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Artificial-weathering test requirements for fire-retardant-treated wood to reproduce optimal chemical retention and moisture conditions

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Abstract

Despite the increasing outdoor use of fire-retardant-treated wood, methods for predicting its service life remain poorly established. With the aim of establishing a method to predict chemical losses from fire-retardant-treated (FRT) wood caused by humid atmospheres and rain outdoors, this study examined the preferable conditions for artificial-weathering tests and demonstrated the acceleration coefficients in these tests (i.e., the ratio of equivalent time to reach the same retention of chemicals in artificial weathering and outdoors) based on the EN927-6 standard. To determine the moisture absorption and desorption levels of FRT exposed to outdoor conditions, an outdoor exposure experiment was conducted. The moisture content was higher in the FRT wood than in untreated wood, regardless of the type of coating, and ranged between 11% (in March) and 50% (in September) of the untreated wood's weight. EN927-6 artificial weathering tests were performed on two groups of specimens with initial moisture contents of 0% and 25%. Retention rates of fire-retardant chemicals after a 2520-h test were compared with those retrieved from 4-year outdoor exposure reported elsewhere. Comparison of these two experiments demonstrated that the acceleration coefficients were 4.1–11.3 in the case of specimens with 0% initial moisture content and 5.1–11.4 in the case of specimens with 25% initial moisture content. The higher initial moisture content produced a more uniform acceleration coefficient. Nevertheless, larger acceleration coefficients were derived from specimens with penetrating or semi-film-forming coatings in both cases. The relationships between the uniformity of this acceleration coefficient and the initial moisture content are discussed from the moisture absorption experiment under constant temperature and humidity and under condensation conditions.

Keywords Fire-retardant-treated wood, Artificial weathering, EN927-6, Acceleration coefficient

Introduction

Wood is becoming widely used as an exterior cladding with an increasing need to reduce the carbon footprint of buildings and with divergence in building designs. In some parts of this cladding, wood is treated with fire-retardant chemicals (FRC) to suppress fire spread within and between buildings. Chemicals impregnated into fire-retardant-treated (FRT) wood move toward the wood surface (efflorescence) along with the moisture absorbed during rainfall and from humid atmospheres, eventually being lost from the wood [1]. Coating of wood can effectively suppress this loss of FRC, but methods for predicting the service life of coated FRT wood are poorly established. Holmes et al. [2] and LeVan et al. [3] conducted outdoor weathering of FRT wood shingles for up to 10 years and artificial weathering according to ASTM

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D 2898 [4] and identified several treatments with acceptable fire performance. Nakamura et al. [5] conducted a modified method of NT Fire 053 [6] on FRT wood and derived a testing condition that established more chemical loss within the same testing duration. Durbrulle et al. [7] conducted artificial weathering using the UV-fluorescent lamp method and bench-scale burning tests on wooden boards to which commercial FRC and several types of coatings were applied. However, the correlation between artificial weathering and outdoor exposure was not discussed by the FRC retention in these studies.

To predict the service life of FRT wood from artificial weathering, the ratio of time in artificial weathering and outdoor conditions to reach the same chemical retention (i.e., the acceleration coefficient) is necessary. Harada et al. [8] conducted artificial weathering based on the xenon-arc lamp method, a general testing method for paints, on several types of coated FRT wood; specimens with some of the abovementioned coatings also underwent outdoor exposure. The results from outdoor exposure and artificial weathering tests were similar in distinguishing which coatings were more suitable for retaining FRC retention [9], but the acceleration coefficient could not be derived because of the thinner sample used in artificial weathering. Using the same coatings and FRC, Takase et al. [10] conducted xenon-arc lamp artificial weathering tests using specimens with the same thickness as those exposed to outdoor exposure and identified that their acceleration coefficients become smaller if film-forming coatings are applied.

The low acceleration coefficient in FRT wood with film-forming coating is possibly due to poor reproduction of efflorescence in artificial weathering. Generally, degradation of film-forming coating on untreated wood initiates from cracks at the corner. Conversely, degradation of this coating on FRT wood initiates from bonding failure at the wood-coating boundary caused by FRC efflorescence beneath the coating film [11]. This efflorescence of FRC is poorly reproduced in artificial weathering.

We speculated that in outdoor FRT wood, moisture penetrates deeper into the wood and subsequently dries to drive out FRC to the wood-coating boundary, whereas moisture cannot penetrate as deeply in artificial weathering as in an outdoor environment. To modify the conditions of artificial weathering for FRT wood, the moisture content in outdoor-exposed FRT wood needs to be clarified as a distribution within the wood or as an overall value. Moreover, artificial weathering equipment is also necessary to capacitate specimens thick enough for actual use and employ a function that enforces moisture absorption. Whereas changes in moisture content outdoors have been reported (Isaksson et al. [12] for uncoated wood and by Derbyshire et al. [13] for coated exterior wood), its value in the case of FRT wood is possibly higher due to the hygroscopic property of the FRC [14]. For artificial-weathering equipment, an equipment for the UV-fluorescent lamp method in EN927-6 [15] might be suitable as this capacitates thick specimens and employs a condensation function. To contrast the moisture conditions of coated FRT wood outdoors and during an artificial weathering test, and to develop an artificial weathering method that provides more uniform acceleration coefficients, this study described the variation in moisture content outdoors, the influence of initial moisture content on FRC loss in artificial weathering, and the effects of coatings on the sorption of FRT wood.

