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Effects of microstructure on acoustical insulation of gypsum boards

Yassine Elkhessaimi, Nicolas Tessier-Doyen, Agnès Smith*

Science des Procédés Céramiques et de Traitements de Surface, UMR CNRS 7315, Université de Limoges, 12 rue Atlantis, 87068 Limoges Cedex, France

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ABSTRACT

This paper focusses on the understanding of microstructural effects related to sound transmission loss and critical frequency of gypsum boards. The determination of the critical frequency, through measurements of the mass per unit area, thickness and Young's modulus, indicates that a microstructure exhibiting large gypsum crystals with prismatic shapes obtained by addition of citric acid, yields a value (for example: ≅ 3700 ± 360 Hz for 1.5 mass% of citric acid additive, board thickness: 14 mm) well beyond the sensitive frequency range of human hearing (350–1500 Hz). Concerning the sound transmission loss, acoustic insulation can be significantly improved by both increasing (i) the mass per unit area of the gypsum board, (ii) the thickness and (iii) the loss factor. A sandwich panel consisting of an assembly of two individual gypsum boards prepared with citric acid combined with a glass wool core of 50 mm in thickness shows very promising insulating performances. This result has been predicted theoretically with a transfer matrix method.

1. Introduction

The human hearing range is commonly given as 20 Hz to 20 kHz but the human ear is most sensitive in the midrange frequencies from 350 Hz to 1500 Hz (Fig. 1). Reduction of noise transmission through floor/ceiling assemblies, through adjacent joining walls between neighbouring units or through windows is a major request in new construction or rehabilitation of dwellings [1]. In this respect, gypsum boards either alone or in a multilayer configuration are increasingly used as facing materials for interior walls and ceilings because of their acoustic properties, as well as their good fire endurance and thermal insulation characteristics. Nevertheless, we believe that progress can still be made in the acoustic insulation of gypsum boards. The central motivation of this work is to examine to which extent the acoustic characteristics can be improved or not and how these characteristics can be related to the physical parameters of the gypsum boards (density, porosity, elastic modulus).

The acoustic insulation of gypsum boards is characterized by a parameter called the Sound Transmission Loss (STL), ex-pressed in decibels (dB). From a physical point of view, it represents the amount of sound that a material is able to insulate. In general, the STL increases with the frequency (the mass-frequency law) [2]. For a specific frequency of noise called the critical frequency (f_c), the STL curve shows a dip (Fig. 2). The fc value of an infinite plate excited acoustically corresponds to the frequency for which the speed of an acoustic wave in air becomes equal to the speed of the natural bending wave [3]. This phenomenon can lead to a notably reduced acoustic insulation of gypsum boards, especially if the dip of STL affects the midrange frequencies (frequencies for which the ear is the most sensitive). The real challenge is to design gypsum boards exhibiting both (i) the highest STL and (ii) a f_c value as far as possible from the midrange frequencies. So, there is a great need to understand the effects of microstructure on STL and f_c of gypsum boards.

In the literature, articles show that the microstructure affects the acoustic absorption of gypsum. Sound absorber gypsum consists of a porous microstructure with interconnected pores throughout [4], with high airflow resistivity, porosity and tortuosity [5]. The gypsum-cork composite was proposed as a potential sound-absorbing material [6], but its acoustic insulating properties have not been evaluated. Some patents reported the process required to obtain gypsum boards with good acoustic insulation, by the addition of a foaming agent to generate porosity [7], or by the addition of an organic polymer to create a composite less rigid than gypsum [8]. However, few research papers investigate directly the effects of microstructural modifications on the acoustic insulation of gypsum.

In this paper focused on this challenging topic, three processing routes were investigated in order to modify the plaster microstructure: (i) preparation of mixtures with different water to plaster mass ratios in order to vary the porosity, (ii) addition of citric acid for controlling the crystal morphology [9,10], (iii) addition of cork in order to design a new composite board. A significant influence of this microstructural modification on STL and fc values of gypsum boards prepared in our laboratory is expected. An accurate comparison with commercial gypsum boards in terms of performances is also presented. Finally, the

* Corresponding author.
E-mail address: agnes.smith@unilim.fr (A. Smith).

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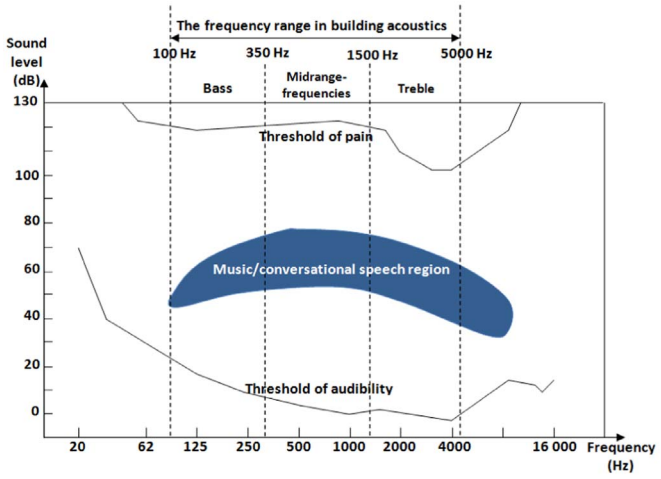

Fig. 1. Audiogram of human hearing.

