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Relationship between Environmental Conditions and Algal Growth on the Exterior Walls of the Ninna-ji Temple, Kyoto

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Abstract

We can find that many building facades are discoloured black and/or green. Some previous studies showed that the soiling of building facades is caused by the growth of airborne algae. The algal growth is strongly influenced by the water supply, including the rain, the condensation, and high humidity. However, the influence of the other environmental factors, such as the solar radiation, the temperature, and the wind on the algal growth, has not been investigated yet. The relationship between the algal growth and the environmental factors on the building facades which the algae grow for long term has not been investigated. Therefore, we quantified the relationship between the algal growth and the environmental factors based on the field survey on the algal growth in Kyoto City and the measurement on the building facades at Kusyo Myojin Shrine, Ninnna-ji Temple in Kyoto, Japan.

Kusyo Myojin Shrine was constructed from 1641 to 1647. Some parts of the roof, walls and the painting were repaired from 2004 to 2006. However, the building facades have already been colored black by the algal growth. To investigate the cause of the soiling by the algal growth, the ambient conditions, and surface temperature and humidity of walls were has measured since 2011. The soiling state of the walls was investigated by the L* values and the photographs of the walls.

As a result, the order of the L* values of the wall surfaces agreed well with the darkness of the photographs. We concluded that the algal growth and death on the wall surface were affected by the surface temperature of the wall.

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Keywords: Soiling of Wall; Airborne Algae; Solar Radiation; Surface Temperature; L* value

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1. Introduction

Many building facades become discoloured black and/or green owing to airborne algae. The discolouration appears on walls, under window frames, on signboards and around cracks in the wall surface. Sometimes, entire wall is blackened by the algae. Previous studies reported that many of these discolourations are caused by algal growth on the wall surface [1,2]. One of the primary issues related to algae growth is the esthetic impact to buildings and other structures. Even a few years after construction, algae can grow on exterior walls. The claddings and paints intended to prevent the algae from adhering cannot be used by all buildings. Furthermore, the effects on the environment of the chemicals in the claddings and paints are of concern. The algal growth is strongly affected by the presence and supply of water to the surface [3,4]. The extent to which it is also influenced by other environmental factors such as temperature, humidity, solar radiation and rainwater has not been clarified. This study, aimed to identify locations that were prone to algal growth and determine the relationship between algal growth and environmental conditions. We surveyed the status of soiling on exterior building walls in Kyoto City and measured soiling and surrounding environmental conditions at the Kusyo Myojin Shrine, Ninna-ji Temple in Kyoto, Japan.

Most airborne algae survive for several hours inside desiccators over a $CaCl_2$ solution (at 30%-33% RH). There is little probability that the algae die because of the drying. The optimum temperature for most algae is 18°C - 25°C. The optimum temperature for *Stichococcus sp.*, the airborne algae, is 21°C and that for *Chlorella luteoviridis* is 24°C. When the airborne algae are exposed to about 35°C, the growth rate becomes zero in most cases [5]. When they are exposed to temperatures over 40°C for a few minutes, the number of the surviving cells decreases [6,7,8,9,10,11,12]. When exposed to extremely high temperatures, the cells die rapidly. If they are returned to the optimum environment after exposure to high temperatures, the algae never grow again.

2. Field survey in Kyoto City

2.1. Survey outline

The survey in Kyoto City was conducted to identify on which parts of the building walls the algae grow and which environmental factors affect algal growth. To study the effects of the local environment, a route passing through water areas (river and pond), green areas and urban areas was chosen. The surveyed area is along the east-west corridor of Ichijo street and Nakadachiuri street running from Kyoto University on the east to Senbon street on the west (Fig. 1). Surveys were conducted in October and November of 2008 and May of 2013. Photographs of exterior walls were taken with a digital camera in order to compare soiled and unsoiled areas. The surrounding environment, materials and the status of walls were documented. On the basis of a review and analysis of the photographs, the extent of soiling on the walls and causes of algal growth were estimated.

