Measuring thermal conductivity of green-walls components in controlled conditions

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Highlights:

- Thermal conductivities are measured in granular state
- Components of green-walls are compared
- The humidity influences more or less thermal conductivities of the substrates
- In the dry state the substrates can be considered as isolating (λ=0.060W/m °C)
- The ivy and the Virginia creeper would be good complements to insulation

Abstract:

This study is the first stage of a larger multidisciplinary research program about the environmental performances and functions of green walls in urban ecosystems. It aims to determine how green-walls contribute to the thermal insulation of buildings by measuring the thermal conductivities of green-walls' components in controlled conditions. The study focused on complex green-wall systems, i.e. with a structure containing substrate in opposition with green-walls based on climbing plants. The four substrates were materials found in commercial substrate combinations. To compare, the thermal conductivities on two plants are carried out. In dry conditions, they showed conductivities of 0.062 W/m C° for sphagnum moss (*Sphagnum cristatum*), 0.060W/m C° for outdoor planting mix, and 0.105 W/m C° for clay balls and 0.051 W/m C° for substrate from a green-wall. Vegetation conductivities were also measured for ivy (*Hedera helix*) and Virginia creeper (*Parthenocissus quinquefolia*). As expected, conductivities were quite high (between 0.220 and 0.274 W/m C°). With the building thermal simulation, green-walls are technically able to improve buildings' insulation.

1. Introduction

There exist two types of green-walls: simple green-walls (intensive) and complex green-walls (extensive) [1]. The simple green-walls use climbing plants of standard ivy which come “to invade” the wall. It is necessary to wait several years to get the desired result. The complex green-walls, generally claiming an intensive maintenance technique, are working in terms of design. In fact, there exist several processes of implementation. Several manufacturers dispute the market and propose various construction processes. But overall, the principle remains the same one: a system of reinforcement is fixed on the wall, leaving a blade of air between this one and the wall. These reinforcements make it possible to place a substrate in the structure to accommodate the plants.

The concept of reconciliation ecology represents one of the major challenges for the future of urban areas [2]. The ecological engineering techniques of living roofs and walls represent a great potential for reconciliation ecology [2]. But, this task is not easy because it faces two main socioeconomic barriers to their constructions: the cost and the cultural perception of nature [2]. Moreover, a French study [3] showed conflicting interests among citizens. Urban populations express a need for natural spaces and intimacy as well as a need for social contacts with a surrounding environment providing many services such as stores, recreation activities or transport network. Several studies examined the effects of green walls on the temperatures of façades [4]. They have a certain cooling efficiency on the immediate environment [5]: they decrease the temperatures more than on a control facade without vegetation [6, 7, 8]. Several factors influence the observed differences of temperatures. They are grouped around three basic mechanisms. The first is the sunlight ray blocked by the vegetation, which creates a shadow and influences facade temperatures. The importance of this mechanism depends on the density and homogeneity of the foliage. The second is the thermal insulation induced by plants and substrate. The thickness, the density and moisture content of the substrate, the foliage density, the air movement in the intermediate spaces, and the capacity to stop the wind are all factors that affect this mechanism. The third is the facade protection against wind. The effectiveness of this last mechanism depends on the facades orientation, the direction and speed of the wind, and the foliage density [5, 6, 9,10, 11, 12]. Precisions on their component’s thermal behavior were given by a model on the thermodynamic transmission process of the vertical ecosystem [13]. But no measurements were found in the literature. The screening effect by the plants of a building was studied recently [14]. The process developed by prediction of the thermal behavior of buildings envelopes in the presence of simple green-walls was applied to a virtual house located at Lille.

The green-walls are put up more and more on the buildings frontages. As this background shows, green-walls are creating a growing interest in research, and they are approached using different methods and scales. Nevertheless, their thermal benefit still not yet completely mastered in thermal simulation. They are always more used for their aesthetic aspect. Many gaps still remain about their ecological and environmental value. More generally, the required design to optimize their ecological, thermal, acoustic and sensory functions still has to be elucidated. Finally the suppliers of green-walls are interested by the determination of the thermal conductivities values to develop their products.

The aim of this study is to develop the integration of the green-walls on the building and to show its benefits on the building frontage. Firstly, the measurement of the thermal conductivity of different substrates for extensive green-wall (sphagnum moss (*Sphagnum cristatum*), clay balls and substrate of a green-wall CVF are made for manufacturers. Secondly, many walls in France are covered with ivy (*Hedera helix*) or Virginia creeper (*Parthenocissus quinquefolia*), it is interesting to look at their thermal interest. Can the green-wall replace a standard thermal insulation? Which thickness of green-walls is it necessary to allow a profitable insulation? Finally, the thermal conductivities knowledge is an asset to develop the databases of the software and thus create more precise thermal simulations.

