Bamboo fiberboards and attapulgite: does it lead to an improvement of humidity control in buildings?

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Abstract. In order to save energy used to heat or cool buildings and to improve the inhabitants comfort, control of humidity inside buildings must be improved. This can be done by using buffering materials able to absorb and release moisture when necessary. Natural fibers and mineral absorbent are good candidates to manufacture such materials. The aim of this research is to mix bamboo fibers with attapulgite to evaluate the influence of this mineral absorbent on the hygric behavior of the fiberboards. The hygric properties are slightly improved by the attapulgite and thus bamboo fiberboards can be used as building insulation materials able to participate to the indoor moisture control.

1. Introduction

Hygrothermal performance of buildings materials relates to the heat/moisture absorption, storage and release when surrounding environment changes. The hygrothermal performance of a whole material comes from the performance of each components performance. For example, the hygrothermal behavior of a building wall depends of the behavior of its elements such timber, plasterboard, insulation materials, masonry, concrete, brick, lime plaster, etc.

The hygrothermal properties include hygric behavior and thermal insulation. They contribute to the heat control in building in winter and summer through reducing heat flow through the walls as well as the need of heating/cooling, and therefore save energy consumption. Effectiveness of reducing energy demand depends on the choice of the materials, with for example good heat insulation properties through low thermal conductivity and high water vapor sorption capacity such as as natural fibers.

The hygrothermal behavior and performance of materials or building can be assessed through experimental testing, physical and numerical modeling. However, it is required to know the detailed characterization properties of such materials.

The wood and lightweight based absorbents bring an excellent hygrothermal performance through the best common buffer. The mechanism of humidity controlling materials based on absorbents was investigated. They can be classified into four groups such: silica gel, inorganic salts, inorganic natural mineral and polymer [1, 2]. The absorbents are well known to have a high equilibrium moisture content at low relative humidity level and fast sorption velocity at the beginning of absorption [3]. They are suitable for building envelopes due to their high water absorption properties. For example, the sepiolite absorbent is one kind of clay minerals; its high specific surface enhances the interfacial interactions between sepiolite and host polymer. It provides good moisture absorption and desorption capacity [4-6]. Moreover, the hygroscopic properties of porous materials are dependent on their microstructure [7, 8]. It means that the sorption ability of materials is directly proportional to the
specific surface area and total pore volume. Thus, the absorbents have good absorption capacity due to their microstructure, which improves the moisture uptake capacity for host materials.

The aim of this study is to study the hygrothermal performance of hygroscopic porous fiberboards from bamboo fibers combined with Attapulgite absorbent at different contents. The average pore diameter, pore surface area and pore size distribution of these fiberboards were investigated and classified according to pore size distribution.

2. Materials and Experiments

2.1. Materials

Bamboo fibers (bambusa stenostachya) were collected at scientific research center for conservation of natural resources, Vietnam. The bamboo fibers preparation, chemical components and length, diameter fibers distribution were exhibited in our previous papers [9]. Attapulgite is a natural porous absorbent with a high specific area, fast sorption/desorption and environmentally friendly. The composition of attapulgite is described in table 1. Its density is about 0.57 g/cm³, and the particles main diameter distributes between 0.30 and 0.85 mm. It was purchased from Eurosorb Ltd, France.

| Component          | SiO₂  | Al₂O₃ | Fe₂O₃ | Na₂O | K₂O  | CaO  | MgO  | MnO  | TiO₂ |
|--------------------|-------|-------|-------|------|------|------|------|------|------|
| Amount (%)         | 55.6-60.5 | 9.0-10.1 | 5.7-6.7 | 0.03-0.11 | 0.96-1.30 | 0.42-1.95 | 10.7-11.4 | 0.61 | 0.32-0.6 |

2.2. Preparation of bamboo fiberboards

The different mixtures between bamboo fibers and attapulgite were prepared with the ratios mentioned in Table 2. Then, they were placed in an aluminum mold (150×150×6 mm) which was covered by an adhesive anti-stick coat. The bamboo fiberboards were then manufactured using an AEM3 automatic hydraulic press. The press conditions were set at 150 kgf/cm²; 160°C for 15 min. The fiberboards were removed from the mold after cooling to room temperature for at least 24 h to prevent warping.

| Materials | Bamboo fibers (wt.%) | Attapulgite (wt.%) |
|-----------|----------------------|-------------------|
| F100      | 100                  | 0                 |
| F100-5APP | 95                   | 5                 |
| F100-10APP| 90                   | 10                |
| F100-20APP| 80                   | 20                |

2.3. Pre-conditioning of samples before testing

In this study, for all the tests, the specimens were pre-conditioned at a relative humidity level of 57%RH and a temperature of 25°C before being tested. This pre-conditioning step is chosen to test the material with conditions close to those in a building.

