



Forest Service
U.S. DEPARTMENT OF AGRICULTURE

FOREST PRODUCTS LABORATORY

Fire Performance and Hygrothermal Properties of Cross Laminated Timber for Military Operations

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Introduction

The USDA Forest Service, Forest Products Laboratory partnered with the U.S. Army Engineer Research and Development Center (ERDC) Construction Engineering Research Laboratory (CERL) to conduct research on thermally modified Advanced Cross Laminated Timber (ACLТ) to support ongoing/expanding research and development efforts for the use of sustainable mass timber products in MILCON. ACLТ is a proprietary CLТ product developed by the Composites Recycling Technology Center (CRTC). For this study six tests were conducted for CERL with the test methodology and respective results provided in this report.

1. Cone Calorimeter Tests
2. Furnace Tests
3. Sorption Isotherm
4. Water Vapor Transmission
5. Liquid Vapor Absorption
6. Thermal Conductivity

Overall, the research tests provided valuable results and insight into evaluating the ACLТ as a potential mass timber product for MILCON.

1. Cone Calorimeter Tests

Background

Flammability tests were conducted using a cone calorimeter in accordance with ASTM E1354: *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter* [1]. The cone calorimeter was developed in the 1980s and is commonly used to determine the heat release rate using the oxygen consumption method [2]. The cone calorimeter test

provides an assessment of materials and fire properties that are indicative of the material fire performance in full-scale fires. The parameters used to determine the response of materials exposed to controlled levels of radiant heating include time to ignition, heat release rate, and mass loss rate.

Materials and Methods

Specimens

The cone calorimeter specimens (Figure 1.1) included unmodified and thermally modified western hemlock. The specimens had dimensions of 100 mm by 100 mm by the material thickness (Table 1.1). The X-Y-Z notation for the specimens was as follows:

- X: Modification/Generation (UM = unmodified, G0 = generation 0, G1 = generation 1)
- Y: Parent board (UM, G0) or modification temperature (G1)
- Z: specimen number



Figure 1.1: Representative images of UM, G0, and G1 specimens.

The materials (Table 1.1) were evaluated using the cone calorimeter located at the Forest Products Laboratory (FPL) (FTT iCone Mini, East Grinstead, West Sussex, UK). Each material type was tested in triplicate for a total of 21 specimens. Prior to testing, the specimens were conditioned for at least 30 days in a 21°C / 50% relative humidity chamber.

Table 1.1: Specimen details

Specimen ID	Initial Mass (g)	Initial Thickness (mm)	Density (g/cm ³)
UM-A-1	117.2	24.9	0.5
UM-B-1	130.5	25.0	0.5
UM-C-1	158.9	25.1	0.6
G0-A-1	108.9	24.9	0.4
G0-B-1	122.4	24.8	0.5
G0-C-1	121.2	25.0	0.5
G1-160-1	121.8	25.0	0.5
G1-160-2	106.3	25.2	0.4
G1-160-3	107.6	25.1	0.4
G1-180-1	124.5	25.2	0.5
G1-180-2	113.1	24.9	0.5
G1-180-3	116.6	25.2	0.5
G1-190-1	110.3	25.1	0.4
G1-190-2	111.5	25.3	0.4
G1-190-3	118.7	25.0	0.5

G1-200-1	109.5	25.1	0.4
G1-200-2	111.8	25.1	0.4
G1-200-3	108.0	24.9	0.4
G1-220-1	106.7	25.1	0.4
G1-220-2	106.3	25.3	0.4
G1-220-3	105.5	25.1	0.4

Test Method

Specimens were loaded in the horizontal orientation with the conical radiant electric heater located 25 mm above the specimen surface (Figure 1.2). The optional retainer frame (Figure 1.2) was used to hold the specimens during the test and as specified in ASTM E1354, the sides and bottom of the specimens were wrapped in aluminum foil and the specimen rested on a ceramic fiber blanket. The retainer frame promotes 1D conduction through the specimen and limits the surface area that is exposed to 88.4 cm². The conical heater was set to produce a heat flux of 50 kW/m² and the spark igniter was used. The tests were terminated two minutes after flaming combustion stopped.

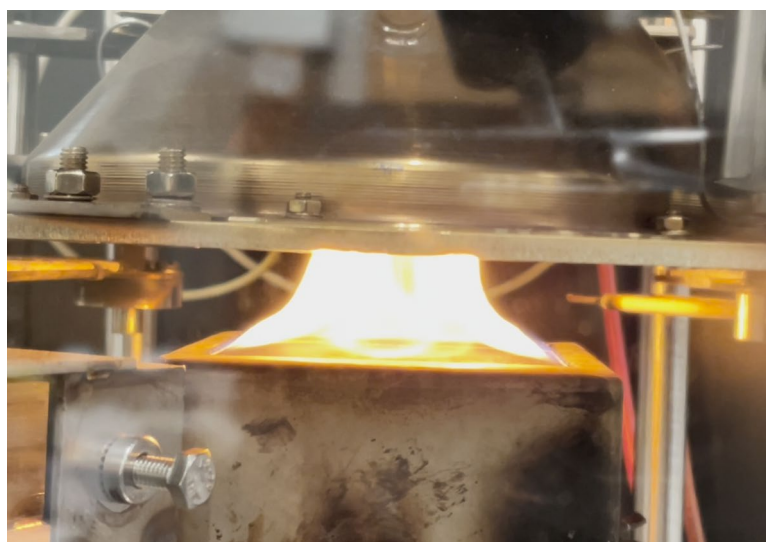


Figure 1.2: Specimen during cone calorimeter test.

Results

The primary results from the cone calorimeter test are the time to ignition (t_{ig}) and curves for heat release rate (HRR) and mass loss rate (MLR) as a function of time. The t_{ig} characterizes the ignitability, which is the ease of ignition of the material, by defining how quickly the sustained flaming combustion occurs when the material is exposed to a heat source at a given incident heat flux. The HRR is the rate at which fire releases energy (power) and the peak HRR (pHRR) is the maximum release rate of heat during the combustion process. The effective heat of combustion (EHC) can be determined by dividing the HRR by the MLR.

Ignition and HRR

Results for ignitability include the t_{ig} (s) and the time for the peak heat release rate (pHRR) (s) (Table 1.2). The transient HRR per unit surface area of the fuel was calculated using the exposed surface area of 88.4 cm².

Table 1.2. Summary of Cone Calorimeter Results

Specimen ID	Peaks			Time to Peaks		Total heat release (MJ/m ²)
	t _{ig} (s)	pHRR (kW/m ²)	pMLR (g/s)	pHRR _t (s)	pMLR _t (s)	
UM	23.7	210.3*	0.5	35.7*	1392.3	229.1
G0	20.0	183.3	0.2	30.7	1215.0	129.2
G1-160	14.3	202.9	0.2	22.7	928.0	122.1
G1-180	19.3	194.4	1.1	28.5	673.5	106.2
G1-190	17.3	197.0	0.8	27.0	599.5	132.1
G1-200	14.3	205.6	0.2	22.0	427.3	120.7
G1-220	13.3	214.2	0.2	19.7	885.0	120.1

*Specimen UM-C-1 had a higher second peak, but the time and value of the first peak were used to calculate the averages provided.

The test averages provided in Tables 1.3 through 1.5 are given based on duration of test in seconds, which is provided in parenthesis. For instance, the average HRR for the first 60 seconds of the test is labeled as 'HRR(60)'.

Table 1.3. Test Average HRR

Specimen ID	Average HRR (kW/m ²) (duration, seconds)				
	HRR(60)	HRR(120)	HRR(180)	HRR(240)	HRR(300)
UM	130.7	108.7	98.2	92.5	88.8
G0	114.4	93.2	84.2	79.3	76.4
G1-160	111.7	88.5	80.1	76.0	73.8
G1-180	118.4	97.4	88.0	83.5	81.4
G1-190	118.0	97.7	88.1	83.1	80.5
G1-200	107.5	85.9	77.1	73.2	71.8
G1-220	109.7	86.8	76.9	72.5	70.9

Table 1.4. Test Average EHC

Specimen ID	Average EHC (MJ/kg) (duration, seconds)				
	EHC(60)	EHC(120)	EHC(180)	EHC(240)	EHC(300)
UM	14.3	14.1	13.5	13.0	12.6
G0	12.5	12.2	11.7	11.5	11.3
G1-160	12.5	12.2	11.8	11.4	11.2
G1-180	12.4	12.0	11.7	8.1	6.7
G1-190	6.6	6.2	5.9	5.6	5.3
G1-200	12.6	12.4	12.1	11.8	11.6
G1-220	13.1	13.0	12.7	12.5	12.3

Table 1.5. Test Average MLR

Specimen	Average MLR (g/s) (duration, seconds)
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ID	MLR(60)	MLR(120)	MLR(180)	MLR(240)	MLR(300)
UM	0.1	0.1	0.1	0.1	0.1
G0	0.1	0.1	0.1	0.1	0.1
G1-160	0.1	0.1	0.1	0.1	0.1
G1-180	0.1	0.1	0.1	0.1	0.2
G1-190	-1.1	-0.5	-0.3	-0.2	-0.2
G1-200	0.1	0.1	0.1	0.1	0.1
G1-220	0.1	0.1	0.1	0.1	0.1

The HRR curves for each specimen as well as the average HRR for each specimen type are provided in Figure 1.3. The curves for all specimens exhibited a sharp, initial pHRR which is accredited to the ignition and rapid exothermic reaction for uncharred lignocellulosic material. The HRR reduces once char forms [3, 4]. The second peak reflects the thermal wave reaching the unexposed side of the specimen and can be affected by many variables including the density, heat flux, material thickness, and backing product [5, 6]. From these curves, we see that the performance of the thermally modified specimens was more consistent between the three specimens tested and that the second peak occurred sooner when compared to the unmodified specimens.

