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The Diversity of Limestone and the Implication for Energy Efficiency of Buildings

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Abstract

Building sector represents about 40% of the world energy consumption. Old buildings, reflect a social and cultural heritage that has to be protected. Although these buildings consume more energy than recent ones, they present a large potential for energy savings. Old buildings are constructed with traditional techniques and local materials. So, those buildings depend on the size, the local style of construction and the material available on site. However, most of them were built with stone. Among the diversity of existing stones, limestone represents 10% of the total sedimentary stock. It is widely used for constructions in many countries as Canada, Belgium and France. Nevertheless, every quarries extract different types of limestone with specific characteristics. Currently, there is no identified relationship between material properties and energy building behavior.

The aims of this paper are to examine the limestone diversity in the world at the scale of the material (porosity, thermal conductivity, vapor permeability…etc.) and to define a link with the thermal building behavior (energy consumption, thermal comfort , pathologies…etc.). The methodology of this work is based on a classification of limestone used in constructions according to several properties. Moreover, we dispose of some limestone buildings which are monitored in order to

study internal temperatures, relative humidity, energy consumption and some pathologies.
The measures highlight differences between types of limestone related to their thermal properties. Few of them can be particularly affected by pathologies. This is the case of Tuffeau (Tufa or Freestone) (a limestone from Loire Valley in France). The important porosity of this material (about 45%) causes water pathologies in building envelopes (black crust, disintegration…) which influence their thermal efficiency.

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Introduction

The new energetic and environmental constraints require the improvement of the energy performance and environmental quality of building. Indeed, building sector represents about 40% of the world energy consumption.

The energy performance is not the same for the whole housing stock. In France, three main periods characterize the entire housing stock. The first part which represents about 10 millions of dwellings was constructed before 1948. It is characterized by a social and cultural heritage. . The manufactured buildings submitted to economic and profitability constraints compose the second part of the housing stock. The last part represents the new buildings which respect the thermal regulation since 1975.

The thermal performances of some dwellings of the three periods were mmonitored. For the old buildings, the mean energy consumption is below 227 kWh/m².year, for buildings constructed between 1948 and 1975, energy consumption has an average of 328 kWh/m².year and for the third part, after 1975, the buildings consume between 80 and 110 kWh/m².year [CAN, 2010]. So, in the context of greenhouse gas emissions, most of the existing buildings have to be retrofitted. The old buildings represent a large potential for energy savings.

These constructions depend on the size, the local style of construction and the material available on site. The majority has been built with stone. Among the diversity of existing stones, limestone represents 20% of the total sedimentary stock. It is widely used for constructions in many countries as Canada, Belgium and France. However, the thermal behavior of limestone buildings is little known. Currently, renovation is copied on new buildings and may cause alterations and degradation of performance of the buildings [ROU, 1990].

At the scale of the stone

Methodology

In the world, there are lots of different kinds of limestone. To list these types, we have conducted a bibliographic research which identified 112 different limestones ([CSTC], [CTMNC], [KUM, 2006]). A table synthesizes their properties as porosity, density and thermal conductivity. Unfortunately the hygric behavior of these stones is little known. Indeed, only 16 stones get their value of hygric characteristics.

We analyzed the properties of the identified stones (porosity, density and thermal conductivity) and we have established relations between these properties. However, results may differ because of measurement protocols.

Physical properties

POROSITY

The characteristic considered here is the open porosity. This property corresponds to the proportion of voids which are accessible by water. Among the 112 identified stones, porosity is measured on a sample of 34 extracted principally in the site of the Scientific and technical center of construction [CSTC].

Porosity varies from 0,4% to 48,1%. In this sample, the majority of stones has porosity lower than 20%. So these stones can be qualified as “hard”. However, the studied sample is not necessarily representative of the real proportion of stones in the nature. These results highlight the diversity of existing stones.

DENSITY

All the studied sources have not measured density. The sample is larger than that for the porosity with 104 stones. As for the porosity, the variation of the density is important: from 1000 kg/m^3 to 2750 kg/m^3. Figure 1 shows the density distribution in the studied sample.

