

Hygrothermal properties of steel fiber reinforced concretes

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Abstract. This paper defines the hygrothermal material properties (thermal conductivity, density, specific heat capacity, vapor diffusion coefficient and resistance, moisture storage function, water absorption coefficient and liquid transport coefficient) of steel fiber reinforced concretes that are widely used for industrial floors, based on laboratory measurements. The measured and calculated material properties are necessary to carry out a dynamic heat and moisture simulation of a component or a building containing steel fiber reinforced concrete layers.

Introduction

In building energy calculations it is fundamental to know the thermal properties of materials. In this paper, the thermal properties of steel fiber reinforced concretes were tested.

Previous research in thermal properties of concretes studied mostly the effect of aggregates [1-7] special high performance concretes, or the effect of elevated temperatures [8-10], but there are few papers dealing with fiber reinforced concretes as well [10-13]. The correlation between the concrete's porosity and thermal or mechanical properties are fundamental [12, 14, 15], such as the relation between the bulk density and the thermal conductivity of the concretes [6]. In previous researches, the additional fiber content was higher, up to 8% fiber volume [10], than the content usually used for industrial floors, which is between 2.5-4.5% steel fiber volume in Hungary, resulting e.g. 20 – 35 kg/m³ steel fibers in the mixture. High density concretes and fiber reinforced concretes have thermal conductivity between 1.5 – 3.2 W/mK at standard temperature according to several researches [3, 10, 14, 16] and standards. Some of the researches indicates, that increasing the steel fiber addition in the concrete results always higher thermal conductivity [12, 14], neglecting that the increased fiber content in the concrete can increase the total porosity of the specimen [15], and may resulting lower thermal conductivity values. Our research investigates this effect also by measuring all of the hygrothermal parameters. Those properties are essential to know, if one wants to perform a coupled heat and moisture transport simulation using steel fiber reinforced concretes.

Heat and moisture transport in materials

For studying Heat and Moisture transport (HAM) of buildings or components, we need to know the temperature and moisture distribution on the boundaries and in the material layers, which depend on each other, as the hygrothermal properties of the materials depends on the temperature and the moisture content as well. Due to this, coupled differential equations needed to solve, The following partial differential equations are required to carry out a 1D HAM simulation. Eq. 1. shows the heat transport equation, while Eq. 2. refers to mass transfer (moisture and vapor transfer):

$$\frac{\partial H}{\partial T} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + h_v \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial p}{\partial x} \right) \quad (1)$$

$$\rho_v \frac{\partial \psi}{\partial \phi} \frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x} \left(\rho_v D_v \frac{\partial \psi}{\partial \phi} \frac{\partial \phi}{\partial t} \right) + \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial p}{\partial x} \right) \quad (2)$$

where:

H	– Enthalpy [J/m^3];
T	– Thermodynamic temperature [K];
t	– Time [s];
x	– 1D domain [m];
λ	– Thermal conductivity [W/mK];
h_w	– Evaporation enthalpy of water [J/kg];
δ	– Vapor diffusion coefficient [kg/msPa];
μ	– Vapor diffusion resistance factor [-];
p	– Vapor partial pressure [Pa];
ρ_w	– Density of water [kg/m^3];
ψ	– Moisture content [m^3/m^3];
ϕ	– Relative humidity [-];
D_w	– Liquid transport coefficient [m^2/s].

The left-hand side of Eq. 1. comprises the heat storage, the heat capacity of the dry material and the heat capacity of the moisture present in the material. The left-hand side of Eq. 2. comprises the moisture storage which is described by the derivative of the moisture storage function. On the right-hand side of the equations we can find the transport terms. Heat transport of Eq. 1. is the sum of the temperature- and moisture-dependent thermal conductivity and vapor enthalpy flow. This heat transport by vapor enthalpy flow is due to water evaporating in one place and thereby absorbing latent heat from this place, and then diffusing to a different place, condensing there and releasing latent heat. This kind of heat transport is often called latent heat effect [17]. Liquid transport of Eq. 2. (through surface diffusion and capillary conduction, both due to a gradient of relative humidity) shows only a relatively minor temperature dependence. Vapor diffusion, on the other hand, is strongly affected by the temperature field, since the saturation vapor pressure increases exponentially with temperature.