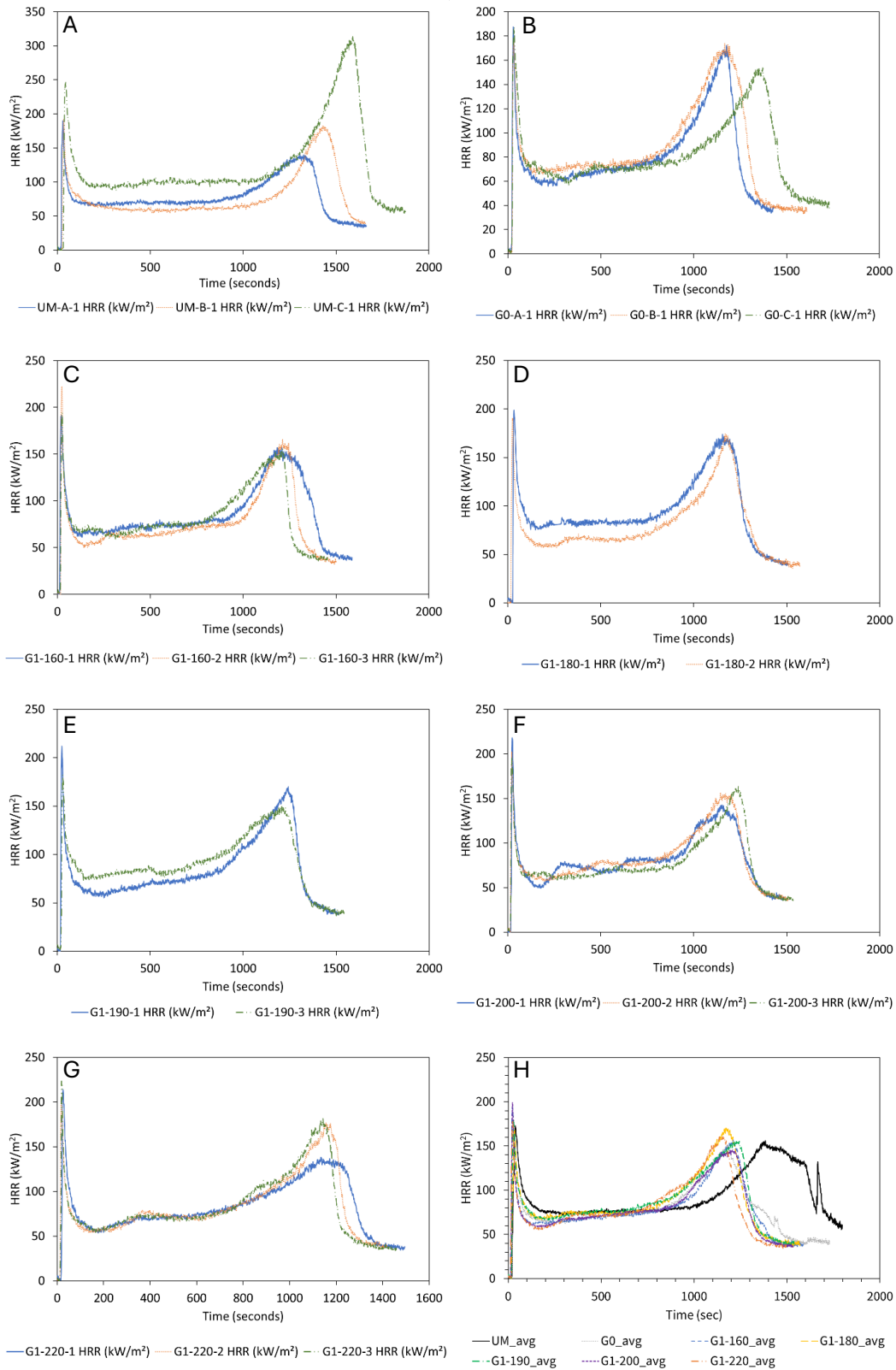


Figure 1.3: HRR curves for each specimen type (A through G) and average curves (H).

Fire Hazard Assessment

To assess the fire hazard of the materials tested, the fire growth rate (FIGRA) and the fire performance index (FPI) are calculated. A low FIGRA and higher FPI indicates better flame resistance.

$$FIGRA = \frac{pHRR}{\text{time to } pHRR} \quad (1)$$

$$FPI = \frac{t_{\text{ignition}}}{pHRR} \quad (2)$$

Table 1.6. Fire Hazard Assessment Values

Specimen ID	FIGRA	FPI
UM	5.89	0.11
G0	5.98	0.11
G1-160	8.95	0.07
G1-180	6.82	0.10
G1-190	7.29	0.09
G1-200	9.35	0.07
G1-220	10.89	0.06

From Table 1.6, the specimens that were not thermally modified or modified at lower temperatures would likely result in slightly better flame resistance.

References

1. ASTM E1354: *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*. ASTM International: West Conshohocken, PA.
2. Babrauskas, V., *Development of the cone calorimeter—a bench-scale heat release rate apparatus based on oxygen consumption*. Fire and Materials, 1984. 8(2): p. 81-95.
3. White, R.H. and K. Sumathipala. Cone calorimeter tests of wood composites. in In: *Proceedings of the Fire and Materials 2013 Conference*, San Francisco, California, USA 28-30 January 2013; pp. 401-412. 2013.
4. White, R.H. and M.A. Diitenberger, Cone calorimeter evaluation of wood products. 2004.
5. Diitenberger, M.A. and R.H. White. Reaction-to-fire testing and modeling for wood products. in *Proceedings, 12th Annual BCC conference on flame retardancy*. 2001.
6. Lindholm, J., A. Brink, and M. Hupa, Cone calorimeter—a tool for measuring heat release rate. Åbo Akademi Process Chemistry Centre: Turku, Finland, 2009.

2. Furnace Tests

Background

As a wood member is exposed to fire it decomposes and, at approximately 300°C, the wood converts to char. This char layer ultimately reduces the load-carrying cross-section of the member. While char is non-structural, it is insulating and protects the remaining cross section. The rate at which this char layer forms governs the fire resistance of wood members for safe use in buildings. Fire resistance is a measure of the ability to resist collapse or other failure during exposure to a fire. A slow rate of char formation



and slow loss of strength of wood under fire exposure allows large wood members to maintain their load carrying capacity despite intense heat and fire.

The fire resistance ratings of structural members and assemblies, wood-based or otherwise, have traditionally been obtained by testing the product or assembly in a furnace in accordance with ASTM International (ASMT) Standard E119, *Standard Test Methods for Fire Tests of Building Construction and Materials* [1] and similar standards. Among other things, ASTM E119 specifies a time-temperature curve that the furnace needs to achieve, often referred to as the “standard fire.” Temperatures on the standard fire curve include 1000° F (538°C), 1700°F (927°C), 1850°F (1010°C) and 1925°F (1052°C) at 5, 60, 120 and 180 minutes, respectively.

Researchers have developed char depth models for wood exposed to the standard fire based on empirically measured char rates. These models allow the remaining cross-section of a member to be calculated to meet the required load-capacity and fire resistance ratings for structural wood building members. The char rate measured under the standard fire is dependent on numerous variables such as species, density, permeability, moisture content, and dimension. However, for practical purposes the commonly assumed nominal charring rate of 1.5 inches/hour (0.6 mm/min) at one hour is used for exposed wood members in the absence of other data.

Cross Laminated Timber

Cross laminated timber (CLT) is an engineered wood product manufactured by gluing perpendicular layers (typically 3, 5 or 7) of dimensional lumber together. The result is an engineered wood panel product that can withstand high structural loads. CLT is commonly used for floor/ceiling assemblies and walls.

The *National Design Specification for Wood Construction* (NDS) [2] char rate model for CLT accounts for potential for char fall-off as the char front approaches the adhesive bond line between each lamination and reduced section properties from having the strength axis oriented in two directions. The CLT char depth model from the 2018 NDS is:

$$a_{char} = n_{lam}h_{lam} + \beta_t \left(t - (n_{lam}t_{gl}) \right)^{0.813} \quad (1)$$

Where,

n_{lam} is the number of charred laminations

h_{lam} is the number of laminations within the CLT

β_t is the linear char rate (1.5 inches/hour)

t is the time in hours

t_{gl} is the time to char through one lamination

The proposed work will evaluate the effect of thermal modification on the char rate of Advanced Cross Laminated Timber (ACLt) to support ongoing/expanding research and development efforts for the use of sustainable mass timber products in MILCON. ACLt is a proprietary CLT product developed by the Composites Recycling Technology Center (CRTC).

Objectives

The main objective of this study was to evaluate the char depths of thermally modified ACLt and compare the results with non-thermally modified CLT. Char depth models could then be developed to compare against commercially available CLT.

