The aim of this monitoring investigation was threefold: to understand in detail the environment in which the historical brick structure was exposed, the current state of deterioration of the structure, and to identify the factors of deterioration. Furthermore, the suitability of these monitoring investigation methods as the initial survey methods for assessing the current status and highlighting the deterioration of historical brick heritage sites was discussed.

2. TOYO-GUMI BRICK IN SARUSHIMA BATTERY

Brick production in Japan started at the end of the Edo period (1853 ~ 1868) and it is considered to have been introduced by foreign engineers. In the Meiji period (1868 ~ 1912), the bricks produced in Japan were widely used in the construction of lighthouses and foreign settlements, sewage systems, and factories. Furthermore, domestic brick production began to expand in various parts of Japan in the 1870s. (Saitou, 2007)

Toyo-gumi bricks are one of the bricks that was produced in Japan during the Meiji period, manufactured by Toyo-gumi, which was founded around 1882 (Figure 2). The Toyo-gumi bricks excavated so far are distributed in the size range of 108～115 mm × 57～61 mm at the headers, and

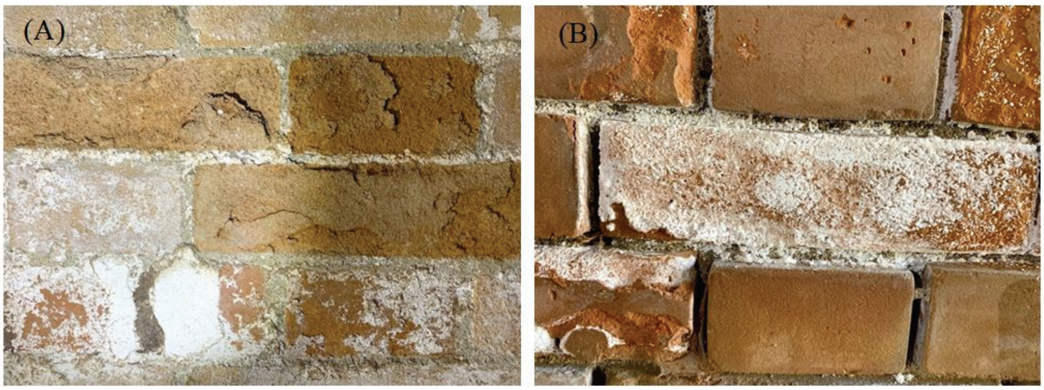

Figure 1. (A) Brick surface with peeling, and (B) Bricks with salt weathering.

Figure 2. Toyo-gumi brick.

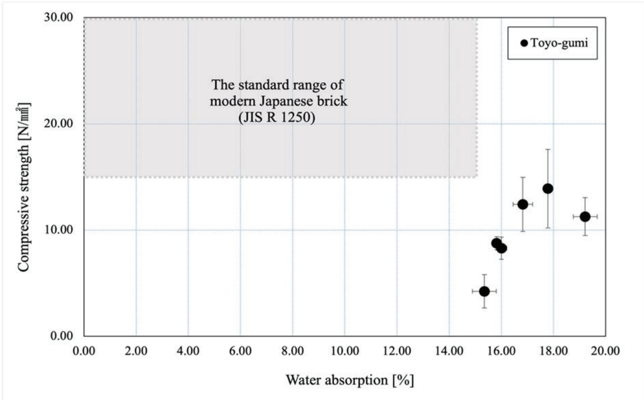

Figure 3. The physical property of Toyo-gumi bricks.

