Thermochimica Acta 588 (2014) 1–10

Contents lists available at ScienceDirect

Thermochimica Acta

journal homepage: www.elsevier.com/locate/tca

Short Communication

# Estimation of the thermal properties of hardened cement paste on the basis of guarded heat flow meter measurements

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ARTICLE INFO

*Article history:*
Received 5 July 2013
Received in revised form 1 April 2014
Accepted 15 April 2014
Available online 23 April 2014

*Keywords:*
Cement
Concrete
Thermal conductivity
Thermal diffusivity
Specific heat capacity
Heat flow meter

ABSTRACT

In the present study, a new analysis method is proposed to measure thermal conductivity, thermal diffusivity, volumetric specific heat capacity, and specific heat capacity of cement-based materials based on the guarded heat flow meter apparatus. We tested hydrated cement paste specimens with 0.4 water-to-cement ratio and applied both steady and non-steady state data to compute thermal properties of the hydrated cement paste. Thermal conductivity and thermal contact resistance were determined as $1.28\,\mathrm{W\,m^{-1}\,K^{-1}}$ and $0.038\,\mathrm{m^{-2}\,K\,W^{-1}}$ using steady state data. Furthermore, using a computerized system of heat flow meters and non-linear regression, we used non-steady state data to measure thermal diffusivity, volumetric specific heat capacity and specific heat capacity of the hydrated cement paste as $4.77 \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$, $2685.4\,\mathrm{kJ\,m^{-3}\,K^{-1}}$, and $1.28\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$. The relative uncertainties of these properties fell within 2–7% range and the residual distributions were validated to follow a normal distribution based on quantile–quantile tests.

## 1. Introduction

The need for improved thermal insulation properties and accurate evaluation of the effects of heat-transfer on energy use and carbon emissions in buildings and structures is widely acknowledged within the engineering community. Good thermal insulation is essential if we are to meet the demands of energy efficiency and decent indoor thermal comfort that are required to achieve a low energy, low carbon and sustainable way of life in future. There are many other applications where good thermal insulation is required to conserve heat or reduce thermal loading on a structure, for example the refractory lining of a rotary kiln in Portland cement clinker production or the radiation shield of a nuclear power plant.

The three key properties that are required in the study of the thermal insulating properties and heat transfer through materials are thermal conductivity, specific heat capacity and thermal diffusivity [1]. Thermal conductivity is a measure of a material's ability to transmit heat by conduction and is one of the basic parameters used to determine properties such as the thermal resistance (*R*-value) or alternatively the overall heat transfer coefficient (*U*-value) of the external envelope (or envelope element) of a building. Specific heat capacity, on the other hand, describes the capacity of the material to absorb, store and release heat. It is widely used in thermodynamic analysis and in Dynamic Simulation Modeling of buildings, to simulate inertial effects and predict heating profiles and annual energy demand. Lastly, thermal diffusivity is the parameter that defines the transient thermal profile during unsteady, transition periods in the heating/cooling cycle. It is the parameter that links thermal conductivity and specific heat capacity.

Cements, and cement products such as concrete, are amongst the most commonly used construction materials in the world. Knowing their thermal properties is important if we are to meet the sustainability challenges that we face. There are two generic approaches to measuring the thermal conductivity of materials: steady state tests and non-steady state tests [2]. The Radial Heat Flow (RHF), Guarded Hot Plate (GHP), and Guarded Heat Flow Meter (GHFM) methods are steady state tests, and the Hot Wire (HW) and Transient Plane Source (TPS) methods are non-steady state tests. The thermal properties of cementitious materials have been tested using these methods. Bentz [3], Bouguerra et al. [4], and Milovanovic et al. [5] used TPS for hydrated cement pastes, Kim et al. [6] applied the Two-Linear-Parallel-Probe (TLPP) method to hydrated cement paste and concrete, and Khan [7] and Mounanga et al. [8] used the HW method for hydrated cement and concrete. Other researchers have applied these test methods to other cementitious materials, such as lightweight concrete and geopolymers [9,10]. Furthermore, Fokaides et al. recently applied infrared thermography to measure the *U*-value of building envelopes [11]. The reported values for thermal conductivity of hydrated cement pastes, at water-to-cement (w/c) ratio of

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http://dx.doi.org/10.1016/j.tca.2014.04.015
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**Table 1**
Literature values for the thermal conductivity of comparable hydrated cement pastes.

| Author | Method | Specimen description | Surface condition | Temperature (°C) | Conductivity ($W\,m^{-1}\,K^{-1}$) |
|---|---|---|---|---|---|
| Kim et al. [7] | Two-linear-parallel-probe | Hydrated cement paste in saturation (w/c = 0.4) | Flat cast | 20 and 40 | 1.16 and 1.13 |
| Bentz [3] | Transient plane source | Hydrated cement paste in saturation (w/c = 0.4) | Flat cast | 23 | 0.94 |
| Milovanovic et al. [5] | Transient plane source | Hydrated cement paste in saturation (w/c = 0.4) | Flat cast | 20 | 1.81 |
| Bouguerra et al. [4] | Transient plane source | Hydrated cement paste in saturation (density = 2100 kg/m$^3$) | Crushed | 20 | 2.85 |