Understanding the material properties in the Eq. 1 and 2 are essential for HAM simulations, therefore, if we want to model a building or a component which contains steel fiber reinforced concrete, firstly, we need to measure the mentioned hygrothermal properties. In this paper, hereinafter we deal with the laboratory measurements of steel fiber reinforced concretes.

Steel fiber reinforced concrete samples

It was relevant in the preparation of the concrete recipes that the specimens should fulfill the requirements of industrial floors regarding compressive strength and consistency that are at least C25/30 and have F3 class consistency. Accordingly, four recipes were made including three ones with steel fiber containing Humix 50 cold formed steel fibers with bent ends and a reference mixture without fibers. In every case, 320 kg/m^3 Lafarge CEM II/BS 42.5 normal initial strength Portland-slag cement and 154 kg/m^3 water were used resulting a water-cement ratio of 0.48. The distribution of the aggregates per fraction is 40% of 0/4 mm, 25% of 4/8 mm and 35% of 8/16 mm. The amount of water in the aggregates is corrected and $1.4 - 1.6 \text{ kg/m}^3$ of superplasticizer Sika Visocrete-5 is also added for achieving the consistency. The compositions of the tested concrete samples are listed in table 1. Each fiber reinforced concrete mixture was prepared a portion of 35 kg and distributed to six standard $15 \times 15 \times 15 \text{ cm}$ cubes and three $20 \times 20 \times 10 \text{ cm}$ cuboids which are made for the measurement of thermal conductivity. During each concrete mixing, the consistency was tested by using a flow table according to EN 12350-5:2009 and the density of fresh concrete according to EN 12350-6:2009.

Table 1. The compositions of the tested concretes

Samples	Fiber type	Aggregates (kg/m ³)	Steel fibers (kg/m ³)	Designed density (kg/m ³)	Fresh concrete density (kg/m ³)	Consistency class
S35	Humix 50	1913	35	2424	2433	F3
S27,5	Humix 50	1916	27.5	2419	2427	F3
S20	Humix 50	1920	20	2414	2447	F3
C	-	1925	-	2401	2403	F3

During each concrete mixing, the consistency was tested by using a flow table according to EN 12350-5:2009 and the density of fresh concrete according to EN 12350-6:2009. The mixtures met the requirements of F3 consistency class and the fresh concrete density did not differ significantly from the designed density. The specimens were one day old when the formwork stripped, then the samples made for compressive strength test were stored in water for 28 days and the samples made for thermal conductivity measurements were stored in water for 7 days, then stored in a conditioning chamber at 23 °C and 50 %rH. The process of making the samples are shown in figure 1.



Fig. 1. Mixing and fiber addition; Cradling; Aftercare; Demoulding

After the concreting process, the samples used in this paper were stored in laboratory conditions for one year before the measurements. During the year and the measurements, the laboratory's air temperature was set to 23 ± 2 °C and the relative humidity was always kept between 45 – 55%.

Thermal conductivity measurements

The specimens were tested using a Taurus TLP 300 DTX guarded hot plate measuring instrument (fig.2.). The specimens were framed by 10 cm thick EPS foam stocks, ensuring that the temperature or humidity in the lab do not affect the results of the measurements and in the specimens measured intermediate 10x10 cm area, one-dimensional steady state heat flow can develop during all three measured temperature stages. Between the samples and the EPS frame, we taped aluminum foil moisture and vapor barrier layer. For the measurement, 1 – 1 cm thick EPS200 layer were added to the top and bottom of the sample to reduce the measurement errors which occurs using guarded hot plate measurement on samples with low thermal resistance. Later, the effect of the EPS200 layers were calculated and compensated back. Before the thermal conductivity measurement, the hardened concrete's bulk density was measured according to EN 12390-7:2009. The stages were set to 15/25 °C, 20/30 °C and the tests ended when relative error in thermal conductivity was under 0.2 %.