2.4. Density fiberboards measurement

The density of fiberboards was determined according to EN 323 standard. The specimens were cut and pre-conditioned at 57%RH and 25°C before being tested. At least five specimens of each material were tested. The density value (kg/m³) was calculated with the formula below:
\[ \rho = \frac{W}{a \times b \times c} \]

where: a, b, c (m) and W (kg) are the length, width, thickness and weight of specimen respectively.

2.5. Hygric characterization

2.5.1. Test facility
In this study, all hygrothermal properties of insulation materials (except for the sorption and desorption isotherms) were measured using closed climatic chamber (called “RH-Box”) (Fig. 1) which is made by two chambers connected by an airlock. Temperature and relative humidity in the RH-Box are controlled by heat exchangers and saturated salt solutions. Two fans inside the RH-Box homogenize the atmosphere when the humidity level is changed, but they are stopped when the experiments are in progress. The mass change of specimens during testing can be measured directly in the chamber through a holder connected with a microbalance located on the top of the chamber. The temperature and the relative humidity inside the RH-box are recorded with hygrothermal sensors with an accuracy of RH± 2% and T± 0.5°C.

![Figure 1: climate chamber RHBox](image)

2.5.2. Kinetics water vapor sorption isotherm
In this study, the kinetics of water vapor sorption at equilibrium state was performed by using RH-Box (Figure 1). It was examined at three successive relative humidity steps: 33% (generated by MgCl₂ solution), 75% (NaCl solution) and 33% again. In addition, before being tested, all the specimens were pre-conditioned at 9% RH with a KOH solution at 25°C. During the period test, the specimen weight evolution is recorded, until reaching equilibrium state, by a precision balance (±0.2 mg), connected to an automatic recording system. The temperature during this experiment was kept constant at 25°C. The water vapor sorption kinetics at equilibrium curves of the specimens were obtained by plotting weight gain/loss percentages function of time.

2.5.3. Moisture buffer value
The moisture buffer values (MBVs) of the materials represent the amount of moisture passing through the open surface of specimens during cycling between 75% RH and 33% RH at 25°C. Before being tested, specimens were preconditioned at 57% RH until reaching a constant mass and five out of six faces were sealed with aluminum tape. Then the specimens were exposed in the RH Box to 75% RH for 8h and moved to 33% RH for 16h. The mass change of specimens was regularly measured during the test period for each relative humidity level. In the Nordtest project [10], the MBV is calculated from three consecutive quasi-steady state cycles (when the amplitude of mass change differ by less than 5%). At least three specimens of each sample were tested. The average values of MBV were calculated using the following equation:

$$ MBV = \frac{\Delta m}{S \times (RH_{\text{high}} - RH_{\text{low}})} $$

Where: MBV is the practical moisture buffer value in g/(m$^2$.%RH), RH$_{\text{high}}$/RH$_{\text{low}}$ (%) is the relative humidity at 75% and 33% respectively, $\Delta m$ (g) is the mass variation during moisture adsorption and desorption at RH$_{\text{high}}$, RH$_{\text{low}}$, and S (m$^2$) is the open surface area of specimen.

Based on the NORDTEST Project, the MBV of materials are then classified into five categories depending on their moisture buffer efficiency: negligible (MBV: 0.0–0.2), limited (MBV: 0.2–0.5), moderate (MBV: 0.5–1.0), good (MBV: 1.0–2.0), and excellent (MBV: 2.0–upwards) [10].

