NONDESTRUCTIVE EVALUATION OF WOOD STRENGTH USING THERMAL CONDUCTIVITY

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Relationships between the coefficient of thermal conductivity (CTC) and the strength properties of wood were investigated. Small clear test specimens were prepared from beech, fir, and pine wood. CTC values of the test specimens were measured based on the ASTM C 1113-99 hot-wire method. Wood density and some mechanical properties were then determined according to related ISO standards. In order to designate relationships between the CTC and mechanical properties, linear regression analysis was performed. Significant linear correlations were found between the CTC and the specific gravity, the modulus of rupture, the modulus of elasticity, and the impact bending strength of the wood from all tree species. However, there was a weak and non-significant relationship between the CTC and the compression strength of the specimens from each tree species. As a consequence, the CTC has a considerable potential in nondestructive evaluation of wood density and strength. However, the reciprocal correlations among the MC-strength, MC-CTC, temperature-strength, and temperature-CTC appear to be most significant limitations for using CTC as a NDE method for wood. Further detailed investigations are needed.

Keywords: Thermal conductivity; Nondestructive evaluation; Wood strength; Beech; Fir; Pine

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INTRODUCTION

Wood is globally one of the principal raw materials presently being used in construction, along with cement, steel, plastics, aluminum, *etc*. The growing world demand for affordable supplies of materials for building, furniture, packaging, paper, and consumer goods of all kinds ensures the future importance of wood-based industries.

Because of its natural origin, wood frequently exhibits an unusually wide degree of variability in physical and mechanical properties as a result of its genetic source, environmental factors (climate, soils, water supply, available nutrients, *etc*.), and also its complex internal multicomponent structure (anisotropy). These variations influence the suitability of wood, in other words wood quality, for a variety of purposes. Consequently, manufacturers and users of wood products are frequently confused about these wide variations of wood properties and they need to know the properties and potential of wood as a raw material for conversion to various products.

Some major developments in the past involving nondestructive evaluation (NDE) technologies have offered great opportunities for the characterization of wood material. NDE technologies currently used in lumber and veneer grading programs have resulted in engineered materials with consistent and well-defined performance characteristics. Through the development and use of NDE technologies, advances have been made in the grading of a variety of wood-based materials, and products used both structural and nonstructural applications. These technologies are an integral part of scanning systems used in the forest products industry to identify and locate defects in wood-based materials. Advances have also been made in the development of NDE technologies for use in the inspection of wood members in structures. In recent years, there has been an increased emphasis to develop NDE techniques for assessing the potential structural quality of green materials (Pellerin and Ross 2002).

The methods employed to evaluate the quality of wood material are based on the assumption that some simple physical properties can be used to give a reasonably good indication of the characteristics that determine such quality (Bucur 2006). Most common NDE techniques utilize acoustic properties (propagation of stress wave or ultrasonic wave) and electrical properties (electrical resistance and dielectric properties) of wood for evaluation of its properties.

In recent years, although the thermal imaging method based on the thermal properties of medium has been used for defect detection in wood, there has been no study concerning the relationship between thermal properties and static elasticity and strength properties of wood. Hence, the basic idea of this study is that the thermal properties of wood can be used to evaluate its mechanical properties, especially thermal conductivity.

Background

Thermal conductivity can be expressed in terms of a coefficient of thermal conductivity (k). According to Fourier's law, in steady state condition, this is the measure of the rate of heat flow through one unit thickness of a material subjected to a temperature gradient, *i.e.*, k is measured in $W{\cdot}m^{-1}{\cdot}K^{-1}$ (Kollmann and Cote 1968; Lienhard IV and Lienhard V 2011). When heat is applied to a body, the vibratory energy of its molecules in that vicinity is increased. These molecules collide with neighboring molecules and, in so doing, transmit to them a part of their newly acquired energy. These neighboring molecules then in turn transmit a part of their newly acquired energy to still other molecules farther from the center of the disturbance (Brown *et al.* 1952).

