Thermal Conductivity Values for Laminated Strand Lumber and Spruce for Use in Hybrid Cross-laminated Timber Panels

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This study examined the thermal conductivity as a function of specific gravity and moisture content for laminated strand lumber (LSL) and red spruce. As part of a larger study of heat and mass transfer in cross-laminated timber panels using laminate comprised of both LSL and spruce, the authors measured the thermal conductivity at four moisture content levels. The results showed that the LSL had a higher thermal conductivity value across the entire moisture content range tested. The average difference was just over 8% and the range for both LSL and spruce was from 0.081 W /m-K to 0.126 W / m-K. Comparisons with published solid wood thermal conductivity values across the range were good. There were no reported values of LSL thermal conductivity at various moisture content levels.

Keywords: Thermal conductivity; Red spruce; Laminated strand lumber

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INTRODUCTION

Thermal conductivity (TC) is a major thermophysical property used to determine the rate of heat flow due to conduction through a material that is subjected to a temperature difference across the surfaces. Thermal conductivity values are typically used in assessing heat transfer and the insulation value of walls in building construction.

As part of a larger study of heat and mass transfer through hybrid cross-laminated timber (CLT) panels made from laminated strand lumber (LSL) and red spruce (*Picea rubens* Sarg.) laminae, the authors determined the through thickness thermal conductivity of multiple samples of both materials for use in modeling heat and mass transfer. The variation of thermal conductivity for LSL with moisture content has not been reported previously. The thermal conductivity of spruce was reported for comparison purposes. The thermal conductivity of LSL as it varies with moisture content has not been previously reported but is needed for the novel use of LSL in ClT panels.

The Wood Handbook (2010) defines thermal conductivity as a measure of the rate of heat flow (W m^{-2}) through a material subjected to unit temperature difference (K) across unit thickness (m). Conduction is defined by Fourier's law under steady-state conditions as shown in Eq. 1,

$$\frac{Q}{t} = \lambda A \left(\frac{\Delta T}{d}\right) \tag{1}$$

where Q / t is the rate of heat conduction, which is the amount of heat conduction through a material in unit time, in watts (W), A is the total cross-sectional area of conducting surface (m^2), ΔT is the temperature difference (Kelvin , K), d is the thickness of the material (m), and λ is the thermal conductivity of the material (–W/m-K).

Typically, thermal conductivity values for building construction materials are measured by establishing a modest (approximately 20 °C) temperature difference across a sample. Measuring the energy input required to maintain the temperature difference allows the assessment of the steady state value of Q. A guarded plate is often used to reduce the heat loss from the edges of the sample and is based on ASTM C177 (2013). A second method used in this study, described in ASTM C518 (2015), is a heat flow meter. In limited testing, the differences between the methods, as measured by bias, are insignificant (Zarr and Lagergren 1999).

The thermal conductivity of solid wood and, presumably, wood-based composite materials is known to increase with specific gravity (dry weight/volume at test), moisture content, temperature, and extractive content (Wood Handbook 2010). The moisture content and density are major factors. Wangaard (1940) and MacLean (1941) have measured the effect of moisture content and have also reported a consistent relationship between thermal conductivity and specific gravity. Although not predicted by Fourier's law and not consistent for small changes in specific gravity, the general trend is that thermal conductivity increases as specific gravity increases. Porous substances transfer heat *via* convection and conduction and the specific gravity effect may be related to the porosity of the wood.

The effect of temperature on the value of thermal conductivity increases as the temperature increases. For example, Troppová *et al.* (2015) found that the conductivity values of oven-dried samples increased 12% whereas those of moist samples (14.2%) increased 61% when the temperature increased from -10 °C to 60 °C. Hence, the higher the temperature, the larger the differences between the conductivity values at oven dry condition and at 14.2% moisture content. The extractive content tends to be less important in most applications.