223～227 mm at the stretchers, and they have a light orange color (Yokosuka city, 2002). The main material of Toyo-gumi Brick was clay collected in Nishio City, Aichi Prefecture, and that it was manufactured by mixing the sand containing mineral fragments of quartz, potassium feldspar, biotite, and granite rock fragments with the main material. Additionally, Cement mortar was used to join the bricks. The cement mortar was made by mixing cement and sand in a certain ratio and adding water, with one volume of cement and three volumes of sand being the standard mix ratio. The cement mortar used at the Sarushima Battery contained shell fragments. It was indicating that sea sand was used (Yokosuka city, 2002). The results of physical property tests of Toyo-gumi bricks indicated that the bricks had a water absorption rate of 17.0 ± 1.6% and a compressive strength of 9.5 ± 3.8 N/mm^2. It is specified that modern Japanese ordinary bricks must have a water absorption rate of 15.0% or lower and a compressive strength of 15.0 N/mm^2 or higher in the current Japanese standard for brick (JIS R 1250). Therefore, it has been found that Toyo-gumi bricks manufactured in the Meiji period do not meet the standards of modern Japanese bricks and they had varied physical properties (Figure 3). Furthermore, the results of thermal analysis (thermogravimetry and differential thermal analysis) and X-ray diffraction (XRD) of the Toyo-gumi bricks suggested that The Toyo-gumi bricks had been ignited at less than 900°C. However, an endothermic reaction was observed between 450°C to 600°C in the differential thermal analysis (DTA). For this reason, it indicated that the firing temperature of the central part of the brick did not reach even 500°C(Fukami, 2019).

Toyo-gumi bricks with the above characteristics were used as building bricks at the Sarushima battery located in Yokosuka City, Kanagawa, Japan. Sarushima Battery is a coastal battery constructed between 1881 and 1884, and it was registered as an officially-designated historical site in 2015. Sarushima Island where the battery was constructed is located approximately 1.7 km off Yokosuka Port (Yokosuka city, 2014), and the island is surrounded by the sea. Brick structures constructed using different brick masonry methods such as Flemish bond and Dutch bond (Figure 4), remain on the site and are considered one of the most important sites for understanding modern politics and civil engineering in Japan.

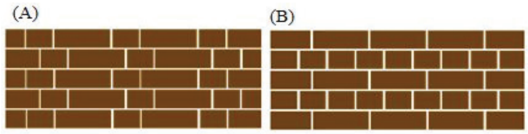

Figure 4. (A) Flemish bond and (B) Dutch bond. (Created by the author.)

3. METHODS

Based on the physical properties of Toyo-gumi bricks which are one of the Japanese historical bricks, the on-site monitoring investigation was conducted for three years and six months from 2017.06. ～ 2020.12. The aims of the monitoring investigation are through observing the brick walls, measuring the temperature and relative humidity (RH) inside the brick structure, and measuring the amount of brick decay from the brick wall, to understand the current state of deterioration and to clarify deterioration factors. In addition, a qualitative analysis using XRD was conducted to identify the materials contained within the brick decay.

3.1. Investigation spot

The investigation was conducted in a brick structure with particularly significant deterioration among the brick structures at the site. The brick structure investigated was the second floor of the north building of an ammunition depot on the south side (f1-2) (Figure 5, 6). The interior of f1-2 measures 4.28 m × 13.56 m. The structure of f1-2 is a tunnel vault with a height of 3.67 m from the floor to the top of the vault. The ceiling is plastered over bricks, but some of the plaster was peeling. Although there are no windows

Figure 5. Map of Sarushima. (Yokosuka city, 2002.)

inside f1-2, there is a window near the entrance that connects to the outdoors. Since there is no door at the entrance of f1-2, it is possible that outside air is flowing in through this window and the passageway from the tunnel to inside f1-2. The partition wall parallel to the south wall and the west wall is constructed with Dutch bond. On the other hand, the east and west walls are constructed with a Flemish bond. According to Yokosuka City's report, it was reported that the east and west walls were the original construction walls and the partition wall was added after the construction of the batteries since Flemish bond was a brick masonry method found in structures built in the Meiji 10s and Dutch bond was used in structures built in the Meiji 20s and later. Moreover, the partition wall parallel to the west wall is considered to have been constructed to prevent moisture from entering the ammunition depot and to discharge moisture from the inside to the outside. In f1-2, a large collapse of the south wall was observed, and the deterioration of the brick surface on the east wall was observed (Yokosuka City, 2014). The area of f1-2 where the survey was conducted is currently closed to the public. Therefore, people do not enter this area except researchers.

3.2. Environmental investigation

Temperature and relative humidity were measured during the environmental investigation. Onset Hobo U23-001 outdoor temperature/ relative humidity data logger was used

Figure 6. (A) The entrance of f1-2 from tunnel, (B) The window near the entrance of f1-2, (C) inside of f1-2, (D) The east wall in f1-2, and (E) 2D diagram of inside f1-2. (Created by the author.)

as the measurement device. The device was placed in the center of f1-2 at a height of approximately 100 cm from the floor (Figure 6E). Temperature and RH measurements were recorded every 30 minutes. The temperature and RH data logger was placed inside the solar radiation shield to obtain accurate data inside the structure. For comparison, the other temperature and RH data logger was also installed outdoors and recorded every 30 minutes intervals.

