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Building materials thermal conductivity measurement and correlation with heat flow meter, laser flash analysis and TCi

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Abstract The most important factor in the worldwide problem of global warming is the emission of carbon dioxide. The 23% of carbon dioxide emissions generated by building construction must be reduced. Reduction in thermal conductivity, especially via improved insulation, is the most basic factor for decreasing energy consumption. Therefore, accurate and continuous thermal conductivity measurements are important in saving energy. This study presents methods for investigating thermal conductivity measurement and compares three methods: the heat flow meter, laser flash analysis, and thermal conductivity analyzer.

Keywords Decrease energy consumption · Thermal conductivity · HFM · LFA · TCi

Introduction

The indiscriminate use of fossil fuels by humans that has been occurring in the past two centuries has led to global warming that is becoming the cause of various natural disasters occurring throughout the world and of global warming. In addition, the indiscriminate use of fossil fuels is resulting in the reduction of their reserves. According to data released by British petroleum (BP), petroleum, natural gas, and coal will run out in about 40, 65, and 155 years, respectively, thereby increasing the sense of urgency on the depletion of energy resources [1]. Accordingly, countries around the world came to a consensus at the convention on climate change in Copenhagen upon recognizing the need for energy conservation. In the case of South Korea, many experts are pointing out the crucial need for energy reduction not only from the pan-global standpoint but also from the economical standpoint since the country depends on energy imports for over 97% of its energy consumption. Currently, South Korea is implementing various policies with the goal of reducing CO_2 emissions by 4% by 2020 compared with that in 2005. This is equivalent to the reduction amount of about 30% compared with that in the Business As Usual condition by 2020, which calls for a significant level of national effort [2]. In addition, the energy consumption breakdown per sector in 2008 shows 58.4% for industry, 22.3% for construction, and 19.3% for transportation. Since enforcing many restrictions in the area of industry for energy reduction could negatively affect the national production amount and thus negative national growth, the need for energy reduction is ever more crucial in the area of construction [1].

One of the most efficient methods for reducing energy consumption in buildings is the reduction of heat loss and acquisition via surface coatings. Since the heat loss and acquisition via surface coatings comprises over 40% of the building cooling and heating overload, its reduction could be effective in the aspect of energy reduction. Using materials with low thermal conductivity during the design and construction of buildings will ensure that the insulation of surface coatings is an effective method of reducing cooling and heating overload, as well as energy consumption. Accordingly, the thermal conductivity of heat insulators is an important element in energy conservation, as is ensuring the reliability of the heat insulator's performance by accurately measuring its thermal conductivity. Currently, the national criteria for measuring

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thermal conductivity in the country consist of stationary state test methods, transient hot-wire method, and laser flash method. Each method uses its own measuring equipment to measure thermal conductivity, and the stationary state test methods use a heat flow meter (HFM) and the laser flash method uses laser flash analysis (LFA). The HFM measures thermal conductivity by using the HFM method of stationary state test principle, while the LFA measures thermal conductivity by using a disk sample with an 8–10 mm in diameter inscribed or circumscribed circle or a 4-mm-thick block polygon plate. In addition, TCi developed by C-Therm uses the Modified Transient Plane Source (MTPS) method to quickly measure thermal conductivity of a small sample. In this study, TCi, HFM, and LFA are employed to measure the thermal conductivity of various construction materials and conduct analysis on the correlation among the measured values.

Experimental materials

The HFM was used for each experiment conducted for the plywood made by increasing the mass percentage between the adhesive and reformed graphite, for the high density fiber (HDF) and wall materials, and for wood flooring. The LFA was used for each experiment conducted for the epoxy adhesive and reformed graphite material mixed in a certain mass percentage, and for HDF made by increasing the mass percentage between the adhesive and reformed graphite.

HFM materials

For the wall material, the plywood was made by increasing the mass percentage between adhesive and reformed graphite to 1 and 5 wt%, the HDF in which the reformed graphite was increased to 1, 2, and 3 wt%, the extruded and expanded polystyrene was used as insulating material, expanded polystyrene, glass wool, mineral wool, regular/waterproof/fireproof plaster board, and laminate/solid wood/plywood floor were used.

LFA materials

For the epoxy adhesive, the epoxy adhesive for flooring purpose, in which the reformed graphite had mass percentages of 1, 2, and 3 wt%, was mixed to create the sample used. In addition, the HDF was made by increasing the mass percentage of reformed graphite to 1, 2, and 3 wt%,

Experimental method

HFM

The HFM (Fig. 1) developed by NETZSCH is a device for conveniently measuring the thermal conductivity through the method stipulated in the “KS L 9016 Test methods for thermal transmission properties of thermal insulations”. The size of the sample should be 300 × 300 mm^2, and the experimental method is as follows [3].

