CHANGES IN SOLAR REFLECTANCE AND COLOR BY AGING OF PAINTED EXTERIOR WOOD

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ABSTRACT

When wood is used outdoors, climatic conditions such as sunlight or rainwater can cause the wood surface color to fade. When a concrete building in an urban area is clad with wood to increase energy efficiency, the increase of the thermal load to the atmosphere caused by the rise of the surface temperature is dependent on the solar reflectance, which varies as the wood surface ages. The purpose of this study is to investigate wood-surface aging and its relationship with solar reflectance. An outdoor exposure test was performed for 30 months with both painted and unpainted test specimens of heat-treated wood, for which the decay durability was known. In addition, the meteorological deterioration factors that influence the surface aging of wood were investigated by a five-month outdoor exposure test in five locations with different climate conditions.

The relationship between solar reflectance and $L^*$, $a^*$, $b^*$, and $\Delta E$ is investigated over 30 months of outdoor exposure. It is shown that solar reflectance and lightness $L^*$ are highly correlated. Surface dirt is found to decrease the solar reflectance by 2–4%. It is thought that the influence of the graying caused by eluviation of lignin and mold growth is significant because the solar reflectance of the unpainted wood surface decreased by 27% over 30 months. The unpainted wood surface was greatly affected by snow and rain, and the color changed. However, it is confirmed that microbial contamination, such as mold, has a far greater influence on the graying and decrease of $L^*$. Furthermore, the painted wood surface had a reduced decrease of $L^*$, and the area difference shrank in the order urethane resin-based paint (film-forming type) > brown acrylic resin-based paint (semi-film-forming) > brown acrylic resin-based paint (film-forming type). The urethane resin-based coating is thick and highly water-repellent, and thus it is thought that this suppressed the water-influenced change of $\Delta L^*$, $\Delta a^*$, and $\Delta b^*$. In addition, the lightening of color caused by visible light advanced with each area. The use of the brown acrylic resin-based paint and the brown acrylic resin-based paint had a greater effect on shrinking the area difference because of the water-repellent effect of the coating and the concealing effect of the pigment.

INTRODUCTION

In recent years, it has become common to clad urban concrete buildings with wood, which has a superior design aesthetic and offers high thermal insulation. The thermal load effect of a concrete building with large thermal capacity was evaluated both internally and externally with regard to the use of wooden cladding from the viewpoint of energy efficiency and a reduction in the phenomenon of urban heat islands. The heat stored by the building during the day and released from the building at night were reduced in the summer by cladding the concrete building with wood, and it was confirmed that wooden cladding helped to reduce the air conditioning load. In addition, heat transfer from the concrete wall was suppressed by the external thermal insulation of the wooden cladding in winter, and this reduced the primary energy use by reducing the heating load. These results indicate that wooden cladding is effective as thermal insulation for otherwise poorly insulated buildings.

When wood was used externally, it was established that the dimensional stability and decay durability were improved by heat-treating the wood at more than 200°C. However, the surface of wood is aged by climatic conditions such as sunlight and rainwater. An externally positioned wooden surface can deteriorate because of solar radiation, water, temperature, wind, dust storms, atmospheric pollutants, and surface contaminants. At sea level, the UV rays in sunlight penetrate 75–100 μm into the wood surface. Lignin, which is a chemical ingredient of wood, has an aromatic nuclear structure and contains a phenolic hydroxyl group. It absorbs UV rays and disintegrates into smaller molecules by photooxidation action by a radical reaction. Color changes occur because of these influences from even brief periods of outdoor exposure. The lignin resinolvent that becomes soluble in water is leached out by rainwater, and the wood surface is eroded. The surface of the wood then becomes a gray color because of the influence of atmospheric pollutants and mold. The characteristic solar reflection of the wood surface is thus changed by aging of the wood surface caused by this weather-related deterioration, and this can increase the sensible heat load to the atmosphere. If this clarifies the relationship between the quantitatively measured color-system value and the solar reflectance, it is thought that this will be effective for calculating the variation of thermal load to the atmosphere caused by the color variation of wood cladding.
paint. The deterioration of the paintwork is evaluated by the color difference (ΔE) before and after outdoor exposure. The weather resistance of the painted wood changes according to the type of paint used; the film-forming type is generally superior to the impregnation type. In addition, the weather resistance of painted wood changes according to the meteorological environment. This is because weather factors that cause deterioration of the wood surface are different in different areas. In particular, Japan is a long country from north to south, with areas as diverse as subarctic Hokkaido and subtropical Okinawa. Therefore, the meteorological environment in Japan can differ greatly. Furthermore, the solar reflectance of a painted surface is reduced by atmospheric dirt. The highly reflective paint that is used to prevent urban heat islands forming has its solar reflectance reduced at an early stage by the adherence of dirt, the removal of which has been shown to restore the solar reflectance.