2. Methodology and theory

2.1. Conduction and conductivity

The thermal transfer through an environment is made possible thanks to three different heating transfer reactions: conduction, convection, and radiation [15]. For the conductivity measurements, the transfer reaction by conduction was used.
The term of conduction describes the distribution inherent to the internal shocks without transport of material. For example, when two solids with different temperatures enter into contact, the element which the highest temperature is placed into the one with a lower temperature.
Such a transfer always shows itself when a material is subject to a gradient of temperature. A heat flux goes across the region where the temperature is the highest towards the region where the temperature is the lowest. The conduction theory rests on the Fourier law. The flow density is proportional in the temperature gradient:

$$\vec{\varphi} = -\lambda \overrightarrow{grad}\,(T) \quad (1)$$

Where
φ = Flux density (W/m^2)
λ = Thermal conductivity (W/mK)
T = temperature (Kelvin)

The energy preservation depends on thermal properties: the thermal conductivity, the thermal diffusivity, and the geometry of the environment. Heat transfer in an opaque, homogeneous solid, without term of source and isotropic is translated by the following equation:

$$\frac{1}{a}\frac{\partial T}{\partial t} = \nabla^2 T \qquad (2)$$

Such as: 'a' represents the thermal diffusivity which is only a function of λ (thermal conductivity) and ρCp (heat volume).

To resolve the heat equation of any environment, it is indispensable to know two parameters; the thermal conductivity and the heat volume. They characterize the thermal transfer in the environment. This project relied on the measurement of thermal properties, especially thermal conductivity of the porous media. The measure is complex because it depends on more parameters as the material, the contact resistance, the measurement time and the thickness.

2.2. Thermal conductivity of porous media

From the resolution of the energy equation [16, 17] many models of calculations of thermal conductivity were developed (Table 1). The models found in literature can give good results for the calculation of the apparent thermal conductivity of porous media. They are predictions tools developed to know the mechanisms of thermal transfer in porous media. It is necessary to specify that the models suggested relate to only the diphasic granular mediums. The solid phase consists of only one phase represented by solid particles. In addition, the fluid is represented by pores filled exclusively with air.

Table 1. Models developed for the simple granular mediums

Parallel	$\lambda_{app} = \sum \varepsilon_i \lambda_i$	Medium made up in several states parallel between them
Series	$\lambda_{app} = (\sum \frac{\varepsilon_i}{\lambda_i})^{-1}$	Medium made up in several states in series between them
Hashin-Shtrikman	$\frac{\lambda_{app_{min}}}{\lambda_f} = \frac{\lambda_s}{\lambda_f} + \frac{\varepsilon}{\frac{1}{1-\lambda_s/\lambda_f} + \frac{\alpha}{3\lambda_s/\lambda_f}}$ $\frac{\lambda_{app_{max}}}{\lambda_f} = 1 + \frac{\alpha}{\frac{1}{\lambda_s/\lambda_f - 1} + \frac{\varepsilon}{3}}$	The medium is isotropic
Maxwell	$\lambda_{app} = \frac{\varepsilon\lambda_f(2\lambda_f + \lambda_s) + 3\alpha\lambda_s\lambda_f}{\varepsilon(2\lambda_f + \lambda_s) + 3\alpha\lambda_f}$	Particles are spherical and no mutual interaction between the particles
Hamilton	$\frac{\lambda_{app}}{\lambda_f} = \frac{\lambda_s + (n_h - 1)\lambda_f - (n_h - 1)\varepsilon(\lambda_f - \lambda_s)}{\lambda_s + (n_h - 1)\lambda_f + \alpha(\lambda_f - \lambda_s)}$	An extension of the Maxwell model to particles ellipsoidal

Where

n = Number of contact per particle

ε = Porosity of the granular layer

α = Relative density

λ_i, λ_{app} = Apparent thermal conductivity of porous media, W/mK

λ_s = Thermal conductivity of the solid phase, W/mK

λ_f = Thermal conductivity of the fluid to the atmospheric pressure, W/mK

ψ = Sphericity referring to the spherical geometry with $n_h=3/\psi$

The problem is complex. It is necessary to develop models, bringing in different physical phenomena (transfer / condensation, contact law between particles, conduction, and convection) and to verify the microstructure of the environment (size, shape of the particles) and to study the state of the constituents of the environment (conductive phase).

