DERIVATION FROM EN927 METHOD FOR EVALUATING THE OUTDOOR DURABILITY OF COATED FIRE-RETARDANT-TREATED WOOD

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ABSTRACT: Conducting an artificial weathering test using UV lamps and water spraying is necessary to predict the outdoor durability of coated fire-retardant–treated wood. This paper describes the results of prototypes derived from the EN927-6 methods, which are artificial weathering methods for coated wood. Modified tests using QUV demonstrated that testing conditions such as the duration of each spray or temperature have different effects on coatings. Thus, low-build coatings tend to be evaluated poorly under the standard cycle. Moreover, maintaining a high moisture content by raising the initial moisture content or lowering the testing temperature speeds up leaching from high-build coatings.

KEYWORDS: Fire retardant, Exterior claddings, Durability, Artificial weathering

1 INTRODUCTION

Fire-retardant chemicals (FRC) effectively reduce the flame spread and heat release in wooden claddings when exposed to fire. The chemical content near the surface is an especially important factor in suppressing the flame spread along fire-retardant–treated (FRT) materials. Under repeated drying–wetting environment, the impregnated chemicals move toward the wood surface [1] because most chemicals are water soluble. If used outdoors, then these accumulated chemicals are easily lost to condensed water or rain. Thus, protection with coatings is important not only from an aesthetic point of view but also to reduce fire risks.

Conducting an artificial weathering test using UV lamps and water spraying is necessary to speed up the development of new coating materials to evaluate how long coated FRT wood maintains the desired amount of FRC. This paper describes the results of modified versions of EN-927 standards [2], which are known as the methods for coated untreated wood.

The degradation of FRT wood is possibly caused by wetting, exposure to the sunlight, and drying. In some existing studies, degradation of coated untreated wood during exterior use is considered [3-5], and in some studies, accelerated tests using a xenon arc lamp method or UV fluorescent lamp method by QUV reproduced aesthetical deteriorations to some extent. Surface cracks and changes in gloss were reproduced using QUV, and changes in colors were correlated using QUV and a Xenon arc lamp [3]. However, attempts to predict FRC retention based on accelerated tests are rarely reported other than in study such as literature [6], while there are some reports related to the outdoor durability such as [7, 8] and fire testing methods for FRT wood after accelerated weathering test [9].

In the evaluation of the durability of FRT wood, moisture absorption should be considered. Figure 1 shows a diagram of the typical deterioration in coated FRT wood. After long-term outdoor exposure, coating cracks and efflorescence followed by leaching of chemicals are common, and many of them originate owing to moisture absorption or desorption.

(a) FRT absorbs more water than untreated wood [10], which means less dimensional stability and more stress on coatings.

(b) Efflorescence occurs at the wood coating boundary [11], which could break the wood coating bonding (only in the case of high-build types of coating).

(c) Water leaches FRC out of wood.
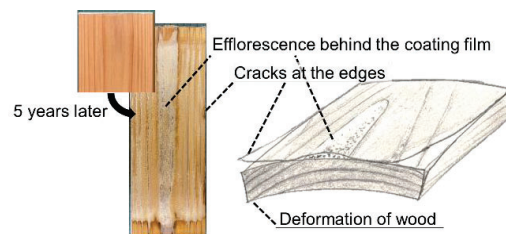
Figure 1: Typical degradation of FRT wood coated with film-forming type material

In this study, most of the testing conditions in EN927-6 were applied, and only conditions related to water absorption and desorption were modified to allow the leaching speeds of FRC to catch up with the degradation (i.e., changes in color) speed of coating materials.

There is also a fire testing method called NT Fire 053 [9, 12] that targets the outdoor usages of FRT wood products. The materials eventually undergo the fire spreading test after being repeatedly exposed to spray and drying (UV

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light is also added in Method 2). Except for the absence of the condensation function in NT Fire 053, this method has similar functions as QUV. Thus, some findings from this study provide implications for a better correlation between NT Fire testing and outdoor exposure.

