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THE EFFECTS OF HEATING TIME ON MECHANICAL PROPERTIES OF WOODEN STRUCTURAL MEMBERS AFTER HEATING AND COOLING FOR CONTINUOUS USE AFTER FIRE

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ABSTRACT: In this study, the effects of heating time on mechanical properties of Japanese cedar (*Cryptomeria japonica*) after heating-cooling were clarified for the purpose of continuous use of medium-large scale wooden buildings after fire. The authors measured modulus of elasticity (MOE) and modulus of rupture (MOR) in oven-dried condition and equilibrium moisture content (EMC), MOE and MOR in air-dried condition after heating-cooling. Residual rate of MOE and MOR is the value calculated by setting the value after heating-cooling at 60℃ for 30 minutes to 1.00. In the oven-dried conditions, the average residual rates of MOR were over 0.92 for heating conditions below 180℃. The average rasidual rates of MOR at 210℃ decreased with increasing heating time as 0.95 for 30 minutes, 0.75 for 3 hours and 0.63 for 8 hours heating. In the air-dried condition, MOE and MOR after heating-cooling were tended to be high at 150℃ for all heating times and decreased with increasing heating time at 210℃. The average residual rate of MOR was the highest value as 1.10 at 180℃ for 3 hours, however, the residual rate decreased as 0.98 for 8 hours heating. EMC decreases with increasing heating temperature and times.

KEYWORDS: japanese cedar, modulus of elasticity, modulus of rupture, equilibrium moisture content

1 – INTRODUCTION

In recent years, research on wooden structural members and law development have been progressing to realise medium-large scale wooden buildings, and many actual buildings have been realised. In these medium-large scale wooden buildings, wooden structural members that was extinguished in the early stages of a fire and did not suffer significant fire damage such as being completely burned down, as shown in ***Fig. 1***, it is desirable to continue using the load bearing part that was once damaged by fire with grinding and replacing the carbonised part of the surface layer from the perspective of carbon fixation in buildings.

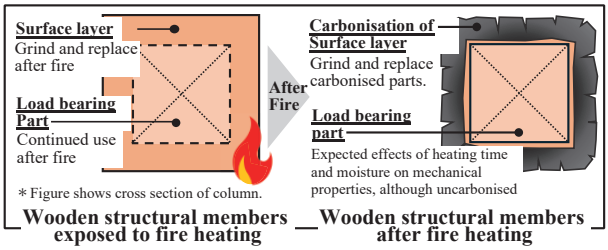

Figure 1. Factors affecting the mechanical properties of wooden structural members after fire heating

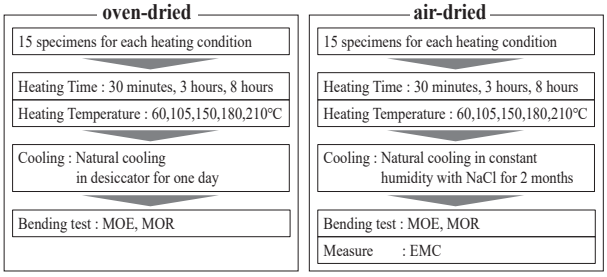

Figure 2. Flow of experiments

As shown in ***Fig. 1***, it is expected that the load bearing parts of wooden structural members after fire would be irreversibly affected on their mechanical properties, even if they are not charred. The surface of the load-bearing part will become completely dry in the early stages after fire due to the evaporation of moisture and the movement of moisture into the wood caused by fire heating. As time passes, the moisture content of the wood will become air-dried condition after going through a moisture absorption process. Previous study that measured the mechanical

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properties of wood that had been heated and cooled to room temperature reported a decrease in MOE and MOR with increasing temperature in the range up to 230°C after heating-cooling in oven-dried condition [1]. However, the heating time is not clearly defined as a parameter, and the mechanical properties when heated for long time have not been studied. Previous study that measured the mechanical properties of wood after heating and returning to room temperature reported the mechanical properties of heat-treated wood [2]. However, this study only focused on Black poplar (*Populus nigra*) that had been heat-treated at 212°C for 2 hours. Moreover, in the study on heat-treated wood regarding the recovery of moisture content after heating [3], it was reported that the moisture absorption rate tended to decrease as the heat treatment temperature increased. It is known that when the moisture content inside wood is high, the mechanical properties of wood decrease at room temperature [4], and it is considered that the mechanical properties of wood after heating-cooling may be affected by changes of moisture content. Therefore, it is considered to be necessary to clarify the effects of moisture content and thermal decomposition on mechanical properties after heating-cooling by comparing and discussing the mechanical properties in the oven-dried condition, removing the effects of moisture content, and the mechanical properties in the air-dried condition, when the moisture content has reached an equilibrium condition. Moreover, when wooden structural members are exposed to fire heating, a temperature gradient is formed from the heated surface to the inside, therefore it is necessary to comprehensively clarify the effects of heating temperature on mechanical properties. In addition, heating time that wooden structural members are exposed is different depending on the expected time of the fire. Therefore, there is also high need for clarifying the effect of heating time on mechanical properties.

