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Visualizing moisture release and migration in gypsum plaster board during and beyond dehydration by neutron radiography

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ABSTRACT

The release and migration of water vapor in gypsum plaster board due to dehydration at elevated temperatures has been visualized by means of thermal neutron radiography. The temporal and spatial degree of dehydration of two gypsum board types, one with and one without fibers, has been followed by quantitative and qualitative analysis of neutron radiographs while the samples were heated on one side up to 600 °C. Gypsum starts to dehydrate at temperatures around 80 °C undergoing an endothermic reaction and releasing water vapor which diffuses through the sample away from the heating source. Evidence of an advancing dehydration front and the formation of a small area with accumulated water ahead of this front have been provided. Furthermore, the accumulation of evaporated water in the paper board between two gypsum layers has been visualized as well. The temperature distribution has been measured by thin thermocouples positioned inside the samples.

1. Introduction

Mechanical properties of porous building materials, including gypsum plaster boards are moisture and temperature dependent. Consequently, understanding the process of heat and mass transfer at elevated temperatures becomes essential in modeling and predicting their behavior when subject to fire. This Characterization of the detailed interrelation between thermal and hygric properties becomes important when designing new mixtures and additives to enhance fire resistant properties as they directly influence the material deteriorations induced by fire.

Gypsum plaster boards in all their diversity [1,2] are produced by drying, cooling and hardening of a slurry between two paper boards. They are highly appreciated as fire resistant building materials, mainly due to endothermic dehydration of crystal water occurring step-wise in the temperature range between 100 and 200 °C [3,4]

$$CaSO_4.2H_2O \rightarrow CaSO_4.\frac{1}{2}H_2O + \frac{3}{2}H_2O \uparrow \quad (1)$$

$$CaSO_4.\frac{1}{2}H_2O \rightarrow CaSO_4 + \frac{1}{2}H_2O \uparrow \quad (2)$$

This endothermic dehydration acts as a buffer for thermal energy transfer and thus postpones considerably the increase in temperature and hence the deterioration of the underlying structures. The heat transfer through gypsum plaster board in case of fire has been studied over decades with varying levels of precision by means of both measurements as well as numerical modeling [3–7], neglecting the role of moisture vapor migration and its impact on the temperature distribution. This is due to higher experimental errors at fire temperature, making it difficult to extract moisture contents from temperature measurements. More recently, studies have been carried out aiming at the coupled heat and moisture transfer in gypsum at dehydration temperature and beyond making use of models with different levels of complexity and approximations [8–10]. In situ and non-destructive documentation of moisture transport in gypsum has recently been carried out using NMR spectroscopy [11]. The two step dehydration of gypsum in the plaster board was confirmed by this method in accordance to TGA reported in earlier work [1,3], but most interesting is the prospect of obtaining information on the pore sizes by NMR spectroscopy. NMR Relaxometry can also give information on the microstructure, the water distribution, and the hydration kinetics without any drying or perturbing preparation [12].

Due to the transient nature of the moisture migration induced by large temperature gradients (both temporal and spatial) in accordance with different fire curves [13], it has not been possible up to now to measure the moisture concentration within gypsum plaster boards of 12 mm thickness during fire exposure. This is due to the lack of appropriate sensors to measure vapor pressure