(1) Open the lid of the HFM device, and adjust the height between the hot plate and the cold plate to insert the material.
(2) Insert the material between the hot plate and the cold plate, and narrow the distance between the two plates until the thickness can no longer be controlled, and close the lid.
(3) Measure the thermal conductivity by using the heat flowing from the hot plate to the cold plate.
(4) Repeat the experiment until the status result of “Fine” is reached.
(5) Stop the experiment at this point and read the thermal conductivity.
(6) Take out the material, and check the condition of the device.

LFA

The LFA (Fig. 2) developed by NETZSCH is a device for conveniently measuring the thermal conductivity through the method stipulated in the “KS L 1604 Fine ceramics—Determination of thermal diffusivity, specific heat capacity, and thermal conductivity of monolithic ceramics by laser flash method”. The size of the sample should be 10 × 10 mm^2 and less than 3 mm in thickness. As for the

Fig. 1 Heat flow meter (HFM)

Fig. 2 Laser flash analysis (LFA)

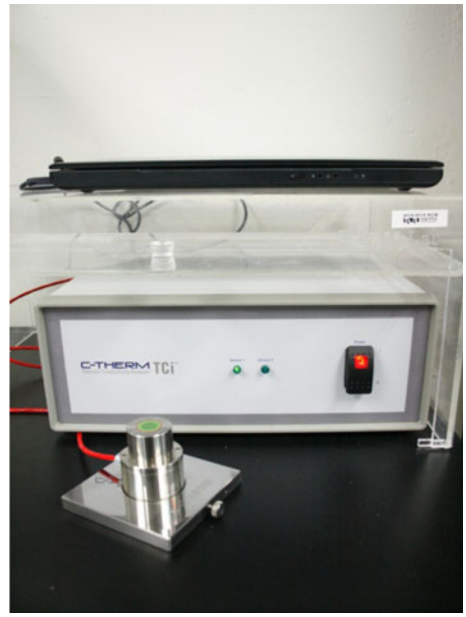

Fig. 3 Thermal conductivity analyzer (TCi)

measurement principle of LFA, the thermal diffusivity is obtained by using the temperature disparity curve for the laser pulse detected at the detector placed on the opposition side of the sample at which the laser is transmitted. The thermal conductivity is obtained by multiplying the measured thermal diffusivity and the specific heat obtained by using differential scanning calorimetry (DSC) and the density of the sample [4–6].

TCi

The TCi (Fig. 3) developed by C-Therm is a device for conveniently measuring the thermal conductivity of a small sample by using the MTPS method. Contrary to other devices, TCi can measure the thermal conductivity of materials in the states of solid, liquid, powder, and mixed. In addition, it can measure thermal conductivity using only one side. The TCi consists of a sensor, power control device, and computer software. A spiral-type heating source is located at the center of the sensor, and heat is generated at the center. The heat that has been generated enters the material through the sensor during which a voltage decrease occurs rapidly at the heating source, and the thermal conductivity is calculated through the voltage decrease data. The experiment method is as follows [7, 8].

(1) Preheat the sensor before placing the material on it.
(2) Place the material in a way that allows heat transmission between the sensor and the material.
(3) If the material is a polymer, ceramic, or metal, leave space from the contact matter to allow full contact between the material and the sample.
(4) Place a 500 g weight on top of the material to allow it to attach to the sensor at an appropriate pressure.
(5) Measure the thermal conductivity of the material using the program.
(6) Separate the material and the sensor after the result is obtained, and finish the experiment upon checking the condition.

Experimental results

Correlation between HFM and TCi

The thermal conductivity and coefficient of correlation measured by using HFM and TCi for the wall materials, the wood flooring, the plywood with an increased mass percentage of reformed graphite, and the HDF are as shown in Table 1. For the thermal conductivity measured using the two devices, the mean value of five separate measurements was used.

