



The cuboid method for measurement of thermal properties of cement-based materials using the guarded heat flow meter

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HIGHLIGHTS

- Contact resistance is calculated and eliminated with a reduced material demand.
- One small cuboid specimen can be tested place of several large slabs.
- Specimen faces do not have to cover the metering area for effective measurement.
- The method is applicable for steady state and non-steady state thermal properties.

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ABSTRACT

Contact resistance can significantly affect the measurement of thermal conductivity of cement-based specimens using contact methods. A new method is proposed which has a reduced time and material requirement compared with the currently accepted methods: the Cuboid method. The Cuboid method requires just one cuboid-shaped sample of relatively small contact area, surrounded by insulation board, while the currently accepted two-thickness and multi-thickness methods require at least two samples of contact area greater than the metering area of the apparatus. Results from the Cuboid method and multi-thickness method were compared for specimens of Polymethyl methacrylate (PMMA) acrylic and hydrated CEM II Portland cement paste. The results differed by just 3.6% and 7.7% respectively for thermal conductivity measured in steady state condition. A non-steady-state method for the determination of specific heat capacity and thermal diffusivity of cement-based specimens, developed from the Cuboid method, is also presented. Relative uncertainties of the results for cement pastes measured in steady-state and non-steady state condition ranged from 2.2 to 11.5%.

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1. Introduction

Heat transmission through the building envelope is responsible for a large proportion of a building's operational energy use. Therefore, with pressure on the construction industry to reduce carbon emissions, there is a need to improve construction materials for operational energy efficiency. In order to better understand thermal behaviour of building materials, accurate measurement of their thermal properties is essential.

Concrete and cement-based products remain the most widely-used and effective construction materials in the world [1],

commonly used in elements of building and house structures such as the walls, roof and floor slabs, columns and foundations. Consequently, focusing on these materials is important if reduction in the energy requirement of buildings is to be realistically achieved, without compromising other factors such as strength and cost. To properly examine a material's energy efficiency, accurate measurement of its thermal conductivity, specific heat capacity and thermal diffusivity is essential, since:

- the thermal conductivity determines its capacity for transferring heat by conduction and its overall thermal resistance;
- specific heat capacity governs its ability to store and release heat with changes in temperature, and therefore the energy efficiency of the building envelope over time when exposed to heating and cooling cycles;

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- thermal diffusivity relates thermal conductivity and specific heat capacity, and describes how its thermal profile changes during transitions between hot and cold temperatures [2].

The present study focuses on steady-state condition measurement and, therefore, accurate determination of thermal conductivity by means of the heat flow meter method. The non-steady-state measurement method presented, to establish values for specific heat capacity and thermal diffusivity, makes use of the values obtained using the steady-state method introduced, and is a development of the methodology introduced by Yoon et al. [3].

According to Yoon et al. [3], the measured values of thermal conductivity of similar concretes and cements reported in the literature vary significantly, even when variations in composition are taken into consideration [2,4–6]. They showed that the differences can be attributed to the contact resistance between the test sample and the sensing device elements, and failure to account for it properly.

Cement-based materials possess an intrinsic surface roughness, so the actual contact area between two surfaces only amounts to a fraction of the nominal area of contact, and heat is only conducted between contact points. Hence, there is resistance to heat flow at the interface between the sample and sensing plate surfaces. This is what is known as the contact resistance [7,8]. The most commonly used methods for measuring thermal conductivity require that perfect contact exists between the sensor and the specimen, so in the real world contact resistance can significantly affect results.

When measuring a material of relatively low thermal conductivity, the contact resistance between the sensor and the specimen surface can be ignored because the material's inherent thermal resistance is so high as to make it relatively negligible. However, when making the same measurement for a material of intermediate or relatively low thermal resistance ($\sim 0.1 \text{ m}^2 \text{ KW}^{-1}$ and above), such as cement-based specimens, the contact component of the total thermal resistance is of much greater significance and must be accounted for to obtain an accurate measurement of its thermal conductivity using a contact method [9].