2.5.4. Water vapor sorption isotherm

The capacity of water vapor storage at different relative humidity levels was measured with conditions inspired by the ISO 12571 standard [11]. At least three specimens (40 mm $\times$ 40 mm $\times$ 6 mm) of each fiberboard were cut and pre-conditioned at 57% RH and 25°C before being tested. When the tested specimens reached a constant mass at 57% RH (weight variation after two consecutive periods of 24h less than 0.1%), they were put in the humidity level of 9% RH at T=30°C. The tested specimens were regularly weighed until reaching a constant mass. After reaching equilibrium, specimens were moved to a higher relative humidity. This operation was carried out up to the maximum relative humidity of 97% RH. The reverse procedure was applied for desorption. Saturated salt solutions were used to control moisture level. The specimens were tested at five different relative humidity levels corresponding to five salt saturated solutions: 9% RH (KOH), 33% RH (MgCl$_{2}$), 57% RH (NaBr), 75% RH (NaCl), and 97% RH (K$_2$SO$_4$) at 30°C. The moisture content variation ($\Delta MC$) of the specimens was calculated using the equation below:

$$ \Delta MC = \frac{m_s - m_0}{m_0} \times 100 $$

where: $m_s$ is the weight at different relative humidity levels and $m_0$ is the constant weight after initial pre-conditioning at 57% RH.

3. Results and discussion

3.1. Characteristics of bamboo fibers

The various components and distribution of the length and diameter of bamboo fibers in this study are shown in figure 2. The results indicate that the length distribution ranges from 0 to 7.0 cm and is mainly concentrated around approximately 1.0–2.0 cm, whereas the diameter ranges from 0.16 to 0.52 mm and is mainly concentrated between 0.24 and 0.40 mm. It can be observed that the bamboo fibers have a relatively narrow distribution of diameter and length. Indeed, the preparation of bamboo fibers using rollers is a suitable method to extract a large amount of fibers of quite homogeneous length and small diameter. In addition, this kind of bamboo contains the same amount of components as other different bamboo fibers, but they differ from the components of other natural fibers [12].
3.2. Hygrothermal properties

3.2.1. Kinetics of vapor sorption at equilibrium state

The vapor sorption kinetics of all fiberboards were investigated as protocol in figure 3a. All specimens were pre-conditioned at 9%RH and 25°C before being tested. The moisture absorption capacity, moisture residuals and sorption behavior of these fiberboards at three equilibriums states (33-75-33% RH) can be observed in figure 3b. In particular, there is a rapid initial uptake and release in three equilibriums states at different relative humidity levels (33% and 75%).

At the first reached equilibrium (33%RH), the F100 absorbed an amount of moisture about 3.2% after two days. During this equilibrium state (RH < 35%) the water molecules are only absorbed as monolayer on the pores surfaces of cell walls [13], leading to the small amount of moisture uptake capacity. Consequently, equilibrium is reached in a short time (about 2 days). At this humidity level, all the boards containing attapulgite showed a lightly higher moisture absorption capacity in comparison to F100 board. They presented a moisture uptake capacity range from 3.9% to 4.7% (figure 3b). Attapulgite improved the moisture absorption capacity for all the boards at this equilibrium (33%RH). This result may be due to the higher moisture absorption capacity of attapulgite at 33% than F100 board (around 4.5% against only 3.3%).

The second equilibrium state was reached at 75% RH after around 4 days of exposure. (figure 3b). The F100 exhibited the lowest moisture uptake capacity about 9%. As at 33% RH, the addition of attapulgite absorbent into F100 leads to increase its moisture uptake capacities at equilibrium state (75% RH). But this improvement is lower than at 33%RH, may be due to the lowest difference between attapulgite alone (around 9.5%) and the bamboo fibers in the board F100 [9]. Indeed, attapulgite absorbent is well known to have a good absorption capacity due to its microstructure (high specific surface area and total pore volume), leading to improve vapor absorption capacity of materials [14]. The attapulgite improves the moisture absorption ability of bamboo fiberboards because it acts as hygroscopic materials, the water molecules may be absorbed into magnesium ions and silanol groups of absorbents structure [15].

In general, in this equilibrium state (33%<RH<75%) the water molecules are absorbed as multilayer and begin to condense in porous capillaries [13].
Figure 3: kinetics of water vapor sorption at equilibrium state: (a) humidity and temperature protocol (9-33-75-33% RH) at 25°C, (b): kinetics curves and moisture sorption capacity of fiberboards.