Experimental

Specimens

Flatsawn boards in two sizes of 300 (longitudinal, L) × 18 (radial, R) × 105 (tangential, T) mm or 300 (L) × 18 (R) × 70 (T) mm were cut from sugi (*Cryptomeria japonica* D. Don) sapwood. The oven-dry density of untreated wood was between 284.5 and 342.1 kg/m^3. Wood boards were treated with FRC using the following procedures as previously described by Harada et al. [9]. The oven-dry mass of untreated wood was measured before FRC treatment. Wood pieces were then placed in pressure impregnation equipment (Yasujima Co. Ltd.) to undergo the Bethel process [16]. The equipment was filled with an aqueous solution of 25 wt% guanidine phosphate-based FRC (Non-nen W200, Marubishi Oil Chemical Co.), and pressure was applied. The pressure condition was initially −0.09 MPa, 30 min for the preliminary vacuum, 0.95 MPa pressure for the following 2 h, and −0.09 MPa and 30 min for the final vacuum. Wood pieces were then removed from the aqueous solution and let to predry for 1 week. Predried FRT wood pieces were then forced to dry in a drying oven. Constant weights after the oven drying process were measured to calculate the initial FRC content as shown in Eq. (1). All the drying processes in this paper were performed under 60 °C temperature to avoid degradation of FRC and coatings. Moreover, all data denoted as oven-dry weights were obtained when the weight changes in a day became < 0.1%, which took approximately 6 weeks for coated FRT wood.

$$\text{FRC content}\ \left[\text{kg/m}^3\right] = \frac{W_{\mathrm{FRT(OD)}} - W_{\mathrm{W(OD)}}}{V \times 1000}, \tag{1}$$

where $W_{\mathrm{FRT(OD)}}$ is the oven-dry weight of FRT wood [g], $W_{\mathrm{W(OD)}}$ is the oven-dry mass of untreated wood [g], and V is the volume of the wood piece [m^3].

The calculated FRC contents are shown in Table 1. Wood pieces with a size of 300 (L) × 18 (R) × 105 (T) mm were left untreated for comparison.

Table 1 Specifications of the specimens

Coating types		Outdoor exposure (Experiment I)		Artificial weathering (Experiment II)		Condensation (Experiment III)	Constant temperature and humidity (Experiment IV)
				Group IMC-0[a]	Group IMC-25[a]		
		Untreated	Fire-retardant-treated wood				
A (no coating)	Untreated wood density [kg/m^3]	295.3	310.4	330.1	308.1	299.4	319.7
	FRC content [kg/m^3]	–	219.1	180.1	218.6	207.3	201.0
Coating B	Untreated wood density [kg/m^3]	310.9	303.3	346.4	293.0	315.2	308.0
	FRC content [kg/m^3]	–	225.0	180.0	227.0	199.7	214.7
	Coating weight [g/m^2][b]	53.4	60.2	55.8	60.2	57.3	57.5
Coating C	Untreated wood density [kg/m^3]	288.9	318.4	335.4	296.6	304.6	324.9
	FRC content [kg/m^3]	–	222.0	180.4	215.2	205.0	200.8
	Coating weight [g/m^2][b]	43.1	51.5	45.4	49.8	50.0	48.8
Coating D	Untreated wood density [kg/m^3]	287.0	314.1	333.5	307.1	304.8	327.3
	FRC content [kg/m^3]	–	229.2	176.4	220.5	211.5	196.0
	Coating weight [g/m^2][b]	135.6	151.6	135.8	146.7	141.9	141.5
Coating E	Untreated wood density [kg/m^3]	295.3	306.8	336.8	325.0	311.2	314.2
	FRC content [kg/m^3]	–	230.8	179.8	214.9	209.8	197.5
	Coating weight [g/m^2][b]	102.7	116.4	104.0	115.1	112.5	112.2
Duplication for each coating types		2	2	2	1	3	12 (4 for each temp [23, 45, 60 °C])
Sizes [mm]		300 (L) × 18 (R) × 105 (T)	300 (L) × 18 (R) × 70 (T)				30 (L) × 18 (R) × 30 (T)

[a] Group determined by initial moisture content before accelerated weathering

[b] Non-volatile content of the coating

Pieces of FRT and untreated wood then underwent coating processes as previously described [9]. One of the five types of coatings shown in Fig. 1 was applied on the front and side faces. These coating types were: A (no coating), B (penetrating-type colored brown, translucent), C (thin-film-forming colored brown, translucent), D (film-forming colored white, opaque), and E (film-forming, clear). Coating D was applied to the back face of all specimens. End grains were covered with epoxy resin and aluminum foil tape. The oven-dry density of untreated wood, FRC content, nonvolatile content of coatings, and number of specimens are described in Table 1.

To compare moisture absorption speeds through each coating type, small wood pieces with a size of 30 (L) × 18 (R) × 30 (T) mm were cut from the coated FRT wood described above. For these specimens, the four side faces and the back face were covered with aluminum foil and epoxy resin as shown in Fig. 2 Experiment IV.

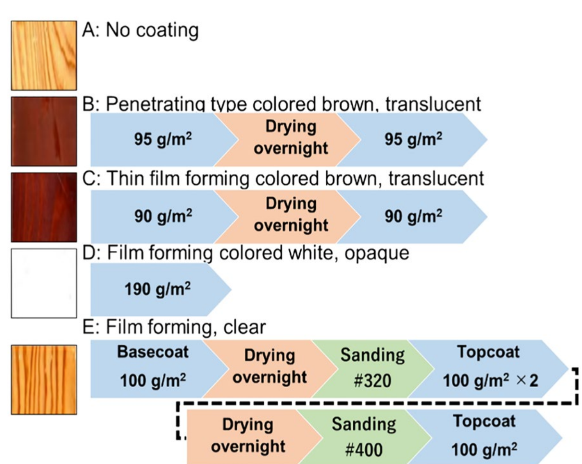

Fig. 1 Coating systems and coating procedures

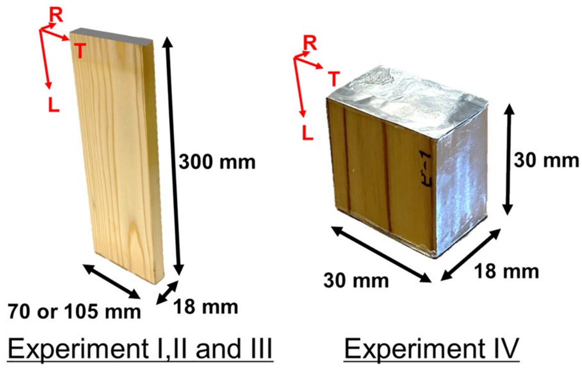

Fig. 2 Dimensions of each specimen

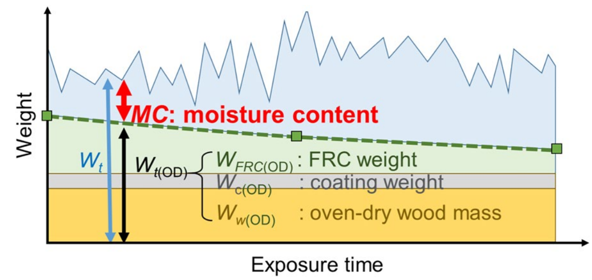

Fig. 3 Estimation scheme of the moisture content within FRT wood

Measurement of yearly moisture content during outdoor exposure (Experiment I)

The untreated and FRT specimens without and with coatings were exposed to outdoor conditions, according to the JIS K-5600-7-6 standards [17]. JIS K-5600 is a modified version of ISO/DIS2810.2: 1999 [18] for domestic use in Japan. Untreated specimens had a width of 105 (T) mm, which corresponds to the recommended size in JIS K-5600-7-6, and FRT specimens had a width of 70 (T) mm, the same size as in artificial weathering in Experiment II. The site was located in Tsukuba, Japan (36° 00′ 35.20″ N, 140° 07′ 55.92″ E, and 22 m above sea level).