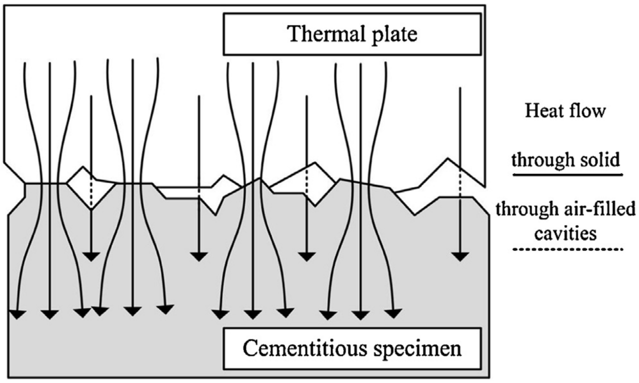

**Fig. 1.** Illustration of heat flow between instrument and specimen.

0.4, measured under saturated condition, are summarized in Table 1. According to Kim et al. [6], the difference in the thermal conductivity between hardened cement pastes with 0.25 and 0.4 water-to-cement ratios was only 0.058 $W\,m^{-1}\,K^{-1}$. Notwithstanding the compositional uncertainty and complexity of cementitious materials, the differences between the values reported are high by any stretch of the imagination and are therefore probably subject to unquantified experimental artifacts as the relevant literature refers to equivalent mix proportioning and similar test conditions.

The purpose of the work reported in this paper is to investigate and understand the reason(s) for these large variations and anomalies, and to develop a consistent analysis method for determining the thermal conductivity and other thermal properties of cementitious materials. In common, the large scatter in measured values of thermal conductivity is developed by the contact resistance between the test apparatus and the sample. Martias et al. took into account the contact resistance to measure the thermal conductivities of gypsum composites [12]. Contact resistance is the interfacial thermal resistance between the specimen surface and the heat flow meter as illustrated in Fig. 1 [13]. As shown in Table 1, crushed cement pastes having rough surface characteristics show very different thermal conductivities compared to other samples because of relative differences in their surface profiles. Because the proportions between porosity and cement matrix play a strong role in determining the density of hardened cement pastes, the identical w/c ratio provides similar density. In the present study, the density of the samples with 0.4 w/c ratio is 2086 $kg\,m^{-3}$, which is similar to crushed cement pastes (2100 $kg\,m^{-3}$). Furthermore, since other data listed in Table 1 has been obtained for hardened cement pastes with 0.4 w/c ratio, the thermal conductivities in Table 1 will be comparable to the results measured by the present study.

The contact resistance is of relevance in almost all measurement techniques, apart from non-contact methods such as the laser flash method [14,15]. The hardened cement paste is a complex porous material that contains both a persistent solid matrix and a void space, of which the dimensional range is from nano-to-millimeters in size [16]. The wide range of pore sizes in a hydrated cement paste provides “inhomogeneous and complex” surface characteristics. For dense cementitious materials, therefore, the effect of contact resistance is severe as they present relatively high thermal conductivities compared to insulation materials and generally rough, non-compliant surfaces. In the present study we present evidence of the significant effect of contact resistance on thermal conductivity measurement tests of cementitious materials. We also introduce a new computational method in which measured experimental data are first compared with outputs from a mathematical model of thermal conductivity in which the effect of contact resistance has been explicitly included. Using this model, we then show how the value of the contact resistance for the sample of material being tested can be calculated to allow the thermal conductivity and other thermal properties of the material to be described. An extension of the new computational method has been developed to enable the use of non-steady state (transient) data from the guarded heat flow meter test to also determine the specific heat capacity and thermal diffusivity. This is a meaningful departure from the traditional steady-state only use of the guarded heat flow meter test. Our proposed unified method for consistent, simultaneous measurement of the thermal conductivity, specific heat capacity and thermal diffusivity of cementitious (and other dense) materials significantly improves the utility of the guarded heat flow meter method. With the “Guide to the Expression of Uncertainty in Measurement” (GUM) [17], the expression of uncertainty provides a uniform basis for the comparison of experimental results and methods. This guide was therefore used for the determination of the standard and relative uncertainties of measured thermal properties.

## 2. Description of guarded heat flow meter apparatus

The guarded heat flow meter apparatus and guarded hot plate are routinely used worldwide for testing thermal conductivity, and many standard test methods are based on these apparatuses [20–22]. The two methods are similar in terms of mathematical theory and apparatus configuration. Their difference is that the guarded heat flow meter determines the density of heat flow relative to the reference material while the guarded hot plate is a direct measurement of the generated heat flow. Furthermore, a modified apparatus based on similar principles, the guarded parallel-plate instrument, has also been used for the thermal conductivity of fluids [23].

A more uniform surface profile can reduce the measurement uncertainty of contact resistance. In order to generate the uniform surface profile, the sample surfaces, however, need to be treated or polished, meaning that a smaller contact area has a practical advantage in terms of effort expended in sample preparation. The guarded heat flow meter apparatus generates one-dimensional heat flow through a test specimen that is firmly sandwiched