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Drying kinetics of building materials capillary moisture

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HIGHLIGHTS

- The drying process of capillary absorbed water of building materials is examined.
- The effect of several environmental factors on the drying kinetics is investigated.
- A first order mathematical model is successfully applied.
- Drying process depends on environmental conditions and on material characteristics.

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ABSTRACT

Drying of building materials capillary absorbed water is one of the main factors that determine buildings materials durability. Thus, the investigation of drying kinetics of capillary absorbed water can be very useful in understanding the causes of decay of building materials and in saving cost and improving the energy efficiency of constructions. In general, environmental conditions, such as air temperature, air velocity and air relative humidity, affect drying kinetics of various building materials.

Most of the drying kinetics mathematical models use as initial moisture content the amount of water resulting by saturation of samples through immersion. In the present work, the drying process of capillary absorbed water, which describes more accurately materials behavior in buildings, was experimentally studied. An existing mathematical model was utilized. Several natural and artificial building materials were selected and examined (stones, clay bricks and natural hydraulic lime based mortars).

The proposed mathematical model was found to fit successfully experimental drying kinetics data. Moreover, this model incorporated the environmental conditions, as well as the materials characteristics on the drying process. Thus, it can be applicable for use in building simulators concerning moisture transfer phenomena in building physics.

1. Introduction

Moisture is one of the main decay factors in building materials. Water penetrates into a building material through capillary rise of ground moisture, rain and condensation of air humidity causing several physical, chemical and biological problems to buildings [1]. Rising damp is the most important and serious decay factor of a building material because it causes condensation in a building envelope and develops appropriate conditions for mold growth and harmful indoor air for occupants, affecting their health and their comfort [2–7]. Porous building materials have the ability to adsorb and desorb moisture with the variations of adjacent conditions. The durability of a building material is compromised when significant amount of moisture accumulates into it for a long time period [8] and the seriousness of the rising damp phenomenon is dependent upon a balance between the upwards flow of water drawn into the wall from the ground through the capillary rise and the water loss by evaporation from the masonry. The moisture content is not only determined by the water absorbed by the material, but also by the amount of water that evaporates, as described by the drying process [9]. Thus, drying of a building component is a crucial process because, in combination with wetting, it regulates the insulation of a building envelope controlling the energy efficiency of the structure [10–12], decreasing the cost of a construction and affecting its life-time [13].

In general, drying is a three-dimensional heat and moisture transport problem and it depends on: [14]

- The material properties (moisture storage and transport)
- The climatic conditions (air velocity, temperature and relative humidity)

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Nomenclature

X	moisture content	T	temperature
X_e	equilibrium moisture content	α_w	water activity
t	time	u	air velocity
t_d	drying time constant	K	drying constant
c_0, c_1, c_2, c_3	empirical constants	S	mean square deviation
b_0, b_1, b_2	empirical constants	X_e^*	predicted equilibrium moisture content
T_r	reference temperature	N	number of experimental points
α_{wr}	reference water activity	p	number of estimated parameters
u_r	reference air velocity		

- The transfer conditions for heat and vapor (surface roughness etc.)

There are few international standards and recommendations for the determination of the drying process of building materials. More specifically, RILEM test No. II.5 assesses the drying capacity of untreated and treated samples [15], while Normal 29/88 is utilized for the drying index determination [16]. Finally, international standard EN 16322 determines the drying behavior of porous inorganic materials used for and constituting cultural property and is referred to the drying of specimens saturated with water after immersion [17]. The abovementioned international standards and recommendations illustrate that the experimental procedure of the drying process is limited to specific conditions of air temperature and relative humidity and to saturated moisture content through immersion.

Nevertheless, beyond the aforementioned standards, there are different methodologies followed by several authors proposing a new drying parameter for building materials [18–21]. This parameter is called drying coefficient, and is defined as the slope of a square-root of the second drying phase duration versus sample height plot, giving a measure for the time it takes to dry out one meter of the material [21]. However, this parameter has not been yet widely applied.

Moreover, many researchers have studied the drying process, either reclaiming some existing drying parameters or connecting the drying procedure with some materials properties [22–32]. However, in the majority of the abovementioned studies, the drying process was performed at building materials saturated with water by immersion and not saturated by capillarity, which corresponds to the rising damp problem.

In the present work, the drying kinetics of building materials saturated with capillary absorbed water is investigated. The drying process was guided at different building materials (stones, bricks and mortars), at three different air temperatures, at three different air velocities and at controlled relative humidity conditions. Also, a mathematical model is proposed in order to fit to the experimental data and to investigate the impact of the environmental conditions on the drying constant of the examined building materials.

2. Mathematical modeling

The drying rate of a porous material depends on the material characteristics and on the drying conditions. The drying process consists mainly of two phases. In the 1st phase the drying front is located at the material surface, and as long as liquid water is supplied to the surface, the drying rate is constant. The rate will depend only on the external conditions, such as temperature, air velocity and relative humidity. In the first phase, the removal of the water vapor molecules will be by diffusion and the drying rate will be constant until the moisture content within the porous material can no longer sustain capillary transport. This moisture content is called the critical moisture content.

At the 2nd phase the drying front starts receding into the material, the drying rate progressively decreases and can be controlled by different mechanisms. This is attributed to the heterogeneity of building materials and the consequent uneven moisture distribution. Thus, the drying rate will be the result of the combination of different mechanisms within the pore system and as it progresses, one or the other mechanism may be the rate controlling one. Materials with smaller pores are able to sustain capillary transport, while, other materials, with a higher number of large pores are no longer saturated with water. Consequently, drying rate will depend on the water evaporation from the remaining liquid water front and subsequent vapor diffusion. Therefore the drying rate changes as the drying progresses [21].

Many moisture transfer models have been developed in the literature to describe the drying process of porous materials [33–40]. Each researcher focuses on different material properties and different environmental conditions in order to describe the drying process in the best way. Zaknoune et al. evaluated the moisture transport coefficients, including experimental drying kinetics, in building hygroscopic porous materials [41]. They developed a one-dimensional mathematical model to predict heat and mass transfer in porous material. Barreira et al. adjusted six different first-order kinetics models, available in the literature, to describe the drying process and to estimate the equilibrium moisture content of External Thermal Insulation Composite Systems (ETICS) and solid red brick samples. They found that the drying time constant is strongly affected by the moisture transfer (at surface or bulk) and by the drying air conditions [42]. Matiasovsky and Mihalka carried out drying experiments for 25 building materials (clay bricks, renovation plasters, mortars, calcium silicates, insulation plasters, etc.) and they confirmed that the drying rate is dependent upon specific structure parameters for each material [43]. Stück et al. accomplished a numerical modeling of moisture distribution under real climate conditions within three different types of sandstone monoliths. They conducted capillary water uptake and drying experiments and developed a numerical model of moisture transport and storage under various climatic conditions. This model takes into account the impact of lithology and pore-radii distributions of the examined materials and connects, among others, the climate conditions with the drying process [44].

Describing the drying process, several computational tools have been developed such as WUFI [45], MOIST [46], GLASTA [47], UMIDUS [48], MATCH [49], EMPTIED [50] etc. Furthermore, some of the aforementioned programs have several limitations as far as their included climate data (e.g. UMIDUS) or their further update and support (e.g. MOIST). Moreover, some programs do not take into account the influence of several environmental conditions (e.g. EMPTIED) or they are based on theoretical and not experimental values of their variables meaning that there is an absence of reliable experimental data. All the aforementioned models differ in