Specimens were fixed vertically with the front face facing south. Untreated specimens were exposed outdoors after being stored under constant temperature (23 °C) and humidity (50%). FRT specimens were exposed immediately after oven-dry weights were measured. Specimens were exposed outdoors for 2 years (from September 2021 to September 2023). During this period, specimens were weighed for the initial 13 months at fixed intervals of 2 or 3 days.

Weighing intervals are independent of climate, and therefore several measurements were conducted during rain. Consequently, water drops were wiped off, and the wood pieces were weighed at room temperature, and briefly exposed as before. Due to this weighing procedure, the actual peaks of the moisture content during rain are slightly higher than the presented value. The moisture content of the FRT specimens was calculated as described in Eqs. (2a), (2b), and Fig. 3, which define the oven-dry mass of each untreated wood piece ($W_{W(OD)}$) as 100%. Changes in $W_{W(OD)}$ during outdoor exposure are negligible (approximately 1%) because the erosion depth after 2 years is estimated to be 250 µm in the earlywood, according to the value of uncoated redwood [19] (density 360 kg/m^3). Contrary,$W_{FRC(OD)}$ in Eq. (2b) decreases during outdoor exposure due to the loss of FRC. To estimate the weight changes due to the loss of FRC, one out of two specimens was oven-dried and weighed every 4 months of exposure (every 6 months for coating types D and E). The results are shown in Fig. 4. Retention rates of FRC (R_t) were calculated according to Eq. (3), and values were interpolated for periods in between.

$$\mathrm{MC} = \frac{W_t - W_{t(\mathrm{OD})}}{W_{\mathrm{W(OD)}}} \times 100, \tag{2a}$$

$$\text{while } W_{t(\mathrm{OD})} = W_{\mathrm{W(OD)}} + W_{\mathrm{C(OD)}} + W_{\mathrm{FRC(OD)}}, \tag{2b}$$

where W_t is the overall weight of the coated FRT wood piece at time t [g], $W_{t(OD)}$ is the oven-dry weight of the coated FRT wood piece at time t [g], $W_{W(OD)}$ is the oven-dry mass of untreated wood [g], $W_{C(OD)}$ is the nonvolatile weight of the coating [g], and $W_{FRC(OD)}$ is the oven-dry weight of FRC at time t [g].

$$R_t = \frac{W_{t(\mathrm{OD})} - W_{\mathrm{W(OD)}} - W_{\mathrm{C(OD)}}}{W_{0(\mathrm{OD})} - W_{\mathrm{W(OD)}} - W_{\mathrm{C(OD)}}} \times 100, \tag{3}$$

where R_t is the retention rate of the FRC at time t [%], $W_{t(OD)}$ is the oven-dry weight of the coated FRT wood piece at time t [g], $W_{W(OD)}$ is the oven-dry mass of untreated wood [g], $W_{C(OD)}$ is the nonvolatile weight of the coating [g], and $W_{0(OD)}$ is the initial oven-dry mass of the coated FRT wood piece [g].

Artificial-weathering tests (Experiment II)

Based on the EN927-6 method, an artificial-weathering test comprising 15 repetitions of a 168-h cycle (24 h of condensation with 48 repetitions of 2.5 h of UV exposure then 0.5 h of spray) was conducted using a QUV/Spray instrument (06-14127-73-Spray manufactured by Q-Lab Co). As shown in Fig. 5, specimens were dried every 504 h in a 60 °C drying oven, and retention rates of FRC were calculated using Eq. (3). For retention rates after 504, 1008, 1512 and 2016 h of artificial weathering, weights after 3 weeks of oven drying were obtained.