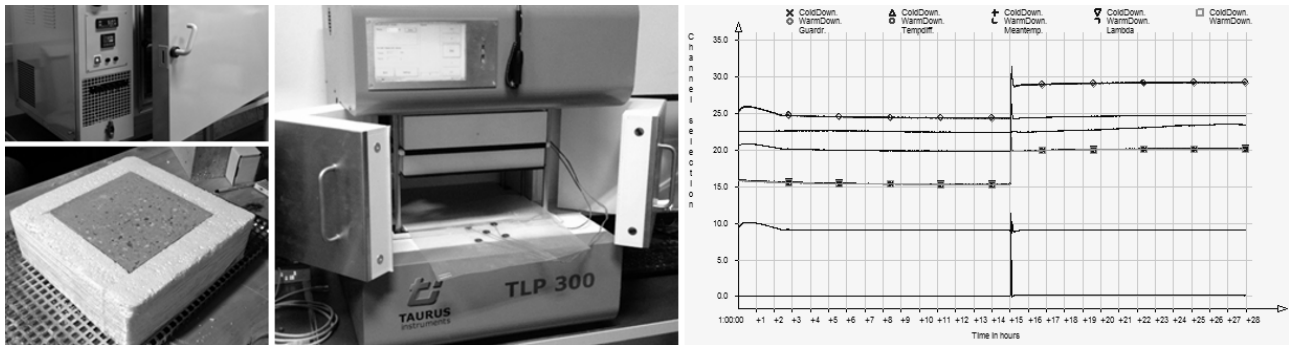


Fig. 2. Thermal conductivity measurements

The measured thermal conductivities given at an average mean sample temperature of 23 °C both dried and laboratory stored (moist) samples. Then, according to EN ISO 10456:2007, the thermal conductivity values of 10 °C can be determined using the following Eq. 3.:

$$\lambda_2 = \lambda_1 \cdot e^{f_r(T_2 - T_1)} \quad (3)$$

where:

- f_r – Temperature conversion coefficient (0,001);
- T_1 – First set of conditions (23°C);
- T_2 – Second set of conditions (10 °C).

The measured values of steel fiber reinforced concretes are listed in the table 2 below at 23 °C and 10 °C according to EN ISO 10456:2007 conditions.

Table 2. Thermal conductivities of steel fiber reinforced concretes

Samples	Measured TC of dried samples @ 23°C, $\lambda_{2,d}$ [W/mK]	Measured TC of moist samples @ 23°C, $\lambda_{2,m}$ [W/mK]	Calculated TC of dried samples @ 10°C, $\lambda_{1,d}$ [W/mK]	Calculated TC of moist samples @ 10°C, $\lambda_{1,m}$ [W/mK]
S35	1,75	1,87	1,73	1,85
S27,5	1,99	2,11	1,96	2,09
S20	2,03	2,16	2,00	2,13
C	1,68	1,79	1,66	1,77

Vapor diffusion coefficient and resistance measurements

Construction materials vapor diffusion coefficients and resistances are measured in a self-made temperature and humidity controlled chamber, using special aluminum measuring pots (in which the relative humidity at the bottom side of the test sample adjusted using $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ resulting 53% relative humidity at 23 °C) and the relative humidity set in the chamber (at the top side of the test sample) using different salt solutions which forms a pressure difference between the two sides of the specimen. Therefore we can measure the water vapor diffusion through the material. The instruments and the measurement setup used is shown in Figure 3.

For the measurements of the steel fiber reinforced concrete samples (and the one without fibers as well), we followed the EN ISO 12572:2001 standard and measured the samples both at dry cup (average relative humidity between the specimen is below 70%) and wet cup (average relative humidity between the specimen is above 70%) conditions. The mass changes of the measuring pots were measured using high precision scales logged every second. The measurement of the sample group was lasted usually a week, while the steady-state vapor migration conditions occurred, then three days of measurement results were used to calculate the results listed on table 3.