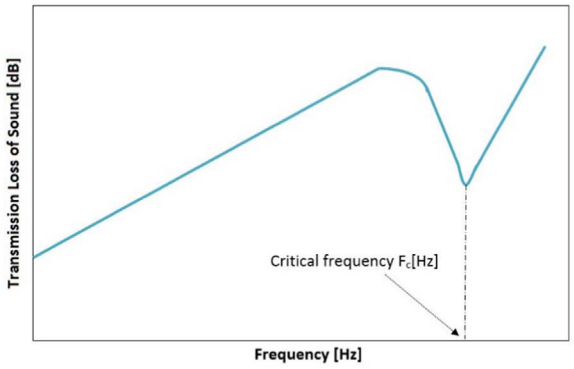

Fig. 2. Typical STL-frequency curve of gypsum boards.

results of prediction of STL in a multilayer configuration using a transfer matrix method are discussed at the end of the last section.

2. Materials and methods

2.1. Materials

The gypsum samples were prepared from plaster. The used plaster was a β-hemihydrate ($CaSO_4$, $1/2H_2O$, purity 91%, Molda 3 Normal©, Saint-Gobain Placo, France) synthesized by calcination of natural gypsum ($CaSO_4{\cdot}2H_2O$). In this study, citric acid $C_6H_8O_7$ (purity 99%, Alfa Aesar, Germany) was added to water in the plaster mix to modify size and morphology of gypsum crystals. Indeed, carboxylic acids are known to influence plaster microstructure [11]. A composite material was prepared by adding dispersed cork granules (1–2 mm, apparent density 200 kg/m^3, Kork-Deco, Germany) in a mixture of water and plaster. These natural cork granules came from wastes of pruning and forest cleaning. Samples from 3 commercials boards noted A, B, and C respectively were also tested for comparison.

2.2. Processing of specimens

As summarized in Fig. 3, the gypsum samples were prepared from a mixture of plaster, water and in some cases additives (citric acid or cork). Since the parameters of preparation could influence the final microstructural properties of gypsum, the experimental procedure was performed with a very precise protocol (especially with a careful time control). First of all, the protocol consisted of mixing thoroughly the powder of starting plaster and the water (with or without additives) using a whisk (mixing time, t_1). The mixing was stopped for a duration t_2 before mixing again (mixing time, t_3). Then the mixture stood for a time (t_4) in a bowl for thickening before casting the board. After setting, the gypsum board was demolded (Fig. 4) and dried for 2 days in an oven at 50 °C. The typical dimensions of the boards were: thickness = 12–18 mm, width = 360 mm and length = 640 mm.

For the three processing routes, the same protocol was followed except that the water to plaster ratio (w/p), the mixing (t_1 and t_3) and the resting times (t_2 and t_4) could change as a function of the composition. Since the porosity of gypsum depends on the (w/p) ratio [12], we chose to vary this ratio between 0.6 and 1.2. Concerning the composite microstructure, the required mixing time leading to a homogenous incorporation of cork particles in the gypsum matrix was t_3 = 15 min (Fig. 5). A short duration of 5 min leads to a rise of cork particles to the surface (Fig. 6).

2.3. Experimental methods

For some compositions, the initial setting time was determined with an Automated Vicat apparatus. The equipment included a program for testing plaster, in compliance with DIN 1168. The time at which the plaster was first added to the water was noted t_M and the time at which the depth of penetration was 22 ± 2 mm above the glass plate, t_S, was automatically recorded. The initial setting time t was given by $t = t_S - t_M$.

Scanning electron microscopy (SEM) observations of the microstructures were investigated at an acceleration voltage of 15 kV using a Cambridge Stereoscan S260 apparatus equipped with an energy dispersive spectroscopy (EDS) microanalyzer. Fracture surfaces of broken gypsum board specimens were observed after applying a 15 nm thick (Au-Pa) conductive layer.

The pore volume fraction of gypsum board specimens was determined from the bulk density, ρ_{app}, and the true density, ρ_{true} , using Eq. (1). The true density was measured with the helium pycnometer (AccuPyc II, Norcross, USA). The bulk density was obtained through the ratio between the mass and the apparent volume of a cuboid sample.

$$\text{Porosity} = 1 - \frac{\rho_{app}}{\rho_{true}} \tag{1}$$

The mass per unit area of the gypsum board is a physical parameter taken into account in acoustic relations. It can be determined from measurements of the apparent density and the thickness:

$$Ms = \rho_{app} \times e \tag{2}$$

The thickness (e) of the specimens was accurately measured with a micrometer caliper (Mitutoyo, Japan).

For flexural strength measurements, the three point bending test technique was carried out using the EZ 20 Lloyd Instrument (AMETEK) testing machine. A span of 58 mm and a deflection rate of 0.5 mm min^{-1} were used for all tests. At least 6 specimens were tested in a three-point bending configuration for mixtures of plaster and water (w/p = 0.6) alone and mixtures containing cork or citric acid. Assuming a homogeneous material, the maximal flexural strength σ_{max} using samples with dimensions of 10 mm × 20 mm × 60 mm was given by relation (3):

$$\sigma_{max} = \frac{3.F_{max}.L}{2.\ b.h^2} \tag{3}$$

in which, F_{max} is the load force at the fracture point, L (mm) is the support span, b (mm) and d (mm) are the width and the thickness of the beam, respectively.

Non-destructive techniques are very sensitive to evaluate in situ elastic properties of cement or plaster based materials [13]. In this study, ultrasonic measurements of Young's modulus, E, were carried out using a pulse echography technique operating in an infinite medium whose principle was already described elsewhere [14–16]. Acoustic waves were propagated through the tested specimen (e = 12–18 mm in