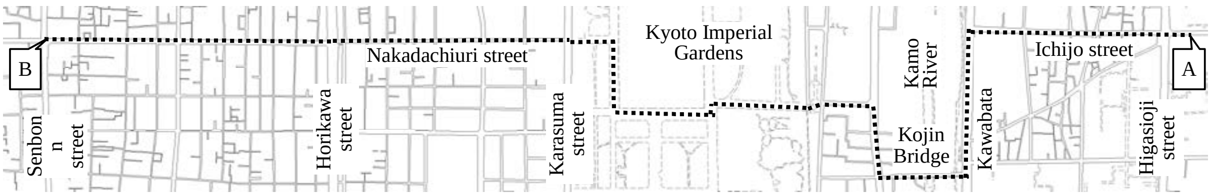

Fig. 1. Survey area.

2.2. Survey results

Soiling of walls by algae was documented on 322 of the 435 buildings surveyed. Because only the parts of the walls visible from the street were surveyed, and roofs, back faces and spaces between buildings were not surveyed, we assumed that more building walls were discoloured. Table 1 lists the building types surveyed and Table 2 lists the number of floors in each building. The numbers of stores and offices were greater than those of the houses because the survey area was located primarily in the urban areas of Kyoto City (Table 1). About 90% of the buildings were low- or medium-rise buildings with five stories or less (Table 2). Most of the south walls received the solar radiation, while north walls received only the defused radiation, because the survey was carried out along the relatively wide streets running in an east-west direction. East and west walls were frequency shaded by the adjacent buildings. The status of algal soiling was documented on buildings within 50 m of water areas, those within 50 m of green areas, and those in the urban area from Senbon street to Karasuma street (Fig. 1). Based on a comparison of algal soiling on these areas, the effect of the regional environment on algal growth appears to be very slight (Fig. 2a).

Soiled walls were very often exposed to rainwater. However, soiling was also observed on parts of the walls that were not exposed to rainwater. Therefore, we categorized soiled areas into two classes depending on the source of moisture contributing to algal growth.

- (1)Wall parts directly exposed to rain (where rainwater hits, flows or is stored) (Fig. 3a). Soiled areas extending down from the roof or the lower frame of windows was often observed. The amount of the rainwater impacting a horizontal plane or window frame was more than that on vertical planes (walls). Algae growth appeared to be concentrated along the course of running rainwater. Soiling was also observed on the lower parts of the walls near the horizontal plane (ground or horizontal eaves). Rainwater does not dry quickly, splashes against the wall and is absorbed by the existing algae. Soiling was also observed around and under clacks, where rainwater can be absorbed and stored there.
- (2)Wall parts that rarely receive rainwater (Fig 3b). In these areas, soiling was observed under eaves that were not exposed to rain and where the water flow was not apparent. In some cases, an entire wall was discoloured. The source of moisture for algal growth in these areas appeared to be water vapour in the atmosphere or moisture absorbed by the wall.

The relationship between the number of soiled buildings, the soiled areas and the directions is shown in Fig. 2b. About 70% of the buildings with algal soiling had areas directly exposed to rainwater, whereas 30% has areas that rarely received rainwater. In both cases, the largest number of soiled areas occurred on north walls, at a frequency of approximately two times that of south walls. Materials surveyed building walls are shown in Fig 2c. In both cases, the soiling occurred the most frequency on painted walls, followed by tiles walls. In Category 1 buildings, the

Table 1. Building types.

Building type	Number of buildings
Housing	136
Stores and offices	195
Apartments	48
Schools and public facilities	31
Temples, shrines and churches	6
Others	19

Table 2. Number of stories of buildings.

Number of stories	Number of buildings
Forth story and less	399
Fifth story and over	18
Others	18

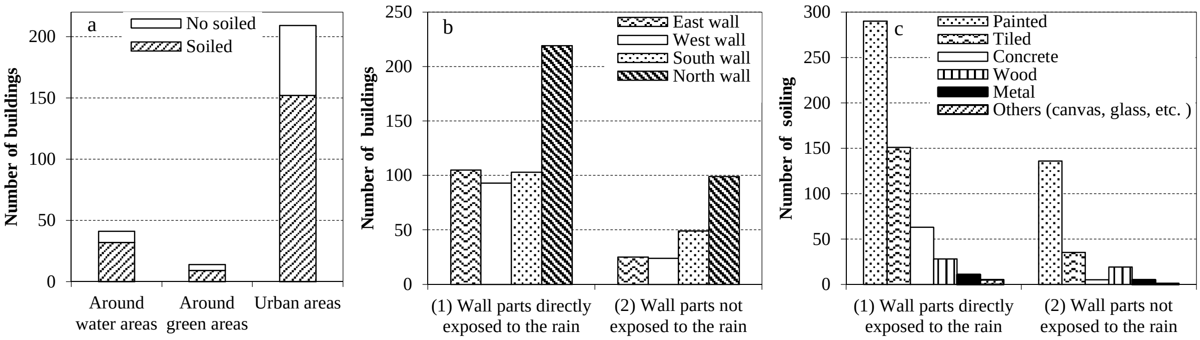

Fig. 2. (a) occurrence of algal soiling by type of local environment; (b) direction of surveyed building walls; (c) materials of surveyed building walls