Due to the connections between atoms, the displacement of one or more atoms from their equilibrium positions will give rise to a set of vibration waves propagating through the lattice, and heat transfer in a dielectric solid occurs through elastic vibrations of the lattice. The solid may be a crystal or it may be amorphous, but each atom has a fixed equilibrium position, and the thermal vibrations can thus be resolved into normal modes. For a perfect crystal, these normal modes are plane travelling waves. Departures from the perfect lattice result in interactions, which are responsible for the statistical equilibrium between the normal modes. The thermal conductivity at liquid helium temperatures is due solely to phonons of the longitudinal mode of vibration (Debye 1912; Pomeranchuk 1941; Klemens 1951; Stephens 1973; Pohl *et al*. 1999).

Jayne (1959) proposed in his well-known hypothesis for NDE of wood-based materials that energy storage and dissipation properties of wood-based materials are controlled by the same mechanisms that determine static behavior of such materials.

Thus, useful mathematical relationships might be achieved between thermal conductivity and static elasticity and strength behavior through statistical regression analysis.

EXPERIMENTAL

Wood Materials

Oriental beech (*Fagus orientalis*), fir (*Abies nordmanniana*), and black pine (*Pinus nigra*) timbers were chosen randomly from timber suppliers of Ankara, Turkey. Twenty clear (free from defects) timber pieces with a dimension of 20×50×360 mm^3 were cut from timbers of each tree species. A total of 60 timber pieces (3 tree species × 20 pieces) were conditioned at 20±2°C and 65±3% relative humidity until they reached their constant weights in an air-conditioned room.

Thermal Conductivity Measurements

A quick thermal conductivity meter, based on the ASTM C 1113-99 hot-wire method, was used. In order to determine the coefficients of thermal conductivity (CTC) of wood, the hot wire of the device was placed on the radial plane of timber pieces in the parallel direction to the wood fibers, as shown in Fig. 1. The measurements were taken from three different points on each timber piece. The QTM 500 device, which is a product of Kyoto Electronics Manufacturing in Japan, was used to measure the CTC. The measurement range is 0.0116 to 6 W/m K. Measurement precision is F5% of reading value per reference plate. Reproducibility is F3% of reading value per reference plate. The measurement temperature is 100 to 1000°C (external bath or electric furnace for temperature other than the room). Measuring time is a standard 100 to 120 s (Sengupta *et al*. 1992).

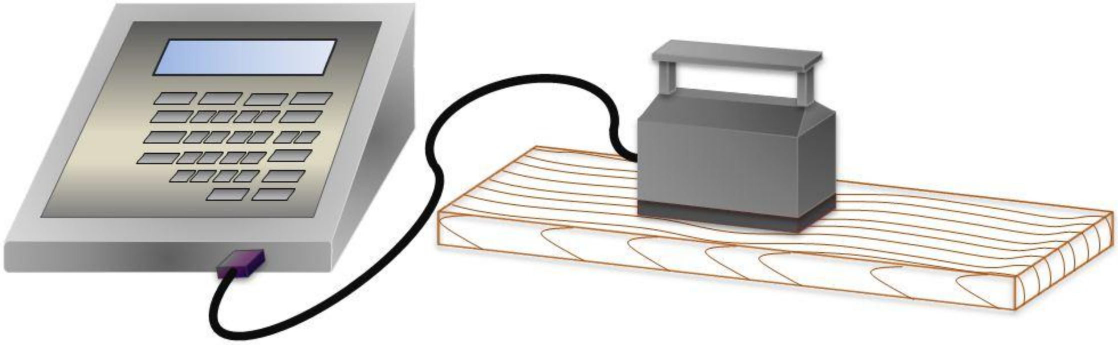

Fig. 1. Test setup of thermal conductivity measurements

Determination of Density and Mechanical Properties of Wood

Following the thermal conductivity measurements, the density of the samples was determined according to ISO 3131 (1975). The bending strength, the moduli of elasticity in bending, the impact bending, and the compression strength tests were tested according to ISO 3133 (1975), ISO 3349 (1975), ISO 3348 (1975), and ISO 3787 (1976), respectively. One sample for each property was cut from each timber piece. A total of 60 samples, 20 from each tree species, were tested for each property.

Data Analyses

Single variable statistic regression analysis was used to determine the relationships between the CTC and the mechanical properties of wood. The relationships between the density and the mechanical properties also were analyzed.