Measurements of solid-wood thermal conductivity are well established, and researchers such as Wangaard (1940), MacLean (1941), Wilkes (1979), Steinhagen (1977), and Goss and Miller (1992), cover many of the detailed studies for solid wood thermal conductivity. Of these studies Wangaard and MacLean generated substantial data and others used their data. For example, Tenwolde *et al.* (1988), developed a non-linear regression equation using MacLean's data. The Wood Handbook (Wood Handbook 2010) reports an equation for thermal conductivity based on the work of several researchers (Eq.2). The equation includes both specific gravity and a specific gravity/moisture content interaction term as factors. Equation 2 was meant for all common hardwood and softwood species. However, if the input data for Eq. 2 were restricted to the common commercial species used for building construction, the specific gravity range would be small and probably not statistically significant,

$$\lambda = G(0.194 + 0.004064M) + 0.01864 \quad (2)$$

where M is the dry basis moisture content (%), and G is the specific gravity.

Siau (1984), using a theoretical analysis based on an electrical conductivity analog, developed Eq. 3 for thermal conductivity, which includes specific gravity, porosity and moisture content of the wood. Siau assumed the applicability of Eq. 3 was for specific gravity values between 0.4 and 1.5,

$$\lambda = 0.510448 - 0.472792\alpha \qquad (3)$$

where a is the square root of the porosity of the wood ($\sqrt{V_a}$), V_a is the porosity of the wood, $1 - G\,(0.667 + 0.01{*}M)$, G is the specific gravity of wood at M, and M is the moisture content (%). The units of λ are W / m-K.

Using the broad dataset of MacLean and others, the constants in Eq. 2 are valid for temperatures at approximately 24 °C and for moisture content (dry basis) values less than 25%. There is also a restriction on specific gravity values, which must be above 0.3. Equation 2 is applicable only to solid wood. Tenwolde *et al.* (1988) mentions that the thermal conductivity of plywood and dry particleboard are approximately 86% and 75%, respectively, of that of solid wood with the same specific gravity, although no measurements of panels are provided. Eq. 2 is to be used with caution, as the underlying datasets are quite variable.

The thermal conductivity data for LSL are scant. Louisiana Pacific Corporation (LP) promotional literature for grade 1.35E LSL that was used for this research states that the thermal conductivity is 0.13 W / m-K, which is substantially higher than solid wood (LP Building Products 2013). No moisture content was specified. Perhaps the closest wood-based composite equivalent to LSL for which thermal conductivity data are available is oriented strand board (OSB). The data for OSB, which has a higher overall density than LSL, was measured by Kamke and Zylkowski (1989) as 0.089 W / m-K at an average moisture content of 4.8%. The average density of the panels was 680 kg / m^3. Similarly, Sonderegger and Niemz (2009) tested the thermal conductivity of oriented strand board with a density of 662 kg / m^3 and 9.5% moisture content and determined an average value of 0.0984 W / m-K. Ward and Skaar (1963) measured the thermal conductivity of "flakeboard" at various temperatures. A typical value inferred from their data had a high thermal conductivity of 0.204 W / m - K for a board with a density of 727 kg / m^3 at 8.3% moisture content and 20.6 °C. However, unlike typical OSB, LSL is made using a steam injection process. Consequently, in LSL, the density profile tends to be uniform (Rowell 2013), whereas in OSB, the profile density is such that the face layers' surfaces are densified and the core layers are not.

EXPERIMENTAL

Approach

The process for measuring thermal conductivity was similar to the common heat flow meter method described by ASTM C518 (2015). The LSL and spruce tested for thermal conductivity were a subset of the material intended for use as laminae for the CLT panels. The testing for this work involved a preliminary assessment of the profile density of the LSL for uniformity, measurements of the thermal conductivity, moisture content, and volume of the samples at the time of testing, and the determination of specific gravity of the materials.

Materials

The laminated strand lumber was manufactured from a mixture of northern hardwood strands (20 cm to 25 cm long; aspect ratio of 150). The LSL used for these tests was made from five different billets by the Louisiana Pacific Corporation in Houlton, Maine. The original size of each sample prior to machining for these tests was approximately 3.8 cm thick × 18.4 cm wide × 3 m long. The initial moisture content of the LSL and spruce samples was 7 to 10 percent, and the initial density of the LSL was about 680 kg/m^3. The initial density of the spruce was about 460 kg/m^3. All samples were conditioned prior to thermal conductivity testing as described below.