The thermal conductivity of wood flooring measured using HFM decreased in the order of laminate floor (0.1254 W/mK), solid wood floor (0.1127 W/mK), and plywood floor (0.0913 W/mK), and that of TCi decreased in the order of laminate floor (0.2200 W/mK), solid wood floor (0.1281 W/mK), and plywood floor (0.0799 W/mK). It has been found that the same order of increase in the thermal conductivities of the wood flooring measured using

Table 1 Thermal conductivity and coefficient of correlation (R^2) of HFM and TCi

Materials	HFM/ W/mK	TCi/ W/mK	Coefficient of correlation (R^2)
Wood flooring			
Laminate floor	0.1254	0.2200	0.938
Solid wood floor	0.1127	0.1281	
Plywood floor	0.0913	0.0799	
Wall materials			
Plaster board	0.1431	0.1110	0.948
Waterproof plaster board	0.2045	0.1180	
Fireproof plaster board	0.2021	0.1385	
Extruded and expanded polystyrene	0.0293	0.0465	
Expanded polystyrene	0.0415	0.0365	
Mineral wool	0.0352	0.0469	
Glass wool	0.0362	0.0432	
Plywood			
Plywood (ref)	0.1097	0.1180	0.985
Plywood (+graphite 1 wt%)	0.1102	0.1320	
Plywood (+graphite 5 wt%)	0.1114	0.1540	
HDF			
HDF (ref)	0.1131	0.0140	0.932
HDF (+graphite 1 wt%)	0.1181	0.0240	
HDF (+graphite 2 wt%)	0.1250	0.0270	
HDF (+graphite 3 wt%)	0.1273	0.0320	

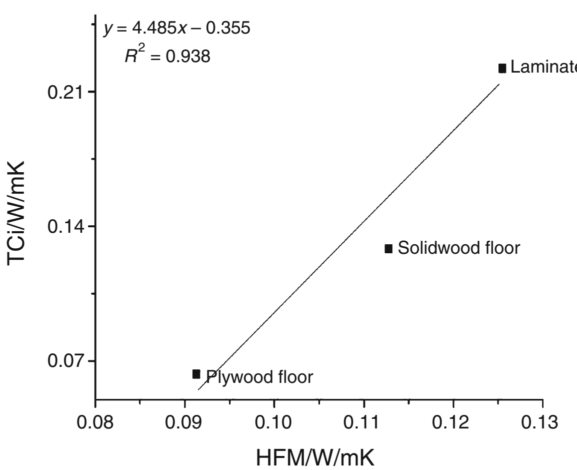

Fig. 4 Correlation graph for the wood flooring thermal conductivity of HFM and TCi

the two devices revealed a correlation between the two devices in wood flooring. In addition, the coefficient of correlation (R^2) was very high at 0.938 (Fig. 4).

The wall materials were mainly divided into two types—insulating materials and plaster board. In the four kinds of insulating materials, generally low thermal conductivities of below 0.05 W/mK were measured in both HFM and TCi, and the plaster board exhibits higher thermal conductivity than that of the insulating material. These results revealed that the thermal conductivity of plaster board measured using HFM was about 2–5 times higher than that of the insulating material, and its the thermal conductivity measured using TCi was 2–4 times higher. Considering a similar such increase, a correlation was found between the two devices and also in the wall materials. In addition, the coefficient of correlation (R^2) was very high at 0.948 (Fig. 5).

The thermal conductivity of the plywood that used adhesive with increased reformed graphite in a certain mass percentage exhibited an increasing pattern with increasing mass percentage of graphite. The rate of increase of the thermal conductivity measured using the two devices was 0.45% for a 1 wt% increase at reference (ref) and 1.54% for a 5 wt% increase at ref in HFM, and was 11.8% for 1 wt% at ref and 30.5% for 5 wt% increase at ref in TCi. Accordingly, the thermal conductivity increase rate of TCi was higher than that of HFM. In addition, a correlation was evident between the two devices in plywood considering that the measured thermal conductivity increased with increasing mass percentage of graphite. In addition, the coefficient of correlation (R^2) was very high at 0.985 (Fig. 6).

The thermal conductivity of the HDF, which was made by using adhesives with an increased mass percentage of reformed graphite, measured using HFM was higher than that of TCi. However, the thermal conductivity increased in the two devices with increasing mass percentage of graphite, and there was a correlation between the two devices in the experiment using the HDF. In addition, the