Not knowing the thermal conductivity of materials, the bibliographical references validated the experimental models. The measurement of apparent thermal conductivity is interested in taking into account two phases: solid and fluid. It is necessary to consider the problem of resistance to contact which can intervene during the measurement.

2.3.Experimentation

To characterize materials, the used device is a horizontal system by the guarded hot plate method [18,19]. It is an experiment in permanent transfer mode (ISO 8302) where one imposes on a plane sample a one-way heat flow, and measures the difference in temperature at the boundaries of the sample. This method rests on the use of a thin plate compared to the dimensions of the sample. The implementation of materials tested is easier. The purpose of this experimentation is to measure thermal conductivities. It is necessary to prevent the thermal transfer by convection by the creation of closed wood box (Fig. 1). Its composition is detailed below.

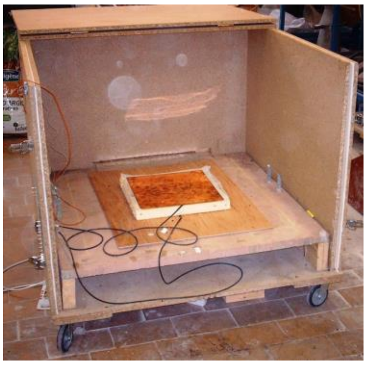


Fig. 1. Overview of the wood box and the device of measure.

The sensors used are a « tangential gradient type ». The tangential gradient fluxmeter intrinsically generates temperature variations in the plane of measurements. Then, these gradients are detected by a great number of thermoelectric junctions connected in a series. Indeed, the sensor generates a Seebeck electro motive forces (EMF) which is proportional to the heat flow. These fluxmeters have a highly conductive copper surface which tends to homogenize the surface temperature and thus to provide average values.

Two fluxmeters with a sensitive area of 30 × 30 cm² are used for this experiment. A first fluxmeter (Φ1) measures the flow, which enters (Fig. 2) and the second (Φ2) measures the flow, which goes out. The average calibration is 262 µV/(W/m²) for the first and 258 µV/(W/m²) for the second, where Φ is the flux density (W/m^2).

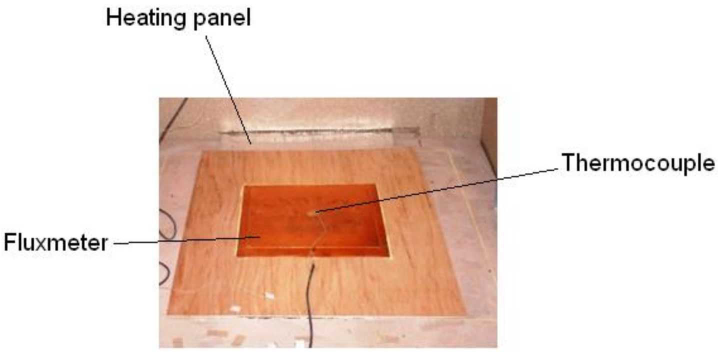


Fig. 2. Detail of the device of measure.

To measure the temperature difference in the borders of the samples, K type thermocouples are used. Its composition is Chromel (alloy nickel + chrome) and Alumel (alloy nickel + aluminum (5%) + siliceous). It allows a measure in a range of wide temperature from -250°C to 1372°C. It is stuck on the surface to measure the temperature (T1).
To allow a unidirectional flow and to avoid the flow loss on the sides, a guard zone was installed around each sensor (Fig. 3).

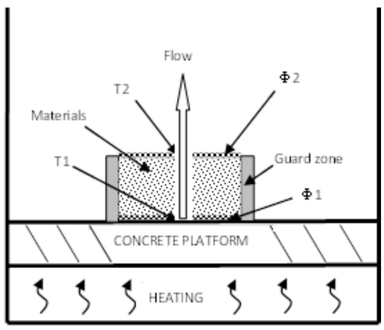


Fig. 3. Principal plan

After the second thermocouple is arranged on its surface (T2), the temperature difference can be measured for the Fourier Law resolution.

To generate the heat flow two devices are necessary. Heating plates heat the surface of concrete to a maximal temperature of 40°C. And a heating resistance homogenizes the temperature of the surface. Furthermore, it will serve for the delicate measurements of plants to obtain a lower temperature (20°C) to avoid the drying of the plants. As a reminder, the measure of conductivity is based on the principle of the guarded warm plate method and the fluxmetric method. It is realized in steady state. The heat flow must be constant in time and uniform in space.