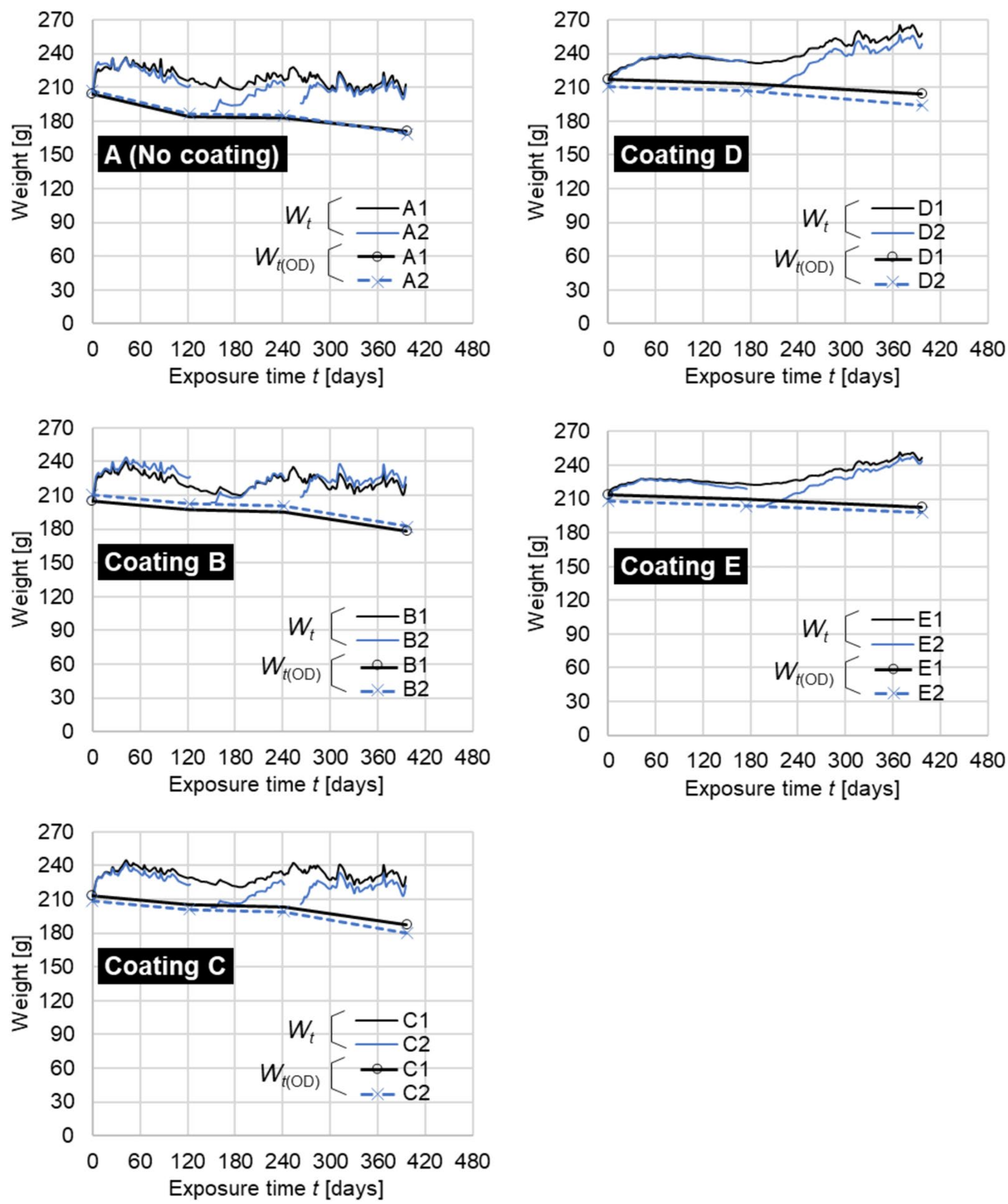

Fig. 4 Weight of the coated FRC specimens during outdoor exposure

These values tended to be higher than values after 6 weeks by 2–4%.

To clarify the effect of initial moisture content (IMC) on FRC retention rates in artificial weathering, two groups that differed in IMC were prepared. As shown in Fig. 5, IMC-0 was continuously dried until being resumed to artificial weathering while IMC-25 was resumed after being conditioned in an incubator set at 45 °C 65% RH. IMC-25 denotes its equivalent moisture content in FRT specimens of approximately 25%. This high equivalent moisture content was due to the hygroscopic properties of FRC [14]. As shown in Fig. 5, oven drying, weighing, and conditioning occurred after every 504 h of artificial weathering.

Moisture content measurement in EN927-6 condensation (Experiment III)

To determine the optimum use of the condensation cycle for accelerating the moisture absorption by the specimens, changes in their moisture content were measured. Specimens with the same FRC treatment, coating types and sizes (Fig. 2) as in artificial weathering were

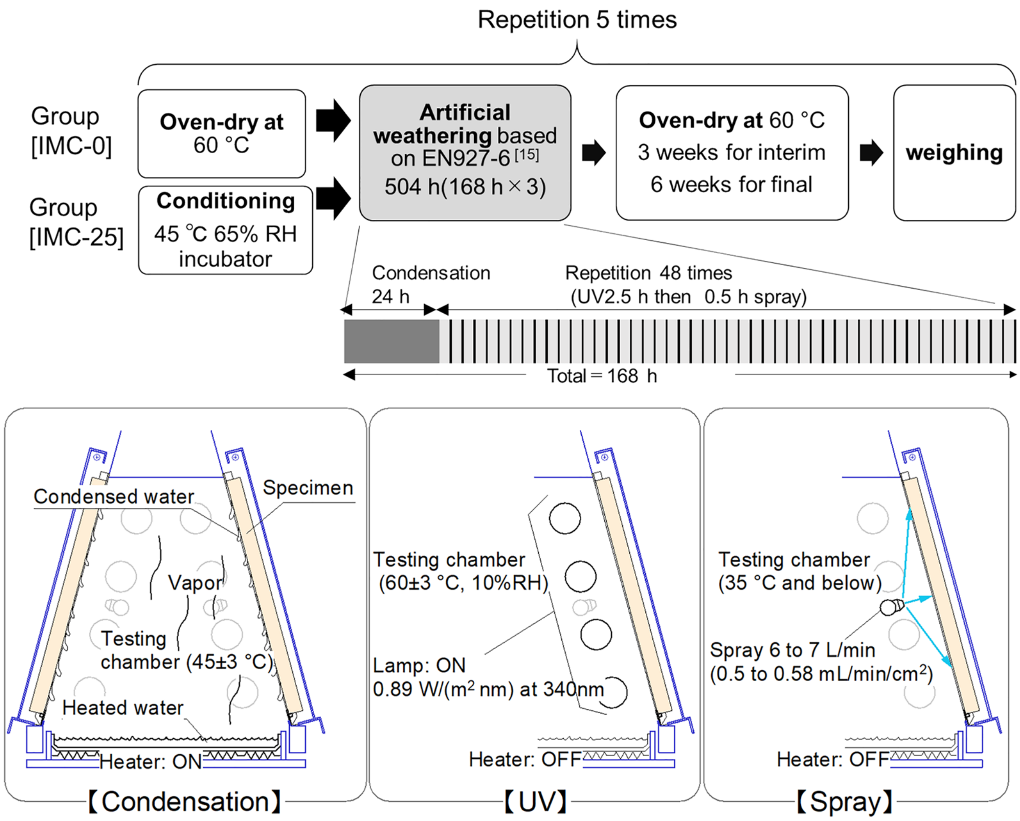

Fig. 5 Procedures within 2520 h of artificial weathering

exposed to EN927-6 condensation conditions for 168 h after measuring their oven-dried weights ($W_{t(OD)}$). During exposure, specimens were intermittently removed, weighed at room temperature after water drops were wiped off, and briefly exposed to condensation as before. The moisture content values were calculated as described in Eq. (2a) assuming no FRC have been leached out during this test.