RESULTS AND DISCUSSION

The results of thermal conductivity measurements, specific gravity, and static strength of samples are listed in Table 1. The CTC and the density were compared directly with the corresponding mechanical strengths. Table 2 shows the results of single variable regression analysis. Multi-variable regression analysis could not be performed because of the strong correlation between the CTC and the density.

Table 1. Results of the Thermal Conductivity Measurements, Specific Gravity, and Static Strength of Samples

Properties	Beech	Fir	Scots Pine
Number of Samples	20	20	20
Coef. of Thermal Conductivity (W/(mK))	0.165 (3.3)*	0.111 (2.8)	0.132 (2.0)
Specific Gravity	0.648 (3.2)	0.388 (4.5)	0.505 (2.6)
Modulus of Rupture (MPa)	132.0 (2.0)	59.0 (3.4)	72.2 (2.0)
Modulus of Elasticity (GPa)	12.4 (5.4)	7.4 (13.3)	10.4 (4.2)
Impact Bending Strength (J/cm²)	8.2 (5.7)	3.4 (12.2)	4.0 (7.4)
Compression Strength (MPa)	21.3 (8.5)	12.8 (7.3)	16.9 (6.1)

*Numbers in parenthesis are coefficient of variation (%).

The relationships between the CTC and the strength properties were found to be similar to the density-strength relationships. This was expected, due to a very strong correlation between the density and the CTC for all tree species (Table 2). Figure 2 shows the relationships between CTC and corresponding specific gravity and mechanical strengths of beech wood. A very strong linear correlation was observed between the CTC and specific gravity, with a coefficient of determination (R^2) of 0.96 (Table 2). The linear correlation between the CTC and MOR was also very strong, with an R^2 of 0.95. However, the linear correlation between the CTC and MOE was less significant than MOR, with an R^2 of 0.48. A useful linear relationship was found between the CTC and impact bending strength, with an R² of 0.62. The compression strength of beech wood showed a relatively poor and nonsignificant correlation with the CTC (R² = 0.17).

Figure 3 represents the relationships between CTC and specific gravity and mechanical strengths of fir wood. Quite good correlations were also determined between CTC and specific gravity and strength of fir wood. An exception was in the case of the compression strength of fir wood. The relationships between CTC and specific gravity (R² = 0.83) and MOR (R² = 0.91) were more significant than the others. Similarly to beech and fir wood, there were good relationships between CTC and specific gravity (R² = 0.93), CTC and MOR (R² = 0.74), TCC and MOE (R² = 0.62), and CTC and impact bending strength (R² = 0.71) of Scots pine wood, as shown in Fig. 4. The compression strength of Scots pine displayed a weak correlation with CTC, with an R² of 0.13 (Fig. 4).

Table 2. Results of the Linear Regression Analysis (y = a + bx)

Tree species	Independent variables	Dependent variables	a	b	R	R²	SEE	Sig.
Beech	CTC	MOE	-1.57	98.64	0.69	0.48	0.496	0.001
		MOR	55.44	539.67	0.98	0.95	0.573	0.001
		CS	--	--	0.41	0.17	1.700	0.074
		IBS	-2.86	77.92	0.77	0.62	0.295	0.001
		Density	0.03	4.35	0.98	0.96	0.004	0.001
	Density	MOE	-2.53	23.08	0.72	0.52	0.478	0.001
		MOR	52.56	122.58	0.99	0.97	0.463	0.001
		CS	--	--	0.36	0.13	1.738	0.121
		IBS	-3.79	18.49	0.83	0.69	0.268	0.001
Fir	CTC	MOE	-19.48	284.25	0.78	0.60	0.635	0.001
		MOR	-8.12	709.70	0.96	0.91	0.596	0.001
		CS	-2.02	157.22	0.45	0.20	0.863	0.037
		IBS	-8.99	131.36	0.84	0.71	0.232	0.001
		Density	-0.18	5.99	0.91	0.83	0.007	0.001
	Density	MOE	-6.68	36.31	0.65	0.43	0.762	0.001
		MOR	19.71	101.27	0.90	0.81	0.895	0.001
		CS	--	--	0.39	0.16	0.887	0.070
		IBS	-4.66	20.84	0.88	0.77	0.205	0.001
Scots Pine	CTC	MOE	-7.13	154.33	0.79	0.62	0.276	0.001
		MOR	9.77	551.00	0.86	0.74	0.754	0.001
		CS	--	--	0.36	0.13	0.979	0.103
		IBS	-8.54	110.28	0.84	0.70	0.163	0.001
		Density	-0.13	5.65	0.96	0.93	0.003	0.001
	Density	MOE	-0.73	21.94	0.66	0.43	0.338	0.001
		MOR	27.91	87.64	0.80	0.64	0.881	0.001
		CS	--	--	0.32	0.10	0.994	0.153
		IBS	-4.99	17.69	0.79	0.62	0.185	0.001