The conductivity value (λ) is calculated by using Fourier Law (3). For it, two temperatures have been measured on the borders of the sample (ΔT) for a surface (S) of 1m² and with a thickness (e) gives the following equation [20, 21]:

$$\lambda = \frac{\phi . e}{\Delta T . S} \text{ (W/mK)} \qquad (3)$$

The measurements are carried out with a portable multimeter and are correct when the device reached the steady state.

The experimental protocol is carried out in the following manner:

- To put on the hotplates and it is necessary to wait a few hours to reach the steady state.
- To make sure of the uniformity of the temperature of the concrete slab. The ΔT should not exceed 1°C. Three thermocouples are distributed on the concrete slab.
- To place the fluxmeter in the center of the concrete slab (a layout is envisaged)
- To place material to be studied with the top of the fluxmeter.
    - For a solid material
      To place the material directly at the top of the fluxmeter.
    - For a granular material
      To place the polyurethane framework of which the interior is covered with geotextile.
      To put the material to be studied within the framework, to fill it to the brim without packing (the material should beforehand be weighed).
      To cover the framework with a film of geotextile in order to avoid resistances of contact
- To place the second fluxmeter at the top
- Lastly, to close the box and to expect the steady state.

2.4. Green-wall components

The substrate characterization for complex green-wall are presented in table 2 and in table 3 for the two climbing plants (Ivy, Virginia creeper).

Table 2. Substrate characterization

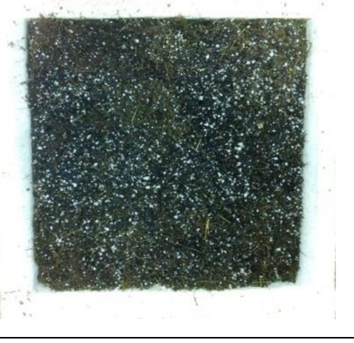
Universal potting substrate	Composition: composted bark, fair peat, plant compost Material dries / total : 35% Material organic/dries : 55% Capacity of retention in water : 600ml/l of substrate pH : 6.5	
Clay balls	The expanded clay is industrially made from natural clay which will successively be dried, reduced to flour, will in some water then will in ovens what gives after all balls or blocks with clay balls. This material has a density between 350 and 700 kg/m^3.	
Sphagnum moss	It possesses a big absorption capacity and retention of the water, the sphagnum moss is a moss which can store 20× its volume in water grace to its very light texture. It is antibacterial what allows a protection against the decay, the diseases and the parasites and it has a pH naturally acid of 4.8.	
Substrate CVF	Industrial composition: Approximately 90 % coconut matting, approximately 10 % of perlite, fertilizer of synthesis	

Table 3. The vegetal palet

Vegetal (%)	Pictures
Ivy	
Virginia creeper	

2.5.Thermal simulation

To complete this study, a modeling was carried out in order to look at the influence of the thermal conductivity of the ivy on consumption energy of a standard house. To determine the influence of the green-wall of a dwelling, the thermal software of simulation instigates TRNSYS 17 has been used. The study case considered thereafter is a house on under floor space. This house is called “House MOZART”: it is a “standard” house representing the average of the French houses in main home. It was defined by EDF in 1994 in co-operation with the CSTB (French Scientific and Technical Centre for Building) and GDF.

The thermal simulation is based on the thesis of Mr. Gossard [22] and a study carried out by the CSTB [23] (for comparison purposes) and to have the data necessary to model the “House Mozart”. The total space of this house is of 100.86 m² with a height under ceiling of 2.3 meter. The results are presented in paragraph 3.5.

3. Results and discussion

3.1. Device validation

To validate the device, two materials have been used: a plain plate extruded polystyrene and sand. The extruded polystyrene has a conductivity value (supplied by the manufacturer) of $\lambda = 0.036$ W/m.K. The measurement gives a conductivity value of $\lambda_{measured} = 0.0377$ W/m.K. For this validation, an error of the conductivity value of the polystyrene extruded is about 4 %. Furthermore, ΔT must be higher for 20°C as required by the trial standard [20]. For the sand, Fillali [16] found a value of thermal conductivity of dry sand of λ = 0.225 W/m.K. The measurement gives a conductivity value of $\lambda_{measured}$= 0.229 W/m.K. The thermal conductivity of sand was measured. The experimental device is validated for porous media.