Comparison of moisture absorption speeds at constant temperature and humidity (Experiment IV)

To compare the temperature dependence of the moisture absorption speed of each specimen without significant FRC loss, the moisture content was measured at constant temperature and humidity using the specimens in Table 1 Experiment IV. Before the experiment, the specimens were conditioned at 45 °C and 11% RH until they reached equilibrium, and their initial weights ($W_{t(OD)}$) were measured. Specimens and petri dishes filled with saturated aqueous NaCl were then placed together in closed containers, and the containers were stored in incubators set to three designated temperatures (23 °C, 45 °C, and 60 °C). The relative humidity controlled by the saturated NaCl salt is 75% ± 1% at these temperatures. During the experiment, specimens were intermittently removed more than twice a week to be weighed. Weighing was conducted briefly at room temperature. The moisture content values were calculated as described in Eq. (2a) assuming no FRC have been leached out during this test.

Results and discussion

Yearly moisture content during outdoor exposure (Experiment I)

Changes in the moisture content of coated and untreated specimens and those in coated FRT specimens calculated by Eq. (2a) are presented in Fig. 6 along with meteorological data. The meteorological data refers to the closest station to the exposure site (Tateno, Tsukuba) and was retrieved from the Japan Meteorological Agency database [20].

The equivalent moisture content of uncoated but untreated wood [21] corresponding to temperature and humidity during exposure was between 12 and 27%. The presented values in coated and untreated wood were similar to this estimation, whereas coated FRT specimens had significantly higher moisture content. After excluding data up to 60 days, the minimum values of moisture content in the coated FRT specimens were as follows: A

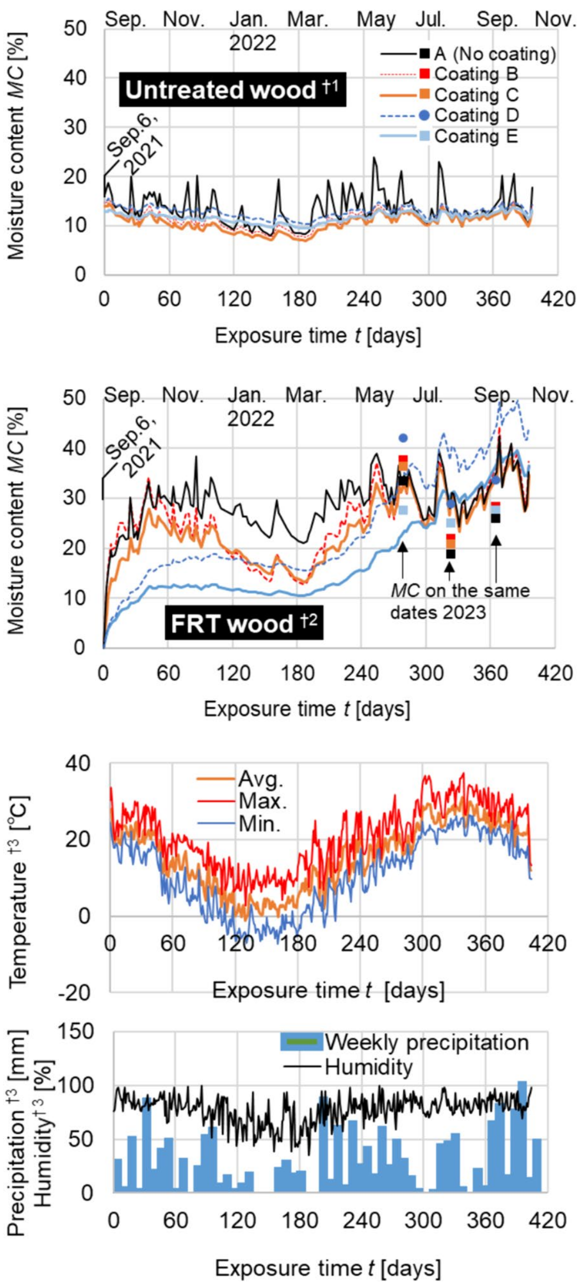

Fig. 6 Yearly transition of moisture content and weather at the site. †1Average of 2 duplications. †2$N = 1$. †3Retrieved from the Japan Meteorological Agency database [20]

(no coating), 20.9% (Mar. 11, day 186); coating B, 12.8% (Mar. 11, day 186); coating C, 13.3% (Mar. 11, day 186); coating D, 15.5% (Mar. 14, day 189); and coating E, 10.5% (Mar. 9, day 184. The maximum values of moisture content were as follows: A (no coating), 42.5% (Sep. 9, day 368); coating B, 44.2% (Sep. 9, day 368); coating C, 41.1% (Sep. 9, day 368); coating D, 49.5% (Sep. 26, day 385); and coating E, 39.7% (Sep. 26, day 385).

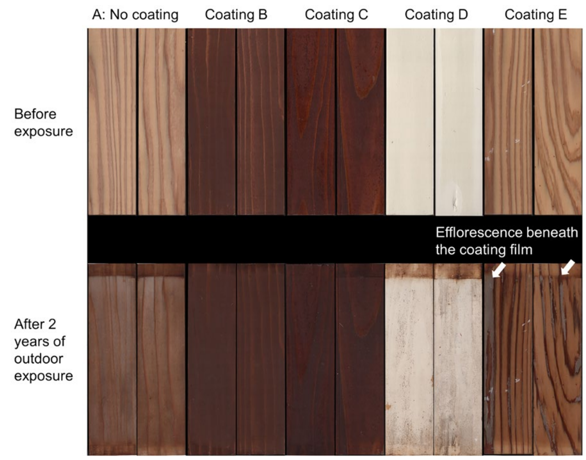

Fig. 7 Exposed faces of FRT specimens before and after outdoor exposure

The moisture content from day 60 to day 180 was constant or slightly decreased and then drastically increased from around day 180. This tendency corresponds to the temperature rise during this period. In the case of coating types B and C, the coating defects were insignificant, while for coating type D, the entire flat area was covered with small holes after 2 years (Fig. 7). At the surface of specimen E, slight efflorescence was observed at the corner around day 230. This efflorescence spread to the latewood area in 2 years (Fig. 7). No coating defects were observed in the flat area of specimen E after 2 years. However, several cracks less than an inch long were observed at the edges.

