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Thermophysical properties of masonry units: Accurate characterization by means of photothermal techniques and relationship to porosity and mineral composition

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HIGHLIGHTS

- Natural stones from exploitable quarries located in Transylvania has been analyzed.
- Thermophysical properties of masonry units were measured by photothermal techniques.
- An image processing procedure for measuring the porosity has been proposed.
- The mineralogical composition and porosity affect the thermo-physical properties.
- Limestone can offer an alternative solution for cladding the walls.

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ABSTRACT

The concerns on saving energy and CO_2 emissions in residential sector made the measures adopted in the last years to be focused on using building envelope materials with low embodied energy and improved thermo-technical properties. Considering that the sustainable behavior of materials during the buildings entire life cycle is much influenced by its mineralogical content, thermo-technical characteristics and physico-mechanical properties, the paper analyze from this point of view three types of masonry units (tuff, limestone, autoclaved aerated concrete) in order to be used as units in masonry works or for wall cladding. The mineralogical content has been determined microscopically in thin sections and by X-ray diffraction while the samples' porosity was measured into laboratory by volumetric methods and by using a new binary image analysis algorithm. Contact photopyroelectric calorimetry and non-contact infrared lock-in thermography have been used in order to measure with high accuracy the dynamic thermal parameters (thermal diffusivity, effusivity and conductivity) of these materials.

The results highlights that mineralogical content, size and distribution of pores directly influence the thermal characteristic of materials and their behavior to moisture transport and decay process in aggressive environment.

1. Introduction

Saving energy and CO_2 emission in construction sectors becomes in the last century an important target in order to reduce the environmental impact and depletion of natural resources (oil, coal and natural gas). It is well known that building energy efficiency depends on the materials included in building envelope members and fuel types used for heating or cooling the interior air space. From a sustainable point of view an efficient building material should resist in normal or aggressive environments, it shall be free from toxic substances, it must have low thermal conduction properties, it must be affordable, recyclable and re-usable at the end of the constructions life cycle [1].

The natural stones have been used in construction for thousands of years as rock [2,3] or as binding or filler materials in mortars or concrete [4,5]. Due to low cost, low embodied energy and ability to store energy, the natural stones as masonry unit are still considered an alternative solution to traditional building material (ceramic bricks or artificial sandstone) which can be used for construction of ecological buildings or wall cladding [6]. In this

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context, some natural stones (volcanic tuffs and limestone) that are spread out on wide areas from Transylvanian Basin and Apuseni Mountains are an attractive alternative for Romanian building material industry.

The autoclaved aerated concrete (AAC) is an artificial building material invented at the beginning of the 20th century by Johan Axel Eriksson [7] and used for masonry works and thermal insulation layer due to its low density and low thermal conductivity. Physico-mechanical properties or thermal characteristics of stones and autoclaved aerated concrete are directly influenced by the size, geometry and the number of pores/volume [8,9].

Natural stones are porous, permeable and water absorbing. The absorption properties depend on the characteristics of pores and the extent to which the pores and capillary structures are interconnected within the stone. The pore size and orientation affect the degree to which moisture is absorbed into the stone and influence the behavior and sustainability of materials [10–12] during the entire lifecycle. Instead of natural stone, the microstructure of autoclaved aerated concrete consists of rounded pores of different size, having an isotropic character.

In the meanwhile the knowledge of thermo-physical properties of building materials is very important for an optimal design and material selection in order to create energy-efficient buildings. The parameters that characterize the insulating properties of a material are: volume specific heat (C), thermal diffusivity (α), thermal effusivity (e) and thermal conductivity (k). In building materials the most frequently investigated parameters are the thermal diffusivity and the thermal conductivity. The thermal diffusivity of building materials are currently measured by the flash method [13,14]. The thermal conductivity measurement is generally performed by a classical steady-state method [13,15], but the accuracy of the method is generally poor and the measurement takes long. The application of stationary classical methods is possible only in the case of samples with exactly determined dimensions (very demanding concerning sample preparation). Due to the large sizes required for sample preparation, the use of these methods is limited for thermal characterization of new materials, being almost impossible to be used for old materials where the dimensions of collected samples are reduced. Also, the stationary methods don't offer the possibility to measure materials with moisture content.

To overcome this shortcoming, non-contact infrared lock-in thermography technique (LiT) is used to measure the thermal diffusivity of natural stones, whereas the photopyroelectric calorimetry (PPE) is used to determine their thermal effusivity. These two thermal parameters have an important meaning concerning heat conduction in building materials: (i) thermal effusivity is a measure of material's ability to exchange thermal energy with its surroundings; (ii) thermal diffusivity measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. In such a way, the thermal conductivity is indirectly determined by using the well-known relationship between the thermal parameters: $k = C\,\alpha$ and $e = (Ck)^{1/2}$.