3.2.Dry substrate

Every material was allowed to dry for 48 hours in a steam room. The basic materials of green-walls were chosen as well as a composition used directly as substrate.

Table 3 presents the results obtained by the measurement of thermal conductivity for an average of three tests. The thickness of the samples is 4 centimeters. The steady state was obtained after 10 hours.

Table 3. Values of thermal conductivity for substrate testing

Substrate	**Thermal conductivity (W/mK)**
Sand	0.225
Universal plant mix	0.062
Clay balls	0.105
Sphaignum	0.060
Substrate CVF	0.051

According to the French standards, an insulating material is recognized as a heat insulator if its thermal conductivity is lower than 0.06 W/m.K. In our case and in the dry state, the outdoor planting mix, the sphagnum moss and the substrate CVF can be considered as heat insulators. But, numerous heat insulators with lower thermal conductivity are available on the market. In fact, the traditional heat insulators have a thermal conductivity included generally between 0.035 and 0.045 W/m.K. Furthermore, if the substrate is dry, it is very likely that no plant can push above.

- ***Mixture of outdoor planting mix and clay balls***

Formulations of substrate of green-walls can contain clay balls. A mixture of outdoor planting mix and clay balls has been realized in the dry state. The results obtained are presented in the following figures.

Fig. 4. Mix ball of clay and plant mix.

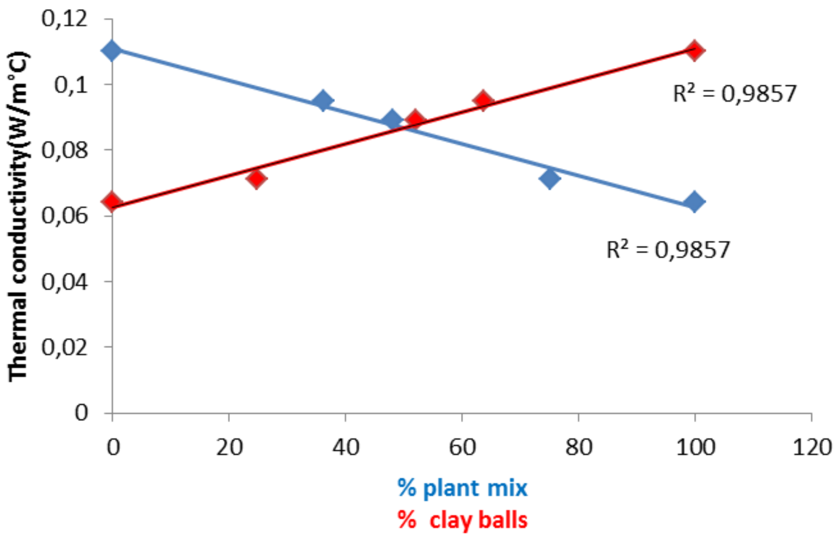


Fig. 5. Variation of the conductivity according to the % of plant mix and clay balls.

The graph gives us as relation (4):

$$\lambda_{mixture} = 0.00025\left(\%_{Clayballs} - \%_{Plantmix}\right) + 0.08675 \qquad (4)$$

3.3.Wet substrate

The next stage consists of studying the substrate in the wet state, here are the results obtained for the outdoor planting mix (Fig. 6) and the sphagnum moss for a 4-centimeter thickness (Fig. 7). The steady state was obtained after 13 hours.

