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Measuring thermal conductivity and specific heat capacity values of inhomogeneous materials with a heat flow meter apparatus

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ABSTRACT

The aim of this study was to observe the suitability of the heat flow meter apparatus for thermal conductivity and specific heat capacity tests of concrete, as well as to determine specific heat capacity values for 14 different plasters. In total, two concrete types, five floor screed plasters, two fixing plasters, six wall screed plasters, and one specialized plaster that had small EPS spheres added into it were tested.

The main novelty value of this research is studying how well heat flow meter apparatus can determine specific heat capacities of inhomogeneous materials. Also, how precisely thermal conductivity could be measured from small concrete specimens of interest. The results measured with the most suitable methods were in line with published values, which indicate that the apparatus was suitable for both tests.

1. Introduction

Thermal conductivity and specific heat capacity are among the most essential material properties of a building material. Thermal conductivity describes the ability of a material to conduct heat, and the specific heat capacity tells how much heat energy is absorbed or released depending on the temperature difference and mass [1]. These values are needed, among other uses, in thermal performance calculations. However, the published values for material properties are usually not sufficient for more accurate calculations. That is due to the fact that individual products in a product group, such as plasters, may have widely varying material properties. As many material properties are listed generically for whole material groups, values determined from the actual products are required to achieve a high level of accuracy in the calculations for a specific case.

There are different kinds of methods to determine thermal conductivity. In the study [2] there is one method presented to determine thermal conductivity of insulation materials. The aim of this study was to observe the suitability of the heat flow meter apparatus for thermal conductivity and specific heat capacity tests of concrete, so it is known whether or not test results of inhomogeneous materials acquired with this apparatus are reliable. Also, specific heat capacity values for 14 different plasters were measured to get more accurate material properties.

Specific heat capacity is usually tested with a calorimeter. One kind of calorimeter for defining specific heat capacity is used in the study [3]. However, the use of a heat flow meter apparatus has recently become possible as well. This is due to the approval of an American standard ASTM C1784-13 [4]. The standard describes how to use a heat flow meter apparatus for measuring thermal storage properties, i.e. specific heat capacity. Research on the subject is conducted by the developer of the apparatus, as well as other instances [5–7] and instructions on how to perform the tests have been given [4,8,9]. Excluding thermal contact resistance is one of the key factors when measuring thermal conductivity since it greatly impacts the accuracy and reliability of results [10–12].

2. Material and methods

2.1. Heat flow meter apparatus FOX50

In this study a heat flow meter apparatus FOX50 that runs on WinTherm50 software was used. The apparatus is developed and manufactured by an American company LaserComp, Inc. The apparatus consists of upper and lower plates, two heat flow meters and protective casing which is preventing the heat losses. Sample to be measured is placed between the upper and lower plates. The upper plate is stationary and the lower plate moves vertically to provide good contact with the sample and minimize interface resistance [13].

The specimen size in this apparatus is rather small, from 50 to 61 mm in diameter and 0–25 mm thick, and the thermal conductivity range is from 0.1 to 10 W/(m K) with an absolute thermal conductivity test accuracy of ± 3% [13]. The apparatus has been calibrated to four different ranges of thermal conductivity values and the most suitable

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Nomenclature

c	specific heat capacity at a constant pressure (J/(kg K))
d	thickness of specimen (m)
d_{total}	thickness of both the rubber sheets and the specimen together (m)
H	amount of heat energy per square meter (J/m^2)
$H_{hfm}(T)$	correction factor to remove the effect of the plates (J/(m^2 K))
m	mass (kg)
q	heat flux flowing through the specimen (W/m^2)
Q	heat energy (J)
Q_1, Q_2	signal values of two separate tests (μV)
Q_{Lequil}	Heat Flow Meter signal at the final steady-state, lower plate (μV)
Q_{Li}	Heat Flow Meter signal value of lower plate (μV)
Q_{Uequil}	Heat Flow Meter signal at the final steady-state, upper plate (μV)
Q_{Ui}	Heat Flow Meter signal value of upper plate (μV)
S_{cal}	temperature dependent calibration factor (W/(m^2 μV))
S_{Lcal}	calibration factor of lower plate (W/(m^2 μV))
S_{Ucal}	calibration factor of upper plate (W/(m^2 μV))
T	temperature (K)
T_{cal}	known temperature for calibration (K)
T_m	average test temperature (K)
ΔT_{ext}	temperature difference between external thermocouples (K)
x	thickness of specimen (m)
δx	depth of the groove (mm)
Δx_1, Δx_2	thicknesses of two separate specimens (m)
λ	thermal conductivity (W/(m K))
λ_{cal}	known thermal conductivity for calibration (W/(m K))
λ_{total}	thermal conductivity of both the rubber sheets and the specimen together (W/(m K))
ρ	material's density (kg/m^3)
τ	time interval (s)

Subscripts

r	rubber sheets
cal	known thermal properties for calibration
U	upper plate
L	lower plate
equil	value at the final steady-state

file based on material's supposed thermal conductivity ought to be used [13]; here the calibration file Pyrex 7740 was used.