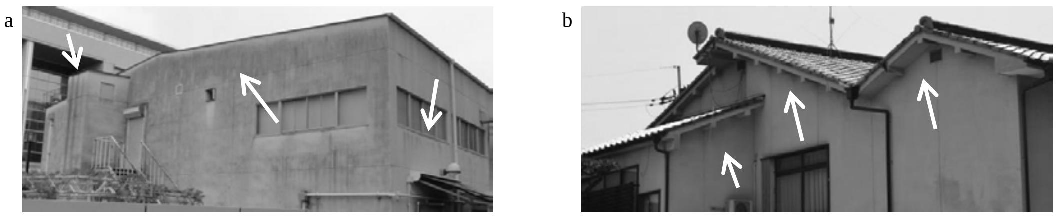

Fig. 3. (a) Walls directly exposed to rainwater; (b) walls rarely receiving rainwater.

direction of the exposed area and the pattern of the rainwater flow generally corresponded to areas of heavier algal growth. However, the algal growth on walls that rarely receive rainwater was not studied in depth. Therefore, we focused on the factors affecting algal growth in these areas.

3. Measurement at Kusyo Myojin Shrine

3.1. Methods of measurement

The Kusyo Myojin Shrine, Ninna-ji Temple, located in the northwestern part of Kyoto City, was constructed between 1641 and 1647. Some parts of the roof, walls and exterior finishing were repaired between 2004 and 2006. The north side is a slope. The areas on the north, east and west of the shrine are surrounded by tall trees, whereas those on the south side contain the approach to the shrine. The ground around the shrine was always moist probably because rainwater flows in from the northern hills. The shrine comprises of three buildings fenced on all sides (Fig. 4a).

Measurements began in October of 2011 and are continuing. Data were collected for ambient temperature, humidity, solar radiation and rainfall from the weather observation station (Weather Bucket, Agriweather Co. Ltd.), which is located at the southeastern corner and is marked by ▼ in Fig. 4. The surface temperature and humidity of the walls were measured using a data logger (T & D Corporation) at the locations indicated by the symbols ▲, ● and ■ in Fig. 4. Air temperature and humidity were measured on both the upper and lower beams at the locations marked by ▲, inside the building at the locations marked by ● and under the eaves of the fence at the locations marked by ■. Although surface temperature and humidity are typically measured on the wall surface, physical contact with the wall was not allowed because of the cultural importance of the Kusyo Myojin Shrine to Japan. We could not help regarding the temperature and humidity measured close to the wall (within 5mm) as the surface temperature and humidity of the wall[1].

The orientation of the walls and the height on the soiling were documented with photographs (Figs. 4b and c). The extent of soiling on the walls was evaluated visually with photographs and quantitatively using the L* value of the L*a*b* colour system. The L* value represent brightness (large when blight), and the small of the L* value correspond to existence of many algal cells. That of the wall surface was measured using a soil colour meter (SPAD-503, Konica Minolta Inc.). The average values were measured three times and further averaged over six points in an area 40×60 cm. These measurements were conducted at eight locations with different orientations and positions.