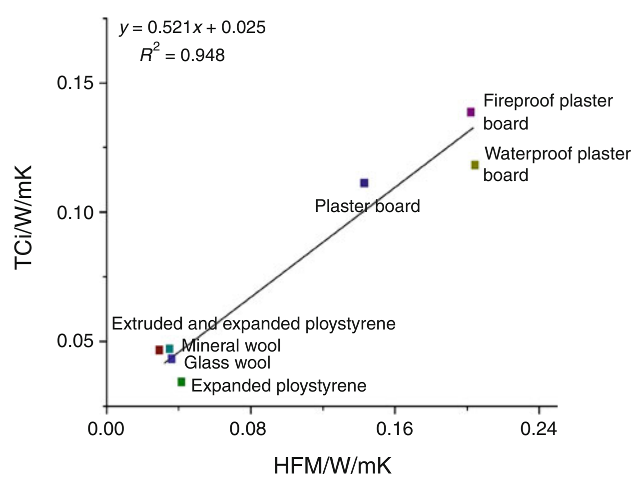

Fig. 5 Correlation graph for the wall materials thermal conductivity of HFM and TCi

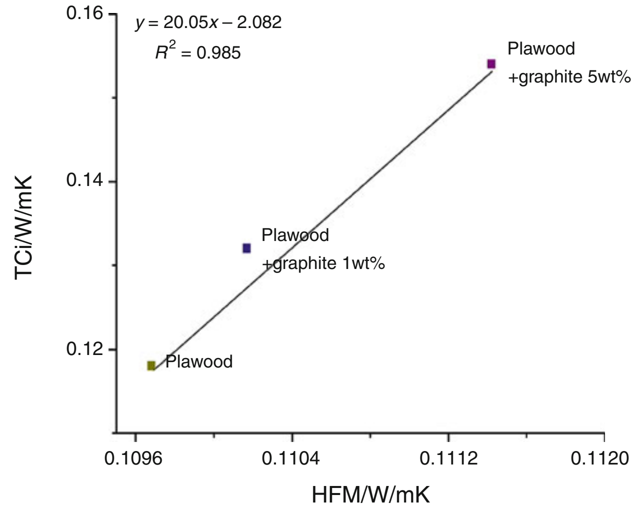

Fig. 6 Correlation graph for plywood thermal conductivity of HFM and TCi

coefficient of correlation (R^2) was very high at 0.932 (Fig. 7).

Correlation between LFA and TCi

The thermal conductivity and coefficient of correlation measured by using LFA and TCi for the epoxy adhesive with an increased mass percentage of reformed graphite and the HDF are shown in Table 2. For the thermal conductivity measured using the two devices, the mean value of five separate sessions of measurement was used.

The thermal conductivity of epoxy adhesive made by mixing reformed graphite in the mass percentage of 1, 2, and 3 wt% was generally higher when measured using TCi compared with using HFM. The rate of increase of thermal

Table 2 Thermal conductivity and coefficient of correlation (R^2) of LFA and TCi

Materials	LFA/ W/mK	TCi/ W/mK	Coefficient of correlation (R^2)
Epoxy adhesive			
Epoxy (ref)	0.711	1.044	0.978
Epoxy (+graphite 1 wt%)	0.759	1.138	
Epoxy (+graphite 2 wt%)	0.854	1.222	
Epoxy (+graphite 3 wt%)	0.912	1.297	
HDF			
HDF (ref)	0.185	0.014	0.504
HDF (+graphite 1 wt%)	0.187	0.024	
HDF (+graphite 2 wt%)	0.185	0.027	
HDF (+graphite 3 wt%)	0.195	0.032	

conductivity measured using the two devices was 6.75% for 1 wt% increase at reference (ref), 20.11% for 2 wt% increase at ref, and 28.27% for 3 wt% increase at ref in LFA, compared with 9.00, 17.04, and 24.23% in TCi, respectively. The thermal conductivity increase rate was similar in the two devices. In addition, there was a correlation between the two devices in epoxy adhesive considering that the measured thermal conductivity increased with increasing mass percentage of graphite. In addition, the coefficient of correlation (R^2) was very high at 0.978 (Fig. 8).

The thermal conductivity of the HDF, which was made by using adhesives with an increased mass percentage of reformed graphite of 1, 2, and 3 wt% measured using LFA was higher than that of TCi. However, the thermal conductivity increased in TCi but not in LFA since the measured thermal conductivity in graphite 2 wt% was lower than that in graphite 1 wt%. Accordingly, the correlation