The procedure to determine thermal conductivity is described in the European standards SFS-EN 12664 and SFS-EN 12667 [14,15], and test equipment requirements for the heat flow meter apparatus are stated in standards SFS EN 1946-1, SFS EN 1946-3 and ISO 8301:1991 [16–18]. The thermal conductivity tests were conducted at the mean temperature of 10 °C. The temperature difference between the upper and lower plate should have been 20 K; however, the difference was greater (26 K) when using external thermocouples, due to a recommendation of the developer. The thermal conductivities of concrete specimens were tested to decipher how reliable thermal conductivity values can be gotten from a small specimen size with relatively large (16 mm) maximum particle size.

When measuring specific heat capacity, the apparatus is suitable for building materials such as concrete, wood and insulating materials with absolute accuracy of ±5% [13] and is in accordance with standard ASTM C1784-13 [4]. Specific heat tests were conducted with plain specimens and PID coefficient alterations. Test temperatures were 10 °C, 20 °C, 30 °C and 40 °C as instructed by the apparatus developer [13]. The average result is therefore the value at 25 °C.

2.2. Specimens

There were two types of concrete specimens: C20/25 and C32/40 specimens. Both had maximum particle size of 16 mm and both were in consistence tolerance class S3. The concrete masses were tested in laboratory: Concrete C20/25 was a mixture of 249.10 kg of cement (CEM I 42.5 R/2), 69.30 kg of ash, 503 kg of rock 0–8, 524 kg of rock 0–8/6, 186 kg of rock 3–8, 394 kg of rock 6–16, 200 kg of filling and 128.30 kg of cold water. Water-cement ratio (w/c) was 0.57. Volume fraction of rock material in concrete C20/25 was 67.91% and mass fraction 77.75%.

Concrete C32/40 was a mixture of 721.60 kg of cement (CEM I 42.5 R), 204.10 kg of ash, 805 kg of rock 0–8, 734 kg of rock 0–8/6, 238 kg of rock 3–8, 1,114 kg of rock 6–16, 437 kg of filling and 326,3 kg of cold water. Water-cement ratio (w/c) was 0.44. Volume fraction of rock material in concrete C32/40 was 61.34% and mass fraction 70.80%.

In addition to concrete tests five floor screed plasters, two fixing plasters, six wall screed plasters, and one specialized plasters that had 1–3 mm EPS spheres added into it were also tested in specific heat capacity tests with heat flow meter apparatus according to standard ASTM C1784-13 [4]. Floor screed plaster 1 was a mixture of resin-cement-quartz sand-based powder and water and its maximum particle size was 3 mm. Floor screed plaster 2 was a mixture of 0.1 kg of water and 0.57 kg of fiber-polyester-special cement-quartz-based powder with 1 mm maximum particle size. Water-powder ratio for Floor screed plaster 2 was 5.70. Floor screed plaster 3 was made of 1.11 kg of fiber-synthetic resin-aluminate/Portland cement-quartz-based powder and 0.2 kg of water. Powder had 1 mm maximum particle size and water-powder ratio was 5.55. Floor screed plaster 4 was a mixture of 0.80 kg of resin-cement-quartz-based powder and 0.2 kg of water. Plaster's maximum particle size was 0.3 mm and water-powder ratio 4.00. Floor screed plaster 5 was a mixture of 0.44 kg of resin-special cement-quartz sand-based powder and 0.1 kg of water. The maximum particle size of Floor plaster 5 was 0.5 mm and water-powder ratio 4.40.

Fixing plaster 1 was made of polymer-white cement-lightweight filler-quartz sand-based powder and water and its maximum particle size was 0.5 mm. Fixing plaster 2 was a mixture of 0.2 kg of water and 0.941 kg of polymer-cement-quartz-based powder which maximum particle size was 0.5 mm. Plaster O1 was made of water and EPS-granulate-cement-based powder, which EPS granulate size was 1–3 mm but maximum rock particle size was unknown.

Wall screed plaster 1 was a mixture of 0.842 kg of polymer-cement-sand-based powder and 0.2 kg of water and its maximum particle size was 3 mm. Wall screed plaster 2 was a mixture of water and polymer-cement-sand-based powder with maximum particle size 2 mm. Wall screed plaster 3 was a light weight smoothing plaster with maximum particle size 2 mm. Wall screed plaster 4 was made of 0.15 kg of water and 0.667 kg of polymer-cement-sand-based powder with maximum particle size 1.5 mm. Wall screed plaster 5 was a mixture of 0.941 kg of polymer-cement-limestone-based powder and 0.2 kg of water. Plaster's maximum particle size was 0.5 mm. Wall screed plaster 6 was a mixture of 0.645 kg of polymer-cement-limestone-based powder and 0.2 kg of water. Plaster's maximum particle size was 0.2 mm.

More specific product formulations are a trade secret of the plaster manufacturer. The manufacturing properties of plasters are also presented in Table 1. Plasters with no exact information about the batch are made by way of manufacturer's instructions. Ingredients are weighted with the scale with accuracy of ±0.1 g and mixed with a laboratory mixer.