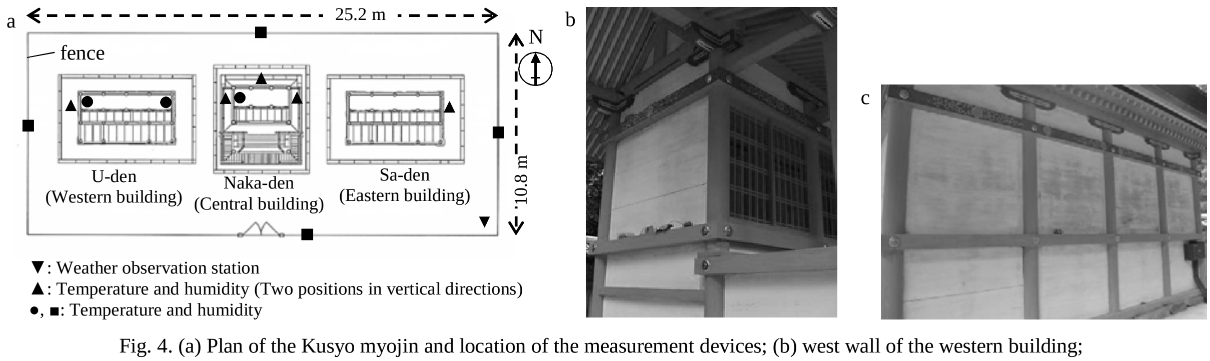

Fig. 4. (a) Plan of the Kusyo myojin and location of the measurement devices; (b) west wall of the western building; (c) north wall of the western building.

3.2. Results of measurements

3.2.1. Comparison of wall discolouration.

The comparison of the discolouration using photographs showed that the north walls were the darkest, followed by the upper parts of the east and west walls and the lower parts of the east and west walls. The extent of discolouration on the south walls was the lowest. On the east wall of the eastern building and the west wall of the western building, the upper parts of the middle and gabled walls were discoloured, whereas on the east wall of and west walls of thecentral building only the gabled walls were discoloured. The mean L* values averaged from west walls of the central building only the gabled walls were discoloured. The mean L* values averaged from August 6 2013 to December 18 2014 are shown in Fig. 5. The L* values of the south walls were the highest at approximately 90. The L* values of the north walls were the lowest, and that of the western building was lower than that of the eastern building. The L* values of the upper part of the walls were lower than those of the lower parts on the east wall of the eastern building and the west wall of the western building. The visual evaluation of discolouration agreed well with the L*value, and thus visual inspection using photographs can be a simple and effective method for evaluating discolouration due to algal soiling.

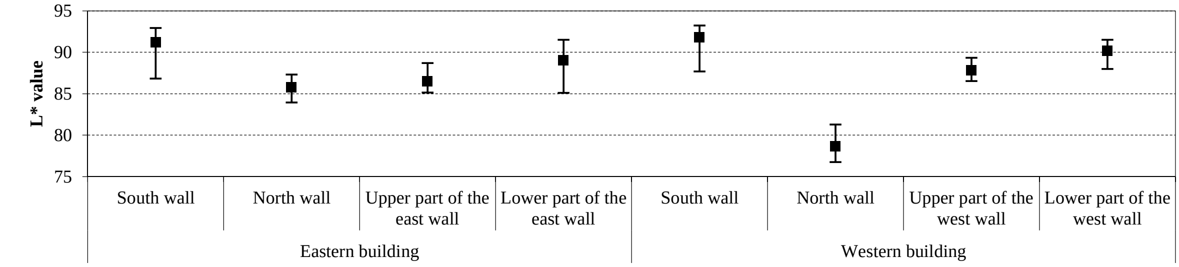

Fig. 5. L* values of each part of the walls.

3.2.2. Ambient temperature and relative humidity.

The ambient temperature and humidity measured at the Kusyo Myojin Shrine and the Kyoto local meteorological station are shown in Fig. 6. The ambient temperatures at the shrine were nearly the same as those at the meteorological station, whereas the ambient humidity at the shrine was higher than that at the meteorological station. The difference in humidity was likely due to the continuously moist ground on the north side of the shrine resulting from flowing water and the solar shading by trees around the shrine. This contradicted the result of the earlier survey, which concluded that the effect of the local environment was low. Although the survey of the soiled buildings within 50 m water areas or the green areas was conducted, the effect of high humidity on algal growth should be assessed over a smaller area.