R: Coef. of correlation; R²: Coef. of determination; SEE: Standard error of estimation

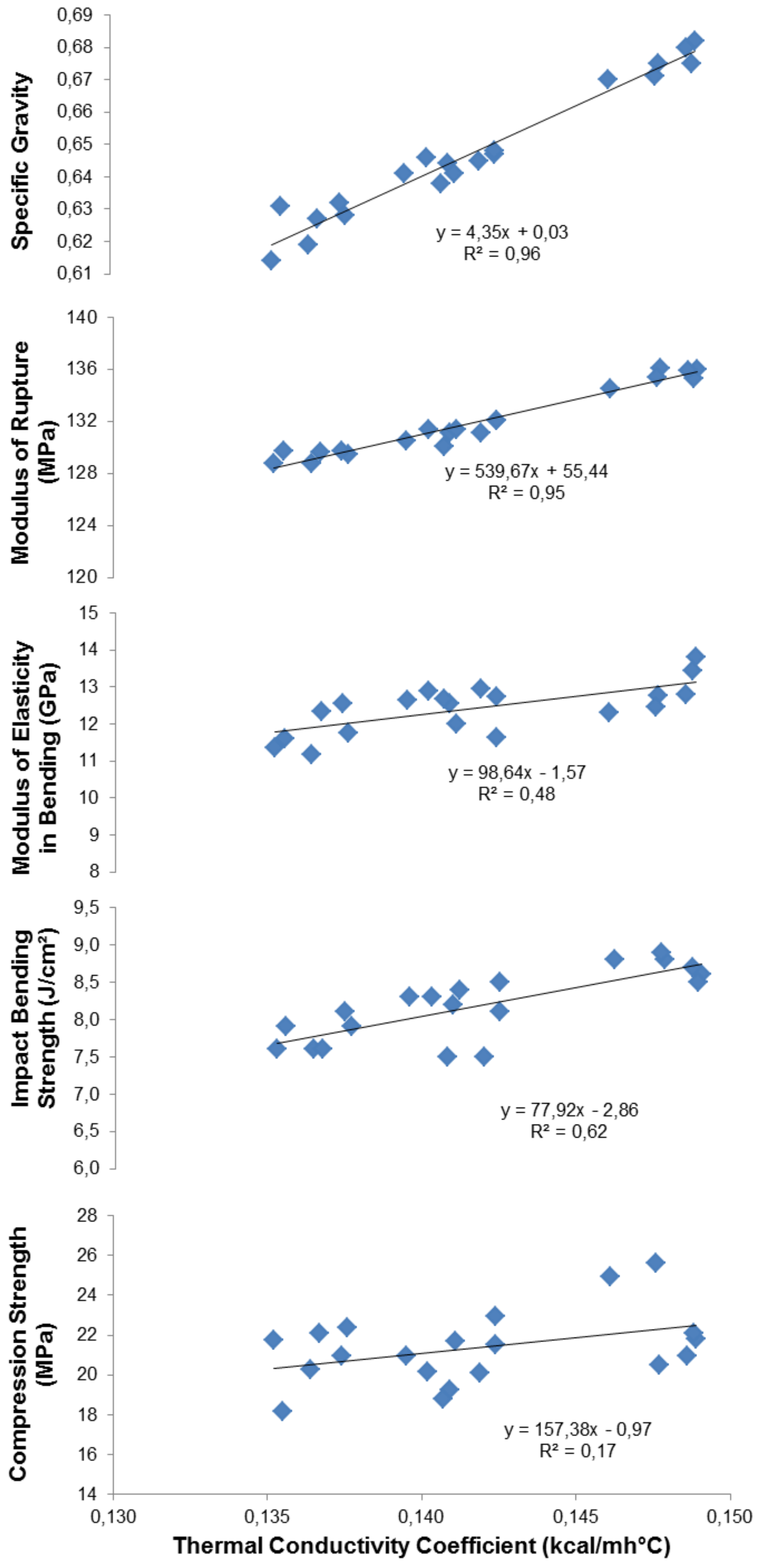

Fig. 2. Relationship between the thermal conductivity coefficient and the mechanical properties of beech wood