2 EXPERIMENTAL SECTION

Pieces of *Sugi* (*Cryptomeria japonica*) FRT wood with several types of coatings (Figure 2) underwent each test, as shown in Figure 3. In this study, QUV accelerated tests, one year of outdoor exposure test, and steady sorption test were carried out.

In the one year of outdoor exposure test, the moisture content of each coated FRT and untreated wood was measured to grasp the extent of absorption and desorption in actual conditions.

QUV tests that have different testing conditions were conducted, and chemical retention after each accelerated test was compared with the four-year-outdoor exposure reported elsewhere [8].

Alongside these unsteady tests, the diffusion coefficient (ID) of each material was measured to discuss how the moisture absorption speeds are affected by testing conditions, as the temperature in the present QUV equipment is often higher than it is outdoors.

2.1 SPECIMENS

As shown in Table 1, three groups of specimens of different sizes were prepared. For outdoor exposure, specimens with a size of 300 mm (longitudinal, L), 18 mm (radial, R), and 70 or 105 mm (tangential, T) were prepared. For artificial weathering, specimens with a size of 300 mm (L), 18 mm (R), and 70 mm (T) were prepared. They were treated with 25 wt% of FRC aqueous under a pressure of 0.95 MPa and dried. The FRC used herein was a guanidine phosphate based FRC.

After impregnation, each front face and both edge grains were coated with one of the five types of coatings as shown in Figure 2. For the remaining faces, the procedures are the same among the coating types. The back face of the specimens were coated with film-forming alkyd (same one as coating D), and both end-grain faces were sealed with epoxy resin and foil tapes. The above procedures are the same as in previous studies [6, 8].

For ID measurement, wood blocks with a size of 30 mm (L), 18 mm (R), and 30 mm (T) were prepared. Sheets of aluminum foil were directly glued to the remaining five faces with epoxy resin to achieve strict one-dimensional absorption.
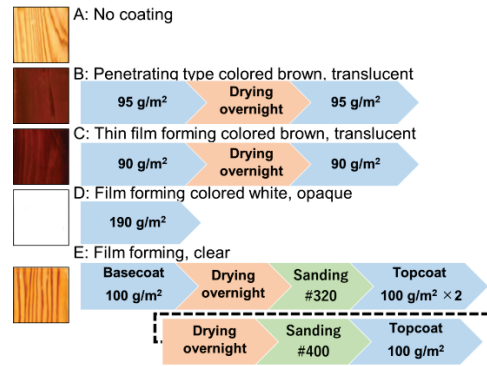

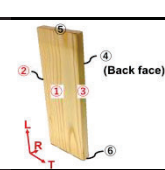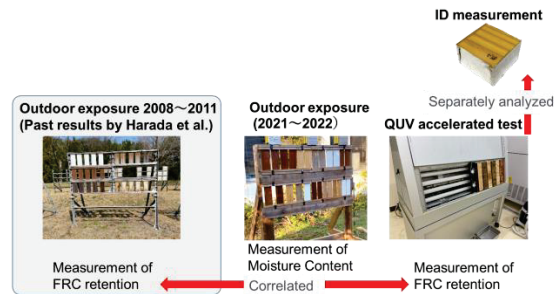*Figure 2:* Coating procedures for weathering tests

Figure 3: Experiment schemes

2.2 MEASUREMENT OF MOISTURE CONTENT DURING OUTDOOR EXPOSURE

On the basis of the outdoor exposure testing method described in Japanese Industrial Standards [13], each specimen in Table 1 underwent outdoor exposure. The site is located in Tsukuba, Japan. Specimens were fixed vertically facing due south. During the exposure, the moisture content was monitored by weighing each specimen almost three times a week. Measurements of moisture content are often performed using electrodes [14-16], but this approach is unsuitable for FRT wood because chemicals are electrically conductive.