From the above, the authors clarified the effects of heating time and temperature on MOE, MOR and EMC of Japanese cedar in oven-dried and air-dried condition after heating-cooling. In this paper, the mechanical properties in oven-dried condition after heating-cooling for 30 minutes, 3 hours and 8 hours, and the EMC and mechanical properties in the air-dried condition after heating-cooling for 3 hours are reported, in combination with the results of study clarifying the EMC and mechanical properties in the air-dried condition after heating-cooling for 30 minutes and 8 hours at each heating temperatures.

2 – METHOD

Fig. 2 shows the flow of experiments. Measurement the mechanical properties in the oven-dried condition was conducted in the following flow. First, all the test pieces were placed in a thermostatic chamber set at 60°C for about two weeks to bring the water content to 3%. After that, the specimens were heated in the thermostatic chamber under each heating condition. Then, to avoid an increase in the moisture content, the specimens were naturally cooled to room temperature in a desiccator for one day. Finally, MOE and MOR were measured.

Measurement the mechanical properties in the air-dried condition was conducted in the following flow. First, the specimens were heated in the thermostatic chamber under each heating condition. After that, the specimens were kept for about two months under room temperature 20°C and relative humidity 75.5 ± 0.2% (according to JIS B7920:2000), using the saturated salt method with NaCl. Finally, EMC, MOE and MOR were measured.

The bending test was a three-point bending test with the span of 280 mm in accordance with JIS Z2101 “Bending Test Method for Wood”, with the loading position in the middle of the span and displacement at 10 mm/min. For bending test, a tensile and compression testing machine (Minebea Technograph TG-50 kN) in the Forestry and Forest Products Research Institute shown in ***Photo. 1*** was used. MOE was measured in a bending test in which force was applied to the specimen within the range that did not reduce the strength of the specimen. MOR was measured in bending test in which force is applied to specimens until they break. EMC satisfied the standards of JIS A1475, which defines the weight of a specimen that changes by less than 0.1% in three consecutive weight measurements taken every 24 hours as the constant weight, and was calculated using oven-dried density after the bending test.

2.1 Specimens

Specimens are cedar, which was selected as a wood commonly used for wooden structural members in Japan. ***Fig. 3*** shows that the dimensions are 320 x 20 x 20 mm and are flawless cedar heartwood cut from a single log. The number of specimens per each heating condition is 15.

2.2 Heating conditions

Heating conditions are 5 heating temperatures (60, 105, 150, 180 and 210°C) and 3 heating times (30 min, 3 hours and 8 hours), for a total of 15 conditions, to comprehensively clarify the mechanical properties of wood after heating-cooling at heating conditions below the carbonisation temperature of the wood. For heating temperatures, the minimum temperature is 60°C so that the EMC goes through a moisture absorption process, and the maximum temperature is 210°C for safety reasons, due to the appearance of a fire at 230°C in pre-tests. For small specimens in this study, a minimum of 30 minutes is considered necessary to match for heating temperatures and the inside temperature of the specimen. In pre-tests, smoke generated above 180°C stopped being generated after about 6 hours in the specimens used in this study. 8 hours was set as the maximum heating time in which mechanical properties of wood could be changed, as this

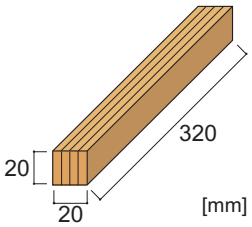

Figure 3. Specimens

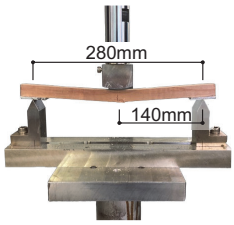

Photo 1. Bending machine

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is considered to be the completion of the change in the main elements of wood. Moreover, to comprehensively clarify the effects of heating time on mechanical properties, 3 hours heating was added. The heating time is defined as the time after the inside temperature of the specimen had stopped rising. Heating was conducted in a thermostatic chamber at the Forestry and Forest Products Research Institute.