Artificial weathering tests (Experiment II)

The FRC retention rates for up to 2520 h of the artificial-weathering test are shown in Fig. 8. In coating types C, D, and E, retention rates were lower in IMC-25 than in IMC-0, with a significant tendency in coating D, where the FRC retention rate at 2520 h was 78.1% in IMC-0 and 57.2% in IMC-25. Using these FRC retention rates and Fig. 9 procedures, acceleration coefficients (ratio of times in artificial weathering and outdoors [9] to reach the same chemical retention) were derived (Fig. 10).

In Fig. 10, the numbers in red correspond to the acceleration coefficient for each coating type from A to E at 2520 h. The relative standard deviations (RSDs) shown in the legends were calculated based on the acceleration coefficients of coating types A, B, C, D, and E; thus, a smaller RSD value implies that their acceleration coefficients are relatively uniform.

As demonstrated in Fig. 10, acceleration coefficients after 1008 h are smaller and more stable compared with those at 504 h. Focusing on charts at 2520 h of artificial

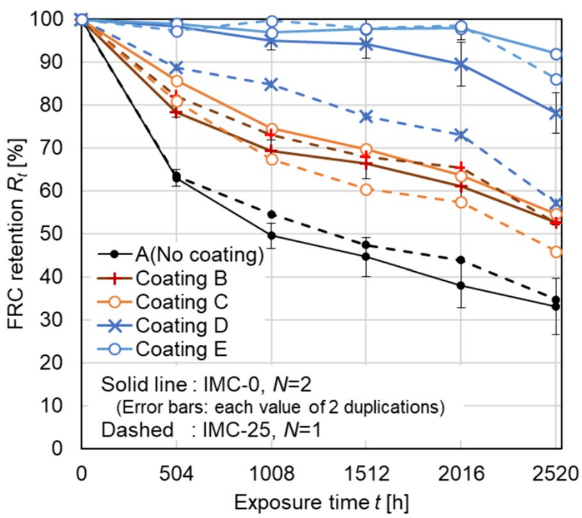

Fig. 8 FRC retention for up to 2520 h of artificial weathering test

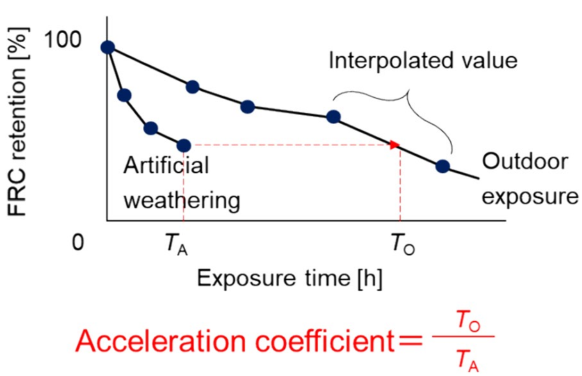

Fig. 9 Derivation procedures of the acceleration coefficient

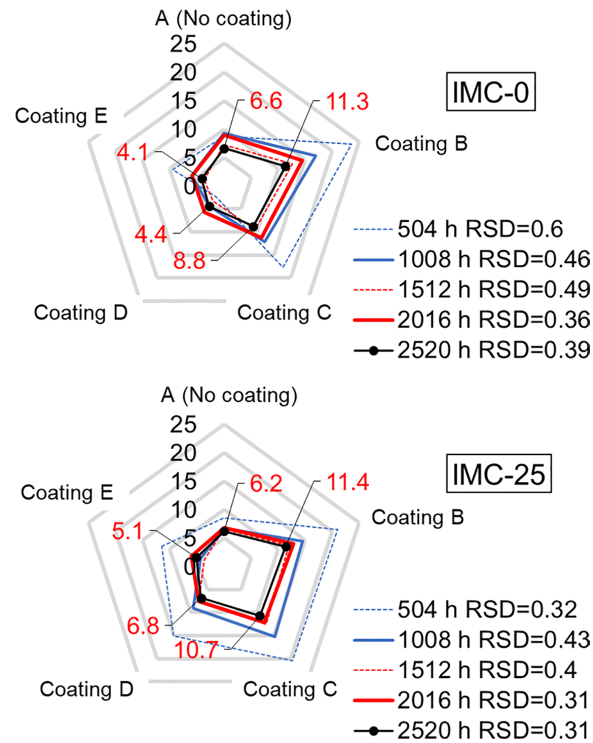

Fig. 10 Acceleration coefficient as evaluated by the FRC retention. RSD: relative standard deviation among acceleration coefficients of coating types from A to E

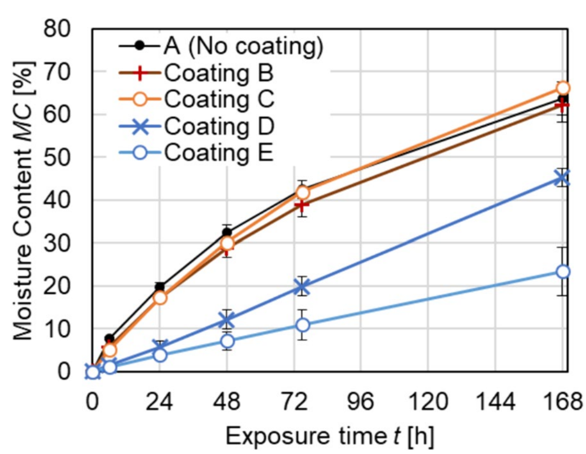

Fig. 11 Moisture absorption during condensation (Experiment III). Plots: average of 3 duplications. Error bars: standard deviations

weathering, acceleration coefficients range from 4.1 to 11.3 with 0% IMC and from 5.1 to 11.4 with 25% IMC. FRC loss was reproduced more uniformly in artificial weathering with high IMC values. Nevertheless, FRC loss tended to be accelerated in the penetrating coating type (B) and semi-film-forming coating type (C) under both IMC conditions.

Results reviewed from the absorption characteristics in Experiments III and IV

Changes in the moisture content of coated FRT specimens calculated from weight changes under condensation conditions (Experiment III) are shown in Fig. 11. In condensation, higher values were observed in specimens A (no coating), B (with penetrating-type coating), and C (with thin-film-forming-type coating). At 24 h, moisture content values were 21% in specimen A (no coating), 18% in coatings B and C, and 4%–5% in coatings D and E (with film-forming-type coating), respectively.