The purpose of the present study is to clarify the relationship between the color-system value of a wooden surface and the secular change of its solar reflectance. In this report, results are presented from a 30-month outdoor exposure test performed with both painted and unpainted test specimens of heat-treated wood for which the decay durability was known. In addition, the recovery of solar reflectance after removal of surface dust was confirmed. Moreover, the meteorological deterioration factors that influence the surface aging of the wood were investigated by a five-month outdoor exposure test in five locations with different climatic conditions.

METHODS

30-month outdoor exposure test

Test specimens

Specimens measuring 22 (T) × 140 (W) × 500 (L) mm were cut from Japanese cedar (Cryptomeria japonica) that had been heat-treated at 220°C, and a test panel of 500 (W) × 500 (L) mm was manufactured. Painted (see below for various codes) and unpainted (N) panels were examined. The painted panels were prepared using transparent urethane-resin-based paint (U-C), brown acrylic-resin-based paint (Ac-B), or brown alkyd-resin-based paint (Al-B). The U-C and Ac-B paints are film-forming paints, whereas the Al-B paint is a semi-film-forming paint. Table 1 lists the exterior paints used in this study and the specimens to which they were applied; one specimen was prepared for each paint type.

Measurement equipment and method

The initial solar reflectance and color of each test panel were measured before the exposure test. The solar reflectance was measured using the Kinoshita method with a combined short- and long-wave radiometer (Eko Instruments MR-50) at the University of Osaka Prefecture in Japan. The reflectance of each object was measured with respect to a known standard wooden board and radiometer. The measurement was performed for 6 min for each test panel, and data were recorded every 5 s.

The surface color at three positions in the center of the test panel was measured in the CIE (1976) L*a*b* color space using a colorimeter (Konica Minolta CR-410). The parameter L* is the lightness, which is positive for lighter colors and negative for darker colors. The parameters a* and b* represent the chromaticity: for a*, positive values indicate red and negative values indicate green; for b*, positive values indicate yellow and negative values indicate blue. The outdoor exposure test was performed at Koshii & Co., Ltd. in Osaka City, Japan. The outdoor exposure was performed for 30 months from January 2014 to July 2016. The test panel was installed horizontally.

During the exposure test, the solar reflectance and (L*, a*, b*) were measured regularly. In addition, (ΔL*, Δa*, Δb*) and the color difference ΔE were calculated as follows:

\[ \Delta L* = L* - L_{0*}, \quad \Delta a* = a* - a_{0*}, \quad \Delta b* = b* - b_{0*} \quad (1) \]

\[ \Delta E = \sqrt{[\Delta L*]^2 + [\Delta a*]^2 + [\Delta b*]^2} \quad (2) \]

A subscript 0 indicates a value before the start of the outdoor exposure test.

For each test panel, surface dirt was removed after completion of the exposure test, and the solar reflectance and (L*, a*, b*) were measured again. Dirt was removed from a painted panel surface with a dust cloth, and from the unpainted surface with a nylon brush. The components of this dirt were analyzed.

Five-month outdoor exposure test in five locations

Test specimens

Specimens measuring 15 (T) × 70 (W) × 150 (L) mm were cut from Japanese cedar (Cryptomeria japonica) that had been heat-treated at 220°C. Painted and unpainted specimens were examined. The painted specimens were painted with the same paints listed in Table 1. Six samples were made for each paint type.

Table 1. Exterior paints used in this study

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of paint</th>
<th>Vehicle</th>
<th>Color</th>
<th>Sample code</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>Unpainted</td>
<td>*</td>
<td>*</td>
<td>N</td>
</tr>
<tr>
<td>No.2</td>
<td>Film forming</td>
<td>Urethane resin</td>
<td>Clear color</td>
<td>U-C</td>
</tr>
<tr>
<td>No.3</td>
<td>Film forming</td>
<td>Acrylic resin</td>
<td>Brown</td>
<td>Ac-B</td>
</tr>
<tr>
<td>No.4</td>
<td>Semi film forming</td>
<td>Alkyd resin</td>
<td>Brown</td>
<td>Al-B</td>
</tr>
</tbody>
</table>

Measurement equipment and method

The color of each test specimen was measured before the exposure test. The color (L*, a*, b*) of the samples was measured with the equipment.

