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Influence of dirt and coating deterioration on the aging of solar reflectance of high-reflectance paint

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Abstract: Cool-roof coatings have received considerable attention worldwide as a solution for the "heat island" effect in urban areas. The solar reflectance of roofs coated with high-reflectance paint is reduced by dirt. We continuously measured the solar reflectance of a roof coated with high-reflectance paint with and without a self-cleaning function for more than two years. The solar reflectance of self-cleaning paint decreased by 0.5% per month over two years, due to the effect of dirt. The solar reflectance of conventional paint decreased by 4% per month over four months after coating and then reached a value similar to that for the self-cleaning paint for two years due to deterioration. With a slight decrease in solar reflectance, the self-cleaning function is effective in mitigating the heat island effect and obtaining continuous energy-savings. We applied the alkyl silicate system as self-cleaning for high-reflectance paint, the solar reflectance was measured continuously at 1 minute intervals, and the actual state of the fluctuation in reflectance over the short and long terms was analyzed with the influence of the altitude of the sun. The deterioration of the coating was also investigated by gloss retention and chalking test.

Keywords: high-reflectance paint; solar reflectance; heat island effect; aging; self-cleaning; dirt; deterioration

1. Introduction

High-reflectance paint is regarded as an important solution for the heat island effect in urban areas. As an effect of high-reflectance paint, the reduction in air conditioning loads and carbon

dioxide have been studied [1–3]. High-reflectance paint can also lower the ambient temperature of the building by reducing the sensible heat released. Many research results on residential [4] and non-residential buildings [5–6] have been reported regarding the effect of these high solar reflectance paints. Recently, many important research about evaluation of building roofs with conventional and reflective coating, and the energy gain of building roof with many color type of waterproofing materials have been reported [7–9].

On the other hand, it has been reported that the solar reflectance greatly decreases in the first 1 to 2 years after painting [10–12]. It has been reported that this decrease in solar reflectance is due to dirt on the roof coating and the adhesion of organisms [13].The reduction in reflectance has been studied in exposure tests using various materials. Changes in solar reflectance are measured every three months and are affected by the location of exposure, it has been reported that the reflectance decreases by approximately 10% to 20% within 3 years [14–15].

Further investigations proposed that the service life of the reflective surfaces may be extended if the surface temperature is lowered during the sunshine hours to reduce the diurnal thermal expansion and contraction [16]. The change in reflectance caused by sun exposure and washing, as well as the simulation of annual cooling and heating load are studied [17].

Various evaluation methods for cool-roof coatings have been studied. Studies have investigated the decrease in the solar reflectance due to soiling of the coating and the relationship between outdoor-exposure and accelerated-aging tests in particular [15,18–20]. In Japan, the main component of soil is carbon. It has been reported that, after 16 weeks of exposure of the white test piece, the reflectance in the visible light region is reduced by about 5 to 10% [21].

We have reported the results of a study on the application of a self-cleaning paint to a cool roof for the prevention of soil deposition and reduction of solar reflectance [22–24]. Self-cleaning paint is used to coat walls in buildings, and its ability to minimize soiling, especially by dirt, has been reported [25].There are two types of self-cleaning systems: a photocatalyst system with titanium oxide [25] and an alkyl silicate system [22–24,26]. The photocatalyst system has high hydrophilicity but cannot be used on organic-based paint because decomposition will occur. In addition to the usual paint layer, two more layers (a protective layer and photocatalyst layer) are required with this system. Therefore, the photocatalyst system is somewhat expensive. On the other hand, the alkyl silicate system works as well on ordinary paint, and the self-cleaning layer with base-coat binder resin is applied via a one-coat process. An acrylic silicon polymer base resin is useful for the formulation of alkyl silicate self-cleaning paint. In sum, this system is a useful self-cleaning paint system with a simple coating process and high cost-performance. We applied this system to cool-roof coatings.