3 – RESULTS AND DISCUSSION

3.1 MOE and MOR in oven-dried condition

Tables 1, 2 and 3 show the average value and average residual rate of MOE and MOR in oven-dried condition after heating-cooling for all heating times. ***Fig. 4*** shows MOE in oven-dried condition after heating-cooling for all heating times. ***Fig. 5*** shows MOR in oven-dried condition after heating-cooling for all heating times. The residual rate of MOE and MOR is the value calculated by

Table 1. MOE and MOR in oven-dried condition after 30 minutes heating

Heating Temperature [°C]		60°C	105°C	150°C	180°C	210°C
Heating Time		30 minutes				
Moisture condition in bending tests		Oven-dried condition				
Temperature in bending tests		Room temperature				
Oven-dried Density (Avg.) [g/cm³]		0.314	0.313	0.313	0.314	0.308
Modulus of elasticity	Average value [N/mm²]	6901	6824	6802	6772	6833
	Coefficients of variation [%]	9.79	9.18	10.01	9.41	9.59
	Residual rate*1 (Avg.)	1.00	0.99	0.99	0.98	0.99
Modulus of rupture	Average value [N/mm²]	72.49	71.57	70.28	72.46	68.90
	Coefficients of variation [%]	8.12	8.75	7.70	6.95	9.53
	Residual rate*1 (Avg.)	1.00	0.99	0.97	1.00	0.95

*1 : Residual rate with the 60°C value of 30 min heating as 1.00.

Table 2. MOE and MOR in oven-dried condition after 3 hours heating

Heating Temperature [°C]		60°C	105°C	150°C	180°C	210°C
Heating Time		3 hours				
Moisture condition in bending tests		Oven-dried condition				
Temperature in bending tests		Room temperature				
Oven-dried Density (Avg.) [g/cm³]		0.309	0.308	0.308	0.305	0.292
Modulus of elasticity	Average value [N/mm²]	6814	6730	6682	6669	6398
	Coefficients of variation [%]	11.07	9.84	9.47	7.85	9.06
	Residual rate*1 (Avg.)	0.99	0.98	0.97	0.97	0.93
Modulus of rupture	Average value [N/mm²]	73.87	73.01	73.20	70.42	54.16
	Coefficients of variation [%]	9.59	7.60	9.23	7.59	12.08
	Residual rate*1 (Avg.)	1.02	1.01	1.01	0.97	0.75

*1 : Residual rate with the 60°C value of 30 min heating as 1.00.

Table 3. MOE and MOR in oven-dried condition after 8 hours heating

Heating Temperature [°C]		60°C	105°C	150°C	180°C	210°C
Heating Time		8 hours				
Moisture condition in bending tests		Oven-dried condition				
Temperature in bending tests		Room temperature				
Oven-dried Density (Avg.) [g/cm³]		0.307	0.309	0.311	0.304	0.287
Modulus of elasticity	Average value [N/mm²]	6770	6692	6721	6636	6040
	Coefficients of variation [%]	10.03	10.45	10.31	10.21	9.09
	Residual rate*1 (Avg.)	0.98	0.97	0.97	0.96	0.88
Modulus of rupture	Average value [N/mm²]	69.78	70.29	71.67	66.97	45.36
	Coefficients of variation [%]	10.47	8.70	8.27	9.46	9.86
	Residual rate*1 (Avg.)	0.96	0.97	0.99	0.92	0.63

*1 : Residual rate with the 60°C value of 30 min heating as 1.00.