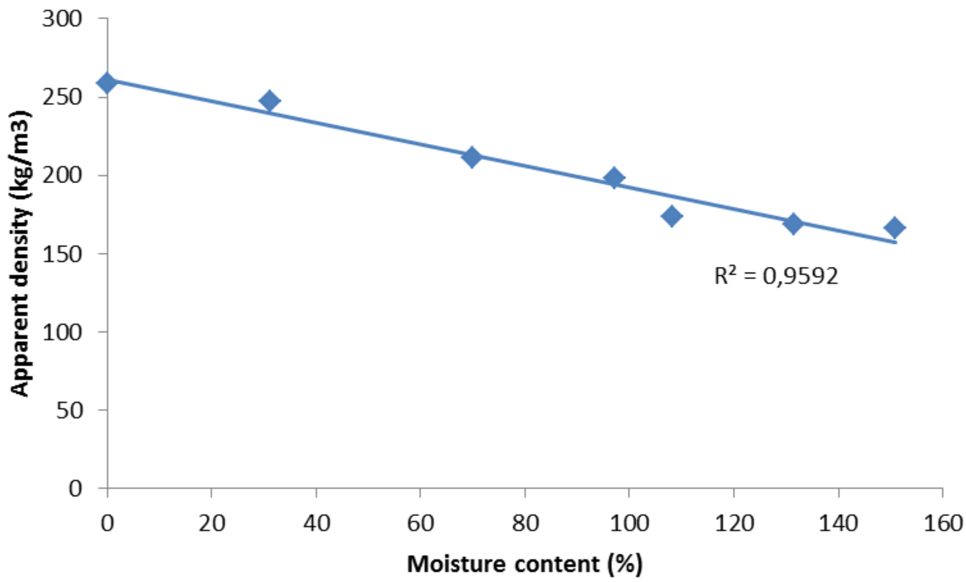


Fig. 6. Apparent densities of the plant mix according to moisture content

The water presence makes the visible density of some compost decrease. Between 150 kg/m^3 and 250 kg /m^3, a decline of conductivity of about 33% is noted by 50 kg/m^3.

$$Apparentdensity_{plantmix} = -0.6851 \times w_{plantmix}(\%) + 260.89 \quad (5)$$

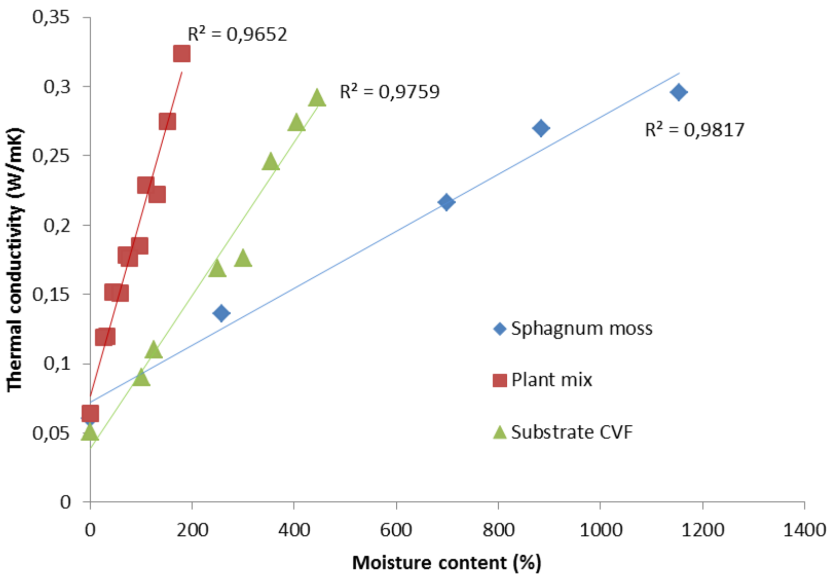


Fig.7. Conductivity of the compost, the sphagnum moss and substrate CVF according to moisture content

What a moisture content w> 10 % as average relation gives us (6) :

$$\lambda_{Plantmix} = 0.0013 \times w_{Plantmix}(\%) + 0.07737 \quad (6)$$

And for the sphagnum moss relation (7) :

$$\lambda_{sphagnum\_moss} = 0.000206 \times w_{sphagnum\_moss}(\%) + 0.071892 \quad (7)$$

And for the substrate CVF relation (8):

$$\lambda_{substrateCSV} = 0.000540 \times w_{substrateCVS}(\%) + 0.04328 \quad (8)$$

Despite the important water presence, the sphagnum moss preserves a low thermal conductivity. Indeed, for a 890 % moisture content, its conductivity is equal to 0.28 W/m°C, compared with the outdoor planting mix, it corresponds approximately to a 150 % moisture content. These results show the importance of the choice of the substrate for the green-wall creation. It is important to control moisture content.

With the relations (3 and 4), the thermal conductivity of materials can be determined with a measure of moisture content (Fig. 8).