This result highlights the large proportion of hard rocks. So, marble is considered as a limestone, its density is about 2700 kg/m^3. Even if it is often extracted, it is not used in dwellings constructions.

RELATION BETWEEN POROSITY AND DENSITY

In the sample of 114 stones, we have the two properties, density and porosity for only 34 stones. A relation between those two parameters has been established with this sample. Figure 2 shows a linear equation between these two properties. The correlation is important with $R^2=0{,}99$. This analyze confirms the major place of calcite in the stone. Indeed for a porosity of 0%, which corresponds to the skeletal structure, the density is 2693 kg/m^3. This value is close to the mean density of calcite: 2710 kg/m^3 [BEC, 2006]. The deviations from the right can be caused by the presence of other minerals and/or by the experimental set-up.

Thermal properties

THERMAL CONDUCTIVITY

As the physical properties, thermal conductivity presents a large variation from 0,35 W/m K to 2,9 W/m K. The considered sample is composed of 34 stones. For them, there is a Gaussian distribution focus on the category 1,0-1,5 W/m K. (Figure 3.).

A relation between the thermal conductivity and density has been established for this sample. An exponential relation gives best results of correlation ($R^2=0{,}8$) as shown in Figure 4. **CANAKCI** and al. [CAN, 2007] have realised a similar study on four Turkish limestones. They also obtain an exponential relation with a correlation coefficient of 0,81 in the worst case. However, it is not possible to compare the two relations because thermal conductivity measurements have been realized for three different water contents. We didn’t consider this point in our analyze.

RELATION BETWEEN THERMAL CONDUCTIVITY AND WATER CONTENT

Thermal conductivity of water is up to 25 times higher than the air one ($\lambda_{eau}=0{,}6$ W/m.K and $\lambda_{air}=0{,}024$ W/m.K). Consequently, thermal conductivity increases with water content. Stones with important porosity are more concerned because they can absorb more water than others.

Figure 5 highlights, with the works of Canacki et al. [CAN, 2007], the influence of water content on thermal conductivity.

The naming LS correspond to 4 different stones; MC is the moisture content and TC thermal conductivity. We can see that moisture content influences thermal conductivity but this influence depends on stone. Somerton (1958) propose a relation to express thermal conductivity of saturated stone as a function of thermal conductivity of dry stone and porosity. The formula is: $\lambda_{sat} = \lambda_{sec}.e^{K.N}$

With: λ_{sat} thermal conductivity of saturated stone (W/m.K),
λ_{sec} thermal conductivity of dry stone (W/m.K),
K a coefficient which depend of the stone (for limestone K=2,1 [POP, 2003]),
N porosity (%).

This formula gives the increasing of thermal conductivity from a dry sample to a saturated one as function of porosity:

$$\frac{\lambda_{sat}}{\lambda_{sec}} = e^{2{,}1.N} \qquad (1)$$

Relation (1) highlights that stones with high porosity are more sensitive to water than the more dense.

At the scale of the wall

Main existing walls

Limestone has been used for a long time. Two forms of stone are used in the construction of a wall: rubble stone or dressed stone (Figure 6.a and b). The majority of constructions is based on these two types of walls. The first is a dressed stone wall with a thickness to 20 from 25 cm. The second one is a rubble stone wall with an average thickness of 50 cm but it can reach 70 cm. Other kinds of walls exist but they are a combination of the precedent walls.

Unlike new constructions, a characteristic of these walls is their heterogeneity. For example, in a rubble stone wall, the place of mortar is significant. **DUGUÉ** and al. [DUG, 2010] estimate in their works that there are more moisture transport in mortar than in stone.

In limestone buildings, walls can include a moisture barrier at the bottom to reduce capillary rises.

Alterations of the walls

CAUSES

We present in this paragraph 3 main causes of stone deterioration [DES, 2000].