Table 1: List of specimens

Testing	Number of repetitions (for each coating)	Fire retardant treatment	Lengtial [mm]	Radial [mm]	Tangential [mm]	Coating procedures	
Outdoor exposure (2021-2022)	2	None	300	18	105		Face ① to ③ : Either coating system A to E Face ④ : Coating system D Face ⑤ and ⑥ : Epoxy resin covered with foil tapes
	2	Phosphate guanidine based	300	18	70		
QUV	1 or 2	Phosphate guanidine based	300	18	70		
ID measurement	1 or 2	None	30	18	30		Face ① : Either coating system A to E Face ② to ⑥: Aluminum foil glued with epoxy resin
		Phosphate guanidine based					

The experiment for untreated wood was conducted from May 2021 to Sep. 2022. For FRT wood, the experiment was conducted from July 2021 to Sep. 2022. The rainy season in Japan is typically between June to the end of July. Thus, the exposure of FRT wood started later to minimize the interference of weight changes due to the loss of FRC.

Values of moisture content were calculated as demonstrated in Figure 4 and Equation (1), which defines the weight of each untreated wood piece as 100%.

$$M = \frac{W_g - W_{FRC} - W_w}{W_w} \times 100 \quad (1),$$

where M is the moisture content [%], W_g is the gross weight [g], W_{FRC} is the weight of FRC approximated with exponential function [g], and W_w is the wood weight [g]. To correct the baseline for the FRC loss during exposure, one specimen for each coating system was separately prepared, exposed to the same environment, and oven dried every 4 or 6 months to be weighed. From the weights measured above, FRC retentions over time were approximated using the exponential function.
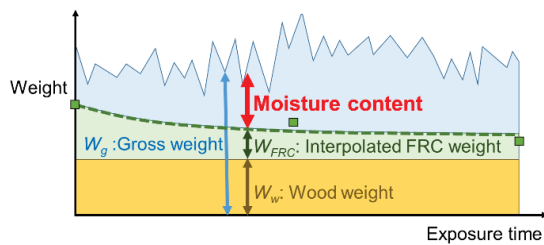

Figure 4: *Estimation scheme of moisture content within FRT wood*

2.3 MODIFICATION OF QUV CONDITIONS

Six conditions that differ in cycles and preconditioning environments were considered as shown in Table 2. The functions named "Condensation", "UV exposure" and "Spray" in Table 2 come standard with Q-LAB QUV/spray equipment. Condensation is typical for QUV equipment and is achieved by condensing hot vapor from a water pan at the specimen surface cooled by ambient air. Among these conditions, cycle S-25% is the closest condition to the EN927-6 standard. The tests were conducted over 504 h of testing time (three repetitions of 168 h cycles) as a unit. All specimens were conditioned beforehand until they reached equivalent moisture content (abbreviated as EMC in Table 2 and later figures), and oven-dried weights were measured subsequently. FRC retentions were calculated using Equation (2). Oven drying took place for three weeks for interim weighing (504, 1008, and 1512 h) and six weeks for the initial and final weights.

$$R_T = \frac{W_t - W_w - W_c}{W_0 - W_w - W_c} \times 100 \quad (2),$$

where W_0 is the gross initial weight [g], W_t is the gross weight after t hours of QUV test [g], W_w is the wood weight [g], and W_c is the weight of coating materials [g].

Changes in colors are estimated to be approximately 17.4 times faster than that under vertical exposure outdoors under QUV standard condition [5]. The amount of water sprayed in QUV is at least 30 times greater than wall precipitation outdoors; 5.76 L/cm² of water is sprayed within 2016 hours in QUV, whereas the wall precipitation at the testing site is estimated to be less than 0.83 L/cm² per year, according to Equation (3) [17].

$$R_w = aR_h U \cos \delta \quad (3),$$

where R_w is the wall precipitation [mm], a is a constant value determined by building size, R_h is the horizontal precipitation [mm], U is the wind speed [m/s], and δ is the horizontal attack angle between a wall and raindrops.

