Static and dynamic thermal characterization of facade with mineral foam insulation using a hot-box apparatus

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Abstract. Reducing heat loss through the envelope of the building had been an efficient way to save on heating and reduce energy consumption of buildings. In Europe, typical exterior walls need to prevent heat loss during cold weather but more and more allow comfortable temperature condition during the hot season. Indoor comfort in hot seasons is dependent on the thermal transmittance and on its dynamic response during hot days. The study presents guarded hot-box measurements of exterior walls build with insulating masonry and insulation boards made of innovative mineral foam used as an insulation material. The masonry is a composite system of concrete block filled with mineral foam to reduce the thermal transmittance. Insulation boards are made of mineral foam and are added to achieve the overall thermal transmittance targeted. Static and dynamic measurements were performed in order to compare thermal transmittance and decrement delay. The results are compared with those obtained from calculations carried out of the same walls through the application of European standards and a finite volume simulation. Uncertainties of the guarded hot-box measurement and calculation methods are discussed. Results shows that with equivalent U-values, the solution offer higher decrement delay compared to a traditional wall using conventional masonry and polystyrene insulation boards.

1. Introduction
For new building and heavy renovation, the thermal performance of a building surface is often fixed by a national building energy regulation to insure comfort and low energy consumption in buildings. Opaque surfaces such as roofs and walls need to be characterized properly in a building engineering office and possibly used in an energy load calculation tool. Beyond regulation, the thermal comfort of the individuals inside the buildings, as well as the energy saving associated depend to a large extend on an accurate characterization of the building components.

The thermal performance of a building surface is defined by the thermal transmittance or U-Value in W/m².K. The value defines the heat flux going throw a surface when a difference of temperature is applied on each side. A typical construction surface is composed of homogenous layers of different materials with specific thermal properties or building elements like a masonry wall composed of several materials. The dynamic response of a building surface can be evaluating the decrement delay in hours.

To characterize a non-homogeneous wall or roof two solutions are available: measurement at construction system level or calculation using the material properties of the different components. The guarded hot-box method is a recognized way to measure the thermal transmittance, U in W/m².K, of a
non-homogeneous construction system as the surface of measurement is large enough to take account of discontinuities of the construction system. The default of the method is a prohibitive cost to allow each construction producer to perform such test. In most cases, numerical calculations can be easily implemented using the thermal conductivity and the thickness of the different layer or a finite element calculation for more complex element as masonry. The numerical estimations are accepted by the relevant standards and speed up the launch of new construction system.

Several studies have already been performed using a hot-box apparatus to link calculated and measured thermal static and dynamic performances of a wall. Martin et al.[1], proposes a procedure to calculate the response factor of the wall from hot-box measurements. The present study will focus on comparing thermal transmittance according EN ISO 6949 [2] and decrement delay according EN ISO 13786 [3].

With the commercial launch of the lightweight cement foam: Airium® as an insulation material, an insulating masonry and insulating panels have been evaluated according the numerical calculation. As the result shows competitive thermal transmittance and high decrement delays, different walls have tested in the guarded hot-box of the LafargeHolcim Innovation Center in steady state and dynamic conditions in order to validate the results.

2. Numerical method for thermal transmittance and dynamic thermal characteristics
In order to calculate the thermal performance of a building component, it is necessary know for the different materials: the thermal conductivity $\lambda$ in W/m.K, the heat capacity in J/kg.K and the density in kg/m$^3$. Most current materials data are available in thermal properties tables or can be measured.

2.1. Thermal transmittance
Thermal transmittance is the performance of the building component in steady state condition. EN ISO 6946 [2] defines the method for homogenous layers. For a non-homogenous layer such as masonry the EN ISO 1745 [4] is applied. A finite element model is used to represent the masonry geometry and thermal conductivities of the different materials. The software Trisco from Physibel [5] has been used in that study. The equivalent thermal resistance, $R$ in m$^2$.K/W, is then estimated to be used in the thermal transmission calculation.

2.2. Decrement delay
Decrement delay is estimated using the EN ISO 13786 [3], the assembly of each layer of the building component is represented by a heat transfer matrix. Considering a sinusoidal heat flux signal with a 24h period on the external side of the wall or roof, the heat flux on the inner side can be calculated. The decrement delay is the time delay between the two sinusoidal fluxes.

3. Guarded hot-box and calibrated hot box testing apparatus

3.1. Description
The hot-box apparatus is localized at LHIC (LafargeHolcim Innovation Center) based in Lyon. It is built following the recommendations of the standard EN ISO 8990 [6]. The aim of this apparatus is measuring thermal properties on steady-state conditions and in dynamic conditions also.