In recent years, thermal imaging methods used to visualize the temperature of the surface of objects has been adapted in wood for various purposes, especially in detection of defects. These techniques utilize the propagation of thermal waves in wood, a process that depends on the frequency, thermal conductivity, density, and the specific heat of wood (Bucur 2003). However, any study regarding the relationship between thermal properties and static elasticity and strength properties of wood has not been found.

Since the correlation between the CTC and the density of the wood was very high, it could be concluded that the correlations between the CTC and the strength or stiffness properties were caused by the density-strength relationship of the wood. However, it should be pointed out that when the correlation coefficients between the density and strength and the CTC and strength are compared (Table 2), it can be seen that the CTC showed relatively higher correlation with the strength than the density except beech wood. This might be due to the heat transfer mechanism in a dielectric solid, as mentioned before. Heat is transferred within a solid by conduction when adjacent atoms vibrate against one another, or as electrons move from one atom to another (Lienhard IV and Lienhard V 2011). In insulators such as wood, the heat flux is carried almost entirely by phonon vibrations (Debye 1912; Pomeranchuk 1941; Klemens 1951; Pohl *et al*. 1999). Thus, it might be concluded that heat flow in a dielectric solid is basically a travelling elastic wave. Furthermore, according to quantum conduction, heat transfer occurs by wave-like motion, rather than by the more usual mechanism of diffusion. Heat takes the place of pressure in normal sound waves. It is known as "second sound" because the wave motion of heat is similar to the propagation of sound in air. Second sound has also been observed in some dielectric solids (Narayanamurti and Dynes 1972). Consequently, in the light of heat transfer mechanism in a solid and Jayne’s hypothesis mentioned above, the elastic vibration behavior of the wood should be another factor that governs the CTC-strength relation.

Density is one of the most important wood properties, since it is a major factor that determines elasticity and strength of wood, as well as its dimensional stability. The methods for determination of density of a certain wood requires sampling of its in laboratory condition. The most common method is based on determination of the density from the weight and volume of samples with regular shape. For samples of irregular shape, immersion methods are more suitable. If sampling of wood is not possible, for instance *in situ* assessment of wood in service, determination of density requires advanced NDE techniques such as radiography, thermography, and microwave radar. However these techniques pose some problems for *in situ* inspection of timber members such as portability, high cost, fear of x-rays and gamma rays, strong regulations, and the control of radiation sources associated with their use. Alternative methods for estimating wood density have been developed utilizing different technologies based on coring, wood resistance to drilling (quasi-nondestructive method), or acoustic properties of the wood composite. In addition to these techniques, we concluded that the thermal conductivity of wood appears to be a very good alternative for *in situ* assessment of wood density nondestructively because of its reliability, low cost, and ease of application. CTC can be measured easily and quickly in wood in service with a portable heat flow meter. It can also be used for detection of deterioration due to close relation between density and deterioration. Furthermore, even if the correlation between the CTC and the strength of