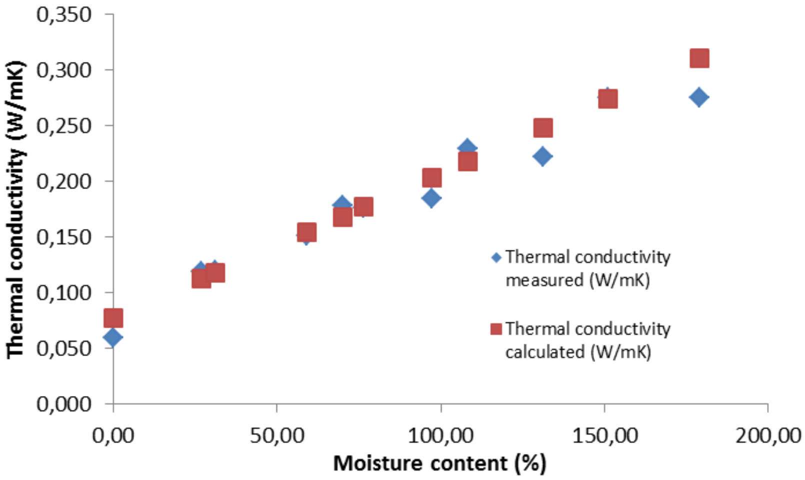


Fig. 8. Comparison between thermal conductivity measured and calculated.

The separation between the measured and calculated conductivities can result from the measure of the moisture content, where a sampling is taken from the global mass.

3.4.Plant palette

To avoid the dry out of plants and to avoid the loss of moisture, the paving concrete was warmed slightly to create a temperature difference of about 10°C. After measurement, the plant was always in the same state. The plant arrangement was realized so as to reproduce a green-wall thickness of 10 centimeters. The foliage implementation is realized to feign a green-wall consisted of sheets and air. Measured thermal conductivities are presented table 4.

Table 4. Measure of the vegetal palet

Vegetal (%)	Thermal conductivity (W/mK)
Ivy	0.239 – 0.265
Virginia creeper	0.220 – 0.274

It is not easy to reproduce the test with the plants. Five tests were carried out to have this measurement range. The results show that the plants don’t bring real thermal insulation. On the other hand, they can help to reduce overheating on the walls in summer [14]. In order to quantify the contribution of a green-wall on a dwelling a modeling on TRNSYS is carried out.

3.5.Thermal simulation

The modeling of the house Mozart was carried out on SketchUp in order to export it on TRNSYS 17 (Fig. 9).

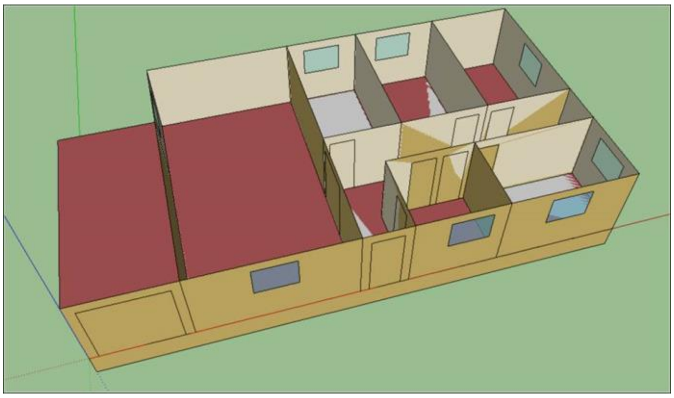


Fig. 9. Modeling of the house Mozart on SketchUp.

To take into account the green-wall (Fig.10), TRNBuild determined these specific properties (λ= 0.25 W/m°C, ρ= 16 kg/m^3 and a heat capacity of 150 Wh/m^3.K).

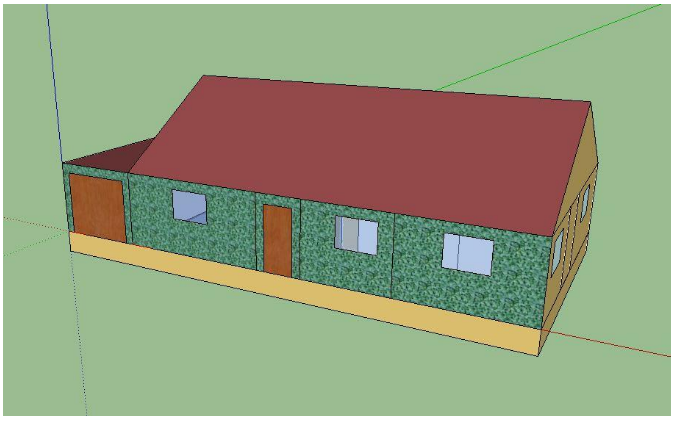


Fig. 10. Modeling of the green-wall of the house Mozart on SketchUp.