Methods and Materials

Intermediate Scale Furnace

The FPL intermediate-scale horizontal furnace (Figure 2.1) is a metal box lined with ceramic/mineral fiber blankets and heated by eight diffusion-flame natural gas burners on the floor of the furnace. The interior dimensions of the furnace were 1.83 m long, 0.99 m wide and 1.22 m high. The ceramic fiber-lined metal cover for the furnace was removable from the top of the furnace. All air for combustion was provided by natural draft through vents at the bottom of the furnace. Six capped furnace thermocouples were located 305 mm from the top of the furnace interior. The gas was controlled so temperature of the capped thermocouples followed the standard time-temperature curve in ASTM E119 (Figure 2.2). Temperature data for the furnace and the specimen were recorded in 5 seconds intervals.



Figure 2.1. FPL Intermediate-scale horizontal furnace without lid or specimen installed.

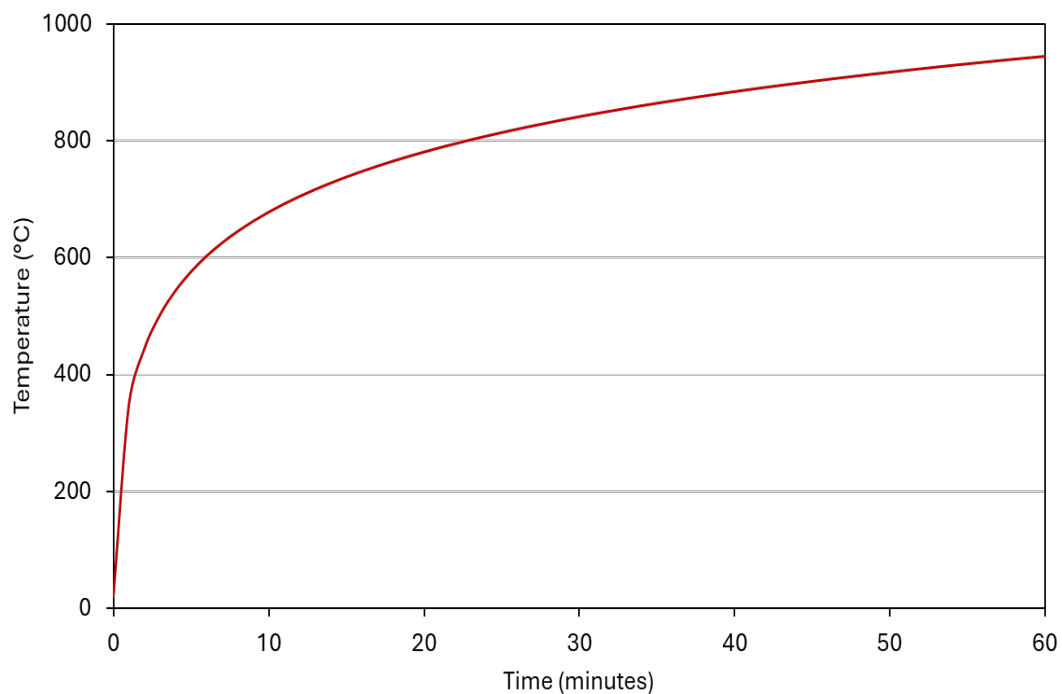


Figure 2.2. Standard time-temperature curve from ASTM E119.

A custom test frame held two specimens per test such that the specimens were installed on the top of the furnace (Figure 2.3). The temperatures at the embedded thermocouples as well as in the furnace were recorded throughout each test. Visual observations of the specimens during the tests were limited.

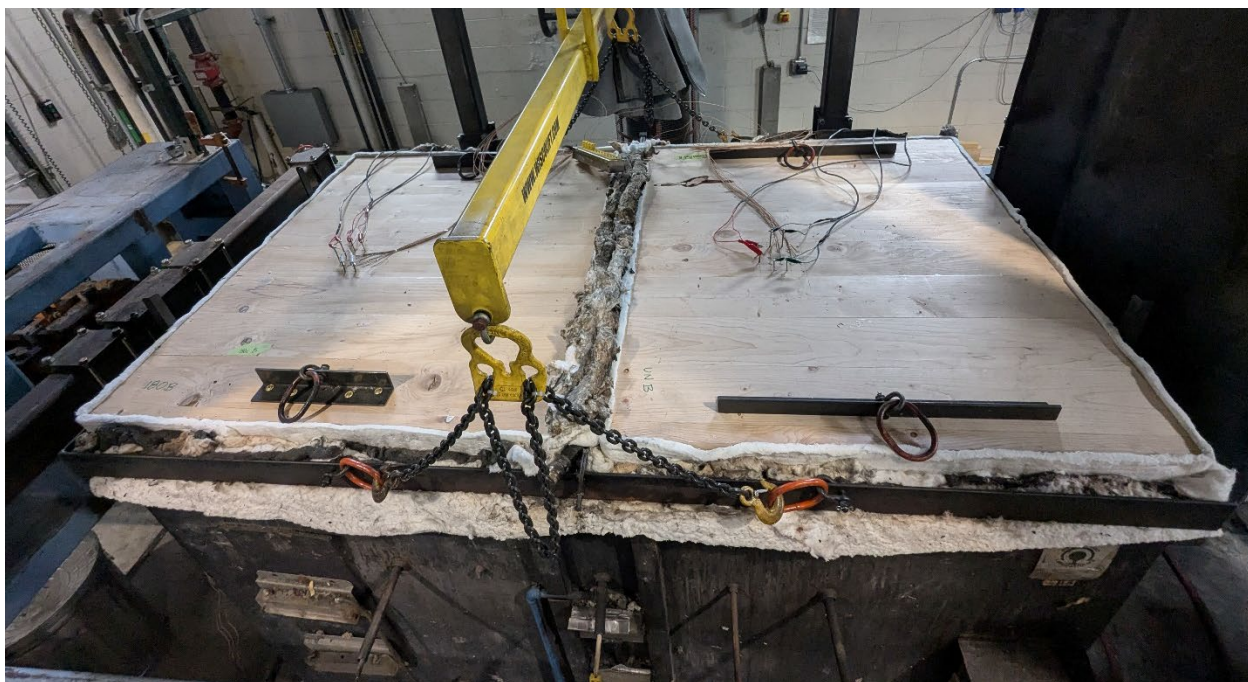


Figure 2.3: View of lid with two specimens installed, separated by a water-cooled bard and noncombustible ceramic fiber.

Post-test analysis

At the end of each 1-hour test, water was applied to the specimens to halt combustion, the custom frame was lifted from the furnace, and the specimens were removed. Post test, the char layer was removed, and the specimens were promptly removed from the furnace and extinguished with water. The residual cross-section at the center of the thermocouple grid was measured for each panel. Both the thermocouple data and the measured residual cross-section data can then be used to develop a char rate model.

Specimen Overview

Nine mass timber panels were developed using Western Hemlock lamellae (1" thick) bonded with an exterior-grade polyurethane adhesive. Six of the panels were thermally modified ACLT at two different temperatures (three panels at 180°C and three panels at 190°C). The wood lamellae are thermally modified before being bonded into the final composite, and thermal modification is performed to enhance the durability of wood. Three unmodified panels were tested as a control. The final dimensions for each panel were 40" by 48" by 3" thick. A total of five tests were conducted with two panels per test such that one of the tests included a dummy specimen in addition to a real specimen.

Instrumentation

To monitor the 300°C isotherm during the tests, thermocouples were installed within the specimens. Each specimen had two thermocouples installed during the manufacturing process: each at the center of the panel with one at each adhesive bond line. Additional thermocouples were installed by drilling holes from the back/non-fire exposed surface (Figure 2.4). The thermocouples were made at FPL from 30-gauge, Type K glass insulated thermocouple wire (Evolution Sensors, K1X-FGXX). The embedded thermocouples were installed every ¼" with the fire-exposed surface being 0". The holes for embedding the thermocouples were aligned on a 2" by 3" grid pattern, spaced 1" apart that was centered within the boards such that the thermocouples would not be affected by any edge gaps between boards. After the thermocouple wires were inserted in the holes, the holes were filled with fire caulk. Two additional thermocouples were installed in the bond lines during the manufacturing process.