Fig. 3. Measurement of vapor diffusion parameters

From the measured values, the following formula is used to determine the vapor diffusion coefficient of concretes:

$$\delta = \frac{d \cdot \left| \frac{m_2 - m_1}{t_2 - t_1} \right|}{A \cdot |p_{chamber} - p_{pot}|} \quad (4)$$

where:

- d – Thickness [m];
- $m_2 - m_1$ – mass change during the steady-state measurement [kg];
- $t_2 - t_1$ – Time difference [s];
- A – The exposed surface of the sample [m²];
- $p_{chamber}$ – Vapor pressure in the chamber [Pa];
- p_{pot} – Vapor pressure in the measuring pot [Pa].

The vapor diffusion resistance factor shows the ratio of the diffusion coefficients of water vapor in air and in the construction material and has a simple interpretation: it is the factor by which the vapor diffusion in the material is impeded, as compared to diffusion in stagnant air and can be calculated using the following equation:

$$\mu = \frac{\frac{84,0998}{462 \cdot p_b \cdot T} \left(\frac{T}{273,15} \right)^{1,81}}{\delta} \quad (5)$$

where:

- p_b – Barometric pressure in the chamber [hPa],
- T – Thermodynamic temperature in the chamber [K].

Table 3. Thermal conductivities of steel fiber reinforced concretes

Samples	Vapor diffusion coefficient, dry-cup, δ_{dry} [10^{-12} kg/msPa]	Vapor diffusion coefficient, dry-cup, δ_{wet} [10^{-12} kg/msPa]	Vapor diffusion resistance factor, dry-cup, μ_{dry} [-]	Vapor diffusion resistance factor, wet-cup, μ_{wet} [-]
S35	1,2569	2,0504	156,7	96,1
S27,5	1,5328	2,3950	128,5	82,2
S20	1,4127	2,3944	140,8	83,1
C	1,2884	2,1121	153,2	93,6

Moisture storage function measurements

In a porous hygroscopic material, like the fiber reinforced concretes, the surfaces of the pore system accumulate water molecules until a specific equilibrium moisture content corresponding to the humidity of the ambient air is reached. The moisture storage function can be measured between the range of 0-97%rH according to EN ISO 12571 and after we can obtain the free water saturation point at 100%rH by immersing the samples in water for 28 days. With that measurement, the apparent porosity of the material can be calculated as well. For the maximum water content, pressure plate measurements are needed.