3.3. Survey of brick decay from a brick wall

3.3.1. Measuring the amount of brick decay

The amount of brick decay from the brick wall was measured by placing three trays, each with a bottom area of 140 cm^2 in contact with the brick wall (Figure 7). The trays were made of polypropylene, cut to a width of 20 cm and a depth of 7 cm (Dispo-tray manufactured by As One corporation). These trays were placed near the right edge of the east wall (Figure 6D.) The measurement was conducted from 2017.06. ~ 2020.03. The brick decay was collected once every month or every two months and weighed. The amount of brick decay was converted to the amount of it per 30 days in each measurement period because of the variation in the measurement period in the month of the investigation.

3.3.2. XRD analysis

XRD analysis was used to determine if the materials that have caused the deterioration were contained in the brick decay collected at each period during the amount of brick decay measurement. A Bruker AXS D8 ADVANCE was used for XRD analysis. The brick fragments were crushed for analysis, and the crushed brick samples were placed in a glass holder for measurement. The measurement conditions were set that the cathode was set to Cu, the voltage to 40 kV, and the current to 40 mA. The measurement range was 5° to 90° with a measurement speed of 0.1 sec/step in 6000 steps.

4. RESULTS AND DISCUSSIONS

4.1. Environment in the Brick Structure on Sarushima battery

The temperature and RH results measured inside f1-2 and outdoors from 2017.06. ~ 2020.12 were shown in Table 1. Moreover, the temperature and RH behavior inside f1-2 was shown in Figure 8. As a result of the monitoring investigation, the temperature and RH inside the brick structure have not changed significantly over the past three years, and that the same temperature and RH behavior was maintained every year. The temperature inside the structure is 1°C to 2°C lower than outdoors, and the range of fluctuation is slightly smaller. However, the RH is higher than that of the outdoors, and the RH reached 100% from June to August, when both temperature and RH were at their highest. Thus, the environment inside f1-2 was found to be high humidity environment.

Moreover, a climograph was created from one year of temperature and RH data for 2018 to understand the annual temperature and RH behavior(Figure 9). The colored markers show the temperature and RH distribution for each month in f1-2, and the dotted line shows the outdoor temperature and RH distribution range. As expected, the temperature is

Figure 7. Measuring the amount of brick decay.

Table 1. Results of the temperature and RH from 2017.06 ~ 2020.12

Year		2018.01~2018.12		2019.01~2019.12		2020.01~2020.12	
Place		f1-2	Outdoor	f1-2	Outdoor	f1-2	Outdoor
Temperature [°C]	Average	15.7±5.67	16.9±7.11	15.4±5.53	17.1±6.53	15.8±5.19	16.2±5.66
	Max	24.3	27.37	24.23	27.85	23.9	24.53
	Min	6.79	6.76	8.25	7.83	9.17	8.76
Relative Humidity [%]	Average	92.9±7.73	76.1±9.93	91.1±8.64	76.9±10.17	91.2±8.06	78.4±9.31
	Max	99.99	89.17	100	92.85	99.99	94.1
	Min	78.23	59.79	73.17	56.03	77.15	63.56