2.3.1 Initial Moisture Content

For some coating materials, conditioning moisture content is practically difficult because of the low permeability of the coating. Conditioning times could be even longer than the testing time. To figure out how much attention should be paid to controlling the initial moisture content, specimens with initial moisture content near 0% and 25% were compared.

Table 2: *Conditions of QUV tests*

Cycle	Preconditioning	QUV exposure cycle as a 1/3 unit	Condensation	Spray	UV Exposure
	Testing shedule as a unit — Pre-conditioning → QUV exposure 168h×3 → Oven dry 60°C, 3 weeks → weighing			QUV details	
S-0%	60°C incubator; EMC<2%	-24h condensation -(2.5h UV exposure then 0.5h spray) during 144h Condensation 24h / Repetition 48 times (UV2.5h then 0.5h spray) Total = 168h	45°C	6~7L/min	· 0.89W/m² at 340nm wavelength · 60°C of ambient temperature
S-25%	45°C 65%RH incubator; EMC≈25% for FRT wood				
M1-0%	60°C incubator	-(16h UV exposure then 8h intermittent spray and condensation) during 144h -24h UV exposure 2h 2h 1.3h Cond.1.3h Cond. 1.3h Spray Spray Spray 16h UV ... 24h UV Total = 168h	45°C	6~7L/min	· 0.89W/m² at 340nm wavelength · 60°C of ambient temperature
M1-25%	45°C 65%RH incubator				
M2-0%	60°C incubator		45°C	6~7L/min	· 0.89W/m² at 340nm wavelength · **50°C of ambient temperature**
M2-25%	45°C 65%RH incubator				

2.3.2 Duration of Each Cycle

Condensation and spray were alternately repeated for eight hours in cycle M1 to enhance water absorption in one wetting cycle. The total durations of each function (condensation, spray, and UV exposure) are the same between cycles S and M1.

2.3.3 Temperature During UV Cycles

To evaluate the effect of temperature on the leaching speed, cycle M2 that differs from cycle M1 only in the ambient temperature during UV exposure was considered. Cycle M2 is the combination of the lowest temperature available in Q-LAB QUV/spray equipment in each function. High temperatures are available (up to 60°C for condensation and UV exposure) but not considered in this study.

2.4 MEASUREMENT OF DIFFUSION COEFFICIENTS

The diffusion coefficient of each material in Table 1 was calculated from weight change under constant temperature (23°C, 45°C, and 63°C) and humidity (65% RH). These environments were achieved using containers with saturated salt (sherbet-like aqueous of NaCl) placed in incubators. Tests under a high humidity (95% RH) were also attempted, but they provided unstable results due to deliquescence, swelling, and seal failure.

3 RESULTS AND DISCUSSION

3.1 MOISTURE CONTENT DURING OUTDOOR EXPOSURE

Figure 5 shows the yearly transitions of moisture content and the weather record. The weather record from the nearest observatory was retrieved from the database of the Japan Meteorological Agency [18]. The actual peak values of the moisture content are expected to be a little high because the measurement did not necessarily take place right after rainfall. Also, the data earlier than day 40 should be excluded because of its unsteadiness. During the testing period at the site (Tsukuba), the equivalent moisture content estimated by relative humidity and temperature [19] is between 12% to 27%. The results for the coated untreated wood generally agreed with this estimation. The FRT wood had considerably high and unsteady values. The eventual moisture content exceeded 30%, allowing the presence of free water even after a short rainfall.

3.2 EFFECTS OF QUV CONDITIONS

Figure 6 shows the amount of FRC lost after 2016 hours of each test. The following sections show comparisons from some aspects.