The effects of the acrylic silicon polymer on solar reflectance and the reduction of air-conditioning loads have been studied. Acrylic silicon/alkyl silicate-based coatings have been reported to achieve a 10% difference in reflectance and 10% reduction in air-conditioning energy consumption when used as self-cleaning cool-roof coatings [22].

We have investigated the effect of self-cleaning technology with an acrylic silicon polymer-based alkyl silicate system on the solar reflectance of a cool-roof coating. From data obtained through real outdoor exposure, we calculated the energy-saving effects of self-cleaning technology using the thermal load calculation model (Energy Plus) for sites in Japan (Osaka), Malaysia (Kuala Lumpur), and Thailand (Bangkok) [24]. In addition, we have found the influence of the annual cycle of the solar altitude in the change of reflectance, and it was suggested that there is a possibility of increase in reflectance due to coating deterioration with whitening of chalking [27].

Deterioration of high reflectance paint has been reported in connection with loss of gloss and chalking of coating surface [28].

In this study, we applied the alkyl silicate system as self-cleaning for high-reflectance pant, the solar reflectance was measured continuously at 1 min intervals, and the actual state of the fluctuation in reflectance over the short and long terms was analyzed with the influence of the altitude of the sun. The deterioration of the coating was also investigated by gloss retention and chalking test. We report on these results.

2. Materials and methods

2.1. Outline of high-reflectance paint and solar reflectance measurement

2.1.1. Outline of high-reflectance paint

High-reflectance paint is a functional paint that can reflect light in the near infrared range to a large degree and suppress the increase in temperature.

The self-cleaning property means that dirt, including the oil component, is raised away by rainwater to enhance the cleaning effect by increasing the cross-link density of the coating film surface to a hydrophilic coating. Figure 1 shows the outline of the type of low-contamination paint used in this study. The paint binder consists of an aqueous two-component acrylic silicone resin composed of a base material of an alkoxyl-group-containing acrylic resin emulsion and a low-contamination imparting agent containing an alkyl silicate and a hydrolysis-condensation catalyst [24,27].
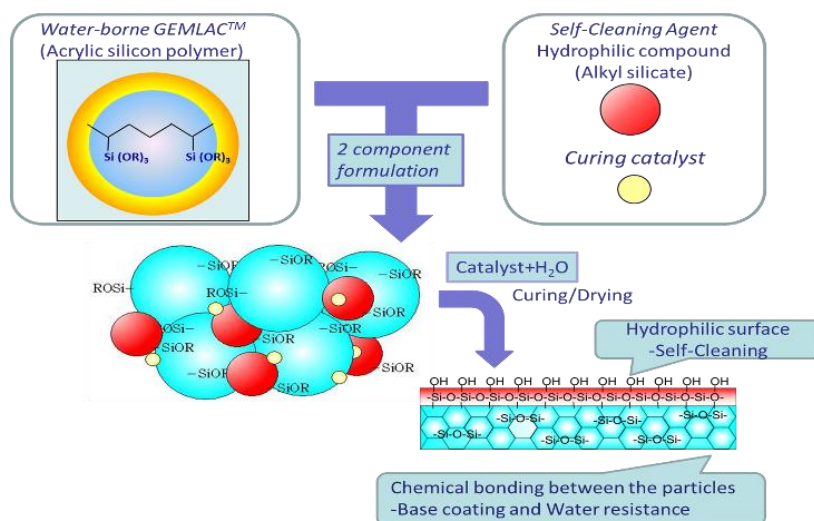

Figure 1. Outline of self-cleaning paint.

2.1.2. Summary of continuous solar reflectance measurements

Measurements were made on the roof of the Structural Control and Monitoring Laboratory building in the Department of Architecture, Kobe University in Kobe, Japan. There are buildings on