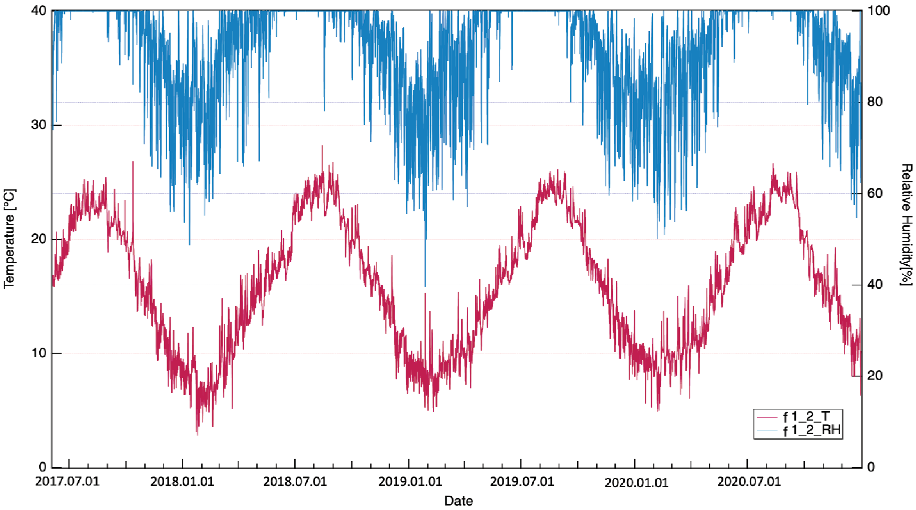

Figure 8. Behavior of the temperature and RH in f1-2.

generally lower, and the RH is higher than that of the outdoors. The temperature and RH are lowest in the winter months of January and February and gradually increase after March which is the spring season in Japan. The RH reaches 100% during the rainy season from June to July and remains high humidity until September, followed by a gradual decrease in both temperature and RH until December. Additionally, this behavior was linked to the outdoor temperature and RH behavior. These results indicated that the temperature and RH in f1-2 changed in tandem with the outdoor temperature and RH behavior, but the environment became slightly cooler and more humid than outdoors. As mentioned earlier, since there is a window near the entrance of f1-2 for outside air to enter f1-2, the temperature and RH behavior in f1-2 seems to be affected by the outside air.

Secondly, the effect of the environment on the moisture absorption and desorption characteristics of the Toyo-gumi brick under the environment in f1-2 was discussed. Figure 10 shows the result of water adsorption/desorption test of Toyo-gumi bricks conducted under 25°C conditions with the cooperation of Environmental System Research Laboratory, Hokkaido University, Japan. In the case of Toyo-gumi bricks, it was found that when the RH exceeded 80%, moisture absorption proceeded, and the amount of moisture contained in the bricks increased. The moisture was then released with the RH decreases. During the moisture release process, little moisture was released from the brick until the RH reached 90%, but moisture was released when the RH fell below 90%. Considering this characteristic together with the temperature and RH environment in f1-2, it is considered that the bricks are in the process of absorbing moisture from February to June, when the RH begins to increase to 75% or more and then, from June to September, when the RH in f1-2 reaches 100%, the bricks retain the moisture they have absorbed. The moisture in f1-2 is considered to be released from October to January, when RH begins to decrease, but due to the moisture absorption and desorption characteristics of Toyo-gumi bricks indicated that they retained more moisture during the moisture desorption process than during the moisture absorption process, even under the same RH environment. Therefore, during the moisture release process, from October to January, although the RH in f1-2 begins to decrease, the RH is still above 90% until November, suggesting that little moisture is released, and that moisture is retained in the bricks. Based on the above results, measurements of moisture content on the brick surface using a moisture meter were conducted from 2018.08. ~2019.12 as an additional survey in this study. Measurements were conducted on a portion of the wall (104.5 cm high, 245 cm wide, total number of bricks was 215) where the amount of brick decay was measured. The results showed that the moisture content of the bricks changed with the seasons. Furthermore, some bricks had a low moisture content of less than 3% and others had the high moisture content of over 20% were mixed on the wall. Additionally, the condition of the brick surfaces was observed. The bricks which the moisture content frequently changed, and the bricks with a moisture content higher than 12% when it rose showed peeling and collapse on the brick surfaces. As these results, the temperature and RH environment in f1-2 seem to be affected by the outside air, and that this environment influence the moisture content change and surface collapse of the bricks.