3.2.1 Initial Moisture Content

Cycle S-25% is the closest condition to the EN927-6 standard. For specimens C, D, and E (considerably high-build types of coatings), more FRC leached under the cycle S-25% than under S-0%. The influence of initial moisture content becomes unclear for cycles M1 and M2.

Initial moisture content seems more important for high-build coatings exposed to short-term spray, due to the low permeability of the coatings.

3.2.2 Duration of Each Cycle

Cycle M1 is the rearranged version of a standard cycle (cycle S). Judging from the fact that most of the specimens leached more under the cycle S than M1, combining condensation and spray as one wetting cycle seems insufficient to enhance the sorption of the coated wood.

3.2.3 Temperature during UV Cycles

Cycle M2 was designed to combine the lowest temperatures available in the present QUV equipment. However, it differs from M1 only in the ambient temperatures during UV exposure. Regardless of the initial moisture content, more FRC tended to leach under cycle M2 than under M1 in the case of specimens A (no coating), D, and E (high-build types of coating).
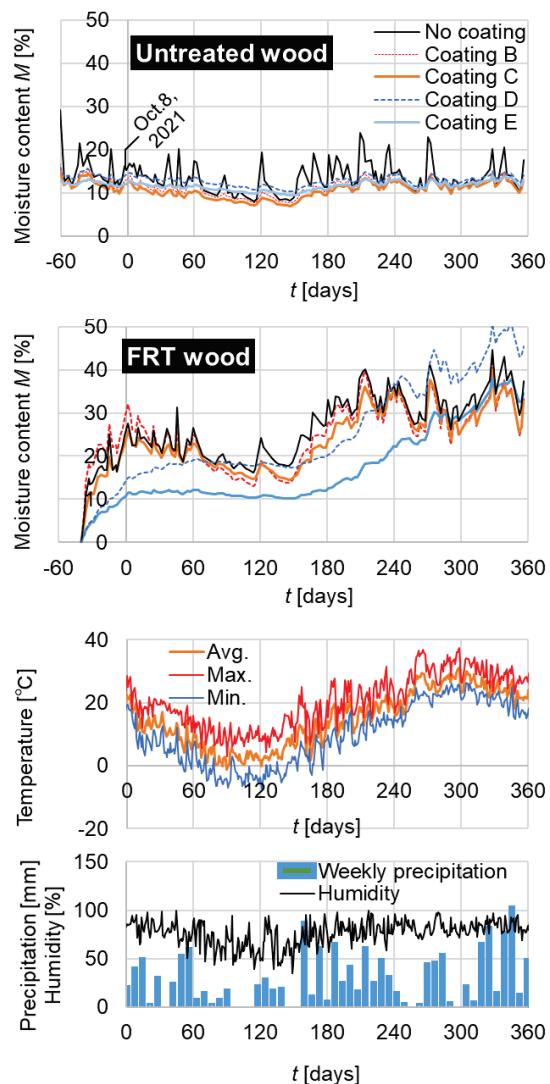

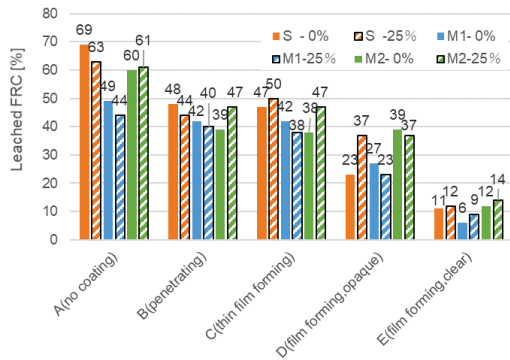*Figure 5: Moisture content and the weather at the site*

Figure 6: Leached FRC during 2016h of accelerated tests

3.3 RELATIONS BETWEEN LEACHING SPEEDS AND DIFFUSION COEFFICIENTS

Table 3 shows the gross (moisture excluding effectiveness of the coating is included) diffusion coefficients according to the method in reports such as [20]. With E defined as shown in Equation (4), its value against the square root of time increases linearly if the sorption follows Fick's law. Figure 7 shows an example of the sorption curves plotted against the square root of time.