In EN927-6 artificial weathering, a 24-h condensation cycle is assigned at the beginning of every 168 h. However, within this period, the amount of moisture absorbed by specimens A, B, and C was larger than that of specimens D and E. The same applies to specimens with low IMC at the beginning of EN927-6 artificial weathering, which is assumed to be a cause of the low acceleration coefficient in coatings D and E in Experiment II.

Changes in the moisture content of coated FRT specimens calculated from weight changes at constant temperature and humidity (Experiment IV) are shown in Fig. 12. The solid line shows the average values of four specimens every 2 or 3 days while plots and error bars (standard deviation) are omitted approximately every 10 days.

Regardless of the temperature conditions, the development in specimens B (with penetrating-type coating) and C (with thin-film-forming-type coating) is similar to that in specimens A (no coating). Specimens D and E (with film-forming-type coating) behaved with more temperature dependence; by elevating the temperature from 23 to 60 °C, the time required to reach 5% of moisture content was reduced by half in specimens A (no coating, 10 days at 23 °C and 5 days at 60 °C) while in specimens E, the duration was reduced to one-sixth (72 days at 23 °C and 11 days at 60 °C). In contrast, as the moisture absorption speed by uncoated FRT wood was affected by temperature, these speeds became more temperature-dependent when the film-forming coating types were applied. Greater differences than those observed in the uncoated specimen were caused by the coating's permeability, which was more temperature-dependent in coatings D and E.

This permeability characteristic provides further explanation on the outdoor exposure results (Experiment I). As shown in Fig. 6, the moisture content of coated FRT specimens significantly increased from day 180 to 320 (from March to July), whereas the relative humidity and precipitation did not significantly increase from day 200 to 300. Instead, the temperature rose from day 180

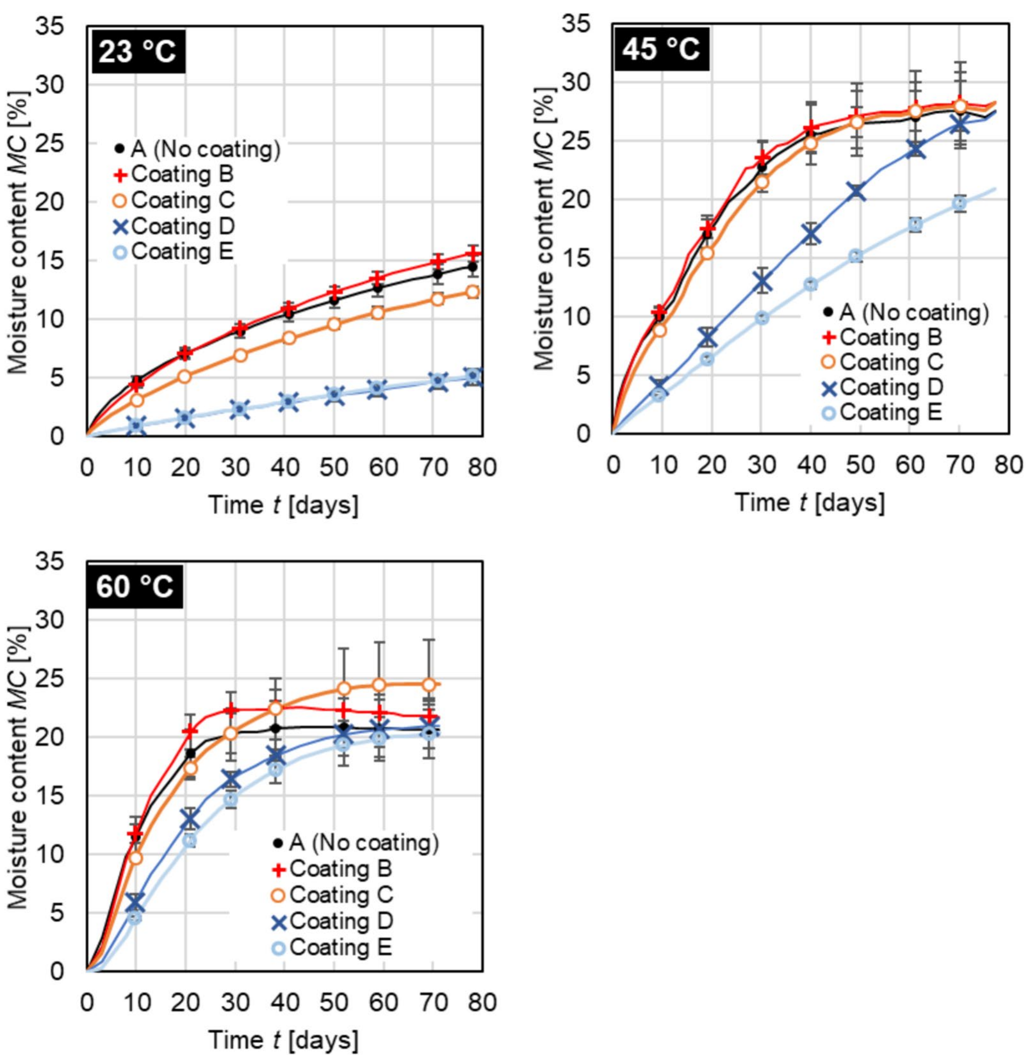

Fig. 12 Moisture absorption at constant temperature and humidity (Experiment IV). Plots: average of 4 duplications. Error bars: standard deviations

to 340. In specimens A, B, and C, moisture content may have been affected by precipitation and relative humidity to repeat increases and decreases in the short term. In specimens D and E, the moisture content values rose from day 200 to 300, and, moreover, the tendency itself seems to have accelerated in this period. Coatings D and E had low permeability as shown in Fig. 12, implying a small amount of moisture absorption in short-term rain. Thus, the increase in permeability with the temperature increase outdoors theoretically contributed to the significant increases in moisture content from day 180 to 320 (from March to July) in FRT specimens with some coating types.