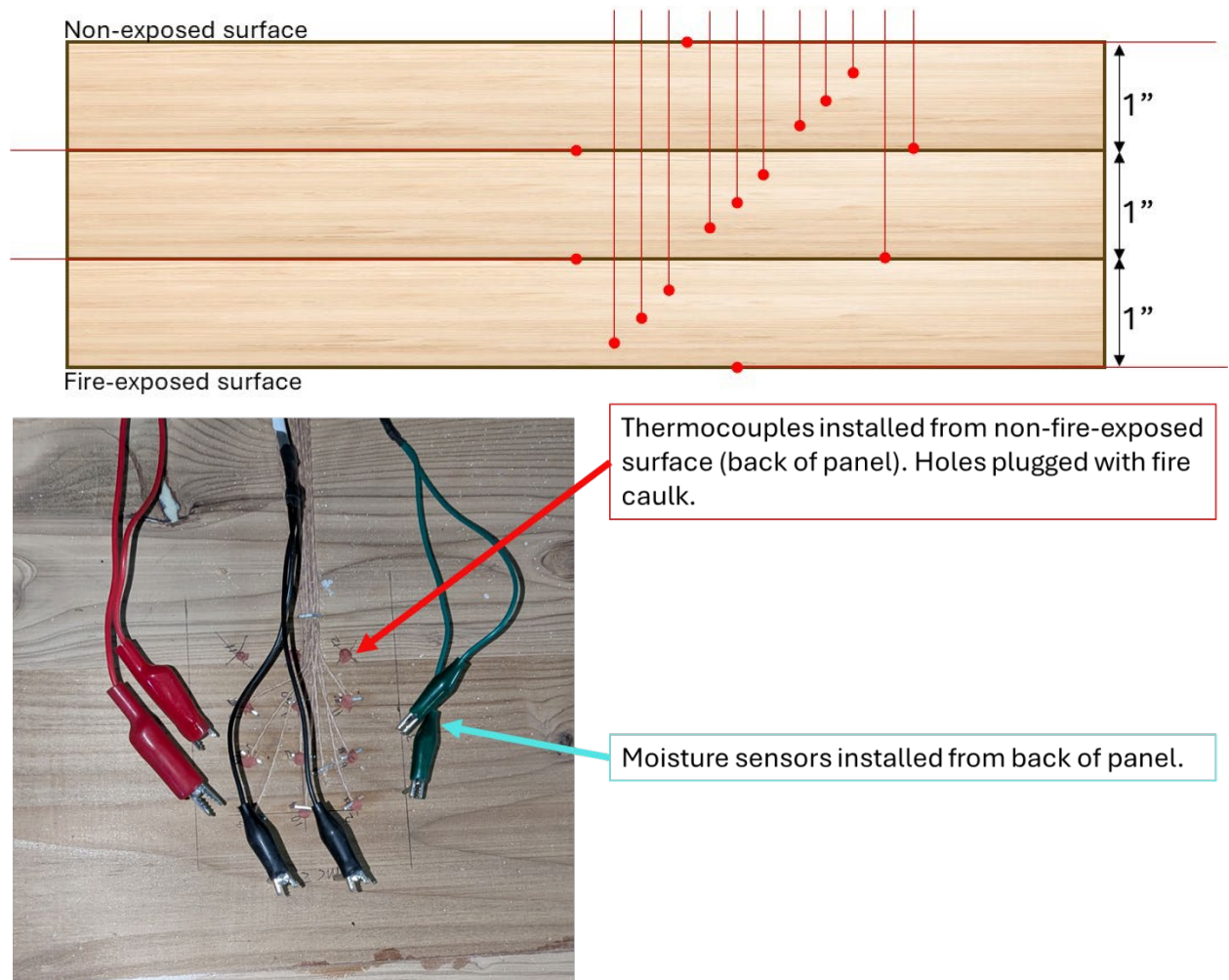


Figure 2.4: Schematic of thermocouple installation depths (top) and thermocouples (small wires) and moisture sensors (black, green, and red clips) installed from back of panel (bottom).

Results

Furnace Operation

The flow of natural gas into the furnace burners is controlled by adjusting a valve to maintain the furnace temperatures as specified by ASTM E119 for a duration of 1 hour. ASTM E119 requires deviations from the area under standard curve to be less than 10% for a test 1-hour or less. For all five tests, the recorded variation in the area under the curve was insignificant (-0.0%).

Thermocouple Results

The results from the thermocouples embedded within the CLT specimens provide a picture of the 1D thermal profile through the specimen at a specified time. The main experimental results of interest are the times to reach 300°C at the various locations within the CLT (Figures 2.5, 2.6, and 2.7), which can be used to determine char rates.

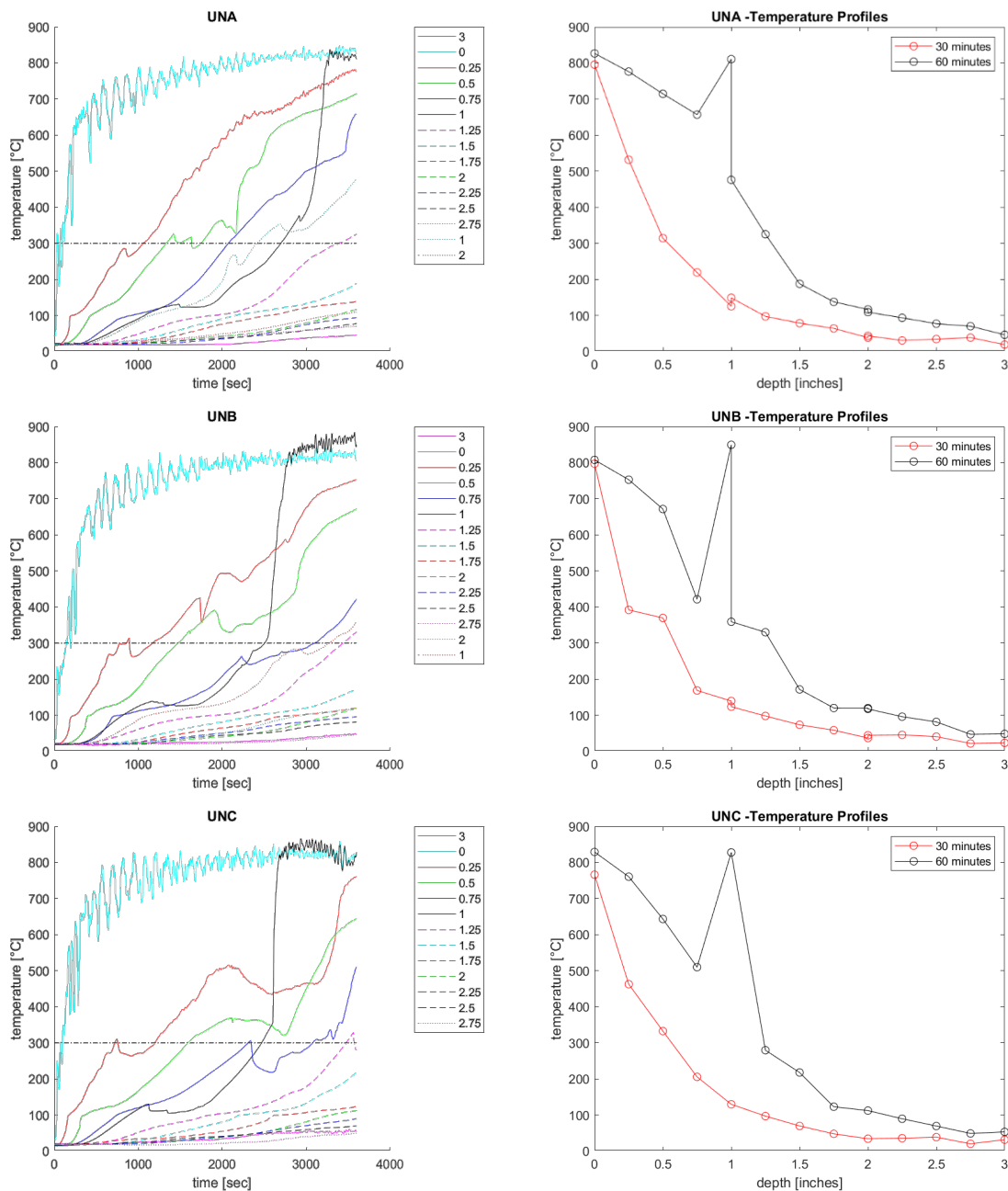


Figure 2.5. Thermocouple results from each unmodified specimen (left). The legends provide the depth of a thermocouple in inches from the fire-exposed surface. The 300°C isotherm is indicated by the horizontal dashed line. Temperature profiles for each specimen at 30 minutes and 60 minutes (right).