Red spruce dimension lumber, nominally measuring 5 cm thick × 20 cm wide × 3 m long (2 in × 8 in × 10 ft long) from a local mill (Pleasant River Lumber Company, Dover-Foxcroft, ME) was also used. The larger pieces of lumber were sorted to remove the large defects and loose knots. Small, tight knots were allowed in the final samples.

Samples measuring 5 cm × 5 cm x 3.8 cm thick from each of the five billets of LSL were machined for profile density testing. Six samples were cut from random locations in the five different LSL billets. The samples were tested in the as-received moisture content condition of approximately 5%.

Samples for thermal conductivity testing from larger spruce lumber and LSL billets were machined to approximately 24 cm long and 6 cm to 9 cm wide. The thickness of all samples was 1.8 cm. The LSL samples were cut approximately in half and sanded lightly on both surfaces to make them flat. The density profile was not affected, as described below. Prior to testing, the samples were conditioned using a Tenney T11-RS (Tenney Environmental, Williamsport, PA, USA) environmental chamber. The nominal equilibrium moisture content settings were 8%, 12%, and 18% dry basis moisture content. The actual chamber settings were set at approximately 23 °C and 85% relative humidity to achieve the first target moisture content of approximately 18%. At each level of testing, once the weights of the small samples were stable they were wrapped in plastic wrap so they would not lose moisture during testing.

After the first testing, the samples were conditioned at 23 °C and 65.5% relative humidity (EMC approximately 12%) until stable, tested, then conditioned at 23 °C and 42% relative humidity to obtain a normal room condition moisture content of approximately 8% before testing a third time. Finally, the samples were placed inside a drying oven at 103 °C to remove the remaining moisture and retested at 0% moisture content. Although the weights were stable before testing within 0.02 g, due to the nature of the materials, they were not at exactly the same moisture condition when tested.

Equipment

The profile density of the LSL was measured using a density profilometer (Siempelkamp Group, Krefeld, Germany) and used Americium 241 as a source of radiation. The scanning increment along the profile was approximately 0.06 mm. The bulk density measurements for the spruce and LSL were conducted with calibrated calipers and a calibrated laboratory balance.

Thermal conductivity measurements were made using a Netzsch Lambda 2000 heat flow meter (NETZSCH Instruments North America, Burlington, MA, USA) using Q-Lab software (NETZSCH Inc., Version 2.12, Selb, Germany) (Fig. 1). The device consists of an insulated box with parallel heated and cooled plates. Each plate measures approximately 30 cm x 30 cm and has centrally located sensors. The sample is held between two plates, one of which is heated, and the other cooled. The temperature difference between the two plates is controlled using the Peltier effect and circulating fluid controlled to achieve a defined temperature drop of 20 °C. Heat flux transducers mounted on each plate measured a voltage proportional to the heat flow through the sample (Netzch 2015). Steady thermocouple and transducer readings indicated thermal equilibrium. The thermal conductivity value was calculated using the Q-Lab software. The device was calibrated before this series using a procedure developed by the manufacturer. The sensors were located on an area measuring approximately 6 cm × 6 cm in the center of the plates and the large sample size acted as a guard against lateral heat flow losses within the heavily insulated box. Multiple preliminary tests showed the heat flow meter to be both accurate and precise when tested against a standard.

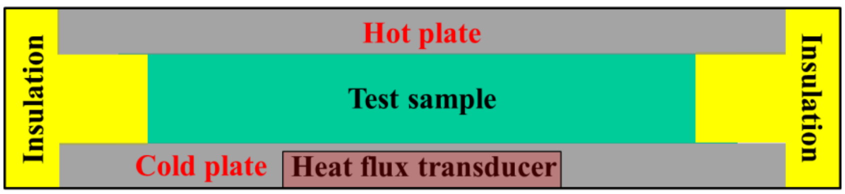

Fig. 1. Schematic diagram of the heat flow meter

Methods

A total of 30 full thickness measurements of the profile density of the LSL were performed. The first and last 40 data points were excluded from the calculation of average density and standard deviation values

All of the moisture content measurements were conducted by weight measurements at the time of testing and by drying the samples in a calibrated laboratory convection oven set at 103 °C (± 2 °C) until the weights were stable at the end of all testing.