The outdoor exposure test was performed at five different locations with different meteorological environments. The outdoor exposure was performed for five months from September 2013 to February 2014. The test specimens were installed at 45° and facing south at each location. During the test, we measured (L*, a*, b*) regularly and calculated ΔL*, Δa*, Δb*, and ΔE.

RESULTS

Change of solar reflectance and color difference during 30-month outdoor exposure test

Change of solar reflectance
Figure 1 shows the spectral reflectance of each specimen before the outdoor exposure test. The main differences among the samples are in the near-infrared region. The reflectances of the painted test specimens (U-c, Ac-B, and Al-B) are similar in the visible range, but that of the unpainted test specimen (N) is slightly higher.

The differences in solar reflectance according to paint type in the outdoor exposure test are shown in Fig. 2. The N solar reflectance was markedly lower after outdoor exposure. It was 40% initially but decreased to 20% in month 7. This decrease continued more gradually, reaching 13% in month 30. The initial value for Al-B was 30%, decreased to 18% in month 7, and reached 13% in month 30. In contrast, from an initial value of 35%, the U-C solar reflectance increased after 1.5 months of outdoor exposure and reached 47% in month 7. After that, the U-C solar reflectance decreased, but nevertheless it was 39% in month 30, which was more than its initial value. The Ac-B solar reflectance increased in month 7 and decreased in month 23. However, no major change was observed overall: the initial value was 23% and the final value was 20%.

**Change of color difference**

Figures 3–6 show the changes in L*, a*, b*, and ΔE, respectively, according to paint type in the outdoor exposure test. For sample N, the L* values increased initially upon exposure but then decreased markedly from month 4, becoming less than the initial value in month 7;

![Image 1](image1.png)

*Figure 1. Measurement results of spectral reflectance before exposure test.*

![Image 2](image2.png)

*Figure 2. Change of solar reflectance according to paint type.*

![Image 3](image3.png)

*Figure 3. Change of L* according to paint type.*

![Image 4](image4.png)

*Figure 4. Change of a* according to paint type.*

![Image 5](image5.png)

*Figure 5. Change of b* according to paint type.*

![Image 6](image6.png)

*Figure 6. Change of color difference according to paint type.*
the trend then became nearly flat until month 30. In addition, the a* and b* values decreased from initial exposure until month 7, followed by a nearly flat trend until month 30.

Kataoka(28) exposed six types of wood to UV and visible light (278–496 nm) with narrow bandgaps (20 nm). Light-colored wood (including sapwood of Japanese cedar) underwent photo-darkening (the L*, a*, and b* values all decreased) and photo-bleaching (the L* value increased and the a* and b* values decreased) when exposed to UV and visible light, respectively. However, the wavelength at which the transition from photo-darkening to photo-bleaching occurred varied among the wood species.29) Tsujimoto(30) reported that the change in color of the wood surface due to sunlight is a competing reaction between light colors for visible light and dark colors for ultraviolet rays. For our sample N, L* increases and a* and b* decrease from initial outdoor exposure until month 4. Therefore, as a result of the competing reaction of visible light and ultraviolet rays, we reason that the light color is advanced by the influence of visible light. Because L*, a*, and b* all decreased afterward, we reason that graying is advanced by influences such as eluviation of the lignin, atmospheric dirt, and mold. As a result, ΔE increased greatly until month 7 and then became nearly flat afterward. The ΔE value after 30 months of exposure was 13.8.

The ΔE of the coatings decreased in the order U-C > Al-B > Ac-B. The Al-B sample showed a decrease of L* and b*, was suppressed in comparison with N. We reason that the influences of UV rays and water were reduced by the pigment and the water-repellent effect of the coating, respectively. However, ΔE of Al-B approached the same value as N in month 30. Because the semi-film-forming coating is thin, we reason that it was changed by graying in a similar manner to N by the eluviation of pigment caused by a decrease of the water-repellent effect. As a result, ΔE continued increasing until month 40 and exceeded that of N in month 23; ΔE after 30 months of exposure was 17.0.

For the U-C sample, the L* value increased greatly until month 4 and increased gently afterward. The a* value initially decreased and then recovered to the same value as before exposure in month 7, but decreased again thereafter. The b* value increased greatly until month 7, became nearly flat after that, but decreased slightly in month 23. Because UV rays are absorbed by U-C, the creation of dark colors by UV rays was suppressed, and we reason that the increase of light colors caused by the visible light was advanced. In addition, we reason that graying caused by the eluviation of the wood ingredient was suppressed because the coating was thick and the water-repellent effect was strong. As a result, ΔE increased greatly until month 4 and continued increasing gently afterward. The ΔE value 30 months after exposure was 19.0. For the Ac-B sample, the L* value was nearly flat, and the a* and b* values increased slightly between months 4 and 7, with little change afterward until month 30. We reason that the change of (L*, a*, b*) was suppressed by the concealment effect of the pigment and the water-repellent effect of the thick coating. As a result, ΔE increased until month 4 and became nearly flat afterward. The ΔE value after 30 months of exposure was 5.2.