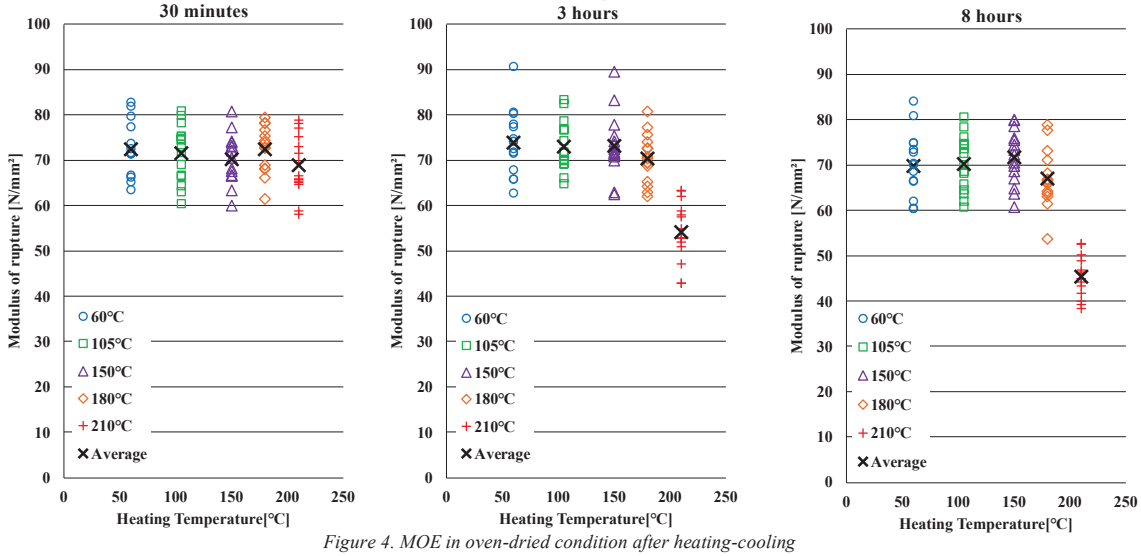

Figure 4. MOE in oven-dried condition after heating-cooling

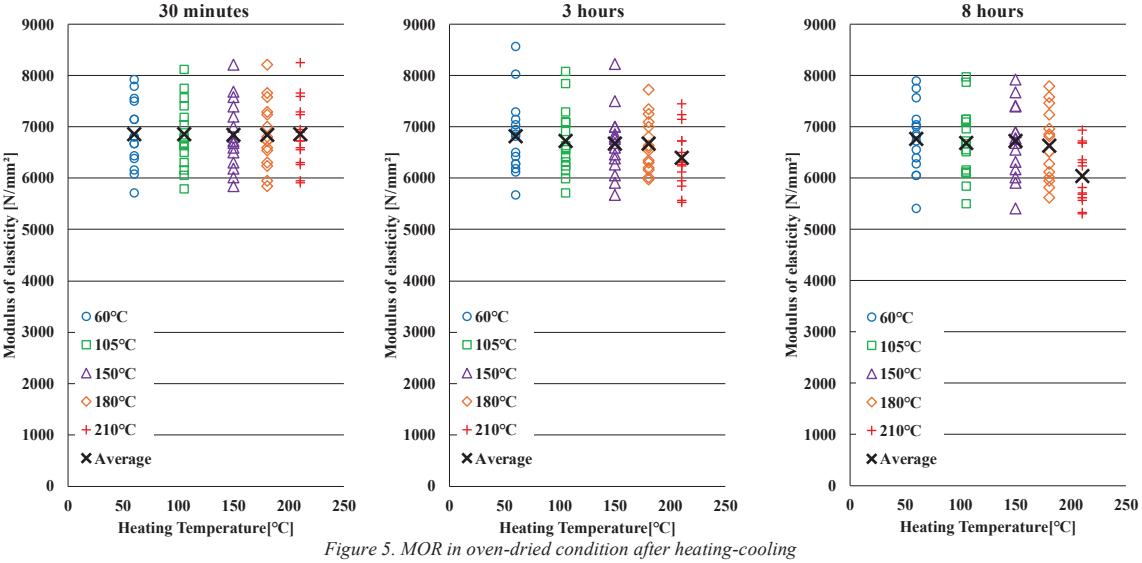

Figure 5. MOR in oven-dried condition after heating-cooling

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setting the value in the oven-dried condition after heating-cooling at 60℃ for 30 minutes to 1.00. ***Tables 1, 2 and 3*** show that the average residual rate of MOE is over 0.88 for all heating conditions and is considered to recover generally to the pre-heating condition. ***Tables 1, 2 and 3*** show that the average residual rate of MOR is over 0.92 for all heating conditions, except at 210℃ for 3 and 8 hours of heating time, and is considered to almost recover to the pre-heating condition below 180℃. At 210 ℃, MOR decreased with increasing heating time as 0.95 for 30 minutes, 0.75 for 3 hours and 0.63 for 8 hours. This shows that the changes in components due to thermal decomposition have caused irreversible changes of MOR.