the north, east, and west sides. The height of the roof top of this one story flat building is 6.2 m, and there are trees across the road on the south side, but shadows do not fall on the rooftop. Figure 2 shows a picture of the rooftop after painting. The roof is made of corrugated sheet metal. The solar reflectance is influenced by the shape, and in this case is smaller than the reflectance of a flat plate due to multiple reflections (absorption). The solar reflectance corresponding to the test roof was calculated based on the roof shape (dimension) and the position of the sun; it was calculated to be about 6% lower than the flat roof [29].
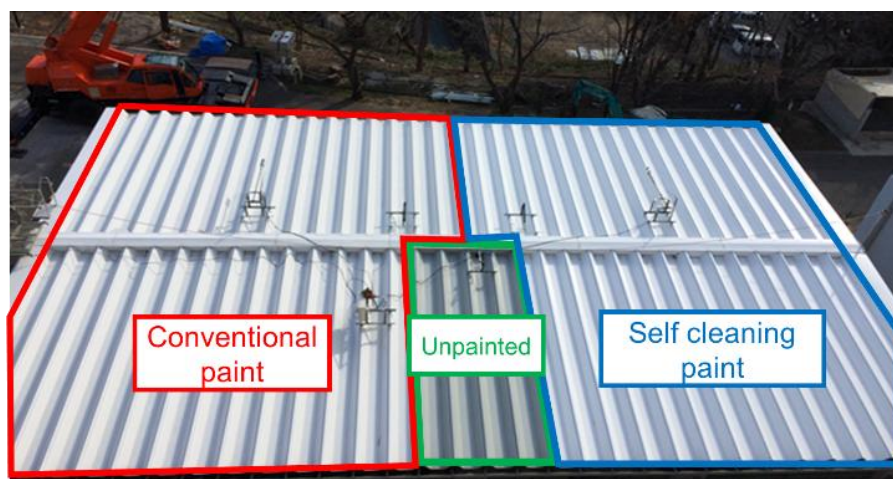

Figure 2. Roof coated with high-reflectivity paint with and without self-cleaning function.

2.1.3.   Measurement of solar reflectance using standard plates (two-point calibration method)

To measure the solar reflectance, two standard plates, one white and one black, with known solar reflectances were each placed on the surface, and the solar reflectance of the target surface was measured by removing the standard plate [30–31]. These measurement results include the influence of solar radiation reflected from surfaces other than the target surface (the peripheral portion of the measurement target). We excluded this influence by using the measurement result when a known standard plate was installed, thereby estimating the solar reflectance only on the target surface. The formula to calculate the solar reflectance using the standard plate is Eq 1,

$$R_A = \frac{R_W - R_B}{\rho_W - \rho_B}\rho_A + \frac{R_B\rho_W - R_W\rho_B}{\rho_W - \rho_B} \tag{1}$$

here, R_A is the measurement of the solar reflectance of the target surface, R_W is the measurement when the white standard plate is installed, R_B is the measurement when the black standard plate is installed, and ρ_A is the solar reflectance of the target surface. The calibration ρ_W is the known solar radiation reflectance of the white standard plate, and ρ_B is the known solar radiation reflectance of the black standard plate. The first term in the equation above represents the form factor and the second term represents the influence around the measurement location. The theoretical values of the geometric shape coefficients are the same. The solar reflectance around the measurement location fluctuates with time. Measurements were made four times a year around the spring and autumnal equinoxes and the summer and winter solstices in three areas: those painted with low-contamination

and conventional paints, and the unpainted area [32].

2.1.4.   Evaluation method of the deterioration of the coating

The evaluation on the deterioration of the high-reflectance paint was evaluated by measuring the gloss retention of the paint surface and the tape peeling test of chalking [28]. The gloss was measured at an angle of $60°$ in the same manner as described in the related prior art, and was shown by the retention rate relative to the initial gloss value. As for the tape peeling test of the chalking, the paint adhering to the tape was visually evaluated with the chalking tape of Japan Paint Inspection and testing Association (JPIA).