Moisture: It is the first cause of degradation. It impacts physically, chemically and biologically the rocks. However, the effects depend on the source of the moisture: some of them are presented here:

- original moisture: it is in the voids of the stone when it is extracted,
- rain: its effects depend on the nature (chemical composition/frequency). The stone and mortar influence water penetration,
- capillary rise: it is the moisture in the ground which rises in materials if there isn't any moisture barrier,
- building problems: it is related to default in construction such as a failing gutter for example.

Crystallization of salts: This mechanism is related to moisture. The transport of CO_2 in the water causes a transformation of calcium carbonate in calcium bicarbonate. At the moment of evaporation, the calcium bicarbonate crystallizes in new voids and clogs them.

Temperature change: A temperature change often causes a volume modification. The mineral structure of stone or the water can be concerned.

EFFECTS

All the sources may cause deteriorations. According to the nature of stone; degradation can be serious for the mechanical structure.

Split-up of thin plates: This degradation is characterized by a separation of the plates on the surface. Its thickness may vary from some millimeters to some centimeters. This deterioration exposes the bottom layer.

Efflorescence: It is the appearance of circles of salts. It is due to evaporation of water loaded with salts. This deterioration may be esthetic when it occurs on the surface. However, efflorescence may cause damages if it occurs the stone.

Formations of crusts: in this part, two different crusts are presented: patina and black crust.

- Patina is the first reaction of stone to the outdoor conditions. This crust is due to dissolution of minerals and accumulation of salts at the surface. Porosity of patina is less important than that of the stone. The problematic of the patina is its split-up of the stone which exposes the bottom layer.

- Black crusts are observed in urban or polluted zones. Particles settle on the stone. Then, they are cemented by salts of the stone. The problem of this deterioration is the same as patina.

Disaggregation: When a place is submitted to frequent moisture, the mortar of minerals is dissolved and salts crystallize. Particles are separated and stone is deteriorated. There is an accumulation of dirt at the bottom of the wall.

At the scale of the buildings

Bioclimatic design

GENERALITIES

Old buildings, constructed before 1948, have architectural characteristics. These properties are influenced by some environmental constraints, as microclimate, close relief, solar shadows, etc. [CAN, 2010]. The envelopes of historical buildings, unlike that of new ones, are heterogeneous: several materials, several thicknesses of wall may be used in the same building .Moreover, close environment (urban or rural zone) has consequences on the energy performance: terraced house or single house, climatic variation between town and country, shadows, etc. So their thermal behavior is strongly dependent on the environment in the site.

We present an example of old construction based on the orientation of the different walls. Figure 7 presents a simple house. Each front of building has a specific construction according to its orientation or its function. Wall 1 corresponds to the main front, the visible wall with the majority of windows and doors. So, it must be more mechanically resistant than the others. Wall 2 is submitted to wind and rain, so it must be waterproof and resistant. A fireplace is generally placed there to drain this front of building. Wall 3 is often oriented to the North with poor solar gains. So its thickness must be greater to reduce thermal losses. Finally, stones that didn't fit on the other walls can be used on wall 4 with the only purpose to close the building.

SUMMER COMFORT WITH THERMAL INERTIA

Thermal inertia is generally associated to old buildings and to summer comfort. We evaluate this phenomenon thanks to two indicators: damping factor and phase difference (relations (2) and (3)).

Damping factor

$$m = \frac{T_{max,ext} - T_{min,ext}}{T_{max,int} - T_{min,int}} \qquad (2)$$

Phase difference

$$\begin{aligned} &\grave{a}\ t_1\ T_{int}(t_1) = T_{max,int} \\ &d = |t_2 - t_1| \\ &\grave{a}\ t_2\ T_{ext}(t_2) = T_{max,ext} \end{aligned} \qquad (3)$$

Limestones allow an appreciable indoor comfort in summer. We present in this paper the monitoring results in two houses (fig?). The first case is located in South of France (84), it is a terraced family home with two facades in contact with another house. This case has a low phase difference (3h) but a good damping factor (4,6). So, the summer comfort is good in this house.

The second case is a single house in tufa(a limestone of Loire valley), located in Indre-et-Loire (37) in France.. Indoor temperature is measured in one room and outdoor temperature on south facade.