$$E = M_t/M_\infty \qquad (4),$$

where E is the dimensionless moisture, M_t is the moisture content over time, and M_∞ is the equivalent moisture content in the ambient air.
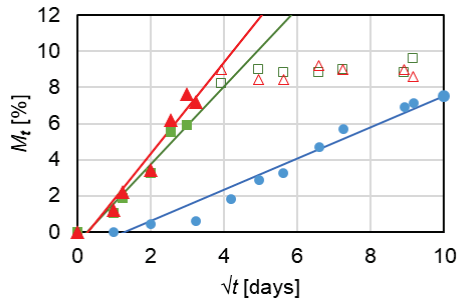

Figure 7: Examples of sorption under steady environments

With the use of the slope up to $E = 0.8$, the diffusion coefficients were calculated using Equation (5)

$$ID = \frac{l^2}{5.1}\left(\frac{dE}{d\sqrt{t}}\right)^2 \qquad (5),$$

where ID is the diffusion coefficient [m^2/s], l is the length equal to twice of the sample thickness [m], and t is the time [s].

As shown in Table 3, the ratios of ID among the coatings are not maintained as long as the testing temperature is higher than that outdoors. The temperature dependence of IDs differs according to the base material (FR treated or not) and the coating materials, and tends to be highly temperature dependent in the cases of specimens D and E (relatively high-build coatings are applied).

3.4 COMPARISON WITH OUTDOOR RESULTS

In deducting the test method for new coating materials, the degree of acceleration is preferably uniform among the types of coatings. With this degree defined as the acceleration coefficient (Figure 8g), their ratio among specimens A to E is presented in Figure 8. For instance, figure 8d shows that the testing under standard condition (cycle S-25%) for specimens A (no coating), D and E (high-build type of coating) is not as efficient as that for specimens B and C.

In all conditions, the acceleration coefficients for the first 504 h are scattered and larger than the values afterwards. The gradual decrease of acceleration coefficients typical for specimen B and C (considerably low-build types of coatings) agrees with Table 3 in that the ID difference between untreated and FRT wood becomes large at high temperatures.

3.4.1 Effects of Testing Cycles

Regardless of the initial moisture content, the acceleration coefficient is reduced especially in specimens A (untreated), D, and E (high-build type of coating) by modifying the cycle from S to M1. As mentioned in 3.2.2,

Table 3: Temperature dependence of diffusion coefficients

	Temperature		No coating	Coating B	Coating C	Coating D	Coating E
	[℃]		N=2	N=1	N=1	N=1	N=1
Control	23	ID* [×10⁻¹¹]	13.75	8.88	9.76	2.78	2.98
	45	ID* [×10⁻¹¹]	40.68	38.34	46.49	16.15	27.94
		(Ratio to 23℃)	(3)	(4.3)	(4.8)	(5.8)	(9.4)
	60	ID* [×10⁻¹¹]	57.5	49.0	46.5	35.7	38.5
		(Ratio to 23℃)	(4.2)	(5.52)	(4.8)	(12.8)	(12.9)
FRT wood	23	ID* [×10⁻¹¹]	22.0	13.1	10.3	0.8	2.6
	45	ID* [×10⁻¹¹]	91.1	58.8	77.5	21.8	28.6
		(Ratio to 23℃)	(4.1)	(4.5)	(7.5)	(27.1)	(11)
	60	ID* [×10⁻¹¹]	232.9	121.7	141.3	68.7	71.4
		(Ratio to 23℃)	(10.6)	(9.31)	(13.7)	(85.4)	(27.5)

combining condensation and spray as one wetting cycle seems insufficient to enhance the sorption of coated wood. In addition, no specimen reached an acceleration coefficient of ~30 just because 30 times more water is sprayed in QUV. These findings imply that most of the water sprayed in QUV simply runs down to wash out FRC on the surface of the specimens. Thus, the amount of water in QUV is greater than that absorbed by the wood.