The experimental design for the thermal conductivity testing is shown in Table 1. As described below, the thickness of the LSL and spruce samples were reduced to 1.8 cm thick. The established size for each thermal conductivity sample was at least 24 cm × 24 cm × 1.8 cm thick. A single test sample consisted of three pieces of either LSL from the same billet or spruce from the same board laid edge-to-edge to form a square. The three conditioned pieces from each sample were individually wrapped in plastic wrap and placed between the plates of the heat flow meter. Styrofoam was placed around the edges of the sample in the heat flow meter chamber to further reduce heat loss. Testing required about 40 min for each sample to thermally equilibrate and for the software to determine the thermal conductivity values.

Table 1. Experimental Design for Thermal Conductivity Testing

Sample Type	Samples	Replicates	Moisture Content Levels	Total
LSL	5	3	4	60
Spruce	7	3	4	84

Excel 2016 software (Microsoft Corporation, Redmond, WA, USA) was used to perform the statistical analysis.

RESULTS AND DISCUSSION

To reduce the potential radiant heat losses from the edges of the samples they were machined to approximately half of their original thicknesses. The reduction in thickness did not affect the solid wood density or specific gravity, but composite panels frequently develop profiles that show densification at the surfaces and lower density in the core. Therefore, further analysis was needed to ensure that the thickness reduction of LSL would not affect the thermal conductivity measurements.

A typical full-thickness profile density scan from the LSL panels used in this research is shown in Fig. 2. The steam injection process used for manufacture generally avoided the surface densification issue seen with typical hot-pressed panels. To quantitatively assess the effect of thickness reduction on density, the profile density values for full-thickness and half-thickness panels from each billet were statistically compared with a t-test. No major differences in density between the thick and thin panel sections were found. Therefore, the authors concluded that thickness reduction would not affect the thermal conductivity values.