The apparatus comprises two climate chambers, a cold chamber reproducing outside temperatures and a hot chamber reproducing interior temperature. The regulation of the two chambers can be made in temperature and in hygrometry. The hot-box chamber covers a temperature range of 10-55°C with a range of hygrometry of 30-95%. In the cold box chamber, the temperature range is 0-45°C with a range of hygrometry of 10 - 95%. During measurement, the temperature fluctuation is +/- 0.2°C in the chambers. The rate of heating and cooling is up to 0.5°C/min.
Figure 1. Apparatus with the 2 climatic chamber and in the middle the wall specimen

Specimen can be built in place (masonry) or put in place by bridge crane (precast wall). The dimensions of the specimen are 3m length and 2.4 m height. The specimen must have a thermal transmittance higher to 0.1 W/m².K in order to measure energy flows with enough accuracy. Two configurations of the apparatus according standard EN ISO 8990 [6] are used for the tests.

Figure 2. 2 configurations for measurement: guarded hot box and Calibrated hot box

The guarded hot box configuration in figure 2, is preferred for steady state measurement to reduce the influence of temperature fluctuation outside the apparatus. For dynamic measurement, a calibrated configuration has been chosen for a better control of the temperature in the metering and climate boxes.

3.2. Guarded hot box configuration for steady state measurement

The thermal transmittance is measured according to the standard EN ISO 8990 [6]. The guarded hot-box method permits to minimize lateral heat flow in the specimen and heat flow through the metering box walls. In this configuration, the specimen measurement size is 1.65m x 1.65m.

All the walls were tested in a steady–state regime in order to define the transmittance of the construction system solution (U) and the thermal resistance value (Rt) The test is done according the standard EN ISO 8990 [6]. The hot box is set to a temperature of 20°C, the guarded hot-box, is fixed to the specimen wall, ventilators and thermal resistance heater side metering box are switch on. The cold-box temperature is set to 0°C. After several days of conditioning, data acquisition is started; and the thermal transmittance is measured when the stability criteria are met.

The uncertainty analysis has shown that the apparatus measures accuracy of 2.5% for a thermal transmittance superior to 1 W/m².K and 3.5% between 1 and 0.2 W/m².K. In the case of highly insulated walls, a specific uncertainty analysis is necessary. With a low heat transmittance, the heat
flux through the wall is small leading to higher uncertainty. In that case, one solution envisioned is to increase the temperature delta during measurement.

3.3. Dynamic regime

The apparatus is set as a calibrated hot-box configuration. The inner metering box is removed in order to have to place the wall in-between the two climate chambers. On the interior side of the wall, the temperature is set at 20°C. On the exterior side of the wall; the temperature is controlled in order to follow a sinusoidal signal between 10 °C and 30°C on period of 24 hours. These settings reproduce the theoretical case that is used to calculate the decrement delay. Five flowmeters Hukseflux type HFP01-10 are placed in the same position on each side of the wall as shown in Figure 3. The cycles are repeated until the reading on the flux meters shows a periodic signal, usually 10 to 15 times.

Flow meters are applied on both side of the test wall as seen in Figure 3. The data extracted shows the sinusoidal signal with a reduced amplitude and time delay. In Figure 4, the time delay between the excited side and the fixed temperature side is equivalent to the decrement delay according EN ISO 17686.

In Figure 4, the black lines represent the different flowmeters on the excited side and the grey ones the flow meters on the fixed temperature side. On both side, the position of the wall have shown the same evolution of temperature, with more noise on the excited part. The noise is due to temperature fluctuation in the air due to the regulation of the air temperature of apparatus. However, the quality of the signal is sufficient to detect the peak of temperature using the average of the signal of each set of flowmeters to estimate the time delay between the two signals with accuracy under 0.5 hours.
4. Description of the sample walls

All the thermal properties of the walls are described in the table 1, where the different layers have been sorted from the interior to the exterior. Each layer is defined as specific material with its respective properties. The vapor diffusion resistance factor is added for information.

4.1. Traditional construction system

Two walls have been tested using traditional construction materials in order to compare the difference of results between measurement and calculation of static and dynamic thermal characteristics. A simple concrete wall (n°1) has been tested as high thermal transmittance sample. It was poured two months in advance and stored in a temperature controlled local to let it set and dry. A concrete wall insulated by exterior polystyrene panels has been tested as a typical solution with an equivalent thermal transmittance of new buildings. The polystyrene boards have been added to the wall n°1 and let dry for two weeks.