Change of color difference in five-month outdoor exposure test in five locations with different climatic conditions

Climatic condition of outdoor-exposure test areas

The monthly averages of global solar radiation, precipitation, and snow accumulation from 2013-03-24 to 2014-02-24 were calculated from the AMDAS data of the Meteorological Agency for the nearest location to each outdoor-exposure test location. The integrated value of global solar radiation showed a tendency to increase with decreasing latitude; Tsukuba and Osaka are at the same level. The area of highest precipitation was Toyama, which was about 2.7 times that of Osaka where there was the least precipitation. The area of highest snow accumulation was Asahikawa, and a certain amount of snow was seen in Toyama. Additionally, the monthly average precipitation values of Tsukuba increased remarkably in October. This was caused by the typhoon that made landfall on 2013-10-16.

Change of color difference

Figures 7–10 show the changes in ΔE, ΔL*, Δa*, and Δb* for N, U-C, Al-B, and Ac-B, respectively, upon exposure for five months in the five measurement locations. The ΔE of N was largest in Asahikawa and Toyama, smaller in Tsukuba and Miyakojima Island, and the minimum values were found in Osaka. The integrated amounts of global solar radiation in Asahikawa and Toyama were around 2/3 of those in the other areas, but those locations had the highest integrated amount of snow accumulation and precipitation. In Asahikawa, where the increase of ΔL was remarkable, there is heavy snowfall in winter, and the monthly average minimum temperature in January and February was −10°C or less.31) During snowfall, the test specimen is covered by snow. When the snow melts and water remains on the test specimen, ice may occur at low temperatures. The surface temperature of the test specimen becomes higher than atmospheric temperature when receiving sunlight during the day, leading to the surface ice thawing and exposure to a significant amount of water.32) It has been reported that water accelerates a photo-oxidation reaction as a catalytic action.33) Therefore, we reason that the lightening of color is produced by the influence of sunlight irradiation and the repeated freeze-thaw cycles, and thus ΔL was increased. In addition, the surface of the test specimen after five months of outdoor exposure was still white, and dirt and mold were not observable. In Toyama, where the decrease of Δa* and Δb* was remarkable, there was a large amount of rainfall from the start of outdoor exposure until month 3, and Δa* and Δb* decreased remarkably during this period. In month 1, black spots that were thought to be mold were observed on the surface of the test specimen, and the sample became dark gray in month 5. In Tsukuba, ΔL increased greatly from the start of outdoor exposure until month 1, and increased gently after that. In Miyakojima Island, ΔL showed the maximum value in month 1 and decreased gently after that. In Osaka, ΔL increased greatly until month 3, and increased gently after that.
The difference in value between locations of the coatings decreased in the order U-C > Al-B > Ac-B. The $\Delta E$ of U-C was largest in Toyama, and smallest in Asahikawa. The $\Delta L$ value was also largest in Tsukuba and smallest in Asahikawa. As explained above, because the coating of U-C is thick and has a strong water-repellent effect, we reason that the changes of $\Delta L^*$, $\Delta a^*$, and $\Delta b^*$ caused by water seen in Asahikawa and Toyama were

![Graphs showing changes in $\Delta E$, $\Delta L^*$, $\Delta a^*$, and $\Delta b^*$ for N, Al-B, U-C, and Ac-B coatings over five months of outdoor exposure in five locations.](image-url)
suppressed. In addition, the lightening of color caused by visible light advanced with each place. Coatings Al-B and Ac-B caused a greater reduction of the difference of value between locations by the water-repellent effect of the coating and the concealment effect of the pigment. The ΔE of Al-B was the largest in Tsukuba and Toyama; it increased from the start of outdoor exposure until month 3, and subsequently became nearly flat. The ΔE of other areas increased from the start of outdoor exposure until month 1, and subsequently became nearly flat; the trend in ΔL was similar to that in ΔE. The ΔE of Ac-B increased in month 1 and subsequently became nearly flat. The trend in ΔL was approximately the same as that in ΔE, but continued to increase slightly in Tsukuba.