The permeability characteristics of coatings also have implications for artificial weathering results (Experiment II). In Table 2, the weights, oven-dried weights, and moisture content values were demonstrated before and after 504 h of the artificial test. The moisture content values were calculated with Eq. (2a) using W_t and $W_{t(\mathrm{OD})}$ values for each testing time t (0 or 504 h). In the IMC-25 group, the moisture content in specimens A, B, and C increased compared with the initial values. Although categorized as film-forming types, specimens D and E behaved differently. Specimen D appeared to maintain its moisture content before and after 504 h of artificial weathering, while specimen E exhibited a decrease in moisture, which fell to 13.3%. This decrease was due to the temperature-dependent permeability of coating E, where the high permeability during the UV cycles (60 °C) and low permeability during the spray cycles (35 °C) allowed the moisture absorbed during spraying to evaporate during the UV cycles. The low moisture content after 504 h in IMC-0 with coating E was also due to this mechanism. Compared to specimen E, specimen D maintained a higher moisture content after 504 h of artificial weathering. As shown in Fig. 12, this was due to the fact that the permeability of coating D during the spray cycles was presumably higher than that of coating E, while it was almost the same as that of coating E during the UV cycles.

In the IMC-0 group, the moisture content values after the first 24 h of the condensation cycle might have been approximately 20% in specimens A, B, and C, and 5% in specimens D and E according to Experiment III (see values at 24 h in Fig. 11). Compared with these values, the moisture content after 504 h of artificial weathering in Table 2 did not significantly differ except for that of specimen A, although the testing cycle ended in a spray cycle. Moisture content values before and after repetitions of UV and spray were approximately the same level, despite slight absorption and desorption during each spray and UV cycle. Absorption and desorption possibly occurred at the very surface of the wood if coatings with low permeability were applied. These moisture absorption and desorption characteristics possibly produced higher FRC retention in artificial weathering in coatings D and E in IMC-0.

These results imply that 45 °C condensation or spray functions in EN927-6 are unsuitable for accelerating moisture absorption by FRT wood coated with the film-forming type. A test that begins with higher IMC (i.e., >40% moisture content as observed during outdoor exposure) possibly provides results whose acceleration coefficients among coating types are more uniform.

Table 2 Weight and moisture content before and after 504 h artificial weathering

Group	Coating type	$W_{W(OD)}$[b] [g]	Before artificial weathering			After 504 h of artificial weathering		
			W_t[c] [g]	$W_{t(OD)}$[d] [g]	MC[e] [%]	W_t[c] [g]	$W_{t(OD)}$[d] [g]	MC[e] [%]
IMC-0	A[a]	137.2	–	173.5	0.0	224.0	164.3	43.3
IMC-0	B[a]	144.0	–	191.6	0.0	209.3	185.5	16.5
IMC-0	C[a]	139.5	–	191.5	0.0	209.4	183.9	18.3
IMC-0	D[a]	138.7	–	203.1	0.0	214.3	200.8	9.7
IMC-0	E[a]	140.1	–	203.7	0.0	211.1	202.3	6.3
IMC-25	A	116.5	236.4	204.8	27.4	230.4	174.7	47.8
IMC-25	B	110.8	234.4	204.1	26.5	228.6	188.7	36.0
IMC-25	C	112.1	230.9	201.2	22.9	215.6	185.6	26.7
IMC-25	D	116.1	240.1	209.7	27.1	233.3	200.3	28.4
IMC-25	E	122.9	241.5	213.3	26.2	227.4	211.1	13.3

[a] Average of 2 specimens

[b] Oven-dry mass of untreated wood

[c] Overall weight of the coated FRT wood piece at time *t*

[d] Oven-dry weight of the coated FRT wood piece at time *t*

[e] Moisture content

Conclusions

To contrast the moisture conditions of coated FRT wood outdoors and during an artificial weathering, and to develop an artificial weathering method that provides more uniform acceleration coefficients, four experiments were performed on FRT wood with and without coating.

To determine the variation in moisture content within the coated FRT wood, an outdoor exposure experiment was conducted. It was found that the moisture content was higher in FRT wood than in untreated wood, and the values in the latter were between 11% (in March) and 50% (in September) of the untreated wood's weight. Even if film-forming coatings were applied, the maximum moisture content reached 50% of the untreated wood's weight.

EN927-6 artificial-weathering tests were performed on two groups of specimens with IMCs of 0% and 25%. The retention rates of FRC after a test of 2520 h were compared with those retrieved from 4-year outdoor exposure reported elsewhere. Comparison of these two experiments demonstrated that the acceleration coefficients were between 4.1 and 11.3 for IMC-0 specimens and 5.1–11.4 for IMC-25 specimens. Higher initial moisture content tended to enhance the loss of FRC from FRT wood with film-forming-type coating. Nevertheless, larger acceleration coefficients were obtained from specimens with penetrating or semi-film-forming coatings under both IMC conditions.

To clarify the effects of coatings on moisture absorption by FRT wood, two types of moisture absorption experiments were conducted. Results indicated that an increase in the coating permeability along with the temperature rise as well as the rise in relative humidity and precipitation contributed to the significant increases in moisture content in outdoor-exposed FRT wood. However, in FRT wood with film-forming coating subjected to EN927-6 tests, moisture content hardly varied or tended to decline throughout 504 h of the whole testing cycle, which was explained by the high coating permeability during the UV cycles (60 °C) and low permeability during the spray cycles (35 °C).

These results imply that 45 °C condensation or spray functions in EN927-6 are unsuitable for accelerating moisture absorption by FRT wood coated with the film-forming type. A test that begins with higher IMC (i.e., >40% moisture content as observed during outdoor exposure) possibly provides results whose acceleration coefficients among coating types are more uniform, this would be a simpler method for predicting the service life of coated FRT wood products.

Abbreviations

FRC	Fire-retardant chemicals
FRT	Fire-retardant treatment or fire-retardant treated
IMC	Initial moisture content
RSD	Relative standard deviation
MC	Moisture content [%]
R_t	Retention rate of the FRC at time t [%]
V	Volume of the wood piece [m^3]
$W_{C(OD)}$	Nonvolatile weight of the coating [g]
$W_{FRC(OD)}$	Oven-dry weight of FRC at time t [g]
$W_{FRT(OD)}$	Oven-dry weight of FRT wood [g]
W_t	Overall weight of the coated FRT wood piece at time t [g]
$W_{t(OD)}$	Oven-dry weight of the coated FRT wood piece at time t [g]
$W_{W(OD)}$	Oven-dry mass of untreated wood [g]

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Author contributions
RT was responsible for the schematic design of the study, executing experiments, and collecting data. AI supervised the moderate conditions in artificial weathering and was a contributor in revising the manuscript. DK provided the data and procedures in the past literature. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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