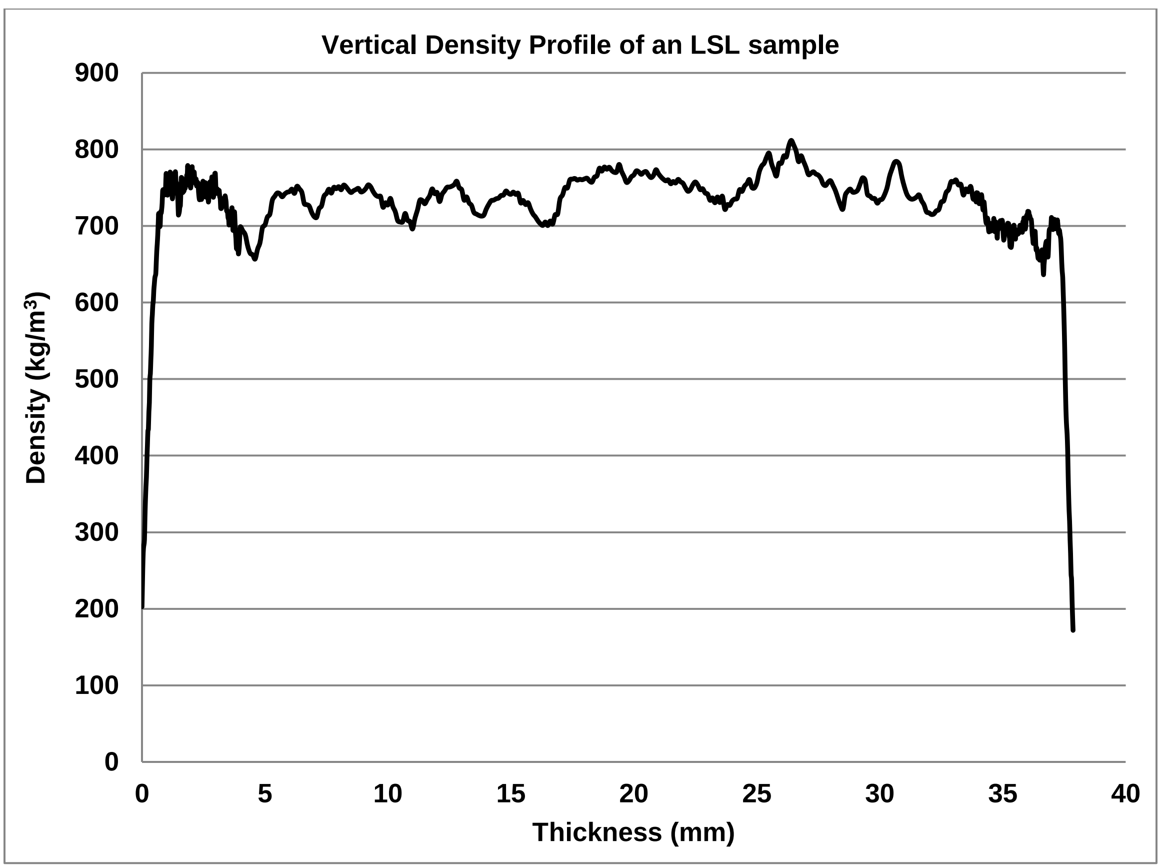

Fig. 2. Typical profile density of the LSL used for these tests

Another concern was the moisture content at the time of testing. Although all samples were held at a specific temperature and at specific relative humidity conditions until the weights were stable, the LSL and spruce did not equilibrate to the same nominal moisture content values. The effect is shown in Fig. 3, and is common when conditioning composite and solid wood samples under similar conditions. The LSL was bonded with approximately 8% polymeric diphenyl methane diisocyanate (pMDI) resin and had a wax level of approximately 0.5%. Both the wax and the resin tended to reduce moisture sorption. When compared statistically at each level above zero, the differences were statistically significant at the 0.05% level.

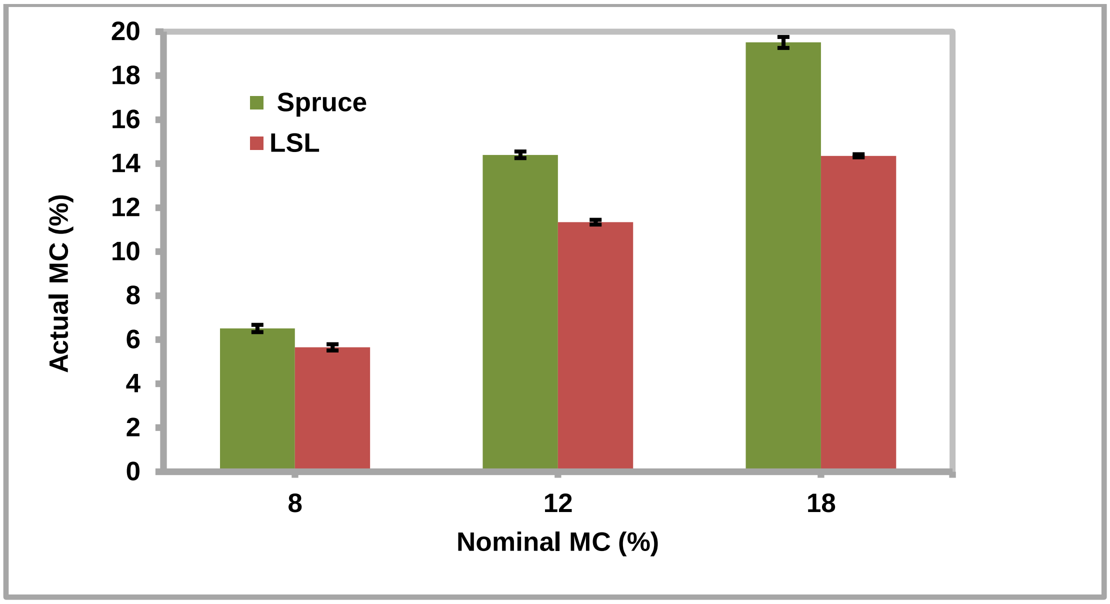

Fig. 3. Moisture content variation between the LSL and spruce samples after conditioning; the bars represent the standard error.

Specific gravity and density vary with moisture content and affect thermal conductivity in a major way. To reduce the moisture-related correlation when determining the relationship to thermal conductivity, most treatments, such as shown in Eq. 2, include specific gravity at the time of test and a moisture/specific gravity interaction term. However, the specific gravity ranges of both the spruce samples and the LSL samples were small. Therefore, when the initial analysis was done separately, the regression analysis for each material showed that the specific gravity was not a significant factor. The average of the thermal conductivity values for each sample of spruce and LSL along with the linear regression fits from the entire data set are shown in Fig. 4. Also included, are the results of applying Eq. 2 using the average specific gravity of the spruce at each moisture content.

