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Thermal properties of historic rural building materials in Czechia

P. Kic[1,*] and P. Neuberger[2]

[1]Czech University of Life Sciences Prague, Faculty of Engineering, Department of Technological Equipment of Buildings, Kamýcká 129, CZ165 21 Prague, Czech Republic
[2]Czech University of Life Sciences Prague, Faculty of Engineering, Department of Mechanical Engineering, Kamýcká 129, CZ165 21 Prague, Czech Republic
[*]Correspondence: kic@tf.czu.cz

Abstract. Due to the different natural conditions, various local natural building materials were used for the construction of rural residential and farm buildings in various locations in the Czech Republic. Currently, it is often a requirement for the modernization of relatively old buildings. The buildings were built with different technologies. Very often only locally available material was used. In many cases, the properties of old materials are not available in the literature. However, it is necessary to know the thermal properties of building materials for the preparation of a reconstruction design. Thermal properties of materials are the basis for determination of heat losses of buildings useful for design of heating systems. The aim of this paper is to compare the research results focused on the thermal conductivity of different old construction materials (stones and rocks) and to show examples of preserved historical agricultural buildings. The results presented in this paper are based on the measurements by the portable instrument Isomet 2104. Authors recognised significant differences between tested materials. The mean values of thermal conductivity λ_m of tested materials: gaize 1.49 W m^{-1} K^{-1}, artificial marble 1.80 W m^{-1} K^{-1}, gneiss 2.36 W m^{-1} K^{-1}, proterozoic shale 2.68 W m^{-1} K^{-1}, granite 3.66 W m^{-1} K^{-1} and quartz sandstone 6.15 W m^{-1} K^{-1}. Differences between thermal conductivity values of stones and rocks should be respected in calculation of heat balance of new or reconstructed buildings to avoid the problems of the formation of thermal bridges.

Key words: dynamic method, measurement, rocks, stones, thermal conductivity.

INTRODUCTION

Due to the different natural conditions, various local natural building materials were used for the construction of rural residential and farm buildings in various locations in the Czech Republic. Currently, it is often a requirement for the modernization of relatively old buildings. The buildings were built with different technologies. Very often only locally available material was used. The combination of different materials with not well known thermal properties can cause significant reduction of thermal insulation and the formation of thermal bridges.

In the world, there are many areas where timber (north of Europe, Scandinavia, mountainous areas of the Czech Republic, etc.) is predominantly used for constructions elsewhere clay was available therefore bricks were produced; in many areas stone and rocks are very common materials, which also have a large heat accumulation (e.g. Italy, central part of Czech Republic and others). The materials from which the buildings were built change their properties due to external climate and chemical changes of materials during the years of use.

In some cases, the properties of old materials are not available in the literature. However, it is necessary to know the thermal properties of building materials for the preparation of a reconstruction design. The diversity of building materials in old rural buildings can be explained mainly by efforts to reduce investment costs and availability of resources. That is why there are used mainly local resources. The building material is therefore also used repeatedly. It is no exception to dismantle the ruins of mansions or buildings damaged by fire and the use of those old materials for new construction.

Historical residential and church buildings around Prague include typical materials: Romanesque style (10^{th} to 12^{th} century) – marlstone, gothic (12^{th} to 16^{th} century) – sandstone, baroque (17^{th} to 18^{th} century) – marble, 19^{th} century – granite. Agricultural structures are not so precisely defined in terms of time and material. Many authors, however, pay attention to building materials used for agricultural construction in their publications. In some cases, these are special constructions such as Conti et al. (2016a); Leso et al. (2017), sometimes using non-traditional material.

A very common problem is the reconstruction of buildings when using a combination of stone with other materials, such as brick masonry or blocks, as there may be a significant reduction in thermal insulation and the formation of thermal bridges (Kollmorgen, 1998; Ladener et al., 2001; Šubrt &Volf. 2003; Tywoniak, 2005).