4.2. Current deterioration of Toyo-gumi bricks and its factors

Deterioration of the bricks in f1-2 based on the environment inside f1-2 and the moisture absorption and desorption characteristics of the Toyo-gumi bricks was discussed. The behavior of the amount of brick decay from the brick wall and RH in f1-2 were shown in Figure 10. The amount of brick decay in f1-2 was found to increase in April, which corresponds to the spring season in Japan, and from June to August, which corresponds to the rainy season to the summer season. In particular, the rapid increase of the amount of brick decay in June 2018, was attributed to the presence of detached brick decay approximately 1.5 cm in diameter in addition to bricks that had collapsed in powdery form within the collapsed bricks. Moreover, the period when the amount of brick decay increased matched with the period when RH in f1-2 increased. However, the tray installation method needs to be improved because when the trays were checked during the survey in July 2018, we found that the trays had tipped over and were not accurately measured. On the other hand, the amount of brick decay tended to decrease from August onward and during the winter season, and few brick decay were observed from the brick walls, especially in January and February of each year. Furthermore, the period of the decrease in the amount of brick decay matched with the period of the decrease in RH. According to the results of an investigation which was conducted in 2002 by Oguchi at the kiln of the Shimotsuke Brick Production Company, Gunma, Japan, the weight of brick decay was

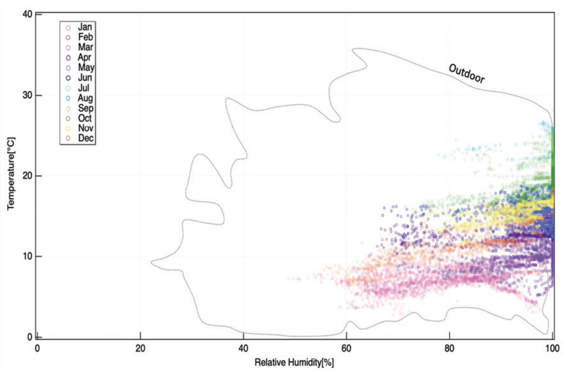

Figure 9. Behavior of the temperature and RH for each month in f1-2.

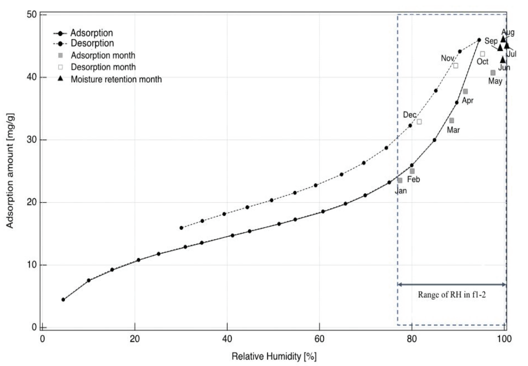

Figure 10. Water adsorption/desorption isotherm of Toyo-gumi brick.

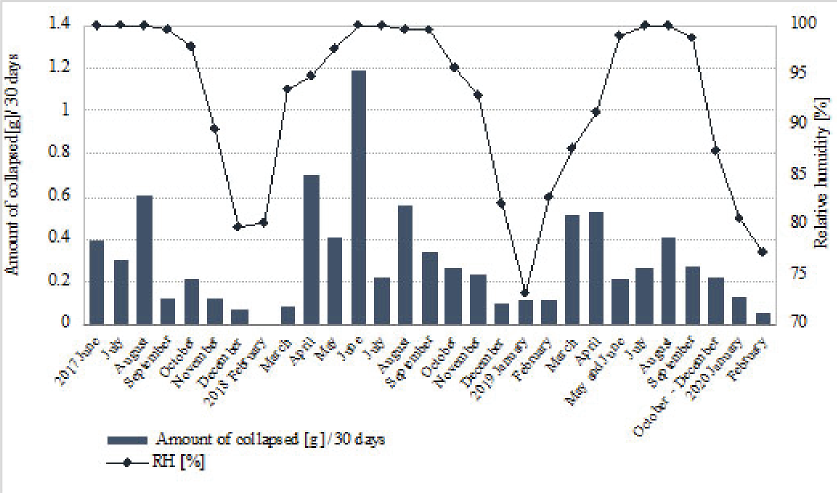

Figure 11. Behavior of the amount of brick decay and RH in f1-2.

reported to increase during period from early spring to late summer, when brick decay is triggered at the periods of increased RH and tidal dissolution of existing salts in the bricks (Oguchi *et al.,* 2002). It has been pointed out that this is because the salts on the surface have absorbed the moisture in the air and become heavier, which adsorbs the brick parts at the time they collapse from the surface and encourages them to collapse together (Kuchitsu, 2005). When considered in conjunction with the moisture absorption and desorption characteristics of Toyo-gumi bricks, the period from March to April, when the amount of brick decay increased the most, matchs with the period when the bricks were in the moisture absorption process and the RH in f1-2 reached over 90%. The correlation coefficient between RH and the amount of brick decay was calculated and found to be positive at 0.5. For these reasons, a relationship was found between the increase in RH in the structure and the collapse of the brick surface.