Moisture storage function

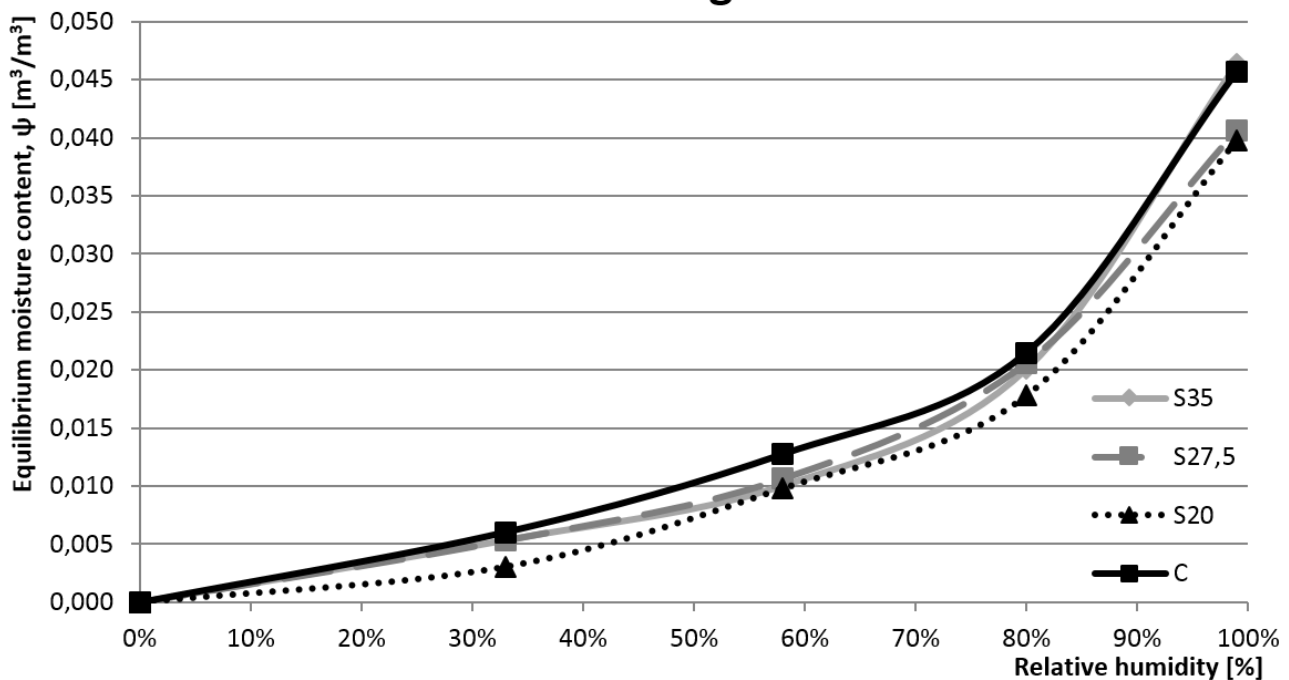


Fig. 4. Moisture storage functions of steel fiber reinforced concretes

In fig. 4. the moisture storage functions of the specimens are shown till 99%rH. The values of the measurements listed in table 4. The apparent porosity of the samples in order are: 4,84%, 4,32%, 4,54% and 4,78% after 28 days in water.

Table 4. Water content of the specimens [m^3/m^3]

Samples	0%rH	33%rH	58%rH	80%rH	99%rH	28 days in water
S35	0	0.00535	0.01004	0.02008	0.04636	0.11317
S27,5	0	0.00531	0.01062	0.02059	0.04061	0.10149
S20	0	0.00307	0.00982	0.01780	0.03981	0.10730
C	0	0.00604	0.01275	0.02147	0.04565	0.11076

Water absorption coefficient measurements

For the calculation of the liquid transport coefficient, the approximate formula requires the knowledge of the water absorption coefficient. In case of measuring the coefficient of construction materials, partial immersion method can be used in accordance with standard EN ISO 15148:2002 (fig.5 shows the measured values using the standard), or short-term immersion is the applicable according to standard EN 1609:2013 in case of insulation products [18].