3.   Results and discussions

3.1. Measurement results and analysis of aging of solar reflectance

3.1.1.   Measurement results of solar reflectance

The solar reflectance of the parts painted with self-cleaning and conventional paints was measured starting on May 10, 2014 using pyranometers (Kipp & Zonen CNR 1, wavelength range 305 to 2800 nm, accuracy ±10%, installation height 50 cm). Measurements were made continuously at 1-minute intervals. Data for the area with the self-cleaning paint is missing from June 3, 2014 to July 2, 2014 because of a poor connection in the measuring equipment. Figure 3 shows the daily solar reflectance (after correction for the roof shape) (May 10, 2014 to January 17, 2017) of the areas with self-cleaning and conventional paints averaged from 10 a.m. to 2 p.m. Data was only used when the amount of solar radiation was 500 W/m^2 or more. The initial values of solar reflectance of the self-cleaning and conventional paints were 87.5% and 87.7%, respectively. The solar reflectance of the self-cleaning paint continued to decrease gradually for two years after the surface was painted. The solar reflectance of the conventional paint sharply decreased in the first 4 months after painting and then rose again.
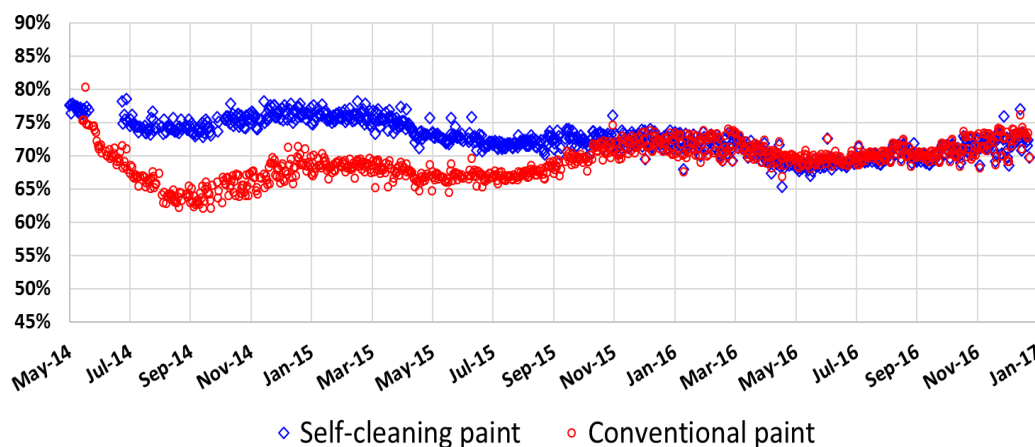

Figure 3. Daily average solar reflectance of self-cleaning and conventional paint (averaged from 10 a.m. to 2 p.m.).

3.1.2. Measurement of solar reflectance using standard plates

Measurements of the solar reflectance using the standard plates were made 8 times, on July 25, 2014 (clear weather day in summer), October 7, 2014 (clear weather day in autumn), December 22, 2014 (clear weather day near the winter solstice), March 31, 2015 (clear weather day near the spring equinox), August 9, 2015 (clear weather day in summer), October 9, 2015 (clear weather day in autumn), January 15, 2016 (clear weather day near the winter solstice), and March 28, 2016 (clear weather day after the spring equinox). Figure 4 shows the results of applying the calibration using the standard plates to the continuous measurements of solar reflectance of the self-cleaning and conventional paints. The calibration formulas are as follows Eqs 2 and 3,

・Self-cleaning paint, winter solstice in 2014:

$$R_A = 0.630 \times \rho_A + 0.235 \tag{2}$$

・Conventional paint, winter solstice in 2014:

$$R_A = 0.654 \times \rho_A + 0.217 \tag{3}$$

We examined the error when the calibration formula (Eq 1) of solar reflectance using the standard plate was applied to the self-cleaning and conventional paints. The form factor (the first term on the right side of Eq 1) is calculated to be 0.60. The form factor of the solar reflectance calibration formula using the standard plate was between 0.61 and 0.67. The form factor is 0.61 when the 1-cm^2 gap is opened on the standard board; it is 0.66 when calculating the distance from the lower end of the radiation budget meter to the surface as the height. From the above, the error is shown to be due to the installation position of the standard plate and the way the distance from the target surface to the equipment is measured. The influence of the surroundings of the measurement location (the second term on the right side of Eq 1) of the self-cleaning and conventional paints is equivalent in summer 2014 immediately after painting, but a decrease in reflectance is seen.
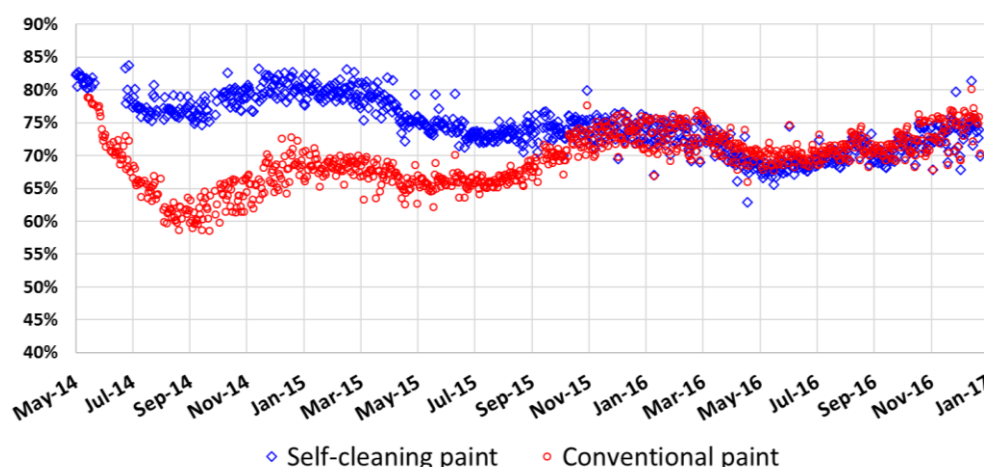

Figure 4. Solar reflectance with calibration formula based on the measurements made in winter 2014.

3.2. Influence of sun altitude, dirt, and coating deterioration on solar reflectance

3.2.1. Influence of solar altitude

The influence of the altitude of the sun was extracted from the difference between the first-order approximation of the measurement of solar reflectance and the measurement, and its characteristics were analyzed. Figure 5 shows the difference between the measurements of solar reflectance of the self-cleaning paint and the first-order approximation and its trigonometric approximation. When the difference from the approximate straight line is approximated by a trigonometric function, in the Eq 4,

$$y = 0.0334 sin(\omega t + 0.026)(R = 0.67) \tag{4}$$

this is small in summer when the sun is high and large in the winter when the sun is low. It changed by almost the same amount in the first and second year.

The relationship between the incident angle and the reflectance is explained by the Fresnel equation [33]. When light enters an interface between substances having different refractive indexes, part of the light is reflected and part of it is transmitted (refracted). It is Fresnel equation that describes this behavior. From this, the reflection law that the reflection angle is equal to the incident angle α, and regarding the refraction angle β, Snell's law,

$$n_1 sin\alpha = n_2 sin\beta \tag{5}$$

is derived. Here, n_1 and n_2 in the Eq 5 are the refractive indexes on the incident side and the transmission side, respectively.

Further calculations using these yield the Fresnel equations for the amplitude reflectivity and amplitude transmissivity of the electric field. Assuming that the amplitude reflectance of the p wave is r_p, the amplitude transmittance is t_p, the amplitude reflectance of the s wave is r_s, and the amplitude transmittance is t_s, show in the Eqs 6–9.

$$t_p = \frac{2n_1 cos\alpha}{n_2 cos\alpha + n_1 cos\beta} = \frac{2 sin\beta cos\alpha}{sin(\alpha + \beta) cos(\alpha - \beta)} \tag{6}$$

$$r_p = \frac{n_2 cos\alpha - n_1 cos\beta}{n_2 cos\alpha + n_1 cos\beta} = \frac{tan(\alpha - \beta)}{tan(\alpha + \beta)} \tag{7}$$

$$t_s = \frac{2n_1 cos\alpha}{n_1 cos\alpha + n_2 cos\beta} = \frac{2 sin\beta cos\alpha}{sin(\alpha + \beta)} \tag{8}$$

$$r_s = \frac{n_1 cos\alpha - n_2 cos\beta}{n_1 cos\alpha + n_2 cos\beta} = -\frac{sin(\alpha - \beta)}{sin(\alpha + \beta)} \tag{9}$$

is derived. However, these codes may differ depending on the definition.