3.2 EMC, MOE and MOR in air-dried condition

Tables 4, 5 and 6 show the average value and residual rate of EMC, MOE and MOR in air-dried condition after heating-cooling for all heating times. ***Fig. 6*** shows EMC in air-dried condition after heating-cooling for all heating times. ***Fig. 7*** shows residual rate of MOE in air-dried condition after heating-cooling for all heating times. ***Fig. 8*** shows residual rate of MOR in air-dried condition after heating-cooling for all heating times. The residual rate of MOE and MOR is the value calculated by setting the value in the air-dried condition after heating-cooling at 60℃ for 30 minutes to 1.00. Because the log used for measuring the MOE and MOR in the air-dried condition after 3 hours heating is different from the log used for measuring them in the air-dried condition after 30 minutes and 8 hours of heating in the previous study [5].

From ***Fig. 6***, it is found EMC decreased with increasing heating temperature for all heating times. This is the same as the measurement results which reported that the moisture absorption rate tended to decrease as the heat treatment temperature increased [3]. In addition, the amount of decrease in EMC was larger for heating times of 3 and 8 hours than for 30 minutes at all heating temperatures. Especially at 180℃ and 210℃, the decrease of EMC with increasing heating time was significant, and ***Tables 4, 5 and 6*** show that the average residual rate decreased by 0.18 and 0.30 for 30 minutes heating, whereas they decreased by 0.32 and 0.52 for 3 hours heating, 0.28 and 0.44 for 8 hours heating. The coefficients of variation were within 5% for all specimen groups and at below 105℃ tended to be less than 2.5%. Based on these results, it is considered a possibility that the decrease of EMC due to the change in the main elements of wood in the small specimens in this study may have progressed sufficiently in more than 3 hours heating, although there may be differences depending on the logs.

Tables 4, 5 and 6 show that the average values of MOE and MOR tended to be high at 150℃ for all heating times. For 3 hours heating, the average values of MOE and MOR are highest at 180℃. Below 150℃, MOE and MOR increased with increasing heating temperature for all heating times. This increase is considered to be due to the decrease of EMC. In addition, comparing the heating times of 30 minutes, 3 hours and 8 hours, the amount of increase and decrease both increased with increasing heating time, except at 180℃. This is considered to be due to the decrease in EMC by the change in the main elements of wood and the progress of thermal decomposition by increasing the heating time. At 180℃, MOR is the highest value after 3 hours heating, however, after 8 hours heating, the average residual rate decreased below 1.00. This is considered to be due to the effect of the heating time, because thermal decomposition becomes more significant at 180℃ [6]. At 210℃, MOE and MOR tended to decrease for all heating times.

3.3 Comparing and discussion

Fig. 9 shows the average residual rate of MOR in the air-dried and oven-dried conditions after heating-cooling. The residual rate of MOE and MOR is the value calculated by setting the value in the oven-dried and air-dried condition after heating-cooling at 60℃ for 30 minutes to 1.00. Because the log used for measuring the MOE and MOR in the oven-dried condition after all heating and them in the air-dried condition after 3 hours heating is different from the log used for measuring them in the air-dried condition after 30 minutes and 8 hours of heating in the previous study [5]. It is considered that the increase in MOR in the air-dried condition with increasing heating temperatures below 150℃ is due to the decrease of EMC with the increase of heating temperatures. Because the residual rates of MOR below 150℃ in the oven-dried condition after heating-cooling were generally 1.00. The average residual rates of MOR in the oven-dried condition after heating at 180℃ were 1.00 for 30 minutes, 0.97 for 3 hours and 0.92 for 8 hours

Table 4. EMC, MOE and MOR in air-dried condition after 30 minutes heating [5]

Heating Temperature [℃]		60℃	105℃	150℃	180℃	210℃	60℃
Heating Time		30 minutes					30 min
Moisture condition in bending tests		Air-dried condition					
Temperature in bending tests		Room temperature					
Oven-dried Density (Avg.) [g/cm³]		0.328	0.326	0.332	0.324	0.316	0.328
Equilibrium moisture content	Average Value [%]	13.09	11.99	10.87	10.71	9.16	13.09
	Coefficients of variation [%]	1.34	2.18	4.31	1.59	3.29	1.34
	Residual rate*1 (Avg.)	1.00	0.92	0.83	0.82	0.70	-
Modulus of elasticity	Average value [N/mm²]	6230	6053	6384	6236	5892	6230
	Coefficients of variation [%]	9.57	9.84	8.12	9.22	13.43	9.57
	Residual rate*1 (Avg.)	1.00	0.97	1.02	1.00	0.95	-
Modulus of rupture	Average value [N/mm²]	53.73	56.32	58.23	56.59	49.28	53.73
	Coefficients of variation [%]	7.50	9.78	6.05	10.84	18.36	7.50
	Residual rate*1 (Avg.)	1.00	1.05	1.08	1.05	0.92	-

＊1：Residual rate with the 60°C value of 30 min heating as 1.00.

