

6th International Building Physics Conference, IBPC 2015

Thermal properties and modeling of fiber reinforced concretes

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Abstract

The aim of the paper is to define the thermal properties (thermal conductivity, density and specific heat capacity) of steel, plastic and glass fiber reinforced concretes that are widely used for industrial floors, and to determine equivalent concrete thermal conductivity values for numerical thermal modelling of steel fibre reinforced concretes. In conclusion with the measurements, simulations and correlations, in the field of building physics and energy design we are able to calculate the fibre reinforced concrete's thermal behaviour accurately.

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Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: fibre reinforced concrete; thermal properties; porosity; thermal conductivity; FEA

1. Introduction

In building energy calculations it is fundamental to know the thermal properties of materials. In this paper, the thermal properties of 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% fiber volume in Hungary, resulting e.g. 20 - 35 kg/m³ steel fibers in the mixture. High density concretes and fiber reinforced

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concretes have thermal conductivity between 2.0 – 3.2 W/mK at standard temperature according to several researches [3, 10, 14, 16]. 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 by measuring the thermal conductivity and porosity of various steel-, plastic- and fiberglass reinforced concretes.

2. 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, seven recipes were made including three ones with steel fiber containing Humix 50 cold formed steel fibers with bent ends (S1-S3), two ones with plastic fiber recipes using Concix ES bi-component polyolefin macro fibers (S5-S6) and one with a mixture having Aveeglass type 12 mm HP E-glass fiber (S7). A reference mixture without fibers is also made (S4). In every case, 320 kg/m³ Lafarge CEM II/BS 42.5 normal initial strength Portland-slag cement and 154 kg/m³ 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 kg/m³ of superplasticizer Sika Visocrete-5 is also added for achieving the consistency. The compositions of the tested concrete samples are listed in table 1.

Table 1. The compositions of the tested concretes

Samples	Fiber type	Aggregates (kg/m ³)	Fibers (kg/m ³)	Designed density (kg/m ³)	Fresh concrete density (kg/m ³)	Consistency class
S1	Steel	1913	35	2424	2433	F4
S2	Steel	1916	27.5	2419	2427	F3
S3	Steel	1920	20	2414	2447	F3
S4	-	1925	0	2401	2403	F3
S5	Plastic	1920	2	2398	2427	F4
S6	Plastic	1923	1	2399	2397	F3
S7	Fiberglass	1924	1	2401	2427	F4

Each fiber reinforced concrete mixture was prepared a portion of 35 kg and distributed to six standard 15x15x15 cm cubes and three or five 20x20x10 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. The mixtures met the requirements of F4 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. (a) Fibers: Steel, Plastic, Glass; (b) Cradling; (c) Storage in water; (d) Demoulding of concrete

3. Laboratory tests

During laboratory tests, the results of each mixture were evaluated by one-sample T-test on 0.10 significance level. Thus, if a sample which was in a sample group of a mixture was considered significantly different by the test, a new mixture with the same recipe was tested as well. S5 and S7 mixture needed additional three samples tested (the averaged values including those extended mixture group results are shown in the table 1 and table 2), because the mixtures with three samples had one specimen which caused that the mixture group did not meet the requirements of the 0.10 significance level. Therefore in S5 and S7 there are samples from two mixtures with the same recipe and with five specimens neglecting the one which caused significantly different results. Furthermore, the S7 fiberglass containing specimens has different bulk density at different mixtures which presumably caused by concreting, resulting a significantly lower thermal conductivity and higher porosity values in the group, although their results match the trends showed in figure 3. The testing machines showed in figure 2 and the averaged results of the laboratory measurements are summarized in table 2.

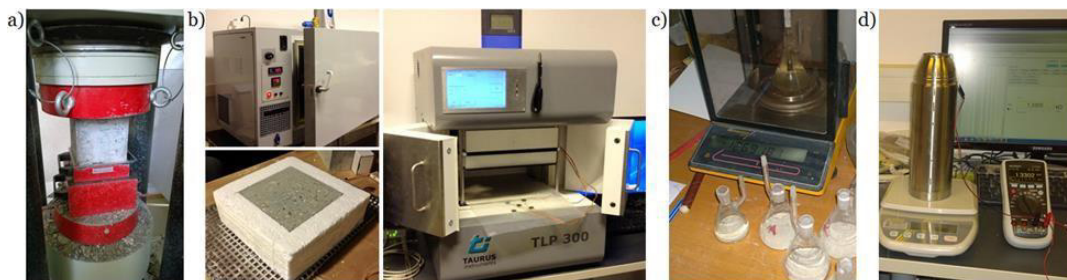


Fig. 2. (a) Compressive strength; (b) Thermal conductivity; (c) Total porosity; (d) Specific heat capacity

3.1. Compressive strength measurement

The compressive strength test was performed on 28 days old standard cubes using a Form+Test Alpha 3-3000 S hydraulic crusher (Fig. 2. a) according to EN 12390-3:2009. From each mixture, three sample cubes were tested, and from the results, the average compressive strength (f_{ck}) of samples were calculated and are shown in table 2. Test results show that additional steel fibers caused increased compressive strength due to the high elasticity modulus of steel fibers, whereas the plastic or glass fibers had no significant impact on the compressive strength.