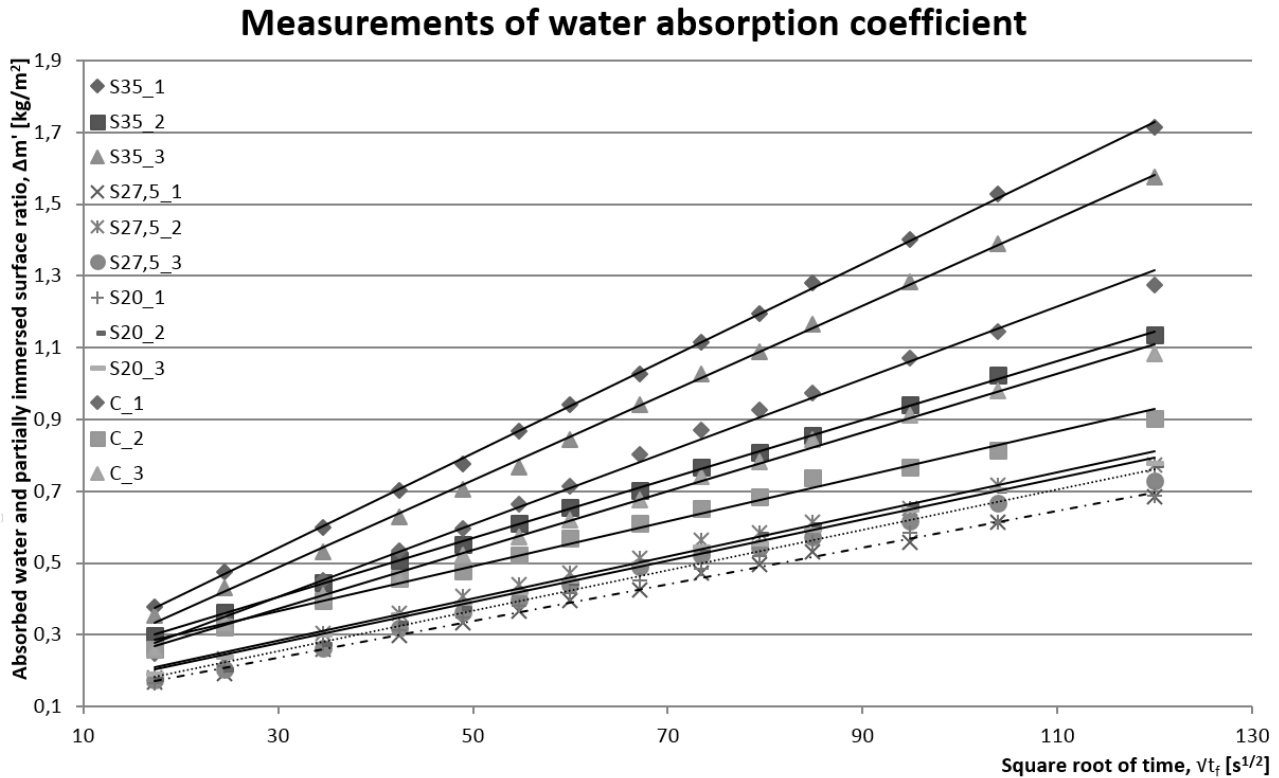


Fig. 5. Measurements of water absorption coefficient

Using the measured values in accordance to the standard, the following formula describes the water absorption coefficient:

$$A_w = \frac{\Delta m'_{t_f} - \Delta m'_0}{\sqrt{t_f}} \quad (6)$$

where:

- A_w – Water absorption coefficient [$\text{kg/m}^2\text{s}^{1/2}$];
- $\Delta m'_{t_f}$ – Absorbed water and partially immersed surface ratio at “ t_f ” end time [kg/m^2];
- $\Delta m'_0$ – Absorbed water and partially immersed surface ratio at “0” start time [kg/m^2];
- $\sqrt{t_f}$ – Square root of time [$\text{s}^{1/2}$];

Liquid transport coefficient calculation

The determination of moisture storage function as the average of the sorption and desorption isotherms are showed before. Therefore the liquid transport coefficient can be calculated with different water saturations depending on relative humidity and using the water absorption coefficient. The liquid transport coefficient can be approximated with the following Eq. 7.:

$$D_w(w) = 3,8 \cdot \left(\frac{A_w}{w_f} \right)^2 \cdot 1000 \left(\frac{w}{w_f} - 1 \right) \quad (7)$$

where:

- w_f – Free water saturation of the construction material [kg/m^3];
- w – water content of the construction material [kg/m^3];

The liquid transport coefficient which necessary for modeling HAM transport can be obtained using the following data for each sample tested listed in table 5 and calculating the water content depending the relative humidity from figure 4 or table 4.

Table 5. The water absorption coefficient and the free water saturation of specimens

Samples	Water absorption coefficient, A_w [$\text{kg/m}^2\text{s}^{1/2}$];	Free water saturation, w_f [kg/m^3]
S35	0.0095	113,2
S27,5	0.0046	101,5
S20	0.0047	107,3
C	0.0069	110,8

Specific heat capacity measurement

Specific heat capacity was determined from reference mixture's specific heat capacity and specific heat capacity of various fibers and contents. The measured specific heat capacity of concrete was 832.4 J/kgK , steel fibers has average of 463.4 J/kgK measured using blending calorimetry (fig.6) with distilled hot water. The common equilibrium temperature was around 88°C – 92°C . Separated component measurement was necessary because of the calorimeters size. Specimens having small weights cannot tested correctly using blending calorimetry, because of the heat capacity and the heat loss of the calorimeter affects significantly the tests.