Table 5. EMC, MOE and MOR in air-dried condition after 3 hours heating

Heating Temperature [℃]		60℃	105℃	150℃	180℃	210℃	60℃
Heating Time		3 hours					30min
Moisture condition in bending tests		Air-dried condition					
Temperature in bending tests		Room temperature					
Oven-dried Density (Avg.) [g/cm³]		0.322	0.320	0.321	0.319	0.305	0.321
Equilibrium moisture content	Average Value [%]	14.60	12.70	11.70	10.73	7.63	15.88
	Coefficients of variation [%]	1.19	1.30	2.08	2.33	2.09	1.95
	Residual rate*1 (Avg.)	0.92	0.80	0.74	0.68	0.48	-
Modulus of elasticity	Average value [N/mm²]	7943	8033	8083	8088	7346	8048
	Coefficients of variation [%]	11.06	9.98	8.63	10.57	13.23	10.60
	Residual rate*1 (Avg.)	0.99	1.00	1.00	1.01	0.91	-
Modulus of rupture	Average value [N/mm²]	61.06	64.16	65.21	66.38	49.17	60.31
	Coefficients of variation [%]	7.81	8.52	8.08	6.97	17.27	10.03
	Residual rate*1 (Avg.)	1.01	1.06	1.08	1.10	0.82	-

＊1：Residual rate with the 60°C value of 30 min heating as 1.00.

Table 6. EMC, MOE and MOR in air-dried condition after 8 hours heating [5]

Heating Temperature [℃]		60℃	105℃	150℃	180℃	210℃	60℃
Heating Time		8 hours					30min
Moisture condition in bending tests		Air-dried condition					
Temperature in bending tests		Room temperature					
Oven-dried Density (Avg.) [g/cm³]		0.326	0.335	0.339	0.331	0.304	0.328
Equilibrium moisture content	Average Value [%]	12.85	11.65	10.67	9.48	7.33	13.09
	Coefficients of variation [%]	0.95	1.33	3.17	4.77	4.59	1.34
	Residual rate*1 (Avg.)	0.98	0.89	0.82	0.72	0.56	-
Modulus of elasticity	Average value [N/mm²]	6274	6337	6714	6161	5337	6230
	Coefficients of variation [%]	8.28	12.15	11.42	9.32	11.26	9.57
	Residual rate*1 (Avg.)	1.01	1.02	1.08	0.99	0.86	-
Modulus of rupture	Average value [N/mm²]	55.90	58.56	59.68	52.58	29.25	53.73
	Coefficients of variation [%]	6.46	13.28	11.28	12.00	26.41	7.50
	Residual rate*1 (Avg.)	1.04	1.09	1.11	0.98	0.54	-

＊1：Residual rate with the 60°C value of 30 min heating as 1.00.

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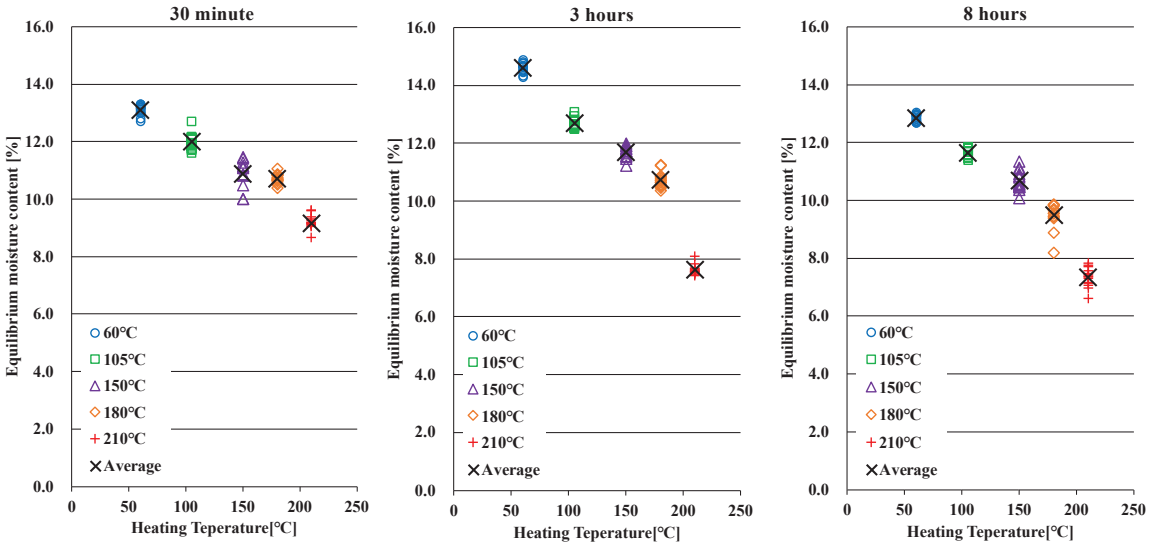