Based on the measured data at each moisture content level, Eq. 4 is the equation of the fitted line for spruce,

$$\lambda \text{ (spruce)} = 0.0013M + 0.089 \qquad R^2 = 0.73 \tag{4}$$

Eq. 5 is the equation of fitted line for LSL,

$$\lambda \text{ (LSL)} = 0.0016M + 0.096 \qquad R^2 = 0.79 \tag{5}$$

where M is the moisture content (%).

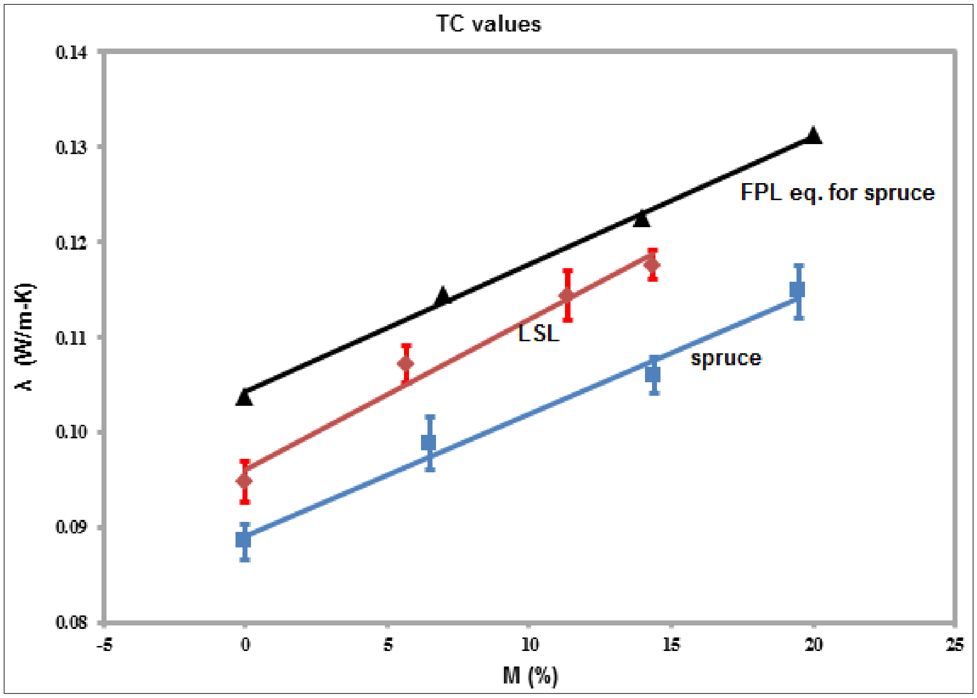

Fig. 4. Average thermal conductivity values for spruce and LSL as well as a plot of Eq. 2 for the spruce data; the standard error of the mean is shown for the measured data values; the moisture content axis is offset for clarity

The error of the estimate was 0.006 for Eq. 4 and 0.005 for Eq. 5. Based on the regression lines for the measured data shown in Fig. 4, LSL had a higher thermal conductivity than spruce. When the raw LSL and spruce thermal conductivity values were compared at 0% moisture content, the differences were significantly different ($p = 0.0004$). The values for spruce predicted using Eq. 2 were approximately 13% higher than the authors' measured values.

Prior to assessing the effect of specific gravity on the two materials, it was necessary to see whether the datasets of LSL and spruce were statistically different. Multiple linear regression analyses were performed for each of the datasets with moisture content and specific gravity as independent variables followed by a F-test done for significance to compare the two models. The resulting p-value was 0.08, implying no significant differences between the models at a confidence level of 95%.

After significance testing, the datasets were combined and a multiple linear regression analysis was conducted on the combined dataset. The result is shown in Eq. 6, and the error of the estimate was 0.005.

$$\lambda = G(0.0172 + 0.00285M) + 0.0828 \quad R^2 = 0.78 \tag{6}$$

In Eq. 6 the symbols are as previously defined.