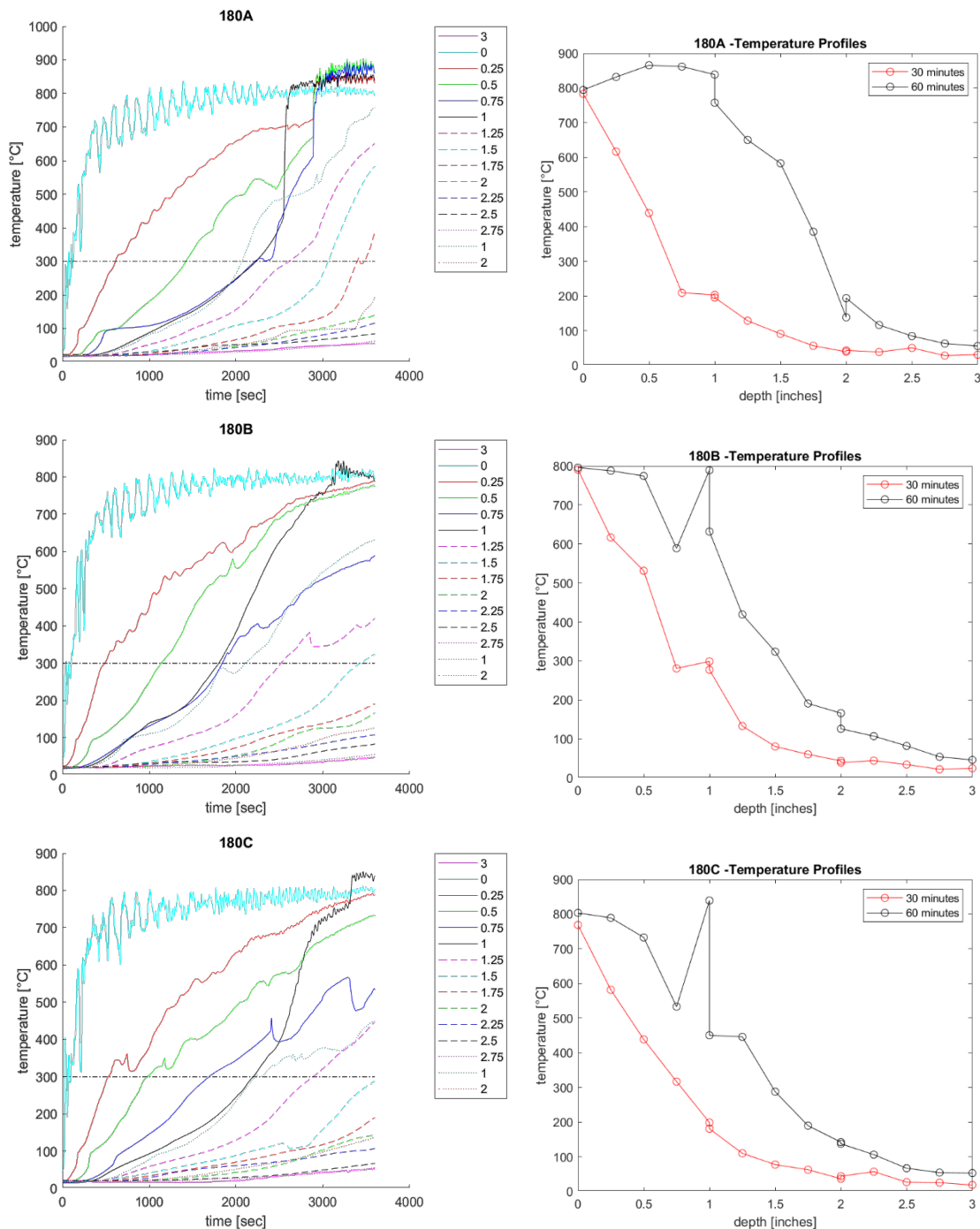


Figure 2.6. Thermocouple results from each specimen thermally modified at 180°C (left). The legends provide the depth of a thermocouple in inches from the fire-exposed surface. The 300°C isotherm is indicated by the horizontal dashed line. Temperature profiles for each specimen at 30 minutes and 60 minutes (right).

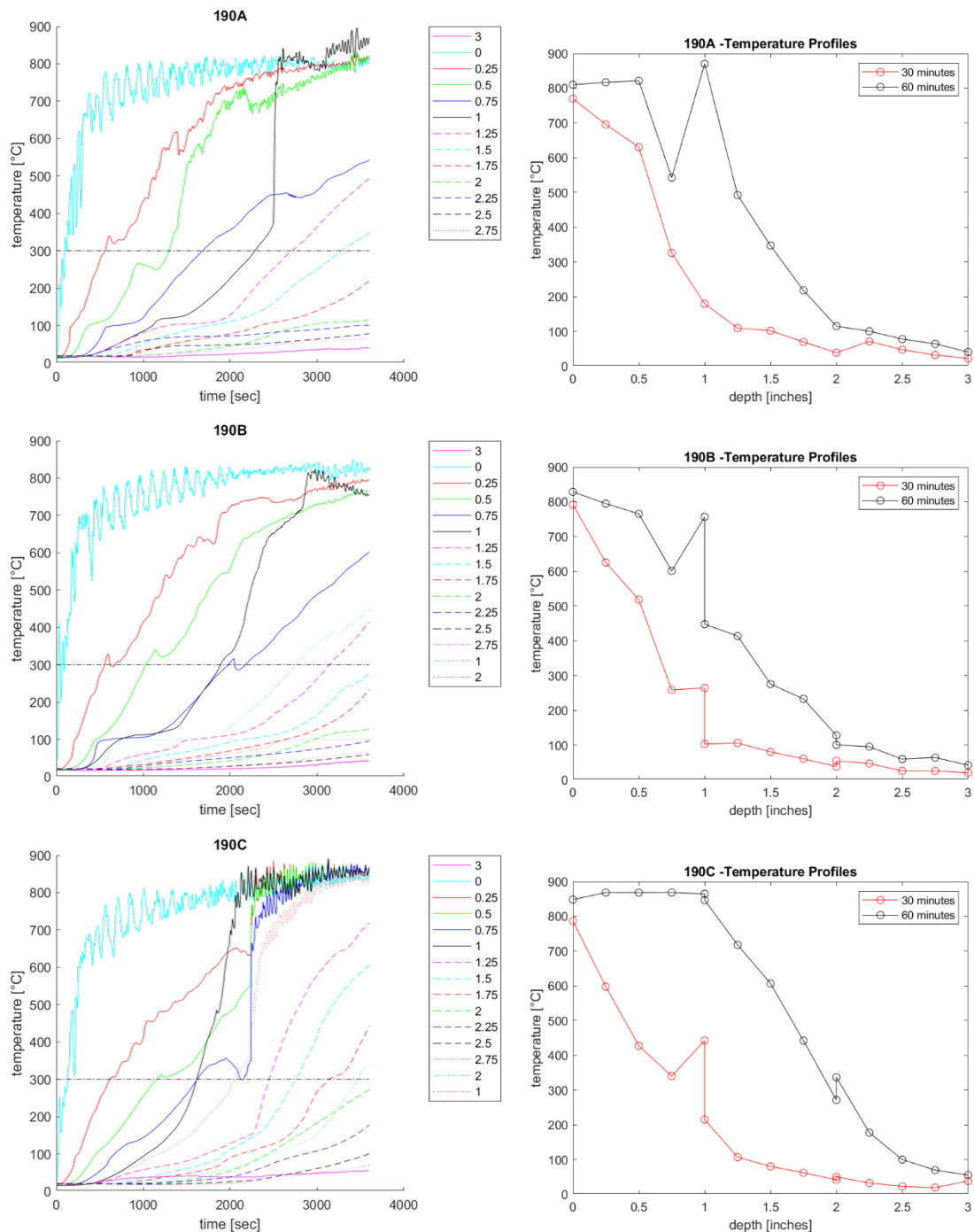


Figure 2.7. Thermocouple results from each specimen thermally modified at 190°C (left). The legends provide the depth of a thermocouple in inches from the fire-exposed surface. The 300°C isotherm is indicated by the horizontal dashed line. Temperature profiles for each specimen at 30 minutes and 60 minutes (right).

Residual Measurements

Post-test analysis was conducted to measure the residual thicknesses for each specimen (Table 2.1).

Table 2.1. Residual measurements in inches.

Specimen	Remaining Thickness (inches)
180A	1.04

180B	1.3
180C	1.4
190A	1.31
190B	1.32
190C	0.9
UNA	1.72
UNB	1.74
UNC	1.69

Char Rates

By combining the results from the thermocouples with the residual measurements (Table 2.2), the char depth with respect to time can be compared to the current CLT model (Figure 2.8).

Table 2.2. Embedded thermocouple results with depth given in inches from the fire-exposed CLT surface and time to 300°C (t_{300}) in minutes. Values provided in these tables were averaged across specimens and rounded to the nearest tenth.

Depth (inches)	t_{300} (minutes)		
	UN_Average	180C_Average	190C_Average
0.00	1.4	0.8	1.5
0.25	14.7	9.1	9.7
0.50	24.5	19.8	19.4
0.75	41.6	32.0	29.4
1.00	42.7	34.7	32.8
1.10	-	-	-
1.25	57.4	44.6	46.2
1.30	60	-	-
1.33	-	48.5	48.9
1.35	-	47.3	-
1.45	-	50.6	-
1.71	-	-	57.4
1.96	-	60	-
2.00	-	-	58.8

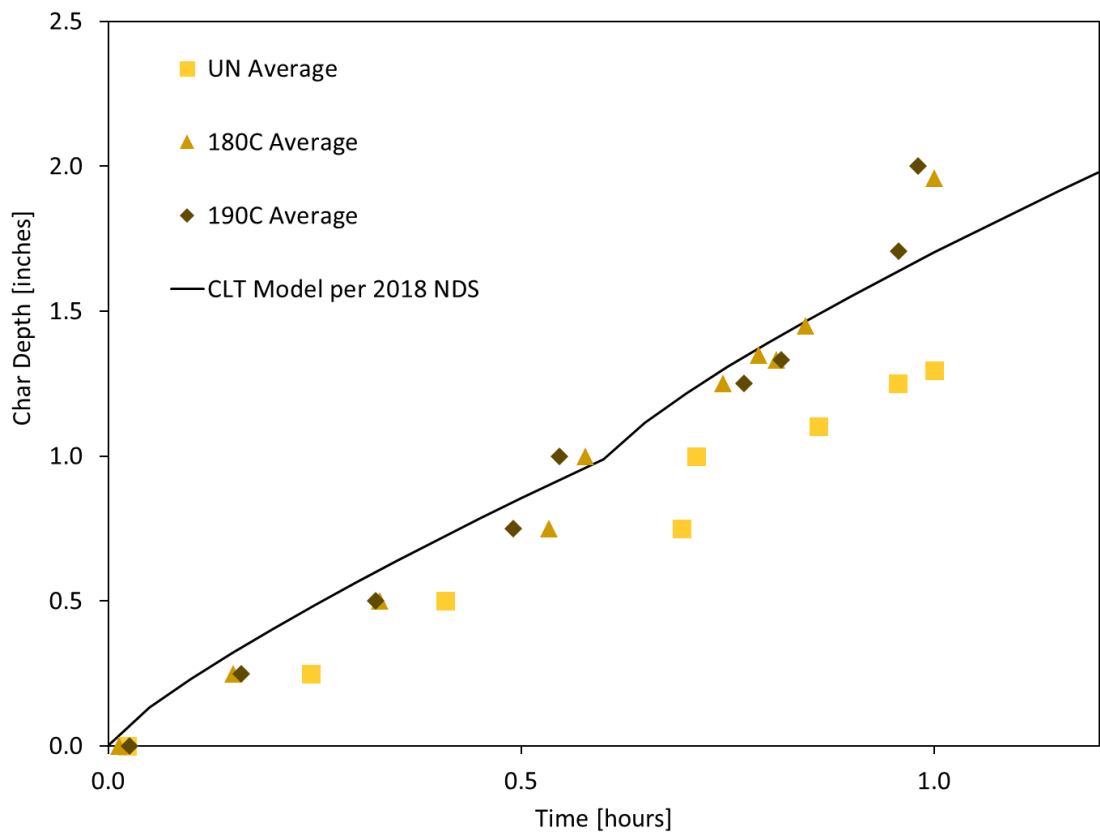


Figure 2.8. Averaged time to 300°C at depths for each thermally modified specimen type compared to the CLT char depth model from NDS.