Since the energy of light is proportional to the square of the amplitude of the electric field, Fresnel equation for energy reflectance R and energy transmittance T can be obtained from the square of the amplitude show in the Eqs 10 and 11. However, when obtaining T, a coefficient due to a difference in refractive index between the incident side and the transmission side and a coefficient

due to an angle change are applied. Considering this, finally,

$$T_{s,p} = \left(\frac{n_2}{n_1}\right)\frac{cos\beta}{cos\alpha}t_{s,p}^2 = \frac{tan\alpha}{tan\beta}t_{s,p}^2 \tag{10}$$

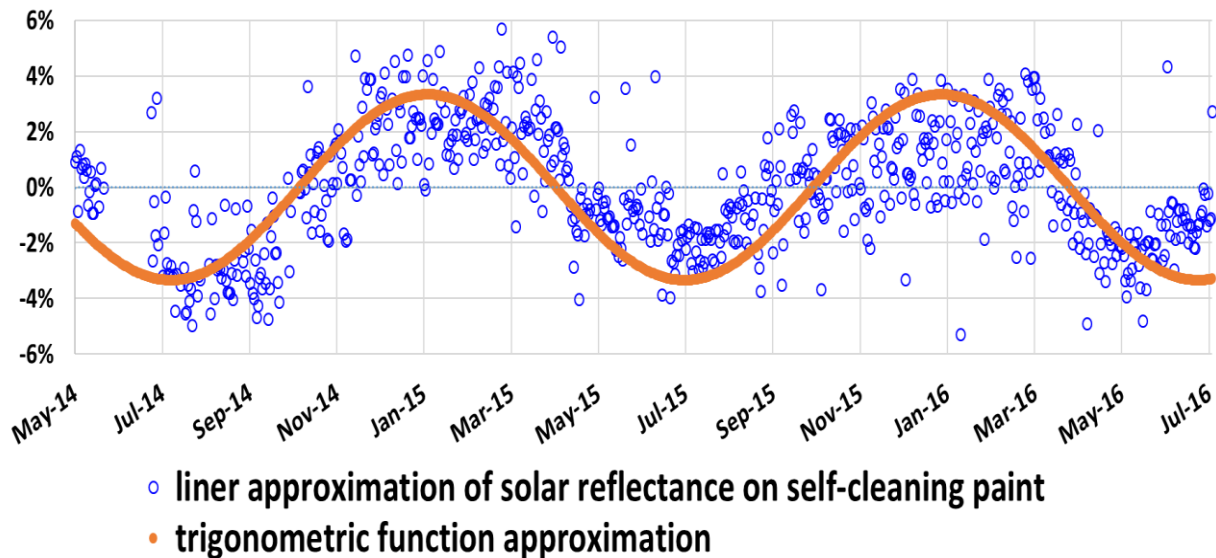$$R_{s,p} = r_{s,p}^2 \tag{11}$$

is derived.

Figure 5. Difference between linear approximation of solar reflectance of self-cleaning paint and its trigonometric approximation.

3.2.2. Influence of dirt and coating deterioration

We analyzed the influence of dirt and coating deterioration on solar reflectance over time by using the data with the influence of the solar altitude removed. Figure 6 shows the solar reflectance and first-order approximation of the self-cleaning paint without the influence of the solar altitude. The approximate expression is Eq 12,

$$y = -0.000145x + 0.814(R = 0.90) \tag{12}$$

The solar reflectance fell by 0.5% per month due to dirt. Figure 7 shows the solar reflectance and first-order approximation of the conventional paint without the influence of the solar altitude. It was approximated by separating the period into two parts: up to 4 months after painting and after 4 months. The approximate expression, up to 4 months after painting is Eq 13,

$$y = -0.00136x + 0.791(R = 0.94) \tag{13}$$

after 4 months after painting, it is Eq 14,

$$y = 0.000129x + 0.625(R = 0.80) \qquad (14)$$

due to the effect of dirt, the solar reflectance decreased by 4% per month for up to 4 months after painting, rising at 0.4% per month after 4 months after painting owing to deterioration in the coating film.