This research aims to address these issues with the development of a simplified method for the precise measurement of thermal conductivity – and subsequently specific heat capacity – that has a relatively low material demand, and does not necessitate the acquisition or preparation of additional materials of similar thermal properties.

Ideally, the effects of contact resistance would be removed entirely, and the need to measure at least two sample thicknesses would be eliminated. According to Tleoubaev et al., this could be achieved by using thermocouples placed into indentations made in the sample surface, although it is acknowledged that this would be a labour-intensive task. Tleoubaev et al. also attempted to eliminate contact resistance by the application of high thermal conductivity grease to the surfaces. Although this did reduce the contact resistance, it did not entirely remove its effects from the system and proved very difficult to repeat [10].

Another means of eliminating the need for two sample thicknesses would be to accurately quantify the contact resistance in advance and factor it into the equation describing the total thermal resistance of the specimen. However, there is no general model that enables prediction of contact resistance between two surfaces of any materials, so in-depth study of the surface conditions and contact details would be required, followed by an analytical solution [8]. This is a more complex strategy that may not even work, and even if it did, it would require more manual work than the two-thickness method, defeating the purpose of the exercise.

An investigation was conducted by Patterson et al. [11] into the use of compliant contact layers to enable the prediction of contact

resistance as a constant value within a reasonable error margin, independent of individual surface characteristics. Its aim was to essentially eliminate the value from the calculation of thermal conductivity and therefore reduce the number of samples required without the need for in-depth surface examination. The results of the investigation demonstrated that the compliant contact layers tested were inadequate for producing such constant surface characteristics and contact resistance was further observed to increase with water to cement ratio, both with and without their use.

The present study continues the search for a simple yet reliable thermal conductivity measurement method by testing a new technique for measuring thermal properties of cement-based specimens, hereafter referred to as the Cuboid Method. The technique requires only one cuboid-shapedⁱ specimen, with face areas that are less than the metering area of the heat flow meter. Using this method would reduce the time and material required for measuring thermal properties using the heat flow meter method, as well as providing more comprehensive two-dimensional results for the material in question by measurement in two orientations.

2. Materials and methods

2.1. Equipment

This technique was applied using a LaserComp FOX 600-800 Guarded Heat Flow Meter, connected to a PC running Wintherm 32v3 software. Also required for completion of the test are insulation board, a saw for trimming the surrounding insulation and a cuboid mould for casting cement and concrete samples. This work was carried out using the FOX 603, pictured in Fig. 1. Jablite Premium Universal Board insulation board (thermal conductivity 0.031 W/m K) was used to form the surrounding insulation.

The heat flow meter method is one that is commonly used for measuring thermal conductivity. It works by applying a temperature difference across the test specimen and measuring the steady state heat flux this induces through the sample in one dimension. The equipment consists of two parallel sensing plates, both maintained at constant temperature. The plates contain within them calibrated heat flux transducers that measure the local heat flux density in either direction, in Wm^{-2} , at the sample's upper and lower faces.

2.2. Applicable mathematical models

2.2.1. Steady-state condition

The heat flow meter's output value for heat flux is the average of the product of two quantities for each plate; the electrical signal from the sensing plate related to the measured heat flux, Q (μV), and its unique calibration factor for that temperature, S ($\text{Wm}^{-2} \mu\text{V}^{-1}$). From this output value, together with the specified temperature difference across the specimen, the total thermal resistance between the two plates can be calculated from Eq. (1), the heat conduction equation [12].

$$q_{\text{total}} = SQ = \frac{\Delta T}{R_{\text{total}}} \quad (1)$$

where q_{total} is the total heat flux measured (Wm^{-2}); S is the specific calibration factor for the heat flow meter ($\text{Wm}^{-2} \mu\text{V}^{-1}$); Q is the heat flow meter's voltage flux signal (μV); ΔT is the temperature difference applied across the sample (K), and R_{total} is the total thermal resistance measured ($\text{m}^2 \text{ KW}^{-1}$). R_{total} is the sum of the sample's intrinsic thermal resistance and the resistance to heat flow, or

ⁱ For the purpose of this research, the broader definition of "cuboid" is appropriate, i.e. a rectangular prism of any given dimensions.

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