DISCUSSION
Relationships between solar reflectance and (L*, a*, b*) and ΔE
We investigated the relationships between solar reflectance and (L*, a*, b*) and ΔE. Figure 11 shows that solar reflectance and L* have a linear relationship with a high correlation. A correlation also exists with b*, but there is no correlation with a* or ΔE. Kuwabara(33) investigated the relationship between solar reflectance and color by measuring the solar reflectance of eight colors of clothes (white, black, ash, red, blue, yellow, and olive color T-shirts, and dark-blue half pants), and reported that solar reflectance is determined purely by lightness, regardless of color. In our study, the material was different (wood versus cotton or polyester), we found a high correlation between solar reflectance and lightness regardless of the material type.

Effect of surface dirt
Table 2 details the solar reflectance after removal of surface dirt, which restored the solar reflectance by 2.2–3.9%. In addition, the values of L*, a*, and b* were also restored slightly. As a result, the influence of dirt on the decrease of solar reflectance was 2–4%. We reason that the influence of graying caused by the eluviation of lignin and mold growth was profound because the solar reflectance of N decreased by 27% over 30 months. We analyzed the dirt chemically using scanning electron microscopy and energy-dispersive X-ray spectroscopy (SEM-EDS). Carbon and oxygen were found to make up 70% of the total composition. Other contaminants included metals such as Ca, Si, S, Fe, and Al. We associate the carbon particles with the combustion of fossil fuels, and with the carbonates found in soil and crushed asphalt. We expect that S and O resulted from SO2, again from fossil fuels, whereas we regard Na and Cl as resulting from seasalt particles.(34) We assume that the elements originating from soil, such as Fe, Si, Al, and Ca, came from dust storms (yellow sand) originating in China. (35)

Effect of climatic conditions on surface L*
Regarding sample N, the surface of the test specimen in Asahikawa was white, and dirt and mold were not observed. We assume that adhesion of atmospheric dirt was suppressed because the surface was covered with snow and ice. In addition, we reason that mold did not grow because the temperature was too low. In contrast, we reason that the test-specimen surface of Toyama became gray in color because of the growth of mold due to suitable atmospheric temperature and rainwater conditions.

Mold is frequently observed to contaminate externally exposed wood surfaces, and is generally of the Hyphomycetes genus such as Aureobasidium pullulans.(10) It has been reported that these surface contaminants can use small molecules, created by photolysis of the wood by UV rays, as a source of nourishment. (14) As a result, the unpainted wood surfaces were greatly influenced by the water from snow and rain, and the color changed by a different mechanism in each case. Nevertheless, we confirmed that the influence of microbial contamination such as mold was a greater factor causing the graying and decrease of L*.

Miyakojima has the largest integrated amount of solar radiation of the five test locations, and the maximum amount of global solar radiation occurred in October, the first month after initial exposure; ΔL and ΔE also achieved their maximum values in the five test locations. However, the amount of global solar radiation greatly decreased from November to December, and ΔL decreased likewise. Therefore, a different result is predicted if the outdoor exposure test is started when the amount of global solar radiation increases the most. Therefore, further study is necessary of the exposure time and the exposure period.

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CONCLUSIONS

This study investigated the relationship between the color system value of the wood surface and the change of solar reflectance during an outdoor exposure test for 30 months, performed with painted and unpainted test specimens of heat-treated wood for which the decay durability was known. In addition, the meteorological deterioration factors that influenced the surface aging of the wood were investigated by a five-month outdoor exposure test in five locations with different climatic conditions. The findings were as follows.

(1) The relationships between solar reflectance and \( (L^*, a^*, b^*) \) and \( \Delta E \) were investigated by the 30-month outdoor exposure test. As a result, it was shown that there was a high correlation between solar reflectance and lightness \( L^* \).

(2) The influence of surface dirt on the decrease of solar reflectance was 2–4%. Because the solar reflectance of \( N \) decreased by 27% in 30 months, we reason that the eluviation of lignin and mold growth had a profound effect on the graying.

(3) The five-month outdoor exposure test performed in five locations with different climatic conditions showed that the unpainted wood surface was strongly influenced by water from snow and rain, and that the color changed by a different mechanism in each case. However, we confirmed that the influence of microbial contamination such as mold was a greater factor causing the gray color and decrease of \( L^* \).

(4) Furthermore, the painted wood surfaces suppressed the decrease of \( L^* \), and the area difference shrank in the order \( U-C > A1-B > A2-B \). The \( U-C \) coating was thick and highly water-repellent, and we reason that the influence of water on \( \Delta L^* \), \( \Delta a^* \), and \( \Delta b^* \) was suppressed. In addition, a lighter color caused by visible light advanced with each area. The use of \( A1-B \) and \( A2-B \) had a greater effect on shrinking the area difference because of the water-repellent effect of the coating and the concealing effect of the pigment.

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