3.2. Thermal conductivity and density measurements

For the thermal conductivity measurement, all cuboid samples were stored in wet conditions for 7 days and after stored 21 days in a climatic chamber. The specimens were tested after 28 days using a Taurus TLP 300 DTX guarded hot plate measuring instrument (fig.2.b.) according to EN 12664:2001. Before the thermal conductivity measurement, the hardened concrete's bulk density was measured according to EN 12390-7:2009. During measurements, laboratory's air temperature was set to 23 ± 2 °C and the relative humidity was between 45 – 55 %rH. 3 weeks in the climatic chamber was enough time to get the samples consolidated to 0.1 % mass change. 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. The stages were set to 5/15 °C, 15/25 °C and 25/35 °C and the tests ended when relative error in thermal conductivity was under 0.2 %. The results are given in the table 2 according to EN ISO 10456:2007 I.b. declared value conditions.

As shown in figure 3, based on researches [10, 12], close correlation expected between bulk density and thermal conductivity of fiber reinforced concretes. Higher density caused increased thermal conductivity. Meanwhile results showed that steel fiber reinforced concretes has higher density and thermal conductivity values than plastic or fiberglass reinforced specimens. However, figure 3 shows that increasing steel fiber content in concrete did not result

in higher thermal conductivity, but lower. The explanation of the phenomenon can be seen in table 2. Specimens with higher fiber content had higher total porosity resulting lower densities as well. Additional fiber content lowers the total porosity of specimens comparing to S4 reference mixture, meanwhile increasing the fiber content, the total porosity increases as well. Figure 3 shows that plastic or steel fibers did not affect the thermal conductivity significantly due to their industry applied small content. All tested specimen's thermal conductivity values were higher than high density and reinforced concrete's values according to EN ISO 10456:2007, besides that our measurements fit previous researches thermal conductivity range [3, 10, 14, 16], but did not prove that additional steel fiber content always increases the thermal conductivity. In case of using the standard's values of reinforced concretes can lead to underestimate the thermal transmittance in case of fiber reinforced concretes.

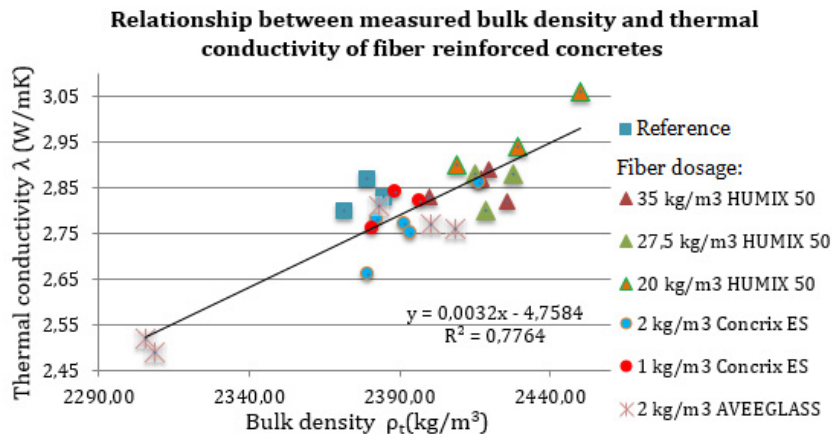


Fig. 3. Relationship between measured bulk density and thermal conductivity of fiber reinforced concretes

3.3. Total porosity measurement

The physical properties of concrete depends especially on porosity, within the distribution of the pores, size and shape [15]. In this paper, only the hardened concrete's total porosity was investigated to get correlations between porosity, density and thermal conductivity of different fiber reinforced concretes. The total porosity of specimens was determined using the bulk densities calculated according to EN 12390-7:2009 and material densities measured with pycnometers (fig.2.c). For the pycnometer test, pulverization of the specimens needed, therefore half of the samples used in thermal conductivity measurements was shredded. Results shows in table 2 that adding small amount of fibers in the mixtures can lower the total porosity, but increasing the fiber content results in higher total porosity. Fibers brings air to the specimen during concreting, therefore increase total porosity and lowers density and thermal conductivity values.

3.4. 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, plastic fibers 625.3 J/kgK and the glass fibers had 802.5 J/kgK measured using blending calorimetry (fig.2.d) 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. Results showed that there is no significant difference in specific heat capacity. The calculated specific heat capacities of an average fiber distribution in mixtures are showed in table 2.

3.5. Average measured results of the laboratory tests

The average measured values of mixture groups studied above showed in table 2.