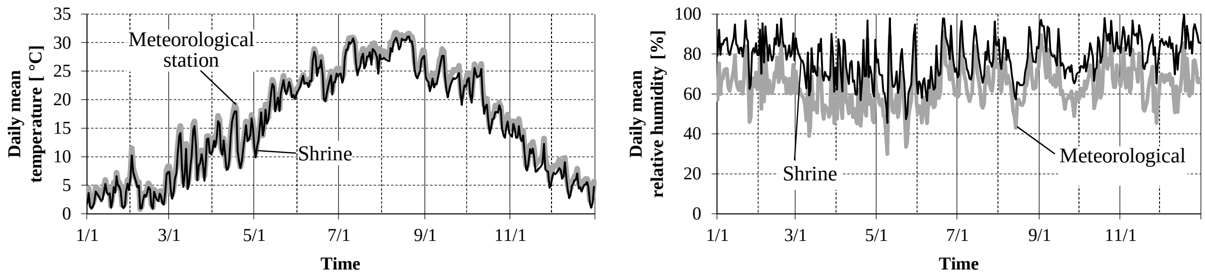

Fig. 6. Daily mean temperature (left) and RH (right) measured at the Kusyo Myojin Shrine and Kyoto local meteorological station.

3.2.3. Relationship between discolouration and wall surface temperature.

Fig. 7 shows the daily maximum temperatures in 2013 (a) north wall of the central building; (b) west walls of the central building; (c) the west wall of the western building (7c). The surface temperatures of the north walls of central, eastern and western buildings were about the same and thus the level of discolouration on the north walls of the eastern and western buildings compared with the surface temperature of the north wall on the central building. On the north wall, the daily maximum temperatures of the upper and lower parts were almost the same and did not increase over 40°C. On the west wall of the central building, the daily maximum temperature of the lower part reached 40°C from April to October, whereas, that of the upper part hardly reached 40°C. On the west wall of the central building, the lower part exceeded over 40°C from March to October, and the upper part reached 40°C from August to September. On the parts of the walls exposed to direct solar radiation, such as the lower part of the west wall, algae was likely to die because of high temperatures. Consequently, the colour of the wall surface was light and the L* value was high. On the parts of the walls that were rarely exposed to direct solar radiation, such as the north wall and the upper part of the west wall, algae rarely died. Accordingly, the wall surface was discoloured and the L* value was lower.

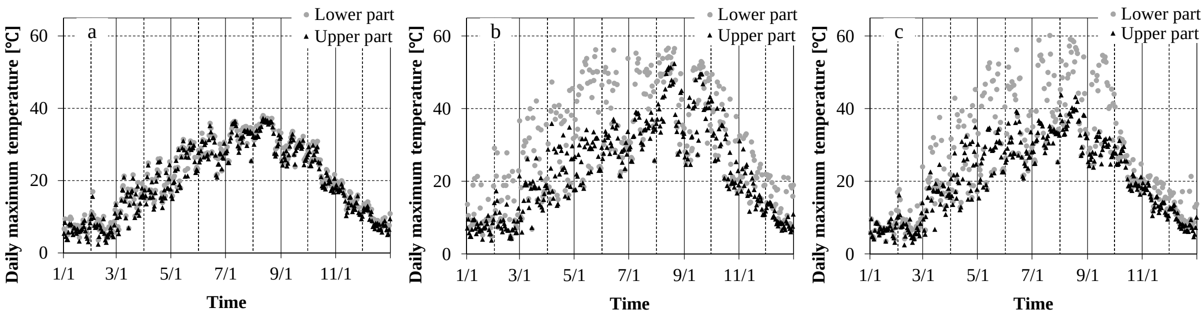

Fig. 7. Daily maximum temperatures in 2013
(a) north wall of the central building; (b) west wall of the central building; (c) west wall of the western building.

4. Conclusion

The purpose in this study was to identify locations of walls prone to algal growth and determine the relationship between algal growth and environmental conditions. The results obtained are summarized as follows.

In Kyoto City, the local environments such as water areas, green areas and urban areas did not clearly affect the extent of algal soiling. Soiling was observed on the walls of about half of the surveyed buildings. About 70% of the soiled areas were directly exposed to rainwater, whereas 30% were rarely exposed to rainwater. The number of soiled areas was the greatest on the north walls.

In the survey at the Kusyo Myojin Shrine, the L* values measured on the wall surfaces corresponded well with the degree of discolouration. The ambient humidity at the Kusyo Myojin Shrine was higher than that observed at the local meteorological station. This was attributed to the flow of rainwater on the north side and in combination with trees surrounding the shrine that shield solar radiation. These factors contribute to the ease with which algae can grow around the shrine. On the parts of the walls where temperatures exceed 40°C, algae cannot grow and is liable to die. Consequently, the wall surfaces in those areas experience little discolouration, and vice versa.

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