Thermal conductivity is the most important parameter of thermal-technical properties of materials. It is used mainly in civil engineering. Its real value is a function several internal and external variables (density, moisture, temperature, porosity, chemical and mineralogical composition and phase composition, crystalline modification etc.). The attention is paid to the problems of insulation properties in different publications, e.g. (Muizniece et al., 2015; Kocova & Kic, 2016; Pleiksnis et al., 2016; Týbl & Kic, 2016; Valasek et al., 2016). The results of thermal conductivity measurements are discussed, e.g. in Conti et al. (2016b).

Thermal properties of building materials greatly affect the indoor environment, especially the indoor temperature of the building during winter and summer. This topic in agricultural constructions is solved, for example, by Kic (2017).

Thermal properties of materials are the basis for determination of heat losses of buildings useful for design of heating systems. Currently used tables of building materials do not include all locally used materials. For some of them, it provides a range of values Ražnjević (1984). Insufficient knowledge of exact values makes calculation of heat losses of buildings more difficult.

The aim of this research is to demonstrate the use of the dynamic method for measurement of a thermal conductivity for determination of thermal properties of materials used for buildings, especially of stone and rocks. It is important to show and confirm that there are significant differences between them. It should be also confirm the ability to obtain more accurate background data included in models used for heat losses calculation of older constructions.

MATERIALS AND METHODS

Five different materials were selected for this research work. The first material is artificial marble. This material is very popular and many companies are producing this material according to their patents. It is useful, to compare it with natural real materials. The artificial stone tested in this research was a marble imitation stone tile. The sample of tested material weighs 1 kg. The surface sensor was used to determine the thermal conductivity.

The second material is gneiss, which is available in many localities in the Czech Republic. A sample of this material was taken from a village in Southwest Bohemia. An example of the use of this local material is a set of buildings in this village of Fig. 1. It is a typical building for the folk architecture of Prácheňsko – the historical territory in the southwest of the Czech Republic. Fig. 1 shows the triangular stone shield of one of the buildings. This material is currently used as a buildings stone for different construction purposes. The sample of tested material weighs 1.95 kg. The surface sensor was used to determine the thermal conductivity.

Figure 1. Original folk architecture in the village Klínovice – stone triangular shield.

Quite frequently used for constructions is also the third tested material proterozoic rock (shale), which is easy to manipulate and prepare for different use in constructions. A tested sample of proterozoic shale was taken near the Prague – Suchdol district, where it is widely distributed. This material is used as a quarry stone. The sample of tested material weighs 1.6 kg. The surface sensor was used to determine the thermal conductivity.

The fourth tested material is granite. Granite is nearly always massive (lacking any internal structures), hard and tough, and therefore it has gained widespread use throughout human history as a construction stone. Granite tables are used extensively because of granite's rigidity, high dimensional stability, and excellent vibration characteristics. Granite – the tested material was a medium-grained grain pattern gradient. The slab was used to build the house as a window sill. The material is currently also very often used for decorative purposes, memorials and paving. The sample of tested material weighs 10.2 kg. The surface sensor was used to determine the thermal conductivity.

The fifth material is gaize. Gaize is a sedimentary rock, a dusty species of marl. Gaize was formed from the finest particles settled on the seabed. It consists of clayey and dusty particles, it also contains limestone components and needles of sea mushrooms of microscopic dimensions (so-called sponges). The amount of these needles determines its strength and durability. In addition to these, there are also frequent remnants of dirconos. The common mineral admixture is glauconite. It has whitish to sandy yellowish-gray color. In Romanesque style, gaize was an important building material. As a building material, gaize were used mainly in Romanesque buildings. The presence of sponge needles increases the quality of stone for technical purposes, especially its strength. Family houses and farm buildings are constructed by use of this material which is available in several localities in the Czech Republic.

Gaize a tested sample of this material was taken in village Horoměřice (near Prague). The use of this material in construction is shown in Fig. 2. This is the original farmhouse in the village of Dušníky (currently part of Rudná near Prague). During its construction was used gaize from nearby quarries. The reason for its use was just its availability, perhaps even lightness and workability. From the quarries from the same area comes the stone of many Prague Romanesque monuments.