Figure 8 shows an importantdamping factor : 8,6 and a phase difference of 8 hours. However, the value of phase difference is difficult to calculate because of the important damping. This house benefits from a summer comfort with an attenuation of the variation temperature and a phase difference which returns heat in the night.

Those two houses have a good summer comfort but it is difficult to generalize to the entire limestone buildings stock.

Relation between indoor and outdoor environments

Five buildings have been monitored in summer between 2007 and 2009 [DGU, 2007]. Outdoor and indoor temperatures and humidity have been measured. Figure 9 presents the existing correlations between outdoor and indoor conditions for each dwelling.

Figure 9 highlights the important correlation of humidity between outdoor and indoor in this category of dwellings. Moreover, Figure 9 assumes that moisture transport has an important place in the wall..

However, the correlation between outdoor and indoor temperatures varies from a building to another. We can suppose that this correlation depends on thermal resistance of the wall because it influences thermal transport.

Energy efficiency

Lots of differences exist between limestone buildings about energy consumption. Figure 10 synthesizes results of six buildings monitoring. It is a little sample which isn't representative of the total diversity of the limestone buildings stock.

These results depend on the source of energy which differs between these dwellings. It is consequently difficult to conclude on a relation with characteristics of the stone. However, Figure 10 highlights the diversity of energy consumption which we can be related to the diversity of thermal conductivity.

Conclusion

This paper presents the large diversity of limestones in buildings. These stones have very different thermal and physical properties. This research highlights that the main problematic is the impact of moisture. Indeed, we have studied the thermal conductivity and noticed that its variation with moisture content is significant. Moreover, humidity is the main cause of pathologies in the wall. The importance of the pathologies depends on the stone and the technical mode of wall (mortar's place).

Moreover, we can find as many hygrothermal behavior than limestone types. However, we can highlight the summer comfort and the important relation between outdoor and indoor humidity.

The aim of this first study is to improve the knowledge of hygrothermal behavior to build a classification of these dwellings. Simultaneously with the bibliographic research, limestone buildings were monitored. Two experimental platforms were constructed in Angers. This kind of study helps the knowledge of hygrothermal behavior without the problematic of occupants. The piece of knowledge acquired will serve retrofitting analyze to propose new techniques for energy efficiency.