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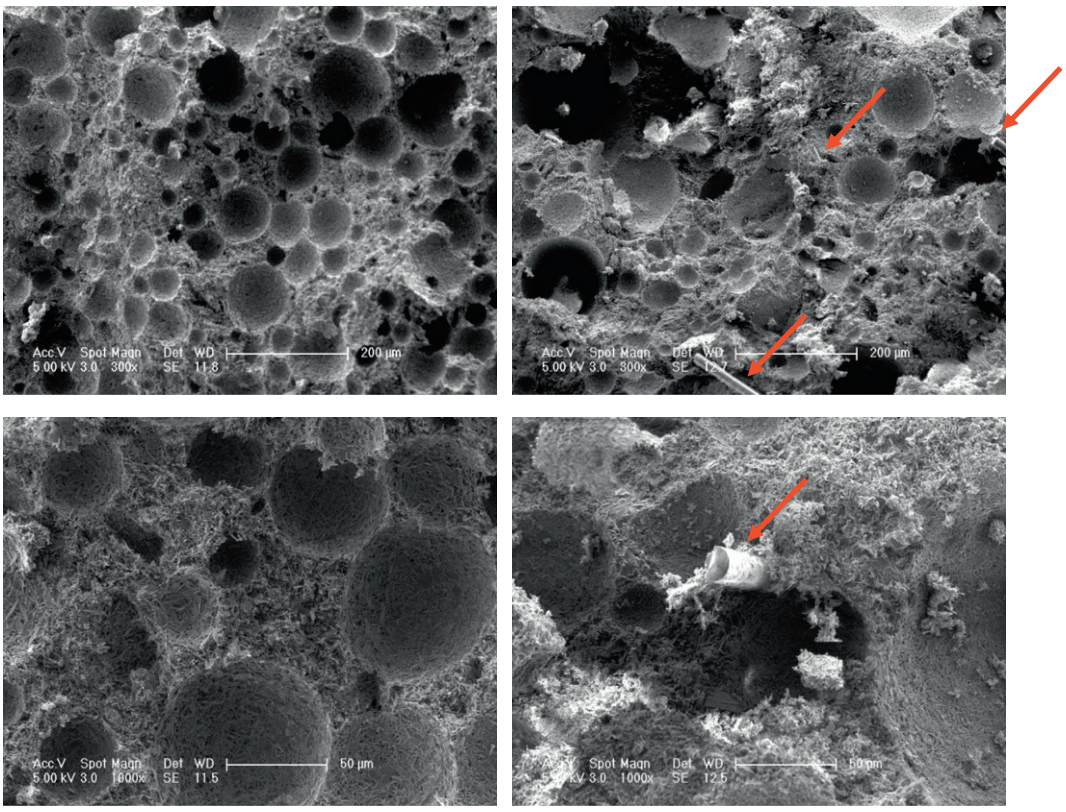

Fig. 1. Scanning electron microscopy at 300x (top row) and 1000x (bottom row) of the pore structure in gypsum plaster board type-1 (left) and type-2 (right). The large pores have diameters from 10 to 100 µm and arrows indicate mineral fibers.

at elevated temperatures at a reasonable precision without damaging their structure.

Thermal neutrons passing through matter are strongly scattered by hydrogen atoms and hence provide a high contrast for water versus the other components of gypsum, irrespective of its liquid or vapor form. This enables one to quantify the change in water content with high spatial resolution [14,15]. The kinetics of the dehydration of gypsum (powder) has been investigated by neutron and X-ray diffraction methods and the occurrence of different sub-hydrates $CaSO_4(H_2O)_x$ ($1 < x < 2$) at different steam pressures investigated [16].

The present study uses neutron radiography to visualize in situ the moisture migration in samples of different open porous gypsum plaster board types and assemblies including layers of paper board. Two commonly used gypsum boards in Europe are one without fiber (GKB named as type-1) and another with mineral fibers (GKF named as type-2), displaying less severe deterioration in terms of crack formation in fire. The porous structure of samples from both types has been investigated by scanning electron microscopy and presented in Fig. 1. The distribution of the large pores seems similar for both types as evidenced by two magnifications. The presence of fibers in the type-2 gypsum is clearly visible. The porosity of the gypsum samples used in these investigations was determined to be around 62% (obtained from mercury intrusion porosimetry) in their delivered condition.

2. Materials and methods

2.1. Materials

Samples of type-1 and -2 gypsum board including paper on one side only (in practice gypsum plaster boards have paper on both sides) were cut in dimensions of $40 \times 10 \times 10$ mm. They were oven dried at 50 °C for one week, weighted with a precision balance (0.0001 g accuracy) and their dry densities determined as 755 and 800 kg/m^3, respectively. This treatment aimed at removing the physically bound moisture and does not affect the chemically bound water i.e. no dehydration or change in porosity occurs. There will be a removal of dried specimens were stored in a desiccator with silica gel prior to the heating experiments to prevent moisture uptake.

Two sample configurations were tested: single layers and double layers. The latter which is often used in building applications, consists of two layers of gypsum facing each other by their paper covers with no nominal gap in between (Fig. 2 inset). Both sample configurations were tested while exposed to the heat flux from the bottom surface only.

In total, four different configurations were heated on one side and the migration of moisture inside them studied by neutron radiography. All sample assemblies were tested without any sealing or insulating on the lateral surfaces so that heat and moisture could also be released through them. The main chemical component of the boards is $CaSO_4 \cdot 2H_2O$ (80%). There is about 10% of $CaCO_3$ which decomposes beyond 700 °C and 10% of inert additives [3].

2.2. Experimental procedure and setup

The experiments were performed at the NEUtron Transmission RAdiography (NEUTRA) beamline of the Paul Scherrer Institute (PSI) in Villigen, Switzerland. This beamline is fed by the Swiss Neutron Spallation Source (SINQ) and is operated with neutrons having thermal spectrum characterized by a Maxwell-like energy distribution function, with a most probable energy level of about