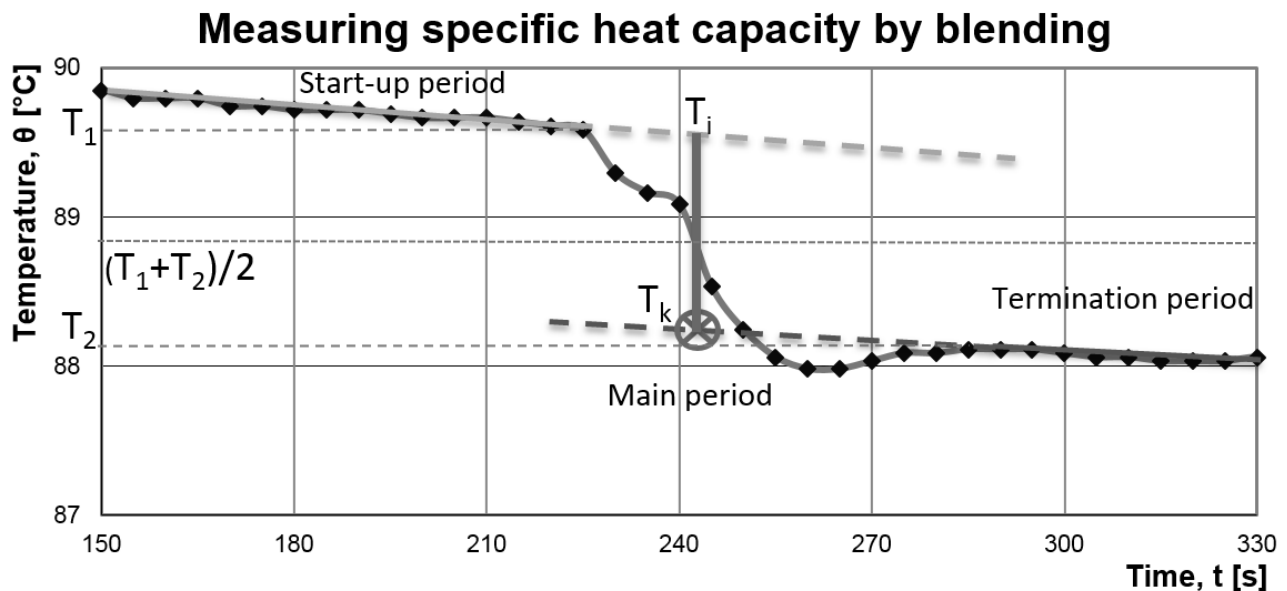


Fig. 6. Measurements of specific heat capacity by blending

Calculating the specific heat capacity from measured temperatures (using PT1000 resistance thermometers and a high precision multimeter), mass and the known properties of the vacuum flask, we need to use the following formula:

$$c_p = \frac{c_v \cdot m_v \cdot (T_k - T_i)}{m \cdot (T - T_k)} \quad (8)$$

where:

- c_p – Specific heat capacity of the specimen at constant pressure [J/kgK];
- c_v – Specific heat capacity of the vacuum flask at constant pressure [J/kgK];
- m_v – Mass of the vacuum flask [kg];
- m – Mass of the specimen [kg];
- T – Temperature of the specimen before blending [K];
- T_k – The common equilibrium temperature after blending [K];
- T_i – Temperature of the water and the vacuum flask before blending [K].

Measured and calculated results shows that there is no significant difference in specific heat capacity of the fiber reinforced and etalon concrete samples, all of the specimens' specific heat capacity varies between 830.7 – 832.4 J/kgK.

Conclusion

The paper shows that there is substantive difference between the measured thermal conductivities and the standard's values for high density or reinforced concretes. Increasing the volume of steel fiber does not increase necessarily the thermal conductivity of the fiber reinforced concretes, because this research showed that the changes in thermal conductivity of fiber reinforced concrete are primarily related to the density which is related to the total porosity. Fibers can brings air to the specimen, and increase porosity, resulting lower density, thermal conductivity, vapor resistance and can increase the water absorption coefficient and free water saturation as well.

Using the result of the paper, in the field of building physics and energy design we are able to model the steel fiber reinforced concrete's hygrothermal behavior accurately.

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