Figure 6. EMC after heating-cooling (30 minutes, 8 hours: [5])

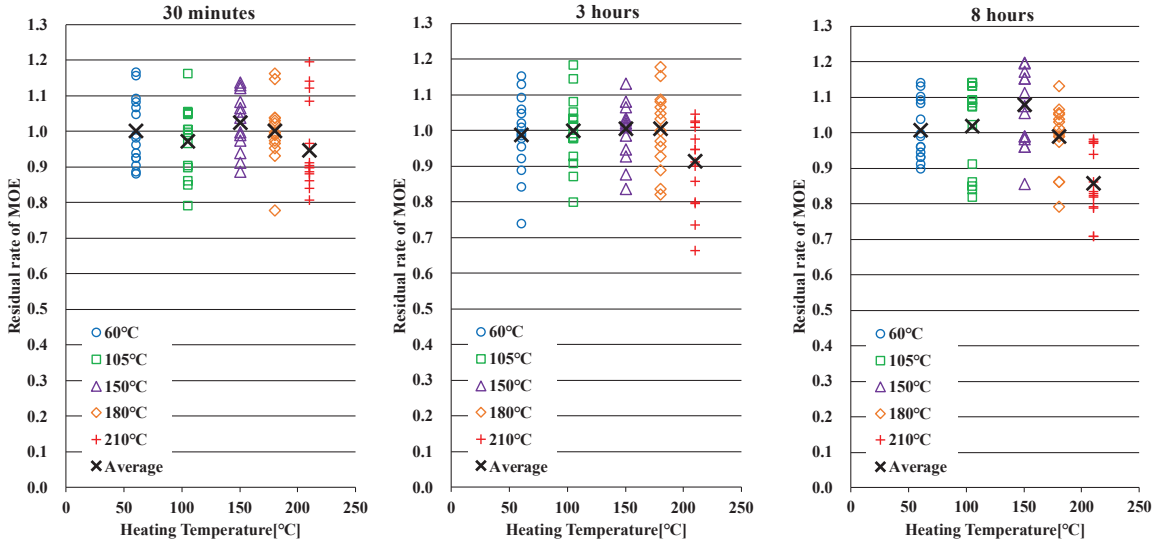

Figure 7. Residual rate of MOE in air-dried condition (30 minutes, 8 hours: [5])