For the hemlock specimens tested, the char depth increased with increasing thermal modification temperatures. However, from Figure 2.8 we see that the char depths for each specimen were similar to the current CLT model, which was developed for unmodified, structural softwood lumber species.

References

1. ASTM E119. Standard Test Methods for Fire Tests of Building Construction and Materials. ASTM International, West Conshohocken, PA.
2. National Design Specification (NDS) for Wood Construction (2018). American Wood Council (AWC). Washington, DC.

3. Sorption Isotherm

Background

A water vapor sorption isotherm is the locus of points that relate the relative humidity (RH) of the environment to the “equilibrium moisture content” (EMC) of a material at a given temperature. The sorption isotherm is of particular importance for wood and other natural materials whose moisture content and material properties experience large changes with RH. EMC refers to the moisture content at which no net gain or loss of moisture occurs and is calculated as the ratio of the mass of water in the material to the dry mass of the material. Instead of a true thermodynamic equilibrium, the EMC is path dependent; it depends on whether the material reached EMC at a given RH from a lower or higher RH.

Methods and Materials

Materials:

Unmodified and thermally modified western hemlock were tested. Three replicates of the unmodified western hemlock were tested. Two replicates of the “generation zero” thermal modification were tested. Finally, one replicate per temperature was tested for the “generation 1” thermal modification. Generation 1 materials were supplied with modification temperatures of: 160°C, 180°C, 190°C, 200°C, 220°C.

Methods:

The sorption isotherms were collected with an automated sorption balance (often referred to Dynamic Vapor Sorption or DVS). In these experiments, a sample of less than 100 mg is suspended from a microbalance that continuously records mass as a function of time. The sample is located in a chamber maintained at constant temperature, and water vapor mixed with inert carrier gas (such as nitrogen) is flowed at a constant rate through the sample chamber. The RH is controlled by mixing dry and vapor-saturated streams of carrier gas using mass flow controllers. With computer control, DVS facilitates rapid step changes in RH and gravimetric measurement of moisture sorption kinetics. Because the resolution of the microbalance is so fine and the mass is continuously and automatically recorded, the EMC is not typically taken from identical successive readings, but instead a “stop criterion” is used to stop collecting data at an RH step and move to the next step. For these measurements, the stop criteria of $5 \mu\text{g g}^{-1} \text{min}^{-1}$ using a 60 minute running slope was used following the suggestion of Glass et al. [1]. The protocol for the sorption method is presented below.

Initial Drying

Settings:

- Initial Temperature = 25 °C
- Flow rate = 200 cm³/minute
- Data collection interval = 20 seconds

Sequence:

- 1) RH Target: 0%, hold at 25 °C for 60 minutes
- 2) Ramp up temperature from 25 °C to 60 °C over 60 min
- 3) Hold temperature at 60 °C for 360 min
- 4) Ramp down temperature from 60 °C to 25 °C over 60 min
- 5) Hold temperature at 25 °C for 120 min

6) Update Sample Weight (to set dry mass)

Sorption Sequence

Settings:

- Temperature = 25 °C
- Flow rate = 200 cm³/minute
- Data collection interval = 20 seconds
- DMDT window = 60 minutes
- DMDT maximum time = 960 minutes

RH Sequence:

- 1) Target: 10%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 2) Target: 20%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 3) Target: 30%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 4) Target: 40%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 5) Target: 50%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 6) Target: 60%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 7) Target: 70%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 8) Target: 80%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 9) Target: 90%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)
- 10) Target: 95%, Stop criterion: DMDT, Value: 5 µg g⁻¹ min⁻¹ (0.0005 %/min)

Analysis:

The moisture content, u , at each relative humidity was calculated from the dry mass (m_{dry}) at the end of the initial drying step at the mass when the DMDT criteria was met (m) thought

$$u = \frac{m - m_{dry}}{m_{dry}}$$

Glass et al. [1] noted that the moisture content calculated from the final mass at a DMDT of 5 µg g⁻¹ min⁻¹ results in a systematic underprediction from “true” equilibrium, and proposed correction factors for the corrected moisture content, u_{cor} , based on the RH step size

$$u_{cor} = \begin{cases} 1.012u & \text{for 5\% RH steps} \\ 1.022u & \text{for 10\% RH steps} \end{cases}$$

These corrections were applied to the raw data for the isotherm plots.

The isotherms were fit with the so-called “ABC Isotherm” [2,3]. This empirical isotherm has been shown to characterize cellulosic materials well and is useful for interpolating isotherm curves. No theoretical sorption isotherm models have been found to be valid for wood, and therefore isotherm data should not be used to calculate thermodynamic properties for wood such as heat of sorption or monolayer coverage [3].

Results

Figure 3.1 contains the sorption isotherm data for the unmodified western hemlock. The isotherms were extremely consistent between replicates below 90% RH. Some deviation can be seen between replicates at 90% and 95% RH.

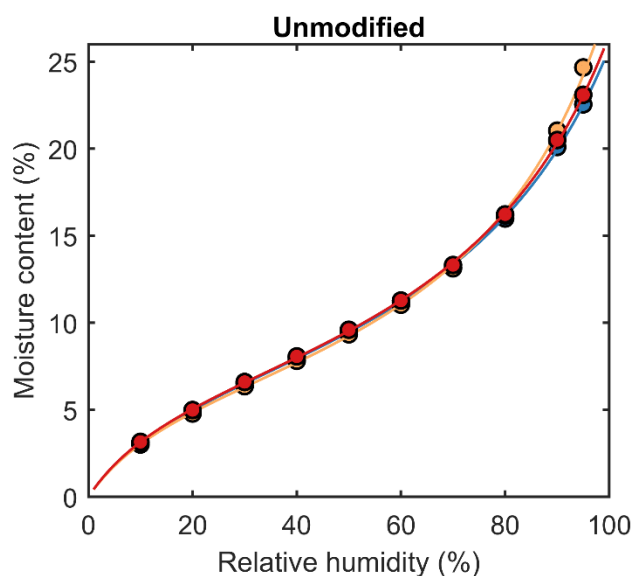


Figure 3.1: Sorption isotherms for the unmodified wood. Different colors represent the three replicates tested.

Figure 3.2 contains the sorption isotherm data for the “generation 0” thermal modification of western hemlock. Compared to the unmodified wood, the isotherms exhibit less hygroscopicity, with the amount of absorbed moisture being less than the unmodified wood. Some small differences can be observed between the two replicates, however, the difference between the two moisture contents was less than 0.01 g g^{-1} .

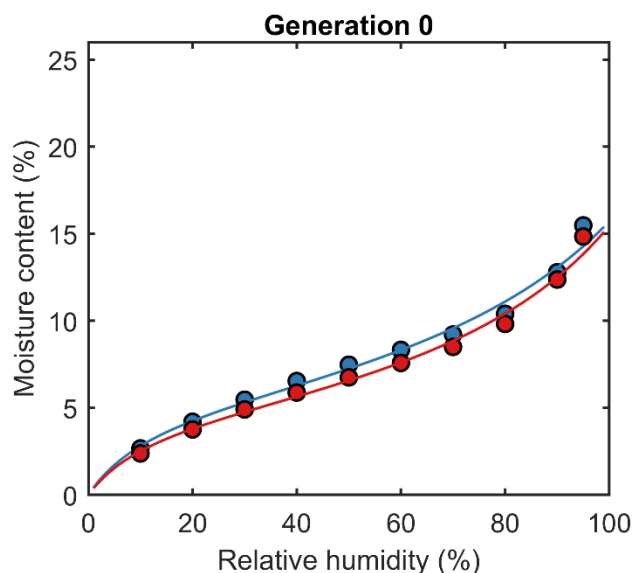


Figure 3.2: Sorption isotherms for the “generation 0” modification. Different colors represent the two replicates tested.

Figure 3.3 presents sorption data for the “generation 1” modification. Several different modification temperatures were tested and clear differences between the modification temperatures can be seen in

the sorption isotherms. As the modification temperature increased, the amount of absorbed moisture content at any given relative humidity decreased.

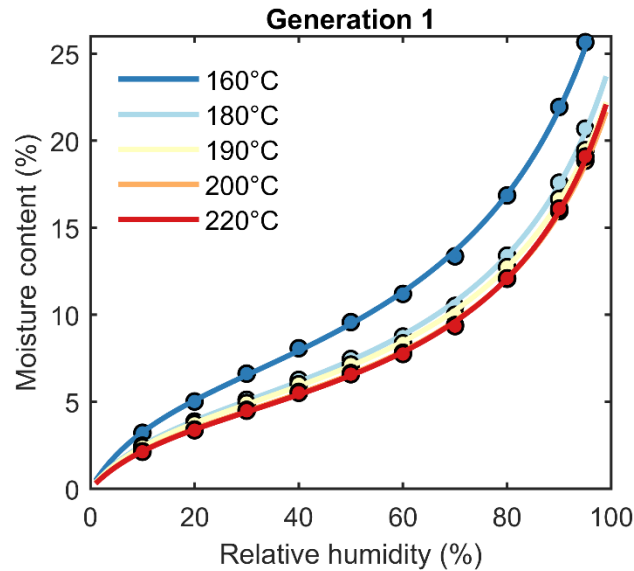


Figure 3.3: Sorption isotherms for the “generation 1” modification. Different colors represent different modification temperatures.