In addition, substances detected in collapsed brick fragments from brick wall at every month were shown in Table 2. In addition to feldspar and mica minerals, which are thought to have been the main constituents of the bricks, Gypsum ($CaSO_4 . 2H_2O$) and Calcite ($CaCO_3$) were detected in the brick fragments. Thenardite (Na_2SO_4), Epsomite ($MgSO_4 \cdot 7H_2O$), and Sylvite (KCl) were detected in addition to previously detected salts in April and May 2018, when the amount of brick decay increased. One possible reason why mirabilite was not detected in the brick decay at this time is that it has been converted to thenardite during the mailing process from the time the brick decay was collected until it was analyzed in the laboratory. Thenardite and epsomite are soluble salts and are known to be more destructive and dangerous than other salts. Specifically, thenardite undergoes a phase change to mirabilite ($Na_2SO_4 . 10H_2O$) when the RH changes from 70% to 100% at 20℃. The solubility of mirabilite is known to be strongly dependent on temperature, and this salt is unstable at temperatures above 32°C. However, when the temperature is lower than 32°C, the range of RH at which the salt is stable expands as the temperature decreases. For example, it has been reported that the transition to mirabilite can occur at 25°C and 80% RH, or even at 0°C and 60.7% RH (Flatt, 2002). Moreover, the pressure generated during this phase change is found to be 50 MPa. (Winkler and Wilhelm, 1970). Since 1 MPa is the pressure at which a weight of about 102 tons acts on an area of 1 m in length and 1 m in width, the 50 MPa generated during the phase change of thenardite to mirabilite is a very large pressure, and it is the pressure that is sufficient to destroy the bricks. In other words, if the environment meets the above temperature and RH conditions, the pressure generated by the phase change of thenardite will promote the fracture of the bricks. Temperature and RH in f1-2 where the brick decay was measured, fluctuates throughout the year in the range of approximately 7℃ to 28℃, 50%RH to 100%RH. That is the environment inside f1-2 meets the conditions for a phase change from thenardite to mirabilite, and it is

Table 2. Substances detected in collapsed brick fragments

Year	Month	Moisture absorption/ desorption conditions of bricks	Detected materials						
2017	June	Retention	Feldspar	Mica	Gypsum ($CaSO_4 \cdot 2H_2O$)	Calcite ($CaCO_3$)			
	July	Retention	Feldspar	Mica	Gypsum	Calcite			
	August	Retention	Feldspar	Mica	Gypsum	Calcite			
	September	Retention	Feldspar	Mica	Gypsum	Calcite			
	October	Desorption	Feldspar	Mica	Gypsum	Calcite			
	November	Desorption	Feldspar		Gypsum				
	December	Desorption	Feldspar		Gypsum				
2018	March	Adsorption	Feldspar						
	April	Adsorption	Feldspar			Calcite	Thenardite (Na_2SO_4)	Epsomite ($MgSO_4 \cdot 7H_2O$)	Sylvite (KCl)
	May	Adsorption	Feldspar	Mica	Gypsum	Calcite		Epsomite	Sylvite
	June	Retention	Feldspar	Mica	Gypsum	Calcite			Sylvite
2019	March	Adsorption	Feldspar		Gypsum	Calcite			
	May	Adsorption	Feldspar	Mica	Gypsum	Calcite			
	July	Retention	Feldspar		Gypsum	Calcite			
	September	Retention	Feldspar	Mica	Gypsum	Calcite			
	December	Desorption	Feldspar		Gypsum	Calcite			
2020	February	Adsorption	Feldspar	Mica	Gypsum	Calcite			

suggested that the repeated occurrence of this phenomenon may have accelerated the deterioration of the bricks due to salt weathering. However, this mechanism of accelerated brick deterioration due to salt hydration needs to be tested empirically, but this study did not include this verification. Therefore, this test needs to be done as a future issue.