A regression analysis was performed on the combined dataset taking only moisture content as an independent variable, and the result showed that approximately 20% of the variation in thermal conductivity was explained by the variation in specific gravity.

Direct comparisons of thermal conductivity from this research and the research of others were not possible due to the lack of published data for LSL. There are a limited number of valid datasets at varying moisture contents available for oriented strand board, which has a similar bulk density. To perform a comparison, a regression equation was developed from the OSB data of Nanassy and Szabo (1978). Also included in the comparison were Eq. 2 from the Wood Handbook (2010) and Eq. 4 from Siau (1984). The results of the comparisons are shown in Fig. 5.

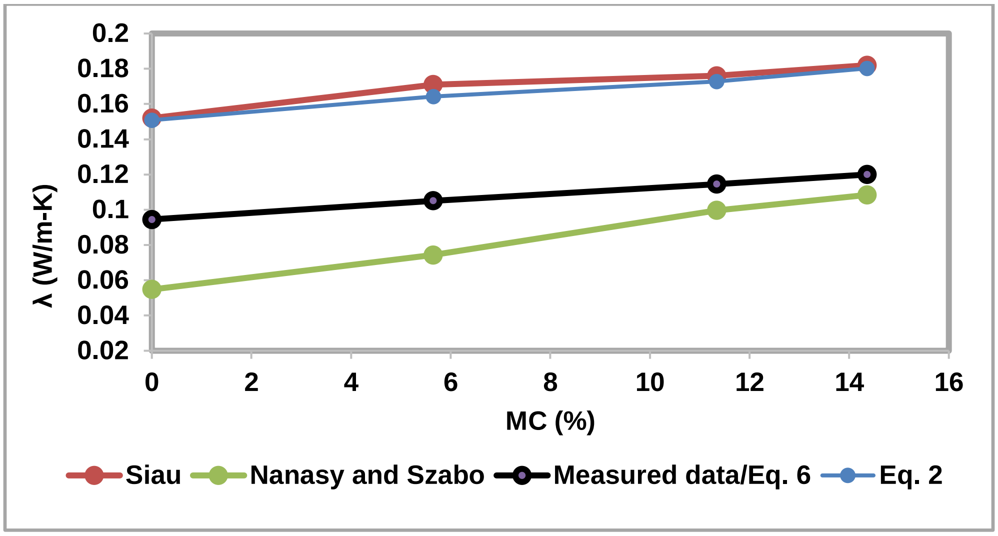

Fig. 5. Comparison of the thermal conductivity values of LSL and OSB at various moisture contents

The thermal data for the theoretically derived Siau equation (Eq. 3) and the Wood Handbook equation (Eq. 2) for solid wood were both approximately 35% higher than the measured data from this report and the measured data for OSB from Nanassy and Szabo. Because the differences were consistent between Eq. 2 and Eq. 6 in the figure, it may be the result of the methodology used to measure the values or the result of variability in the datasets leading to Eq. 2. Further investigation is needed.

The insulation values of construction materials are reported as *R*-values (Thermal Resistance-values) and are the reciprocal of the thermal conductivity value divided by the thickness, assumed here as 2.54 cm for convenience. The system international (SI) unit for the *R*-value is m^2 k / Watts and in the United States, *R*-values are commonly expressed in terms of Imperial units of ft^2. h. ^{o}F / BTU-inch. The fitted regression line for the *R*-values for all of the data is shown in Eq. 7,

$$R = G(-0.0426 - 0.0068M) + .0299 \qquad R^2 = 0.77 \qquad (7)$$

where the symbols are as previously defined. The units of *R* are m^2 -K / Btu.

The range of the *R*-values was 0.202 m^2 - °K / Btu to 0.245 m^2 - °K / Btu (1.145 Btu-in / ft^2 - h - °F to 1.391 Btu-in / ft^2 - h - °F). At all moisture content levels, the value of *R* for spruce was slightly higher than that of LSL.