Figures

Figure 1. Distribution of density in a sample of 104 stones

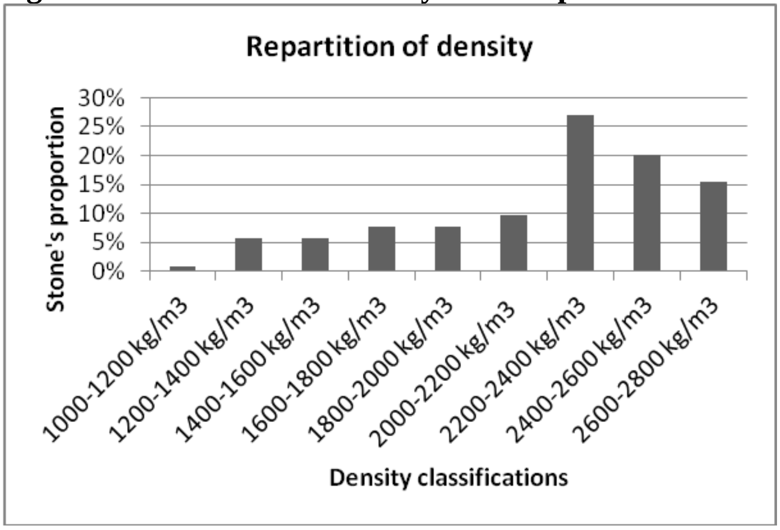


Figure 2. Relation between density and porosity

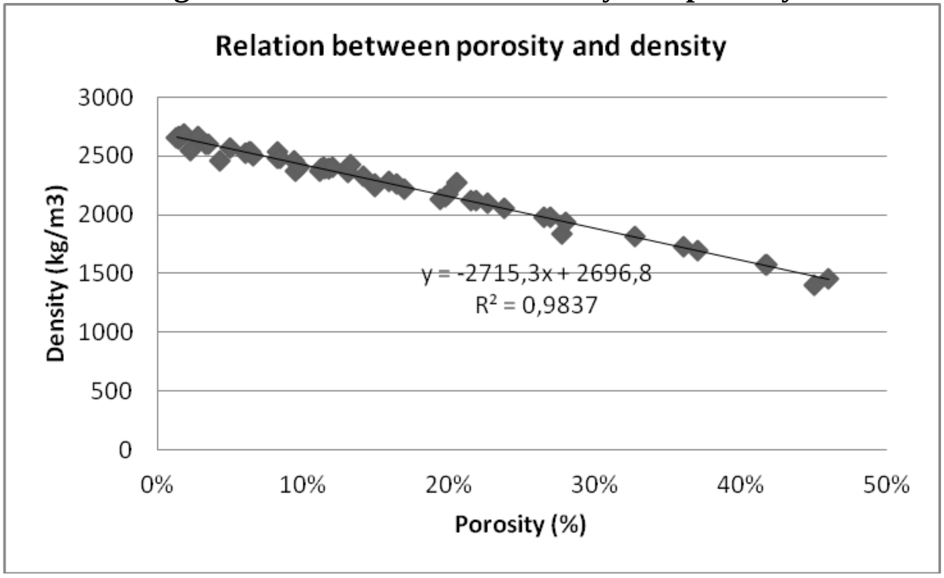


Figure 3. Distribution of thermal conductivity in a sample of 34 stones

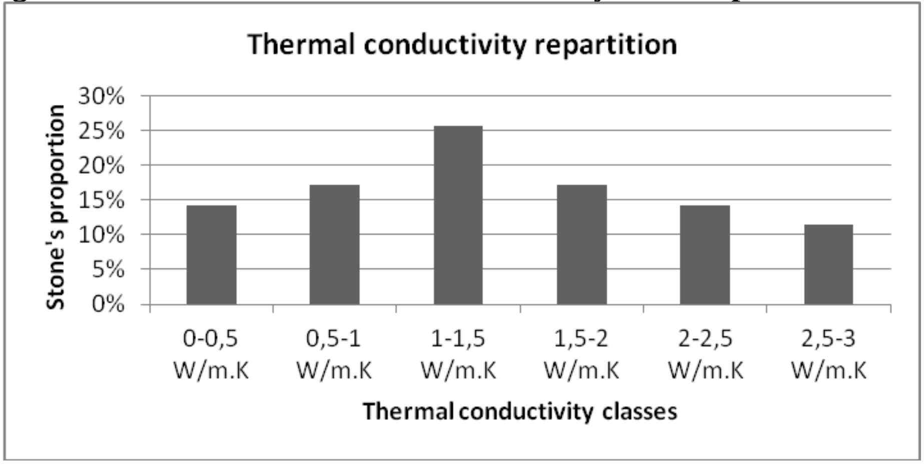


Figure 4. Relation between thermal conductivity and density for a sample of 34 stones