Figure 2. Reconstruction of a farmhouse in the village Dušníky.

This material is common in many areas of the Czech Republic (Marešová, 2006). According to additions its properties differ significantly. For example, quartz admixtures can be assumed in the test sample. The sample of tested material weighs 0.64 kg. The surface sensor was used to determine the thermal conductivity.

The sixth material is a quartz (quartz sandstone). It is a material whose component (quartz) is characterized by the highest values of the coefficient of thermal conductivity. The sample was taken near the village of Horoměřice. Quartz crystals prevailed in the sample. Near the village there is also gaize. As a building material, sandstone was used mainly in Gothic buildings. The sample of tested material weighs 3.15 kg. The surface sensor was used to determine the thermal conductivity.

For measurement of thermal conductivity the Isomet 2104 instrument (Applied Precision Ltd, Bratislava) with surface sensor was used. Isomet 2104 (Applied Precision Ltd., 2018) is a portable instrument controlled by microprocessor, to which the manufacturer supplies exchangeable needle and surface sensors of various ranges. The calibration constants are stored in the sensors memory.

This instrument measures the thermal conductivity, temperature and specific heat capacity of compact and loose materials. For the thermal conductivity is permissible measurement error 5% of reading + 0.003 W m^{-1} K^{-1}. The measured values can be stored in the internal memory of the instrument. The content of memory is accessible via display. Data can be transferred via RS-232 interface to a PC. The instrument can be powered from AC or battery.

To determine the thermal conductivity of the material is used unsteady method. This compared to stationary methods significantly reduces the time of measurement. The device analyses the time dependence of thermal responses to impulses of heat flux supplied to the material. The heat flux creates scattered electric output from the resistor located in the sensor. The sensor has a thermally conductive connection with the analysed material. Temperature resistance is sensed by a semiconductor sensor.

Temperature variation as a function of time is tested in discrete points. The obtained points are interleaved by regression polynomials using the method 'least squares'. The coefficients of the regression polynomials are used to calculate the thermo-physical parameters using analytical formulas.

Air temperatures and relative humidity were measured by sensor FHA 646–21 with operative range from -30 to +100 °C with accuracy ± 0.1 °C, and air humidity by capacitive sensor with operative range from 5 to 98% with accuracy ± 2% connected to the measuring instrument ALMEMO 2590–9 (Ahlborn GmbH, Germany).

There was used for the indirect measurement of material moisture the capacitive sensor FH A696–MF with operative range of mineral construction materials from 0 to 20% with accuracy 0.1%. The sensor was connected to the data logger ALMEMO 2690-8 (Ahlborn GmbH, Germany).

Ten measurements were carried out for each experimental material. Measurements were carried out under laboratory conditions by the air temperature of 25–26 °C and relative humidity 31–36%.

Each sample of the tested compact materials was measured ten times and, if possible, the surface sensor was attached to the sample at a suitable representative site to eliminate any potential differences in the structure. To improve the adhesion of the probe to the measured material, the contact surfaces were painted with thin layer silicone grease. Before each measurement, the sample was temperature-stabilized to ambient temperature. The surface for the probe was adjusted by grinding. The sample size of the material always exceeded the manufacturer's requirements. The probes were calibrated at the factory in 2017.

The obtained results of measurement were processed by Excel software and values of thermal conductivity were verified by statistical software Statistica 12 (*ANOVA and TUKEY HSD Test*). Different superscript letters (a, b, c, d) mean values in common are significantly different from each other in the row (*ANOVA; Tukey HSD Test;* $P \leq 0.05$), e.g. if there are the same superscript letters in all the columns it means the differences between the values are not statistically significant at the significance level of 0.05.