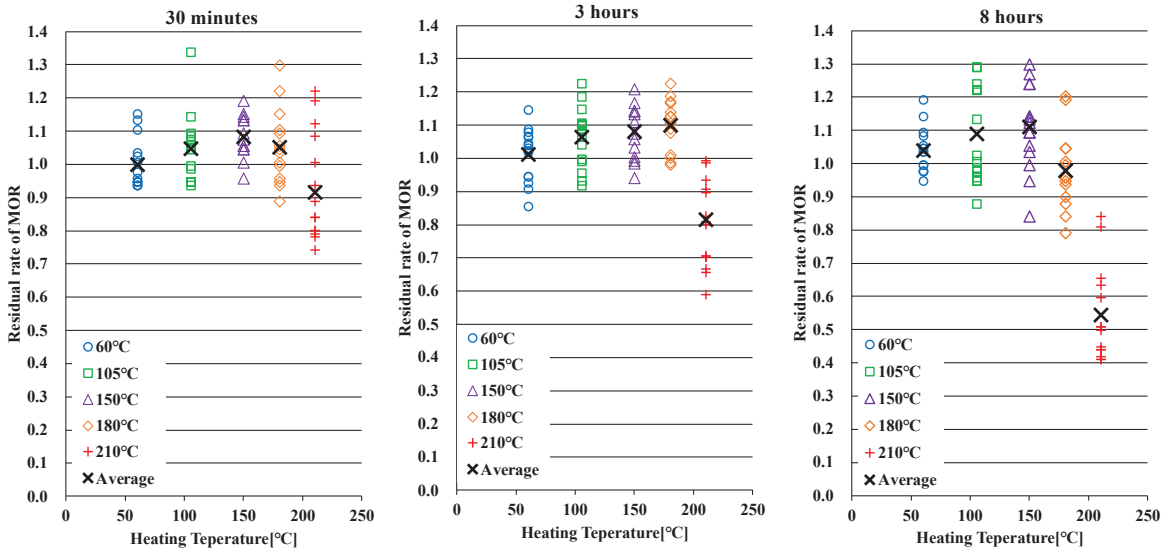

Figure 8. Residual rate of MOR in air-dried condition (30 minutes, 8 hours: [5])

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of heating. The average residual rates of MOR in the air-dried condition after heating at 180 °C were 1.05 for 30 minutes, 1.10 for 3 hours and 0.98 for 8 hours of heating. After heating-cooling at 180°C, MOR in the oven-dried condition decreased with increasing heating time, while the average residual rate of MOR in the air-dried condition was the highest at 3 hours of heating with a value of 1.10. The 180°C is possibly the heating temperatures at which the decrease of strength by thermal decomposition and the increase of strength by the decrease of equilibrium moisture content due to heating are opposing each other, depending on the heating time. This shows a different trend in MOR after heating-cooling with increasing heating time in the oven-dried and air-dried conditions. From the above, it is possible that the heating time exposed to 180°C could be the criteria for determining whether or not there is an irreversible damage in strength due to thermal decomposition.

4 – CONCLUSION

From these experiments, the following conclusions can be drawn.

(1) Average residual rates of MOE in oven-dried conditions after heating-cooling was found to be more than 0.88 for all heating conditions and generally recovered to the pre-heating condition. Average residual rates of MOR in oven-dried conditions after heating-cooling were over 0.92 for heating conditions below 180°C and recovered to the pre-heating condition. In contrast, the average rasidual rates of MOR at 210°C decreased with increasing heating time as 0.95 for 30 minutes, 0.75 for 3 hours and 0.63 for 8 hours.

(2) EMC in air-dried condition after heating-cooling decreases with increasing heating temperature and heating times. MOE and MOR in air-dried condition after heating-cooling were found to be high at 150°C for all heating times and decreased with increasing heating time at 210°C. MOR in air-dried condition was the highest value after heating-cooling at 180°C for 3 hours, however, after 8 hours heating, the average residual rate was 0.98.

(3) Average residual rates of MOR in the oven-dried condition after heating at 180°C were 1.00 for 30 minutes, 0.97 for 3 hours, and 0.92 for 8 hours. In contrast, in the air-dried condition, the values were 1.05 for 30 minutes, 1.10 for 3 hours, and 0.98 for 8 hours. Based on a comparison of MOR between the oven-dried and air-dried conditions, the heating time at 180°C could be a criterion for determining continuous use after fire.

5 – ACKNOWLEDGEMENT

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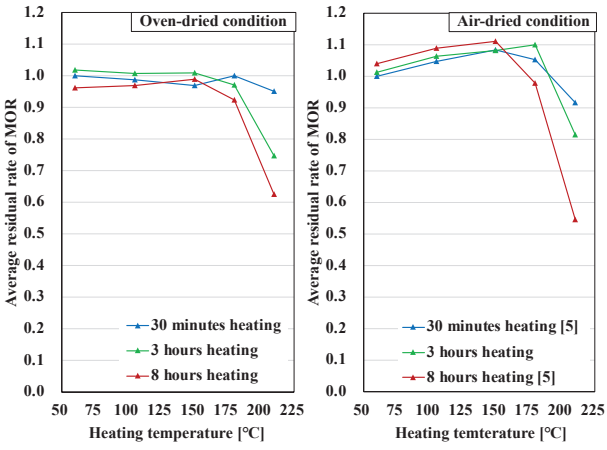

Figure 9. Average residual rate of MOR

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