**Table 1.** Thermal properties of wall layers. The data concerning traditional materials such as concrete or render have been collected in a thermal properties table [7]. The thermal conductivity and density concerning Airium ® products have been measured internally.

| Wall | Layer                  | Thickness [m] | Thermal conductivity [W/m.K] | Specific Heat [J/kg.K] | Density [kg/m³] | Vapor diffusion resistance factor µ [-] |
|------|------------------------|---------------|-----------------------------|------------------------|-----------------|----------------------------------------|
| 1    | Concrete               | 0.16          | 2.30                        | 1000                   | 2302            | 80                                     |
|      | Concrete               | 0.16          | 2.30                        | 1000                   | 2302            | 80                                     |
|      | White Polystyrene      | 0.14          | 0.038                       | 1500                   | 16              | 60                                     |
|      | Render                 | 0.01          | 0.570                       | 1000                   | 1100            | 6                                      |
| 2    | Concrete               | 0.16          | 2.30                        | 1000                   | 2302            | 80                                     |
|      | Airium Spray           | 0.14          | 0.058                       | 1000                   | 150             | 3                                      |
|      | Render                 | 0.01          | 0.570                       | 1000                   | 1100            | 6                                      |
| 3    | Fabtherm Air 1.8       | 0.2           | 0.113                       | 1000                   | 740             | 10                                     |
|      | Gypsumboard            | 0.013         | 0.210                       | 1000                   | 700             | 10                                     |
|      | Black Polystyrene      | 0.06          | 0.032                       | 1500                   | 20              | 60                                     |
| 4    | Fabtherm Air 1.8       | 0.2           | 0.113                       | 1000                   | 740             | 6                                      |
|      | Render                 | 0.01          | 0.570                       | 1000                   | 1100            | 10                                     |
| 5    | Fabtherm Air 1.8       | 0.2           | 0.113                       | 1000                   | 740             | 6                                      |
|      | Render                 | 0.015         | 0.570                       | 1000                   | 1100            | 6                                      |
| 6    | Airium insulation panel| 0.2           | 0.060                       | 1000                   | 147             | 3                                      |
4.2. Innovative construction system

The innovative solutions are using the new technology insulation material Airium® developed by LafargeHolcim. It is a foamed concrete technology that is used as an insulation material. Each solution is a specific material made with Airium® technology. They are illustrated in the Figures 5-6-7.

Wall n°3 is a concrete wall with an external insulation layer made of AiriumSpray®, an expanding foamed concrete designed to be applied like an insulation mortar with either render or cladding finish. The product is currently in the development phase and should be available in some countries in 2022. After application of AiriumSpray®, the wall was let to dry for 4 weeks.

In walls n°4,5 & 6, the masonry Fabtherm Air® 1.8 from Fabemi has been tested. The masonry is an assembly of a lightweight concrete and a insulation made of Airium® with a declared thermal conductivity of 0.044 W/m.K. The masonry wall has been certified by calculation with thermal resistance of 1.77 m².K/W [8]. It is considered in calculation as equivalent material with a thermal conductivity of 0.113 W/m.K.

Wall n°5 is an assembly of the Fabtherm Air® 1.8 and an internal polystyrene insulation layer. This is the most typical application of the product for the French market.

Wall n°6 is an assembly of the Fabtherm Air® 1.8 and external Airium® boards with a thermal conductivity of 0.060 W/m.K.

The wall n°5 was assembled immediately after delivery from the factory and tested. Concerning walls n°4 & n°6, the blocks were placed in a room with a controlled relative humidity at 50% for 6 weeks to dry the masonry blocks.

All the thermal properties of the walls are described in the Table 1, where the different layers have been sorted from the interior to the exterior.

5. Results

For each wall, the thermal transmittance and decrement delay have been calculated using the methodology described in the relevant standards. In parallel the walls have been tested in the hot-box apparatus in order to measure the same characteristics. The results have been synthetized and compared in the Table 2.

For the first two walls, the error on thermal transmittance is under 2% for a thermal transmittance between 0.25 and 4.17 W/m².K. The result relative error is lower than the uncertainty of measurement of the hot-box apparatus and we can conclude that the thermal transmittance estimation can be calculated and measured with the hot-box apparatus with a good accuracy. Decrement delay shows an error of up to 4.1% for the concrete wall that is compatible with the uncertainty of 0.5 hour due to the noise in the signal during measurement.
For walls 3 to 6, the tests have been performed in the same condition. Wall n°3 with Airium Spray has shown a difference of 3.4%. As most of the insulation of the wall is due to the Airium Panels, the cause has been identified as a small variation of thermal conductivity among the 7.2 m² of panels due to the experimental production conditions. As some panels were less insulating we think this factor impacted the overall result. Decrement delay is equivalent.