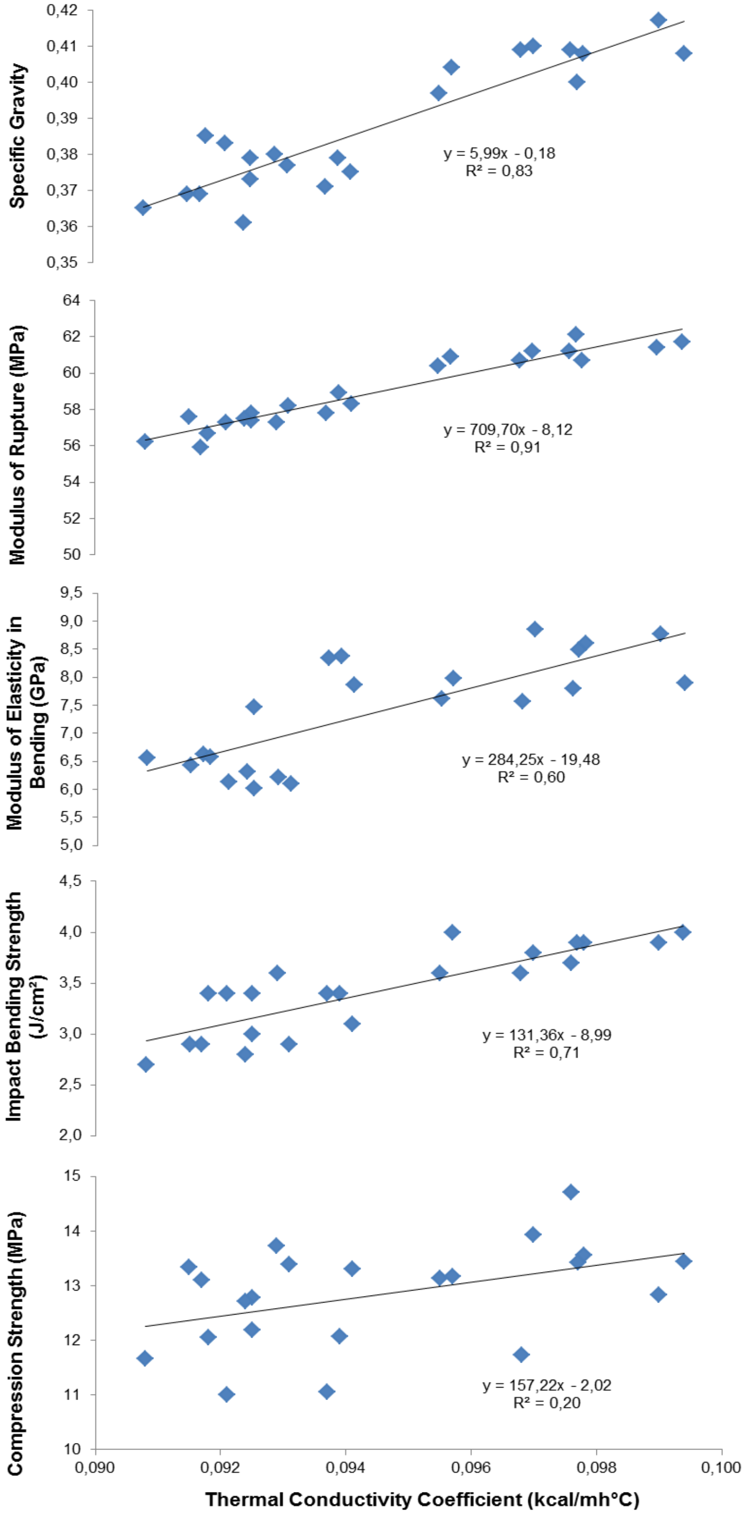

Fig. 3. Relationship between the thermal conductivity coefficient and the mechanical properties of fir wood