The analysis by the mean square error between approximate curve and actual measured value of Figures 6 and 7 were calculated and were 4.9% and 7.0%, respectively. The root mean square error was 2.2% and 2.6%, respectively. This is considered to be relatively small by removing the influence of the solar altitude, as compared with the fluctuation range including the influence of the solar altitude being about 6% in Figure 5.

The deterioration of the coating from the gloss value was confirmed immediately after painting (May 14) and at 2 years and 10 months (March 17), as well as the gloss retention rate, and peeling test of the chalking tape (Table 1). For the self-cleaning paint, the gloss retention was high, the adhesion of powder to the chalking tape was small, and chalking was considered to have not occurred. Therefore, according to the original characteristics of the self-cleaning paint, dirt adhesion was small and the reflectance gradually decreases. On the other hand, in conventional paints, the retention of gloss was low, and the adhesion of powder to the chalking tape was high, which was considered to cause chalking. It was considered that the decrease in initial reflectance of the conventional paint was due to dirt adhesion, and the reflectance then increased due to whitening of chalking.
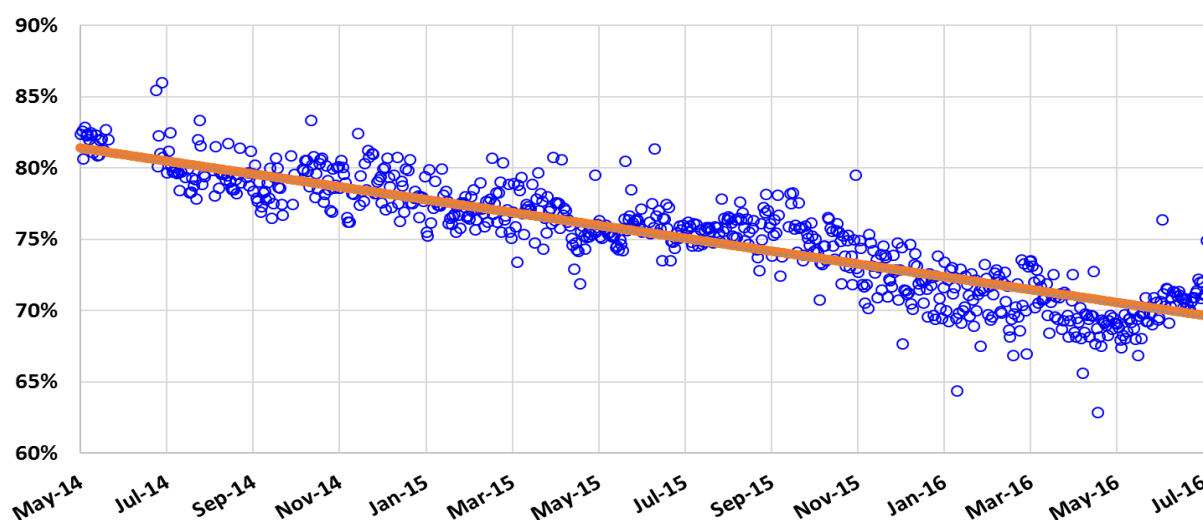
○ **Solar reflectance on self-cleaning paint removed the sun altitude effect**