The final equilibrium state was reached at 33%RH, there was a rapid initial release in desorption process, and equilibrium state was reached after 2 or 3 days. So, these boards can quickly adapt when environmental surrounding conditions changes. But, the amount of moisture uptaken in absorption process (from 33% to 75%RH) was not totally discharged in desorption process (75%RH to 33%RH) for all the boards. The amount of residual moisture remained in boards can be seen in figure 3b. The phenomenon is explained via the capillary condensation hysteresis due to moisture trapped inside large pores with small necks (ink-bottle effect) [16].

3.2.2 MBV results
The MBV results of different fiberboards were calculated from three consecutive steady state cycles of moisture uptake and release per unit of exposed area (figure 4).

Figure 4: The three consecutive quasi-steady state cycles of moisture uptake and release of all specimens, used for MBVs calculations
Figure 5 shows the average MBV results of all fiberboards. The F100 possesses an average MBV about 1.7 g/(m².%RH) corresponding to a “good” moisture buffering capacity. The addition of different attapulgite absorbent contents into F100 board leads to a significant increase of average MBVs from “good” to “excellent” moisture buffer categories as in Nordtest Project. The MBVs range from 2.1 to 2.3 g/(m².%RH) (figure 5). As for the kinetics, it results from the higher moisture buffering performance of attapulgite absorbent than bamboo fiberboard F100. The behavior is the same as for kinetics: attapulgite increases slightly the ability of the boards to sorb moisture but the influence of the amount of attapulgite is not significant.

![Bar chart showing average MBV results of all particleboards](image)

**Figure 5: Average MBV results of all particleboards**

### 3.2.3 Water vapor sorption isotherms

Figure 6 presents the vapour sorption isotherms capacity of all fiberboards at different relative humidity levels. The different components of the fiberboards are associated with the different amount of moisture storage in materials. F100 exhibited an amount of moisture absorption about 10.5% at 84% RH, which was lower than for boards containing different attapulgite contents at all relative humidity levels. In particular, while the maximum moisture absorption of F100 was 10.5% at 84% RH, the value of F100-5APP slightly increased to about 11%. The two boards F100-100APP and F100-20APP exhibited the same amount of moisture uptake about 13% at 84%RH. The results are in accordance with the previous characterizations (kinetics, MBV): adding attapulgite increases slightly the moisture absorbing capacity of the boards. But, here, the amount of attapulgite has a small influence (10% of absorbent is required to significantly increase the moisture absorption capacity for humidity level above 20%)
On the other hand, the absorption isotherm of attapulgite is close to type IV isotherm given by IUPAC classification with an interconnected mesoporous system (2-50 nm) [14, 17, 18]. The vapor absorption isotherms curves of bamboo fiberboards are similar with S-shaped accordance to type II, which characterizes the absorption of mesoporous and macroporous materials given by IUPAC [19, 20]. After adding attapulgite at different contents to the boards, the absorption isotherms curves are still kept S-shaped Type II.

The curves of water vapor desorption were always located above the absorption curves of all fiberboards. The hysteresis between absorption and desorption of these fiberboards was observed in figure 6. The hysteresis behavior is generally associated with the pores interconnection, porosity characterization and the capillary condensation of fiberboards. Moreover, it could also be attributed to the ink bottle effect, related to the moisture trapped inside the pores with small entry [16, 21]. Additionally, the high affinity of attapulgite for water may prevent discharge of water during desorption process leading to high hysteresis for fiberboards with attapulgite. Indeed, the water molecules were kept in magnesium ions and silanol groups and into the interlayers of Attapulgite structure. Thus, the water molecules which have formed hydrogen bonds during absorption procedure are not able to be released easily and then the moisture content uptaken is not entirely discharged during desorption procedure. It can explain why the hysteresis is higher for the boards with 10 and 20% of attapulgite.

4. Conclusion
Different types of bio-insulation bamboo fiberboards have been made from bamboo fibers and different attapulgite contents by thermo-pressing. The hygrothermal properties have been investigated. Addition of attapulgite into a bamboo board leads to the increase of the moisture uptake capacity at different relative humidity levels. It also increases the moisture buffer value and then the buffer ability.

The shapes of absorption curves are in good agreement with the S-shaped curves of the literature and they can be classified as type II according to IUPAC classification. To conclude, depending on the hygrothermal performance of different bamboo fiberboards, they can be used as building insulation materials which can participate to the indoor moisture control. They can be also used for the thermal insulation of ceilings or in attic spaces.
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