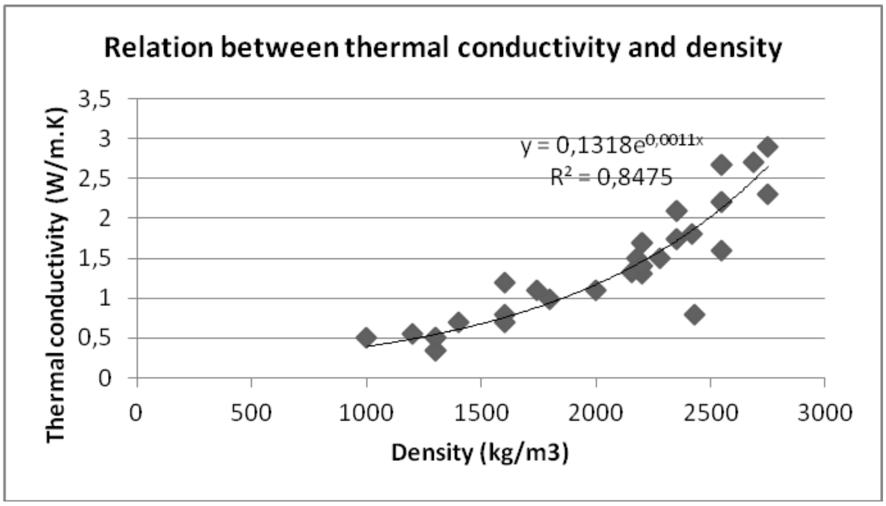


Figure 5. Influence of moisture content on thermal conductivity for 4 limestones (Source: [CAN, 2007])