This study is focused on the influence of porosity and mineralogical content of a volcanic tuff (sample S1), limestone (sample S2) and autoclaved aerated concrete (sample S3) on their thermo-physical and mechanical properties. The basic idea is that the pore geometry, size and their distribution and the mineralogical composition can affect the thermal performance and the sustainable behavior of the material and buildings as a whole. For this purpose, an accurate characterization of thermophysical properties of the investigated samples by means of photothermal techniques is required.

An image processing approach based on binary image analysis (BIA) is proposed in order to accurately calculate the average porosity and pore's size distribution. Prior image analysis methods for measuring porosity distribution were developed [16,17]. The results obtained by BIA are comparable to volumetric methods.

2. Research methodology

2.1. Mineralogical analysis

Mineralogical and structural investigations of samples were performed by petrographic analysis (in thin sections) and X-ray diffraction.

2.2. Physico-mechanical analysis

The physico-mechanical analysis is consisting of the following investigations: the total porosity, the apparent density (ρ_a), the capillary water absorption coefficient (w) and the compressive strength (f_b).

An image processing approach based on the binary image analysis (BIA) was proposed in order to accurately calculate the porosity in the investigated samples, and compared with the results obtained into laboratory. The method for image processing is described below.

2.2.1. Porosity amount by binary image analysis

For the binary image analysis, the samples were cut along one direction and micro photographed by using an Optika B-383MET microscope. Within the acquired images, the bright areas correspond to the material pores, whereas the dark ones represent the bulk. The estimation of the surface coverage corresponding to the material pores within the captured images may lead to the porosity determination. Our proposed workflow of image processing included the following three steps: (1) pre-processing for intensity inhomogeneity correction (2) anisotropic diffusion for noise removal and (3) maximum entropy thresholding for image segmentation.

It is well known that the intensity inhomogeneity reduces the accuracy of classical image segmentation approaches. Thus, we successfully applied the local entropy minimization approach proposed by Salvado et al. [18] to correct severe intensity inhomogeneity over the acquired images. Further on, in the second step, the anisotropic diffusion [19] was used to remove noise, whereas the essential information was retained and enhanced. Considering the diffusion process, selective conduction coefficient was used either to privilege high contrast edges in the case of small size pores, or to privilege wide regions over the smaller ones in case of increased size pores. In the last step, a maximum entropy algorithm was computed for each image pixel [20]. The thresholding procedure assigned the pixels' intensity to one of the two groups: foreground (high value) or background (low value), corresponding to the samples' pores or material, respectively. In doing so, the resulted binary images reveal the percentage of pixels assigned to the material pores relative to the total number of pixels corresponding to a specific sample.

2.3. Thermophysical properties

Thermal effusivity measurement has been carried out by contact photopyroelectric calorimetry (PPE) in front detection configuration, and thermal diffusivity has been measured by infrared lock-in thermography (LiT).

The pyroelectric effect consists in the induction of spontaneous polarization in a noncentrosymmetric, piezoelectric crystal, as a result of temperature change in the crystal. In principle, in the PPE method, the temperature variation of a sample exposed to a modulated radiation is measured with a pyroelectric sensor, situated in intimate thermal contact with the sample. The main advantages of this technique were found to be its simplicity, high sensitivity, non-destructive character and adaptability to practical restrictions imposed by the experimental requirements.

Concerning the PPE detection configurations, two of them, "back" and "front", respectively, have been mainly applied for calorimetric purposes. In the back configuration, a modulated light impinges on the front surface of a sample, and a pyroelectric sensor, situated in good thermal contact with the sample's rear side, measures the heat developed in the sample due to the absorption of radiation. PPE technique, in front detection configuration, is based on the direct irradiation of a pyroelectric sensor in intimate thermal contact with the investigated sample [21]. If the sensor is opaque, part of the radiation is absorbed on its front electrode and transformed into heat. The heat developed in the sensor propagates through the sensor-sample system, the sample acting as a heat-sink. Due to the thermal gradient between the two electrodes, the sensor generates an electrical signal which is a complex quantity, both amplitude and phase of the signal depending on the thermal parameters of the sample. In particular, the phase of the PPE signal is given by [22]:

$$\tan\Theta = \frac{(1+R_{mp})\exp(-x)\sin(x)}{1-(1+R_{mp})\exp(-x)\cos(x)}; \tag{1}$$

with $x = a_pL_p$, $R_{mp} = (1 - b_{mp})/(1 + b_{mp})$, $b_{mp} = e_m/e_p$.

In Eq. (1) R_{mp} represents the reflection coefficient of the thermal wave at the 'm' interface, L_p is the geometrical thickness of the pyroelectric sensor, e represents the thermal effusivity and a is the reciprocal of the thermal diffusion length ($a = 1/\mu$),