The assumptions of simulation are

Heating:

- 19°C except for garage, roofs and underfloor space
- Power = limited to 7.5kW per zone
- Radiative share = 70%

Occupation:

- 3 people present of 17:00 at 8:00 the week and all the day the safe weekend in the garage, roofs and underfloor space

Internalloads:

- Illumination: 5 W/m^2, leaves convective = 40% fluorescent tube
- Use cooks: 240W, radiative share 90% to 777.6 kJ/h (from 19:00 to 20:00 the week and 11:00 to 12:00 the weekend)

Not air-conditioning

Ventilation

- Kitchen: 0.4 vol/h
- Bathroom: 0.2 vol/h

Infiltration

- Heated zones: 0.1 vol/h
- Not heated zones: 1 vol/h

The results are given in table 5.

Table 5. Comparison of the annual statements with and without ivy

House Mozart					
Annual statement in kWh/an					
Needs for heating	Solar contributions	Internal contributions	Losses by the walls	Losses by ventilation	Losses by the infiltrations
Without green-wall					
8454	3147	1442	-8734	0	-4309
Green-wall in the south (5cm of Ivy)					
8204	3147	1442	-8449	0	-4344
Green-wall in the south (10cm of Ivy)					
8167	3147	1442	-8417	0	-4340

Figure 11 presents the reduction of heating of housing with presence of a green-wall.

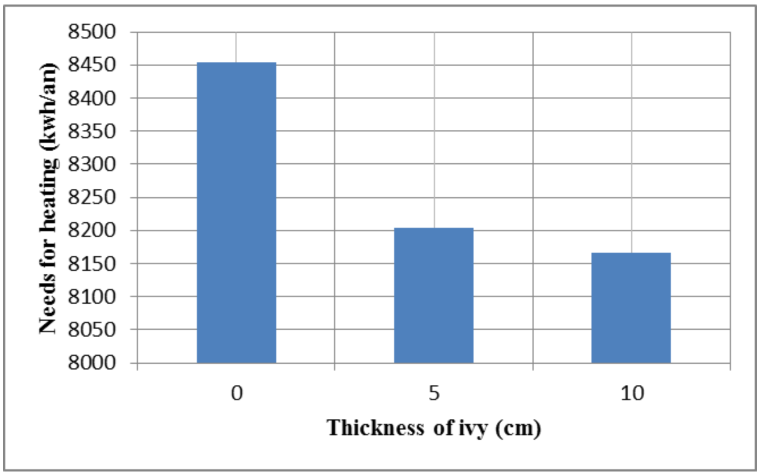


Fig. 11. Comparison for heating with or without ivy.

By modeling the green-wall, a reduction in the production of heating of 3% has been noted which remains low. An ivy addition of 5 cm does not make it possible to have a better performance in insulation. It is necessary to do a more complete study of the thermal performances of the green-walls and integrated the influences of the other phenomena related to the presence of the vegetation [4, 14, 24].

4. Conclusion

This study gives concrete values of thermal conductivity of the components of the complex green-walls for manufacturers. This preliminary study enabled us to find conductivity apparent being able made up a green-wall. This approach remains in conditions controlled with measurements in the laboratory. The measures bring thermal knowledge for the manufacturing of complex green-walls. The manufacturers can develop their product. The green-walls made up of sphagnum have the best thermal conductivities in wet condition. Moreover, it is important to control the moisture of the substrates to obtain the best thermal conductivity. The manufacturers can add sensors moisture in the substrate to find a balance between thermal conductivity, moisture and growth of the plants.

The green-wall materials cannot be used as a replacement to classic types of insulation. On the other hand, they can be used to complement other types of insulation. Their presence controls the solar thermal radiations and thus ~~to~~ avoid overheating in summer.

Concerning the simple green-wall, to obtain a wall respecting the wall insulation (R = 3 m^2.K/W) with 20 cm of ivy or Virginia creeper and with a veil in concrete of 20 cm would be to add a complementary insulation (λ = 0.04 W/mK) of:

- For the Virginia creeper : 8.2 centimeters
- For the Ivy : 8 centimeters

The thermal insulation investigation shows that 5 cm of ivy makes it possible to reduce the needs for heating. The increase of the ivy thickness to 10 cm does not make real improvement of the insulation. The first results of thermal simulation show the interest of the green- walls on the building. It is important to take them into account in thermal simulations in design offices.

Furthermore, the measure of thermal conductivity is realized on rough materials and provides an intrinsic value of the material; it does not take into account its use. It would be necessary to pursue experiments on exposed sites to measure its influence on the thermal comfort of the house.

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