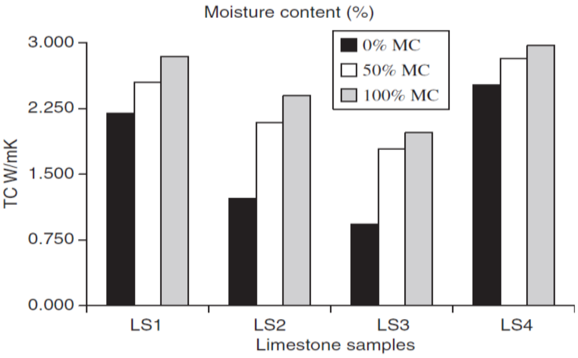


Figure 6. a. Rubble stone wall and b. Dressed stone wall

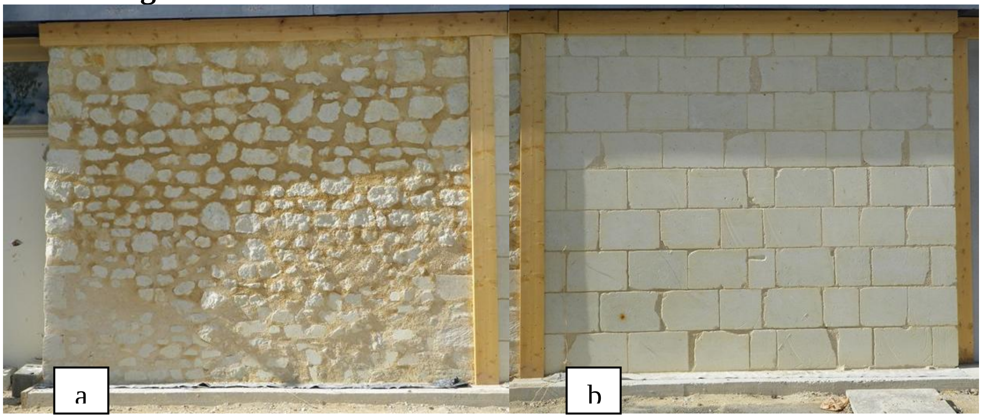


Figure 7. Simple example of a house structure as a function of orientation

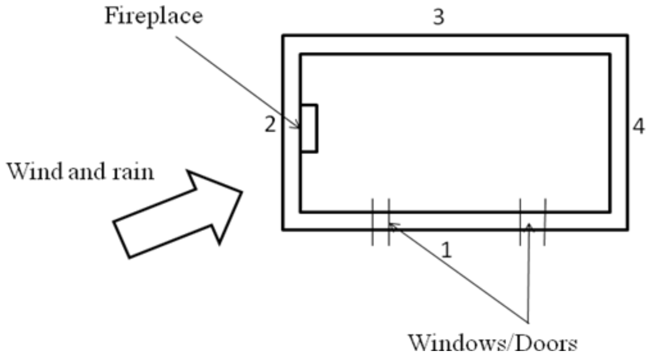


Figure 8. Measured temperatures in a single house of Tuffeau in France

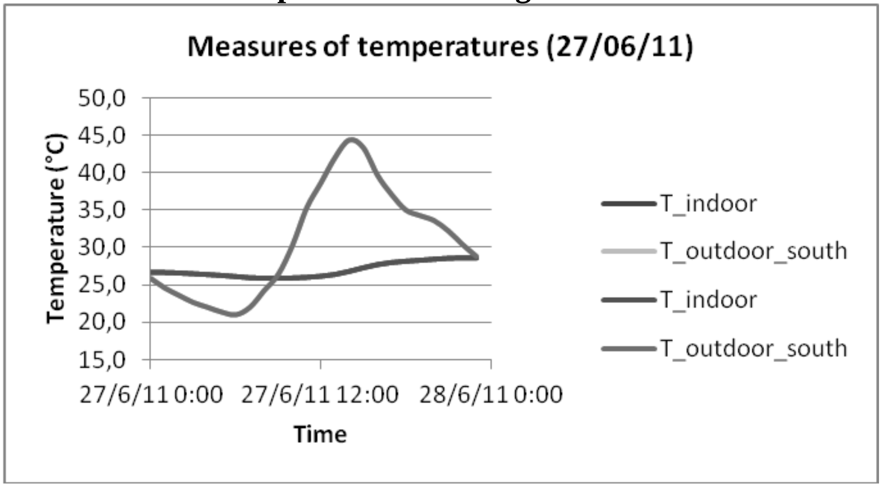


Figure 9. Correlation between outdoor and indoor humidity and temperature of 6 dwellings

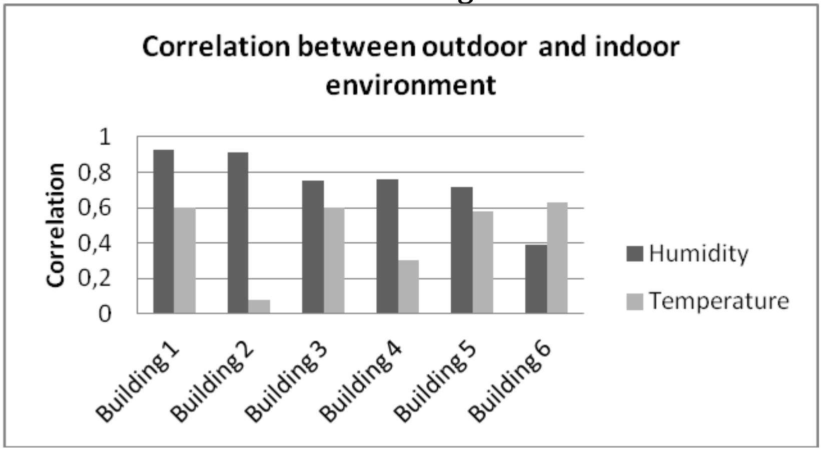
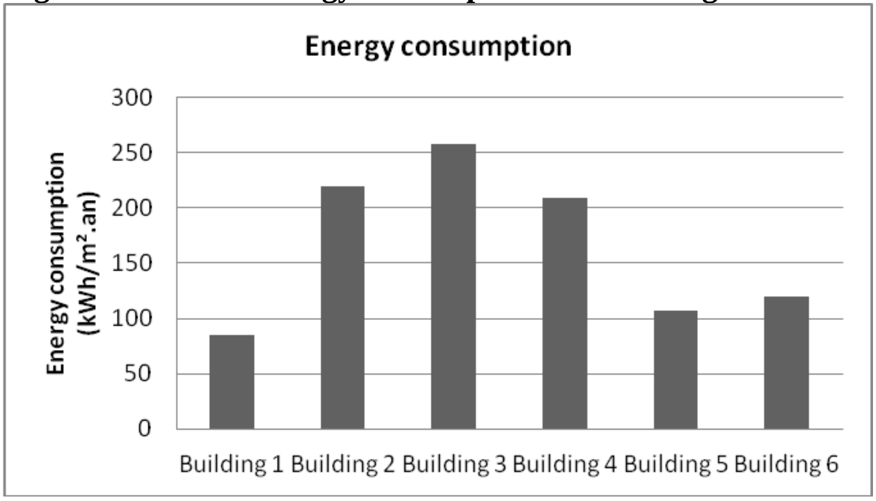


Figure 10. Annual energy consumption of 6 buildings in France



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