Figure 3.4 shows four ABC isotherm fits: the average of the unmodified specimens, the average of the “generation 0” modifications, and the highest and lowest temperatures for the “generation 1” modifications. It can be seen from this comparison figure that the modification at 160°C has little impact on the sorption isotherm; with this isotherm being very close to the unmodified curve below 80% RH and slightly higher than the unmodified curve above this relative humidity. In contrast, both the generation 0 and 220°C modifications show an appreciable decrease in the amount of absorbed moisture. Between these two, the generation 0 modification shows the most pronounced decrease in absorption, especially at high relative humidities. While similar to the 220°C isotherm below 70% RH, the generation 0 modification has a much slower increase in moisture content with RH at high relative humidity, whereas the 220°C isotherm shows a similar sharp bend upward at high relative humidity.

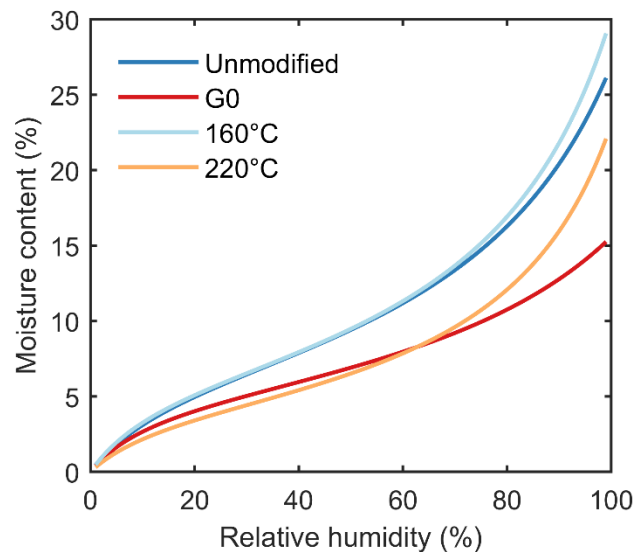


Figure 3.4: Comparisons of the unmodified, generation 0 (G0), and generation 1 modifications (extreme temperatures only).

The sorption isotherm data suggest that the generation 0 and 220°C wood modifications will exhibit the most dimensional stability of the modifications tested.

References

1. Glass, S.V.; Boardman, C.R.; Thybring, E.E.; Zelinka, S.L. Quantifying and reducing errors in equilibrium moisture content measurements with dynamic vapor sorption (DVS) experiments. *Wood Science and Technology* 2018, 52, 909-927, <https://doi.org/10.1007/s00226-018-1007-0>.
2. Zelinka, S.L.; Glass, S.V.; Thybring, E.E. Myth versus reality: Do parabolic sorption isotherm models reflect actual wood–water thermodynamics? *Wood Science and Technology* 2018, 52, 1701-1706, <https://doi.org/10.1007/s00226-018-1035-9>.
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4. Water Vapor Transmission

Background

The migration of water molecules through porous materials in the building envelope can lead to either moisture accumulation or drying, depending on the conditions [1]. Water vapor transmission refers to the net movement of water molecules from one side of a material to the other side when there is a difference in water vapor pressure. Water vapor permeability is a material property that relates the rate of water vapor transmission through a material (mass per unit area per unit time) to the gradient in water vapor pressure (change in vapor pressure across the thickness). Vapor permeability is expressed in SI units of $\text{kg m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$.

Water vapor transmission through wood depends on the wood species, direction (longitudinal, radial, tangential), density, connectivity of the pore structure, and moisture content [2]. The primary pathway is diffusion of water vapor through the pore structure, but this usually does not provide a continuous path. Water molecules must cross the cell wall (or pass through bordered pits or other features) to get to the next void. As relative humidity (RH) increases, the moisture content of the cell wall increases, and the mobility of water molecules within the cell wall increases. The overall water vapor transmission (reflecting both vapor diffusion through the pore structure and cell walls) thus increases with increasing relative humidity.

Materials and Methods

Specimens

Three unmodified western hemlock boards (UM-C, UM-D, UM-E), each with a grain angle near tangential, were sanded to 20 mm thickness. Two specimens were cut from each board into rectangular prisms with rounded corners (12 mm radius) to fit the profile of a Pyrex dish (Figure 4.1). Dimensions were 168 mm along the grain by 116 mm across the grain. Specimen edges were coated with neoprene paint to provide a vapor-tight seal. One specimen from each board was used in dry cup tests (3 replicates) and one from each board was used in wet cup tests (3 replicates). Dry bulk density was measured using 100 mm x 50 mm x 20 mm specimens cut from the same boards (four replicates each from three boards) and was $589 \text{ kg m}^{-3} \pm 19 \text{ kg m}^{-3}$ (mean $\pm$ standard deviation).

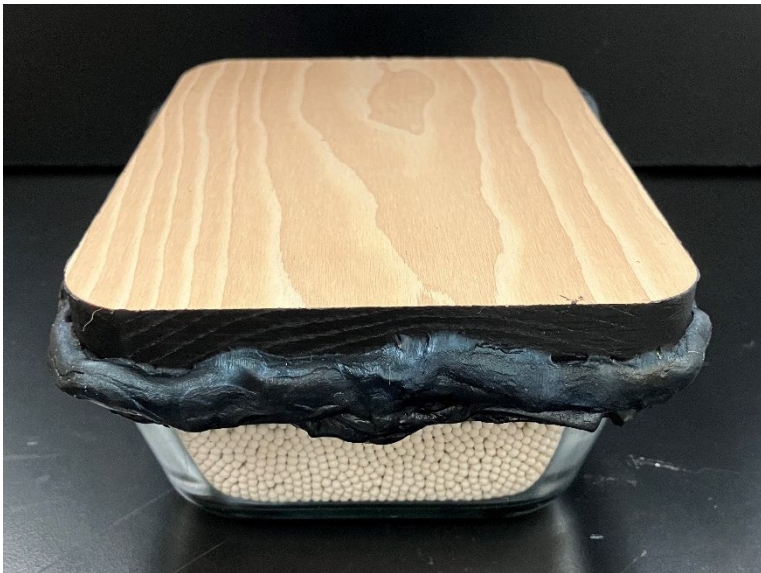


Figure 4.1. Unmodified western hemlock specimen with edges coated with neoprene paint, sealed with butyl tape to Pyrex dish containing A3 molecular sieve desiccant.

Test method

Measurements were conducted according to the desiccant method (dry cup) and water method (wet cup) of ASTM E96/E96M, *Standard Test Methods for Gravimetric Determination of Water Vapor Transmission Rate of Materials* [3]. Prior to testing, specimens were conditioned at 22°C and 50% RH for two weeks. Specimens were sealed with butyl tape to Pyrex dishes, which had been partially filled with either A3 molecular sieve desiccant (Delta Adsorbents, Roselle, IL) or deionized water. Specimens were mounted such that the bottom surface was flush with the dish, leaving an air gap between the specimen and desiccant of about 10 mm (dry cup) or 25 mm (wet cup). Assembled dishes were placed in an environmental chamber nominally set to 22°C and 50% RH. Each dish was weighed on an electronic balance at approximately 24-h intervals. After completion of the measurements with the chamber at 50% RH, additional measurements were conducted with the chamber nominally set to 23°C and 80% RH. Temperature/RH dataloggers were placed in the chamber to record conditions during the measurement period. Mean recorded conditions are listed in Table 4.1.

Table 4.1. Chamber conditions during steady-state period of water vapor transmission measurements.

	Standard measurement	Additional measurement
Mean temperature (°C)	22.4	22.3
Mean relative humidity (%)	54.0	73.1

Water vapor permeability was calculated based on the mass flow rate at steady state, the specimen thickness and surface area, and the vapor pressure difference. The calculations account for the diffusion resistance of the still air layer between the desiccant and the specimen as well as the boundary layer mass transfer resistance [3].

Results

Figure 4.2 is an example plot of mass gain vs. time for a dry cup assembly. Water vapor migrates from the ~50% RH chamber through the specimen into the desiccant. The mass flow rate at steady state was

determined from the slope of a linear fit to the last eight data points. Water vapor permeability results are summarized in Table 4.2. The increase in vapor permeability with increasing mean RH is consistent with literature data, and values are within the range of other softwoods for moisture transport across the grain [4].

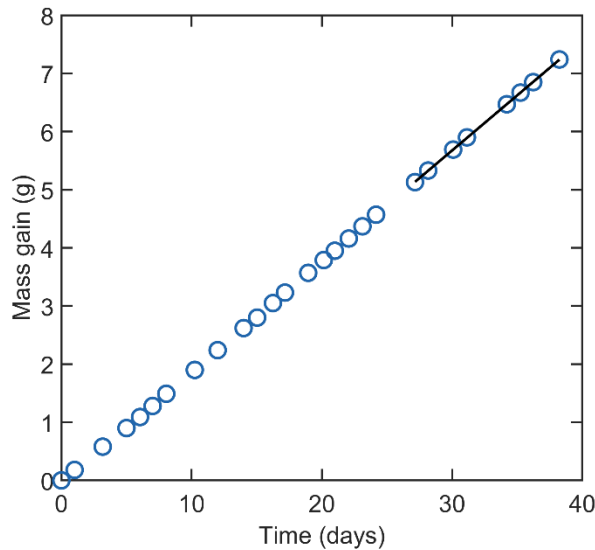


Figure 4.2. Mass gain vs. time for a dry cup assembly, with linear fit to steady-state period.