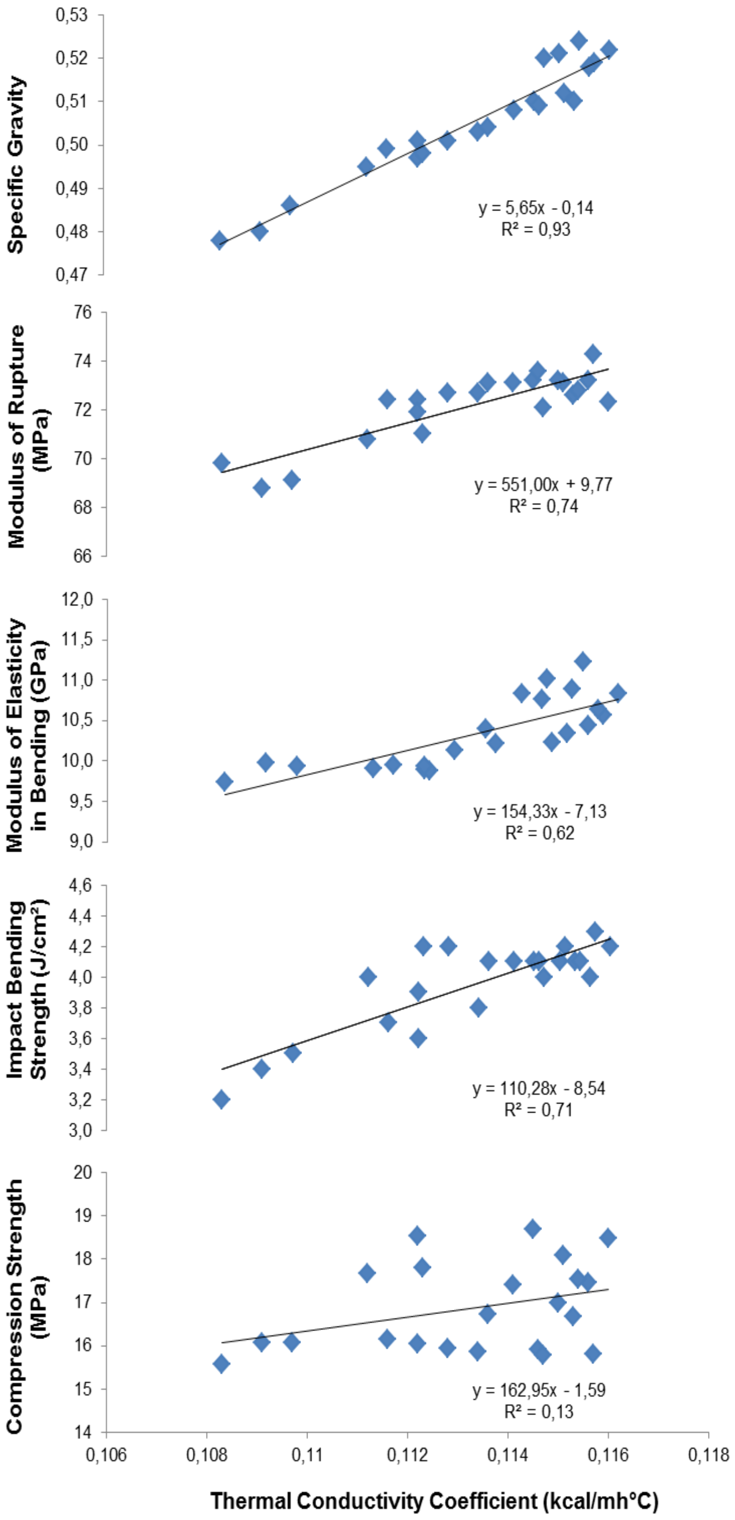

Fig. 4. Relationship between the thermal conductivity coefficient and the mechanical properties of Scots pine wood

wood is caused by density-strength relation, CTC still might be used to estimate residual strength of structural wood members via wood density.

It should be pointed out that the relationships given in this paper were found for small, clear (free from defects) wood specimens at air-dry (12%) moisture content (MC). It is well known that the elasticity and strength of wood is influenced considerably by its MC and defects such as knots, checks, slope of grain, *etc*. Temperature is another factor that affects elasticity and strength of wood. It is also well known that CTC is also affected by MC and temperature, but the correlations may be reciprocal. As wood dries below fiber saturation point (FSP), the elastic moduli and strength increases while CTC decreases. A similar correlation is also valid for the temperature. These reciprocal correlations may be the most-significant limitations to be overcome for using CTC to NDE of wood. Further detailed investigations are needed.

CONCLUSIONS

1. Significant correlations were found between the coefficient of thermal conductivity and the specific gravity, as well as the strength properties of all tree species studied in this research, except for compression strength.
2. The relationships between the coefficient of thermal conductivity and the modulus of rupture were more significant than the other strength values.
3. The results indicate that the correlation between the CTC and the strength is governed to a large extent by the density-strength correlation. However it is also concluded that the elastic vibration behavior of the wood should be another factor that governs the CTC-strength relation.
4. CTC tests have a good potential to be used as an alternative *in situ* NDE method to assess density and residual strength of wood.
5. The reciprocal correlations among the MC-strength, MC-CTC, temperature-strength, and temperature-CTC appear to be the most significant limitations for using CTC as a NDE method of wood. Further detailed investigations are needed.

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