Table 2. Results of the laboratory tests

Samples	Avg. bulk density (kg/m ³)	Avg. compressive strength, f_{ck} (N/mm ²)	Avg. thermal conductivity (W/mK)	Avg. material density (g/cm ³)	Avg. total porosity (%)	Avg. specific heat capacity (J/kgK)
S1	2420.70	63.645	2.86	2.59	7.47	830.7
S2	2420.44	64.495	2.85	2.56	6.19	831.1
S3	2429.38	61.950	2.97	2.55	5.47	831.5
S4	2378.34	56.648	2.83	2.57	7.46	832.4
S5	2397.57	56.464	2.76	2.58	7.14	832.0
S6	2388.81	56.272	2.81	2.56	6.51	832.2
S7	2397.36	56.651	2.67	2.56	7.75	832.4

4. Finite Element Analysis of steel fiber reinforced concretes

Firstly, 3D model of an average steel fiber was made with Autodesk Inventor. The Humix 50 steel fibers are described 50 ± 1.5 mm length and have 1 ± 0.02 mm diameter. To determine the average content of the three mixtures, 50 randomly chosen steel fibers weight were measured with an average of 0.304 g. Therefore to simulate S1 and 20 kg/m³ steel fiber content, 264 pieces of steel fibers were randomly oriented in a 20x20x10 cm specimen. For the S2 mixture, 362 pieces and for the S3 mixture 461 pieces of steel fibers are needed. In reality, volume of steel fibers can slightly differ in the same mixture's specimens depending on concreting process. In the simulation, 5 different randomly oriented models were made for each mixture. The orientation of the fibers were checked using collision test to avoid the intersections between steel fibers. Then the geometry models of virtual specimens were simulated by using Autodesk Simulation CFD software (fig. 4). For the meshing, simplex tetrahedral elements were used. The thermal conductivity of steel fibers set to 55 W/mK and the equivalent thermal conductivity of concrete was iterated and chosen to get the measured thermal conductivities of each sample. Therefore the simulation was calibrated by the concrete's thermal conductivity. The boundary conditions were 20 °C and 0 °C on sides without surface resistance. these may be placed next to each other to save space. For example, see Fig. 1.

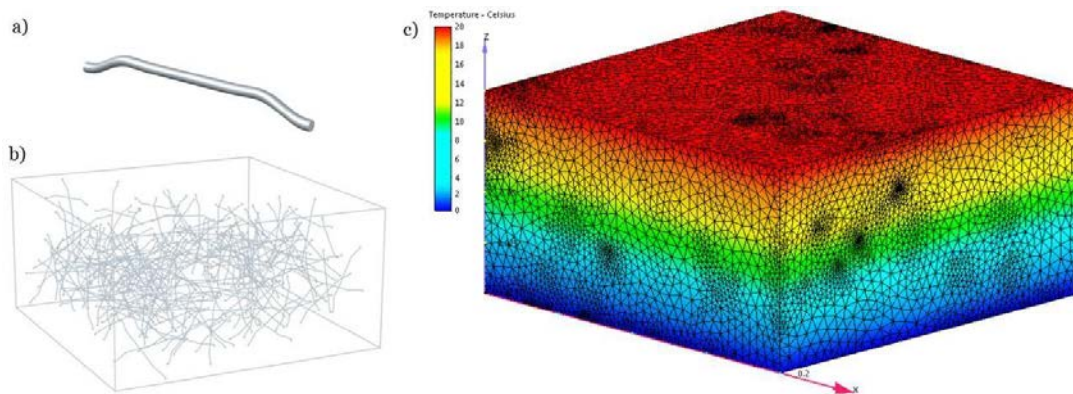


Fig. 4. (a) Geometrical model of HUMIX 50 steel fiber; (b) Steel fiber distribution in a sample; (c) FEA of a sample, temperature distribution

After the simulation, the heat flow from a surface was retrieved and the thermal conductivity of the sample was calculated. The iteration of the concrete's equivalent thermal conductivity was done until the difference between measured and simulated values were lower than 0.2 %. The results of the three sample group summarized in table 3.

Table 3. Results of the calibrated simulation

Samples	Steel fibers (kg/m ³)	Measured thermal conductivity (W/mK)	Steel thermal conductivity (W/mK)	Eqv. concrete thermal conductivity (W/mK)	Simulated avg. thermal conductivity (W/mK)
S1	35	2.86	55	2.78	2.8625
S2	27.5	2.85	55	2.80	2.8548
S3	20	2.97	55	2.93	2.9732

As the results shown, the equivalent concrete thermal conductivities used to get the measured data decreases exponentially with increasing steel fiber addition. Therefore in the tested range, according to FEA, the following equation describe the equivalent concrete thermal conductivity, where m_{sf} is the steel fiber content:

$$\lambda_{c,eqv} = 0.0009778 \cdot m_{sf}^2 - 0.06378 \cdot m_{sf} + 3.8144 \quad (1)$$

5. 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 bring air to the specimen, and increase total porosity, resulting lower density and thermal conductivity. In conclusion with the measurements and correlations, in the field of building physics and energy design we are able to calculate accurately the fiber reinforced concrete's thermal behavior.

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