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Characterization of hygrothermal properties of sandstones—Impact of anisotropy on their thermal and moisture behaviors

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ABSTRACT

Sandstones are widely used in historic buildings. To assess energy and moisture performance of these buildings and find suitable retrofit strategies, thermal and hygric properties of sandstones are needed. Sedimentary structure of sandstones leads to their directionally dependent properties. In this paper, hygrothermal properties of four sandstones are experimentally investigated and each sandstone is characterized in the directions parallel and perpendicular to the bedding plane. Thermal properties of the studied sandstones are comparable between two directions, while moisture transport properties have a pronounced directional dependence. Lower liquid water conductivity and water vapor diffusivity occur in the perpendicular direction, which is validated by the phenomena observed from water absorption and drying tests. By conducting a benchmark case, the influence of hygrothermal property anisotropy on the thermal and moisture responses of the construction is illustrated. The results show that the property anisotropy has a weak impact on the thermal behavior, but has a strong influence on the moisture behavior, which further affects the thermal behavior due to material's moisture dependent thermal conductivity.

1. Introduction

To meet the European Union 2020 climate and energy targets, it is necessary to minimize energy consumption of both newly erected dwellings and existing buildings [1]. Retrofit of historic buildings plays a significant role in terms of improving energy efficiency, reducing greenhouse gas emission, and maintaining sustainability of the building environment [2]. Good knowledge of the existing structure and applied materials, as well as the local environment, is fundamental to finding the most appropriate retrofit strategy. Sandstones are widely used in historic buildings for their easy workability, remarkable durability, good compressive strength, and a great quantity. Standing for a natural building material, sandstone does not need further technical producing process compared to concrete and brick, thus this material has a little environmental impact. Dependent on the composition, sandstones exhibit a variety of textures and colors which make them very attractive and elegant from the esthetic perspective. Therefore, this material is also popularly used in the newly erected buildings.

Thermal and hygric properties of building materials determine the hygrothermal behavior of building envelope, which further impacts on indoor comfort, indoor air quality, building energy needs and service life [3–5]. Only few researchers have studied the hygrothermal aspects of natural sandstones. Krus [6] reported moisture related basic characteristics of four types of German sandstones to study their hygrothermal behaviors. Mukhopadhyaya et al. [7] measured hygrothermal properties of two Canadian sandstones used for claddings. Kočí et al. [8] worked on the mechanical, hygric, and thermal properties of three types of sandstones originating from Czech Republic to assess the service life of historical building envelopes made of sandstones. They also emphasized the importance of material characterization on the performance analysis of a structure. The properties of the sandstones in the aforementioned studies are listed in Table 1.

Sandstones are formed by weathering and erosion of the preexisting rocks, followed by transport and sedimentation of detritus. The deposited detritus is further consolidated by compaction and cementation during the process of diagenesis [9]. This particularly geological setting leads to a distinct bedded structure. Therefore, the characteristics of sandstones, e.g., mechanical, thermal, and hydraulic properties, vary with directions. The directional dependency on any type of measurement is called anisotropy [10]. Many building materials, e.g., wood and extruded earth brick, show directionally dependent properties [11,12]. The strength anisotropy and hydraulic anisotropy of sandstones have been well acknowledged in the rock engineering and geoscience [13–15]. However,

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Nomenclature

HAM	heat, air, and moisture
A_w	water absorption coefficient (kg/m^2 s$^{0.5}$)
k_l	liquid water conductivity at near saturation (s)
p_c	capillary pressure (Pa)
pC	logarithmic capillary pressure, $pC = \log(-p_c)$ (log Pa)
R_v	gas constant of water vapor (J/kg K)
T	temperature (°C)

Greek symbols

ρ	bulk density (kg/m^3)
c	specific heat capacity (J/kg K)
λ	thermal conductivity (W/m K)
θ	moisture content (m^3/m^3)
θ_{por}	open porosity (m^3/m^3)
θ_{eff}	effective saturation moisture content (m^3/m^3)
θ_{cap}	capillary saturation moisture content (m^3/m^3)
$\theta(pC)$	moisture retention function (m^3/m^3)
μ	water vapor diffusion resistance factor (–)
φ	relative humidity (–)

Subscript

l	liquid water
v	water vapor
dry	dry-cup measurement
wet	wet-cup measurement

a systematic study on the directionally dependent hygrothermal property of sandstones is still lacking and the relevant impact of the anisotropy has not been investigated yet in building science.