Table 4.2. Water vapor permeability results.

High RH side (%)	Low RH side (%)	Mean RH (%)	Water vapor permeability ($\text{ng m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$)	
			Mean	Standard deviation
54	0	27	1.64	0.45
73.1	0	36.6	3.34	0.73
100	54	77	11.25	1.74
100	73.1	86.6	13.09	2.15

References

1. ASHRAE. 2025a. Heat, air, and moisture control in building assemblies—fundamentals. ASHRAE Handbook—Fundamentals, Ch. 25. Peachtree Corners, GA: ASHRAE.
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5. Liquid Water Absorption

Background

The liquid water absorption coefficient refers to the rate of water uptake through one surface of a material when it is partially immersed in water. Water uptake is often linear when plotted as a function

of the square root of time, and the absorption coefficient is expressed in SI units of $\text{kg m}^{-2} \text{s}^{-0.5}$. This property is important for building envelope materials that may be exposed to rain or other sources of water either during construction or during the service life of the building.

Materials and Methods

Specimens

Three unmodified western hemlock boards (UM-C, UM-D, UM-E), each with a grain angle near tangential, were sanded to 20 mm thickness. Two specimens were cut from each board into rectangular prisms with dimensions of 100 mm along the grain x 50 mm across the grain. Specimen edges were coated with neoprene paint to provide a water-tight and vapor-tight seal to limit absorption to one surface and prevent any outward drying. Dry bulk density was measured using specimens of the same size cut from the same boards (four replicates each from three boards) and was $589 \text{ kg m}^{-3} \pm 19 \text{ kg m}^{-3}$ (mean $\pm$ standard deviation).

Test method

Measurements were conducted according to ASTM C1794, *Standard Test Methods for Determination of the Water Absorption Coefficient by Partial Immersion* [1]. Prior to testing, specimens were conditioned for two weeks in a room maintained at 22°C and 50% RH. Specimens were immersed in water to a depth of a few millimeters, periodically removed, blotted to remove surface droplets, weighed on an electronic balance to $\pm 0.0001 \text{ g}$, and immersed again. Mass measurements were taken after 5 min, 15 min, 30 min, 1 h, 4 h, and 24 h of immersion. Specimens were reconditioned at 22°C and 50% RH for three months, and the measurements were repeated with the specimens flipped for water absorption at the opposite surface. The liquid water absorption coefficient was determined from the slope of a plot of water uptake (mass absorbed divided by surface area, kg m^{-2}) versus the square root of time ($\text{s}^{0.5}$).

Results

Figure 5.1 is an example plot of water uptake vs. the square root of time for one specimen, along with a linear regression. Liquid water absorption coefficients are summarized in Table 5.1. For some specimens, the values obtained for original vs. opposite surfaces were similar, but for other specimens the values differed considerably. This may be caused by differences in wood structure at these surfaces, such as slope of grain (the surface might not be exactly parallel to the axial direction of the tree). The liquid water absorption coefficients obtained here for western hemlock are within the range of other softwoods for absorption perpendicular to [2, 3].

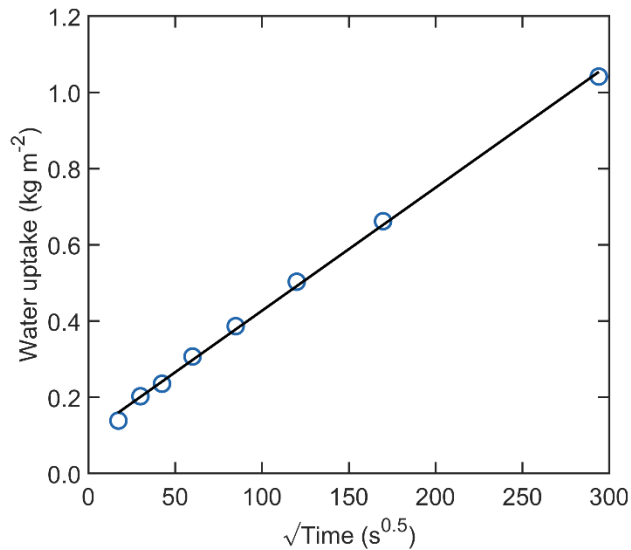


Figure 5.1. Water uptake vs. the square root of time, for an example specimen, with linear regression.

Table 5.1. Liquid water absorption coefficient results.

Specimen	Liquid water absorption coefficient (kg m ⁻² s ^{-0.5})	
	Original Surface	Opposite surface
UM-C-1	0.0018	0.0017
UM-C-2	0.0019	0.0021
UM-D-1	0.0036	0.0040
UM-D-2	0.0032	0.0024
UM-E-1	0.0046	0.0019
UM-E-2	0.0034	0.0019
Mean ± SD	0.0027 ± 0.0010	

References

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6. Thermal Conductivity

Background

For porous materials, the apparent thermal conductivity is a property that relates the rate of heat flow through a material (energy per unit area per unit time) to the applied thermal gradient (change in temperature across the thickness). The term “apparent” is used because heat transfer is not purely by conduction; radiative heat transfer across pore surfaces also contributes to the measured heat flow. This property is commonly measured for insulating materials but is important for any material that is used in the building envelope. Thermal conductivity is expressed in SI units of $\text{W m}^{-1} \text{K}^{-1}$. A related quantity is thermal resistivity, the reciprocal of thermal conductivity. Thermal resistance is the product of thermal resistivity and thickness. It is common in the U.S. building industry to express values in imperial (inch–pound) units. Thermal resistance, or R-value, is expressed in $\text{h ft}^2 \text{°F Btu}^{-1}$, and resistivity (R-value per inch of thickness) is expressed in $\text{h ft}^2 \text{°F Btu}^{-1} \text{in}^{-1}$.

The apparent thermal conductivity of wood depends on grain orientation, density, moisture content, and temperature [1]. Prior measurements of cross-laminated timber (CLT) composed of unmodified western softwood species [2] were consistent with values calculated from a generic equation in the *Wood Handbook* [1]. The generic equation is for heat transfer in wood across the grain near room temperature, as a function of density and moisture content.

Thermal modification reduces the density of wood (see Section on Cone Calorimeter Tests) and its equilibrium moisture content at a given relative humidity (see Section on Sorption Isotherm). Both factors contribute to reducing the thermal conductivity of thermally modified wood in comparison to unmodified wood.

Materials and Methods

Specimens

Two CLT specimens were provided (Figure 6.1), both composed of three layers of thermally modified western hemlock. Both specimens had dimensions of approximately 610 mm x 610 mm. The first specimen (CLT 1) had a 3-mm-thick adhered carbon fiber composite facer and a total thickness of 52.5 mm (each western hemlock layer was 16.5 mm thick). CLT 1 was handed to FPL personnel while visiting CERL (Champaign, IL) in May 2023. The second specimen (CLT 2) had a total thickness of 75.9 mm (each layer was 25.3 mm thick). CLT 2 was shipped from CRTC to FPL in December 2023.



Figure 6.1. Thermally modified specimens, CLT 1 (left) and CLT 2 (right).

Test method

Prior to testing, the specimens were conditioned at approximately 27°C and 35% relative humidity for two months. Thermal conductivity was measured using a heat flow meter apparatus (Figure 6.2) according to ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus* [3]. The top and bottom sides of each specimen were maintained at 14°C and 34°C, respectively, for a mean temperature of 24°C. Heat flux through the specimen was measured at five locations on each side until the values converged. The mean value at steady state was used for analysis.



Figure 6.2. Heat flow meter apparatus (Fox 637, LaserComp, Wakefield, MA).

Results

Measured thermal conductivity values are summarized in Table 6.1. The difference between specimens (0.116 and 0.112 W m⁻¹ K⁻¹) is not practically meaningful, given measurement uncertainty

($\pm 0.003 \text{ W m}^{-1} \text{ K}^{-1}$). The thermal conductivity of the carbon fiber composite facer was not measured separately, but its influence is expected to be minor given the small thickness (3 mm).

Table 6.1. Summary of thermal conductivity measurements.

Specimen	Total thickness (mm)	Thermal conductivity ($\text{W m}^{-1} \text{ K}^{-1}$)	R-value per inch ($\text{h ft}^2 \text{ }^\circ\text{F Btu}^{-1} \text{ in}^{-1}$)
CLT 1	52.5	0.116	1.24
CLT 2	75.9	0.112	1.29

Thermal conductivity of the CLT panels measured here can be compared with generic literature values for unmodified wood (at room temperature with heat transfer across the grain). Using a specific gravity of 0.45 (estimated from values for thermally modified wood in the Section on Cone Calorimeter Tests) and moisture content of 5% (estimated for thermally modified wood at a relative humidity of 35% based on the Section on Sorption Isotherm) the *Wood Handbook* equation [1] gives a thermal conductivity of $0.115 \text{ W m}^{-1} \text{ K}^{-1}$. This estimated value falls within the range of measured CLT values in Table 6.1.

References

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