Figure 6. Solar reflectance and first-order approximation of the self-cleaning paint without the influence of the solar altitude.
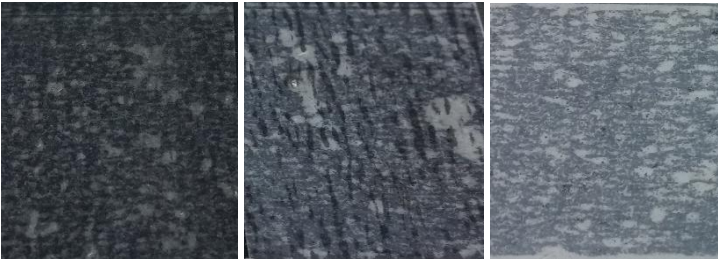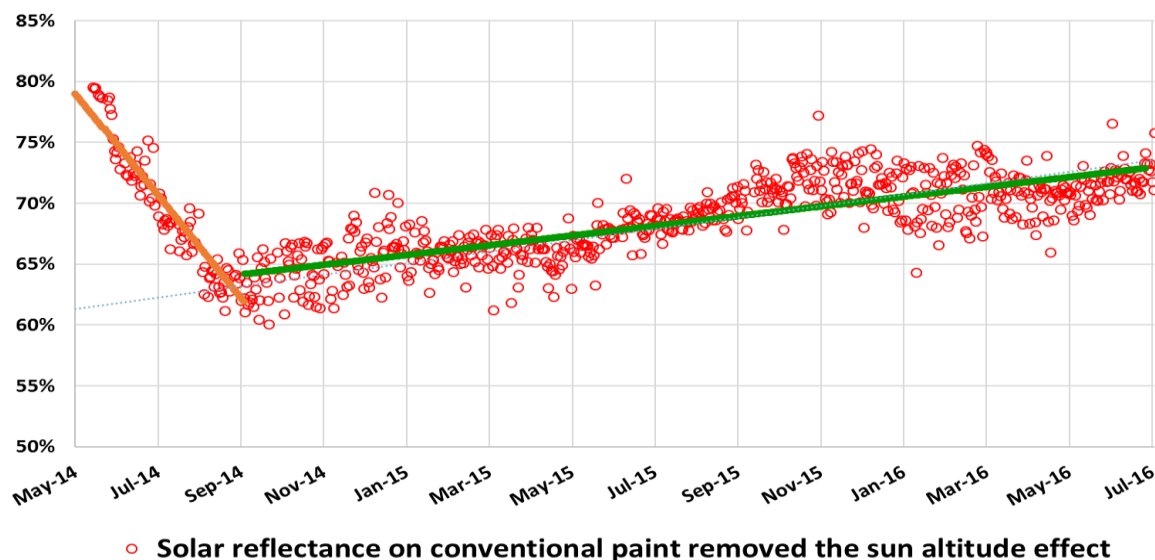
Figure 7. Solar reflectance and first-order approximation of the conventional paint without the influence of the solar altitude.

Table 1. Gloss retention and result of tape peeling test.

Evaluation items and dates		Self-clening paint	Conventional paint	Unpainted
60 ° gloss	14-May (initial)	34.0	44.9	34.9
60 ° gloss	17-Mar	24.0	19.8	4.72
60 ° gloss retention(%)		70.6	44.1	13.5
Peeling test of the chalking tape	17-Mar			

4. Conclusion

The solar reflectance of a roof coated with high-reflectance paint with and without a self-cleaning function was continuously measured for more than two years. The solar reflectance of self-cleaning paint decreased by 0.5% per month over two years, due to the effect of dirt. The solar reflectance of conventional paint decreased by 4% per month over four months after coating and then reached a value similar to that for the self-cleaning paint for two years due to deterioration. The influence of the altitude of the sun was extracted from the difference between the first-order approximation of the measurement of solar reflectance and the measurement. The influence of dirt and coating deterioration on solar reflectance was analyzed by using the data with the influence of the solar altitude removed.

The deterioration of paints was evaluated by the gloss retention rate and the peeling test of

chalking. According to the original characteristics of the self-cleaning paint, dirt adhesion was small and the reflectance gradually decreased. In conventional paints, the retention of gloss was low, and the adhesion of powder to the chalking tape was high. It was found that the decrease in initial reflectance of the conventional paint was due to dirt adhesion, and the reflectance then increased due to whitening of chalking.

Acknowledgments

Conflict of interests

The authors declare no conflict of interest.

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