In addition, as mentioned earlier, the moisture absorption and desorption characteristics of Toyo-gumi bricks was considered in conjunction, the period from March to April, when the amount of brick decay increased the most, coincided with the period when the bricks were in the process of absorbing moisture. Furthermore, it is possible that the RH in the brick structure reached over 90%, which may have increased the amount of moisture absorbed by the bricks, and the salts contained in the bricks may have become heavy and collapsed together with the brick parts.

For these reasons, it is found that the one possible factor causing deterioration of the bricks at the Sarushima Battery is the RH in the brick structure and several types of salts contained in the bricks. In addition, it was identified that brick decay at the Sarushima Battery is triggered during the spring season, when the bricks absorb moisture from the air, and during the summer season, when they retain a large amount of moisture inside the bricks. However, the results of the temperature and RH investigations and the site conditions suggested that airflow from the outside air may have been one of the factors that affected the collapse of the bricks. Therefore, there is a need to investigate airflow in the structure and their influence on the collapse of the brick surfaces in future surveys. Additionally, it is necessary to identify the origin of the salts as a future task because this survey did not reach the identification of the origin of the salts contained in the bricks.

5. CONCLUSIONS

The long-term monitoring investigation at the Sarushima battery, where one of the modernization heritages built with bricks exposed to the unique environment was conducted to understand the state of deterioration of the bricks and to elucidate the causes of the deterioration. The main conclusions derived from this study are as follows.

- Temperature and RH investigation, measurement of brick decay from the brick wall, and XRD analysis of the collapsed brick fragments were conducted as the long-term monitoring investigation methods. The results of the temperature and RH investigation showed that the temperature and RH inside the brick structure changed in tandem with the outdoor temperature and RH behavior, but the environment was slightly cooler and more humid than the outdoor environment. Furthermore, it was found that the RH reached 100% during the rainy season from June to July and remained at this high humidity level until September.

- The measurements of the amount of brick decay indicated that the amount of brick decay at the Sarushima Battery increased most in April, which is the spring season in Japan, and from June to August, which corresponds to the rainy season and summer season in Japan. These periods coincided with the period when the RH inside the brick structure decreased, and the moisture absorption and desorption characteristics of the Toyo-gumi bricks indicated that the bricks were in the process of absorbing moisture.
- It is possible that the amount of water contained in the bricks increased during the moisture absorption process, and the salts contained in the bricks became heavier and collapsed together with the brick parts. Therefore, it is found that the RH in the brick structure is one of the factors causing deterioration of the bricks. This study also identified that brick decay at the Sarushima Battery is triggered during the spring season, when the bricks absorb moisture from the air, and from the rainy season to the summer season, when they retain a large amount of moisture.
- Several different types of salts were detected in the collapsed brick fragments. In particular, thenardite was detected during the period when the amount of brick decay increased, and the environment within the brick structure matched the conditions for the phase change from thenardite to mirabilite to occur, suggesting that the repeated occurrence of salt phase changes may have accelerated the deterioration of the bricks due to salt weathering and is the other factors deteriorating the bricks at the Sarushima Battery.
- However, since we were unable to clarify the effects of other factors such as air flow in the structure on the deteriorated bricks and the origin of salt, which was identified as one of the deterioration factors, it is necessary to consider new survey methods and conduct additional surveys to investigate these factors.

Therefore, the methods used in this study are appropriate as the initial survey methods for investigating the current conditions and identifying the causes of deterioration, because it is possible to understand the environment within the modernization heritages, to grasp the details of deterioration progression, and to identify the characteristics of deterioration progression and its factors through long-term investigation using the simple methods. The knowledges of this study can be used to suggest a good temperature and RH environment for the preservation of brick heritages and a time ideal for conducting conservation treatments in the future. Since the origin of salts, one of the degradation factors did not determine in this investigation, it is necessary to conduct additional survey to determine the origin of salt, and to find more effective conservation methods for heritage sites once the origin of salt is clarified.

ACKNOWLEDGEMENTS

This study was made possible by the generous cooperation of the Yokosuka City Board of Education in conducting field investigations, sampling, and providing brick materials. The moisture adsorption/desorption test of brick samples was conducted in cooperation with Environmental System Research Laboratory, Division of Human Environmental Systems, Graduate School of Engineering, Hokkaido University. We would like to take this opportunity to thank all those who contributed to this study.

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