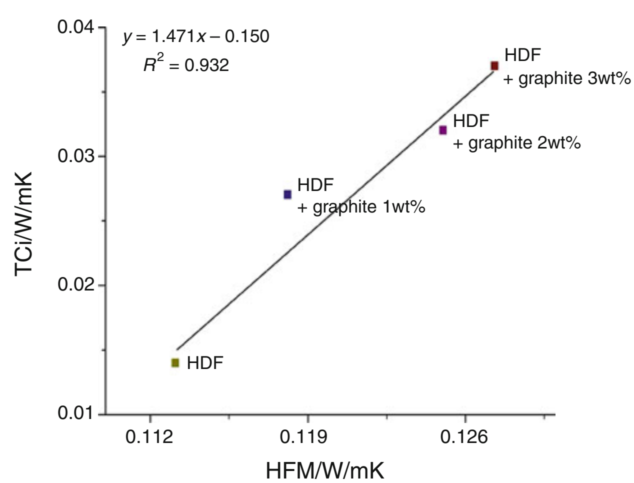

Fig. 7 Correlation graph for the HDF thermal conductivity of HFM and TCi

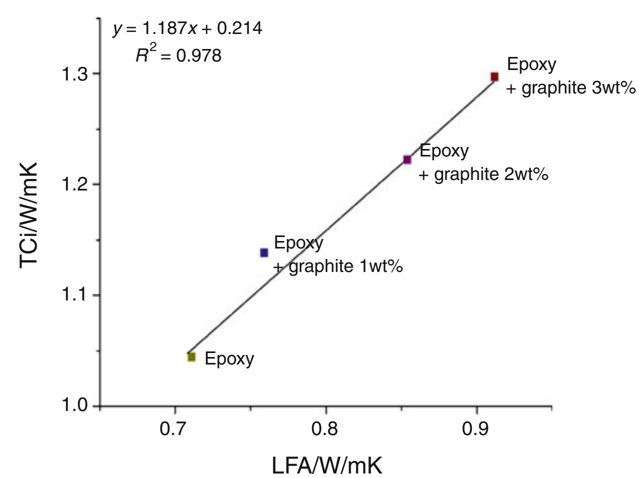

Fig. 8 Correlation graph for the Epoxy adhesive thermal conductivity of LFA and TCi

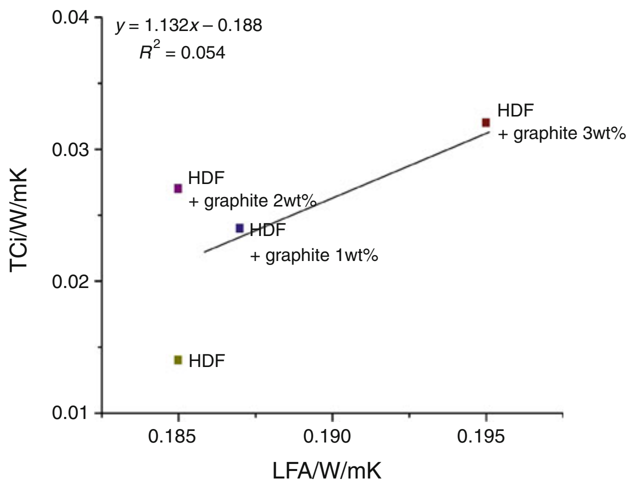

Fig. 9 Correlation graph for the HDF thermal conductivity of LFA and TCi

between the two devices in the experiment using the HDF was very low, as the coefficient of correlation (R^2) was 0.504 (Fig. 9).

Conclusions

This experiment was conducted to measure the correlation in the thermal conductivities measured using TCi, as well as HFM (KS L 9016) and LFA (KS L 1604) that are included in the existing KS standard.

An examination of the correlation by measuring the thermal conductivity of various materials using HFM and TCi revealed a high coefficient of correlation (R^2) of more than 0.9. Accordingly, the thermal conductivity measured using TCi can be accepted with confidence, as the thermal conductivity measured using HFM and TCi showed a high correlation for wood flooring, wall materials, and plywood with an increased mass percentage of reformed graphite and HDF.

The thermal conductivity measured using LFA and TCi for the epoxy adhesive with an increased mass percentage of reformed graphite showed a high coefficient of correlation (R^2) of 0.978. Accordingly, the thermal conductivity measured using TCi for the epoxy adhesive with an increased mass percentage of reformed graphite can be accepted with confidence. However, the thermal conductivity measured using LFA and TCi for the HDF with an increased mass percentage of reformed graphite showed a very low coefficient of correlation (R^2) of 0.504 because the thermal conductivity in the LFA experiment did not increase consistently. Based on this result, the value obtained by using LFA cannot be accepted with confidence since it is not suitable for measuring the thermal conductivity of consistent materials such as HDF.

Contrary to the existing method, TCi can conveniently measure thermal conductivity by using various sample shapes. The device is expected to find wide application and use in various areas due to its small size that allows convenient measuring of thermal conductivity even in places of spatial restrictions.

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