### Table 2. Comparison of Numerical and experimental results of thermal transmittance and Decrement delay

| №  | Wall Description                        | Calculus Thermal Transmittance (W/m².K) | Measurement Thermal Transmittance (W/m².K) | Relative Error | Calculus Decrement Delay (hours) | Measurement Decrement Delay (hours) | Relative Error |
|----|----------------------------------------|----------------------------------------|-------------------------------------------|----------------|----------------------------------|-------------------------------------|----------------|
| 1  | Concrete Wall                          | 4.17                                   | 4.23                                      | 1.4%           | 4.1                              | 4.3                                 | 4.1%           |
| 2  | Insulated concrete wall                | 0.250                                  | 0.251                                     | 0.4%           | 9.8                              | 9.7                                 | -0.3%          |
| 3  | Airium Spray on concrete wall          | 0.377                                  | 0.390                                     | 3.4%           | 10.7                             | 10.5                                | -1.4%          |
| 4  | Fabtherm Air 1.8                       | 0.515                                  | 0.546                                     | 6.0%           | 9.7                              | 9.7                                 | -0.1%          |
| 5  | Insulated Fabtherm Air 1.8             | 0.221                                  | 0.256                                     | 15.8%          | 12.4                             | 13.0                                | 5.1%           |
| 6  | Airium Panels & Fabtherm Air 1.8       | 0.221                                  | 0.238                                     | 7.7%           | 16.6                             | 16.2                                | -2.4%          |

Walls n°4, 5 & 6 have shown a measured thermal transmittance up to 15.8% compared to prediction. After analyzing the different factors, the main cause is due to the high water content inside the masonry block which leads to increase the thermal transmittance. Knowing, the declared thermal conductivity is given with a water content stabilized at 23°C-50% relative humidity, the protocol was updated for walls n°4 and n°6 in order to let the masonry blocks dry. In any current building construction, the masonry blocks will be able to dry after the building is finished. On the other hand the measured decrement delays are close to the calculus according to standards. Comparing walls 5 and 6 with the equivalent thermal transmittance, we measured that the decrement delay is 3.2 hours higher with Airium® panels. The Airium panels tested are seven times denser, 2.5 times thicker than polystyrene boards and placed in the exterior side of the wall. Higher thermal mass per m² and insulation on the exterior of the wall explains the decrement delay increase to 16.2 hours.

### 6. Comments

According the results, the hot-box apparatus measurements are coherent with calculation based on traditional and more innovative construction systems. However for measuring the thermal transmittance, it is mandatory that the wall in the apparatus is representative of the material assembly that is used in calculation. A specific attention on the humidity of the different materials is required, especially with cement based product as products can be delivered with high water content.

Decrement delays are coherent as well, but the calculation is sensitive to the heat capacity of the heavy materials. A sensitivity analysis has shown that increasing the heat capacity of the wall may lead to extend the decrement delay of one hour. A more rigorous comparison will require that all thermal characteristic of the material should been measured.
7. Conclusions
Properly estimating the thermal performance of building components is key for the construction sector. It relies generally on calculations and simulation according to standards and measurement at the material scale. In this study, we tested regular walls and innovative ones in order to verify their thermal transmittance and decrement delay. As the walls are often composed of several materials, it is often necessary to use tables of materials data that may be not accurate enough to properly estimate the overall real thermal performance. With the launch in several countries of Airium® products, a lightweight foam concrete as a thermal insulation material, typical tests have been performed at the material scale like thermal conductivity using a guarded hot-plate apparatus.

The study intends to compare the thermal transmittance and decrement delay of several walls using calculations and a hot-box apparatus. The measurements on a simple concrete wall and an insulated concrete wall showed comparable results to calculations. Several walls using Airium® products have been measured in the same conditions. A first test with wall n°5 has shown a 15% higher thermal transmittance than expected due to high water content in the masonry. For the other test, the masonry blocks were properly dried before testing. The tests show a measured thermal transmittance up to 7% higher than calculation. Considering uncertainties due to the measurement apparatus, to material properties and to building assembly between theoretical case and practical case we consider that the two methods give equivalent results. Decrement delay using the calculation and measurement revealed to be equivalent with maximum error of 0.6 hours (5.1%).

The study confirms that the walls with Airium® products have an equivalent thermal transmittance as predicted by calculation when they are in the same hydric condition, with a thermal transmittance as low as 0.221 W/m².K. As Airium® products are denser than other insulation materials, the different walls offer high decrement delay up to 16.2 hours when combining insulating masonry and Airium® panels. Such high values offer more comfortable indoor climate during heat peak, thus reducing air conditioning installation needs in buildings.

Acknowledgments
Authors wishing to acknowledge assistance of Fabemi for supply the masonry blocks and the rest of the team of the LafargeHolcim Innovation Center involved on the wall assembly and measurements.

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