3.4.2 Effects of Testing Temperature

The variation in acceleration coefficient evaluated from RSD is smaller in M2 than M1.

In spite of the ID tendencies shown in Table 3, the acceleration coefficients for specimen D and E shown in figure 8 do not decrease when the testing temperature is lowered from M1 to M2. This finding indicates that, due to the increase of equivalent moisture content by lowering the temperature during UV cycles, the absorbed water was able to remain as free water and enhance the leaching of FRC.

4 CONCLUSIONS

The preferable conditions of artificial weathering tests for FRT wood are narrowed down through the following findings:

1. FRT wood exposed outdoors in Tsukuba could exceed 30% of moisture content, regardless of their coating type.
2. The temperature dependence of the diffusion coefficient differs among the coating materials and base materials, resulting in various acceleration coefficients during QUV tests.
3. Keeping moisture content high by raising the initial moisture content or lowering the testing temperature speeds up the leaching from FRT wood coated with

high-build coatings. In other words, the durability of FRT wood combined with these coatings tends to be overestimated under the QUV standard condition if the initial moisture content is low. This finding suggests that tests merely following EN 927-6 could also overestimate durability of these materials because it could take more than a year for these materials to reach equilibrium if the specimens are conditioned at 20°C, designated temperature in the EN 927-6.

A single type of fire-retardant chemical and five types of coatings demonstrated the difficulty of accelerating their degradation to the same degree, especially at high temperature. Acceleration coefficients can be more stabilized not by speeding up unsteady sorption during spray but by keeping testing chamber more humid throughout the testing time. Reducing the thickness of the specimens might be another effective way of speeding up moisture absorption without raising the temperature. Further experiments are being conducted.
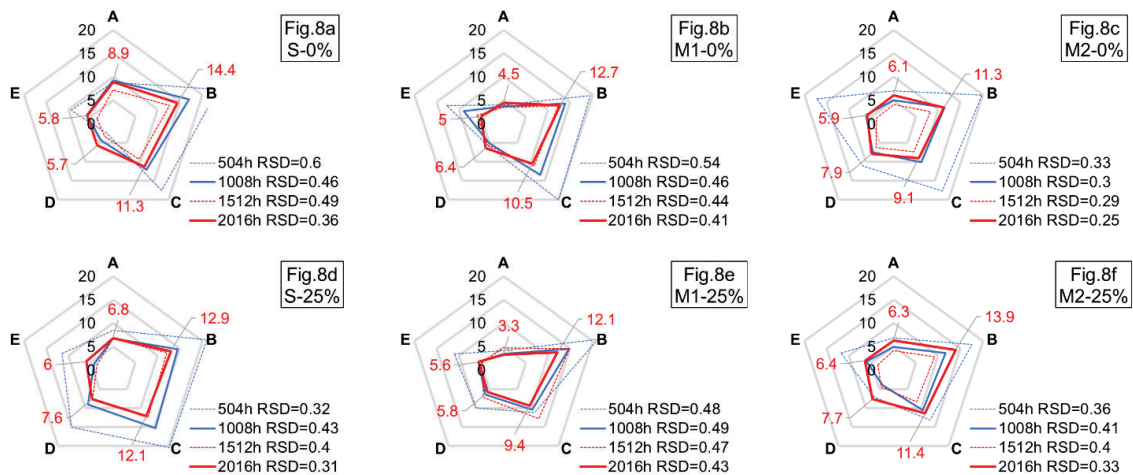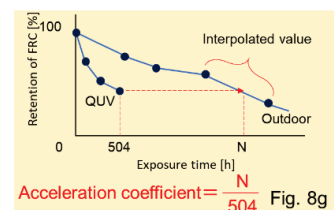

Figure 8: Acceleration coefficients in each test

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