CONCLUSIONS

The data for LSL reported showed the variation of thermal conductivity with moisture content for both LSL and spruce as measured using a heat flow meter. Summary results were as follows:

1. Repeated measurements of samples from different billets (LSL) and dimension lumber pieces (spruce) were consistent and the range of thermal conductivity values was narrow.
2. The data showed that LSL had a slightly higher thermal conductivity value than spruce and the average difference was approximately 8% across the range of moisture content values.
3. The difference in thermal conductivity between LSL and spruce was significant at 0% moisture content ($p = 0.0004$).
4. Both materials compared favorably as thermal insulators across a range of moisture content values that might be encountered if LSL and spruce were used for the manufacture of CLT panels.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Agriculture and Food Research Initiative Special Research Grants Program – Competitive Grant No. 2013-34638-21491 from the National Institute of Food and Agriculture, U.S. Department of Agriculture and the USDA McIntyre Stennis program project ME041712. The authors would also like to acknowledge the Northeast Lumber Manufacturers Association (NeLMA), LP Building Products, Pleasant River Lumber Company, and the Henkel Corporation for providing materials used in the study. This is MAFES report #3536.

REFERENCES CITED

ASTM C177-13 (2013). "Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus," ASTM International, West Conshohocken, PA.

ASTM C518-15 (2015). "Standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus," ASTM International, West Conshohocken, PA.

Goss, W. P., and Miller, R. G. (1992). "Thermal properties of wood and wood products," in: *Thermal Performance of the Exterior Envelopes of Buildings V*, Clearwater, FL, USA.

Kamke, F. A., and Zylkowski, S. C. (1989). "Effects of wood-based panel characteristics on thermal conductivity," *Forest Products Journal* 39(5), 19–24.

LP Building Products (2013). "LP solidstart LSL – Material properties," (https://lpcorp.com/resources/product-literature/technical-guides/lsl-doorwindow-component-tech-note-uk/), Accessed 10 June 2017.

MacLean, J. (1941). "Thermal conductivity of wood," *Heating, Piping, and Air Conditioning* 13(6), 380–391.

Nanassy, A. J., and Szabo, T. (1978). "Thermal properties of waferboards as determined by a transient method," *Wood Science* 11(1), 17-22.

Rowell, R. M. (2013). *Handbook of Wood Chemistry and Wood Composites* (2nd Ed.), CRC press, Taylor & Francis, Boca Raton, FL.

Siau, J. F. (1984). *Transport Processes in Wood*, T. E. Timell (Ed.), Springer-Verlag, Heidelberg, Germany, pp. 245.

Sonderegger, W., and Niemz, P. (2009). "Thermal conductivity and water vapour transmission properties of wood-based materials," *European Journal of Wood and Wood Products* 67(3), 313-321. DOI: 10.1007/s00107-008-0304-y

Steinhagen, H. P. (1977). *Thermal Conductive Properties of Wood, Green or Dry, from -40 to +100 C: A Literature Review* (FPL-GTR-9), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI.

Tenwolde, A., McNatt, J. D., and Krahn, L. (1988). *Thermal Properties of Wood and Wood Panel Products for Use in Buildings* (Report No. DOE/USDA-21697/1; ORNL/Sub-87- 21697/1), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI.

Troppová, E., Švehlík, M., Tippner, J., and Wimmer, R. (2015). "Influence of temperature and moisture content on the thermal conductivity of wood-based fibreboards," *Materials and Structures* 48(12), 4077-4083. DOI: 10.1617/s11527-014-0467-4

Wangaard, F. F. (1940). "Transverse thermal conductivity of wood," *Heating, Piping and Air Conditioning* 12(7), 459-464.

Ward, R., and Skaar, C. (1963). "Specific heat and conductivity of particleboard as a function of temperature," *Forest Products Journal* 13(1), 31-38.

Wilkes, K. E. (1979). "Thermophysical properties data base activities at Owens-Corning Fiberglas," in: *Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings, ASHRAE SP*, Kissimmee, FL USA, pp. 662-677.

Wood Handbook (2010). *Wood as an Engineering Material* (FPL:GTR-190), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI.

Zarr, R. R., and Lagergren, E. S. (1999). "Interlaboratory 'pilot run' study of small heat-flow-meter apparatus for ASTM C 518," *Journal of Testing and Evaluation* 27(6), 357-367. DOI: 10.1520/JTE12163J

Article submitted: May 30, 2017; Peer review completed: September 9, 2017; Revised version received and accepted: October 2, 2017; Published: October 6, 2017.
DOI: 10.15376/biores.12.4.8827-8837