RESULTS AND DISCUSSION

Main parameters of tested material samples which are density ρ_m and moisture w_m of materials, temperature t_a and relative humidity RH_a of air during the measurement are given in the Table 1. This table also contains statistical indicators of measured thermal conductivity λ_m. The data are the mean values ± SD (standard deviation). Different letters (a, b, c, d) in the superscript are the sign of high significant differences *(ANOVA; Tukey HSD Test; $p \leq 0.05$).*

Table 1. Density ρ_m and moisture w_m of materials, temperature t_a and relative humidity RH_a of the air during the measurement and resulting values of thermal conductivity λ_m of tested materials. Different letters (a, b, c, d) in the superscript are the sign of high significant difference (*ANOVA; Tukey HSD Test*; *$P \leq 0.05$*)

Parameter	Material					
	Artificial marble	Gneiss	Proterozoic shale	Granite	Gaize	Quartz sandstone
m, kg	1	1.95	1.6	10.2	0.64	3.15
ρ_m, kg m^{-3}	2,041.0	2,110.0	2,318.8	2,924.7	2,356.6	2,333.3
w_m ± SD, %	8.2 ± 0.2	5.8 ± 0.5	8.5 ± 1.4	7.2 ± 0.2	23.4 ± 0.5	4.6 ± 0.4
t_a ± SD, °C	25.9 ± 0.5	25.8 ± 0.4	25.1 ± 0.5	26.0 ± 0.2	23.3 ± 0.1	25.8 ± 0.5
RH_a ± SD, %	32.2 ± 1.0	32.7 ± 0.9	32.2 ± 0.8	31.9 ± 1.0	32.8 ± 1.4	32.4 ± 1.1
λ_m ± SD, W m^{-1} K^{-1}	1.80 ± 0.12^a	2.36 ± 0.33^b	2.68 ± 0.16^b	3.66 ± 0.07^c	1.49 ± 0.01^a	6.15 ± 0.30^d

SD – Standard deviation.

Table 1 shows that the lowest value of thermal conductivity λ_m = 1.49 W m^{-1} K^{-1} was measured on the sample of gaize. Very low, statistically not significantly different from gaize was the thermal conductivity λ_m = 1.80 W m^{-1} K^{-1} measured on the sample of artificial marble. It can be caused by the composition of ingredients and used for the production of this material. The composition provides artificial marble having a deep appearance characteristic of marble and having properties according to the composition. This material has also the lowest density 2,041 kg m^{-3}.

The differences between the thermal conductivity of gneiss λ_m = 2.36 W m^{-1} K^{-1} and proterozoic shale λ_m = 2.68 W m^{-1} K^{-1} were not statistically significant. Granite was the heaviest tested material and also its thermal conductivity λ_m = 3.66 W m^{-1} K^{-1} was bigger than previous materials.

Surprisingly the biggest values of thermal conductivity λ_m = 6.15 W m^{-1} K^{-1} were measured on the samples of quartz sandstone. This value is more than twice higher than gneiss or Proterozoic shale.

CONCLUSIONS

The results of measurements presented in this paper can be used for practical information useful for design and calculation of heat balance of new or reconstructed buildings. Significant differences of thermal conductivity of tested materials should be recognised and respected.

There are important differences between thermal conductivity values of stones and rocks used in the constructions. The thermal conductivity varies according to the tested materials from $\lambda_m = 1.80$ W m^{-1} K^{-1} to 6.15 W m^{-1} K^{-1}.

The results obtained by the dynamic unsteady method of measurements correspond to the thermal conductivity values mentioned in the literature (Ražnjević, 1984; Eppelbaum, 2014). A comparison of samples 5 and 6 shows that even materials occurring in one locality may have very different thermal properties. The use of the chosen method for determination of thermal conductivity of the material used for a particular historical building can significantly improve the determination of thermal losses of the building. The quartz contained in rocks significantly increases their thermal conductivity (sample 6).

A very common problem is the reconstruction of buildings when using a combination of stone with other materials, such as brick masonry or blocks, as there may be a significant reduction in thermal insulation and the formation of thermal bridges. The used instrument can detect locations of a perimeter construction with different thermal conductivity.

Portability and short duration of the tests make it ideal for the use outside the laboratory. It will be useful in real conditions for inspection and audit activities on already completed buildings. Described method can be used for this purpose as it is available and enough precise.

The presented method of measurement and obtained results can be suitably used in the preparation of laboratory exercises for university students of engineering study.

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