This paper studies the hygrothermal properties of building sandstones, with special focus on the influence of the property anisotropy on their thermal and moisture behaviors. Section 2 describes the sandstones investigated in this research. Section 3 presents the experimental methods to measure the hygrothermal properties of sandstones. A material model is also introduced to characterize the stones oriented in the directions parallel and perpendicular to the bedding plane. The results and discussion are illustrated in Section 4. Section 5 explores the impact of hygrothermal property anisotropy of sandstones on the thermal and moisture behaviors of a masonry wall.

2. Material

Four natural sandstones originating from Germany are analyzed in the present study: Arholzen, Karlshafen, Sander, and Schleerither sandstones. They are widely used for building constructions, sculptures, and monuments. The petrography and fabric of the sandstones are listed in Table 2 and their photos are presented in Fig. 1.

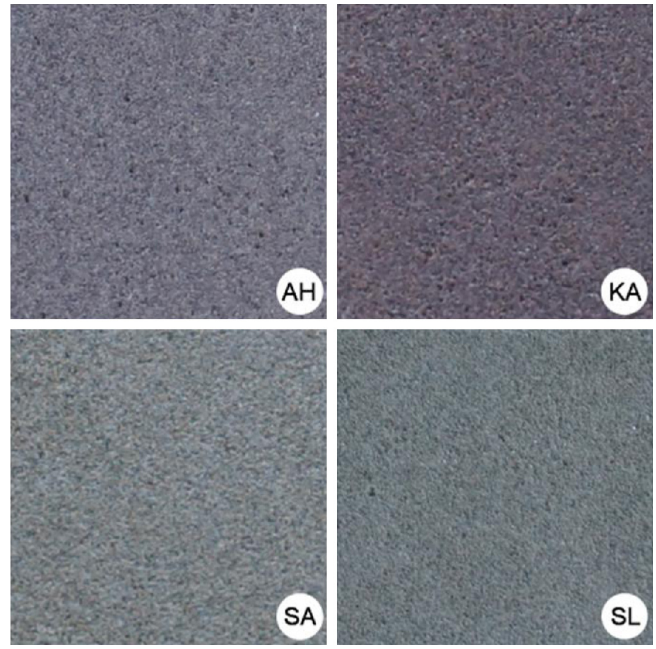

Fig. 1. Photos of the investigated sandstones.

Arholzen and Karlshafen sandstones belong to Weser sandstone occurring in the area of the upper Weser and the lower Diemel. These two stones date from the Lower Triassic and are characterized by a sublitharenitic composition. They are fine-grained stones with a red color, while Karlshafen appears a little bit darker. Both stones have a relatively high content of quartz cement, a moderate to well sorting, and a good resistance to weathering [16].

Sander sandstone is a brownish to olive-green rock formed in the Upper Triassic. It comes from Sand am Main, Bavaria and is a feldspathic litharenite with fine- to medium-sized grains. This moderately- to well-sorted sandstone has a low content of quartz cement and is classified as not weathering resistant [16].

The grayish-green and fine-grained Schleerither sandstone originates from Schleerith, Bavaria. This stone dates back to the Upper Triassic. It has a relatively high content of lithoclasts, and thus can be classified as litharenite. Schleerither sandstone shows a well sorting and has a medium resistance to weathering [16].

3. Experimental methods and material characterization

The presence of oriented grains and stratification in sandstones leads to their directionally dependent properties, mainly different

Table 1
Hygrothermal properties of sandstones from the literature.

Country of origin	Name	ρ [kg/m^3]	θ_{por} [m^3/m^3]	θ_{eff} [m^3/m^3]	λ [W/m K]	c [J/kg K]	θ_{cap} [m^3/m^3]	$\mu_{(0–50\%)}$ [–]	A_w [kg/m^2 s$^{0.5}$]
Germany [6]	Baumberger	1980.0	0.230				0.21	20.0	0.044
	Obernkirchner	2150.0	0.140				0.11	32.0	0.046
	Rüthener	1950.0	0.240				0.20	17.0	0.300
	Sander	2120.0	0.170		1.60	850	0.13	33.0	0.020
Canada [7]	St. Canut	2495.0		0.064	1.04				0.007
	Nepean	2380.0		0.117	0.99				0.003
Czech Republic [8]	Kocbeře	2227.7	0.161		3.53	754		12.7	
	Libnava	2191.0	0.179		2.71	721		11.6	
	Záměl	2075.9	0.228		2.10	694		11.8	