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Innovative use of giant reed and cork residues for panels of buildings in Mediterranean area

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A B S T R A C T
The environmental impact of buildings has to be assessed not only in reference to the energy consumed by their use but also with reference to the energy inside materials with which they are made of. The "Sick Building Syndrome" (SBS) is increasing. It was discovered that the major causes are linked to chemical contaminants from indoor sources such as building materials, inadequate ventilation, excessive use of Heating, Ventilation and Air Conditioning (HVAC) and volatile organic compounds (VOCs). The insulation building materials have a relevant role in the SBS for the capacity, not only to limit the use of HVAC but also to limit the emission of pollutants inside a building environment. The present paper reports an up- to-date review of some innovative uses of wastes deriving from agricultural production in order to build walls and partitions for Mediterranean houses. Some test methods of building elements, made with giant reed and agglomerate cork which are two typical natural materials of the Mediterranean area, are illustrated. These vegetal materials are often residues deriving from agricultural production, the agricultural residues are often a problem for farmers or firms because the organic wastes are considered dangerous and the disposal of such material is very expensive, therefore the reuse of the wastes is the best way to recycle these materials. This paper analyzes a cavity wall panel made with a wood skeleton on which two double crossed layers of giant reed stems were fixed and a multilayer agglomerated cork wall with a double cavity multilayer BOTH 20CM THICK. The dynamic thermal analysis carried out for the houses with the proposed walls highlights a better environmental performance of buildings with agglomerated cork and with giant reed walls rather than brick walls. The production of CO_2 for the indoor environmental thermal control of the house with giant reed walls is less than 1/2 and the house with agglomerated cork walls is less than 1/4 compared to the brick wall house.

1. Introduction

Throughout the world, buildings are responsible for about 1/3 of the greenhouse gas emission and consume about 40% of resources. The environ- mental impact of buildings has to be assessed not only in reference to the energy consumed by their use but also with reference to the energy inside materials with which they are made of .Pollution of buildings not only refers to the external environment but also the internal one and influences the occupant's life. The request of green buildings is developing all over the world. Over the last few years, people are increasingly concerned about the quality of life inside buildings. On the other hand the "Sick Building

Syndrome" (SBS) is increasing It was dis- covered that the major causes are linked to chemical contaminants from indoor sources such as building materials, inadequate ventilation, excessive use of Heating, Ventilation and Air Conditioning (HVAC) and volatile organic compounds (VOCs) The insulation building materials have a relevant role in the SBS for the capacity, not only to limit the use of HVAC but also to limit the emission of pollutants inside a building environment. The disposal of buildings could have another hard impact on the environment. In fact building materials could become wastes, therefore, hard to dispose of. When building materials are natural or derived from organic materials, the disposal would not represent a critical source of environmental pollution.
Unfortunately most of insulation material used drive from mineral wool (52% of market share) and plastic

(41%), whereas only a small part is natural. Furthermore, natural materials, during their growth, capture the CO_2 of the environment, im- proving it. Definitely, the correct use of natural materials as insulation for buildings could give a lot of advantages such as:

- lower energy necessary to produce building elements lower energy to control indoor
- environmental temperature better well-being and comfort for the building's occupants
- lower impact to the environment during the phases of use and disposal
- CO_2 environmental capture

Furthermore, if natural materials are derived from agricultural or forestry wastes, the advantages increase greatly.

In the past the use of agricultural or forestry residues was widely utilized in rural farms as building components (e.g. roofs, walls, sheds, fences, etc.), or as complementary materials (e.g. insulation materials, tie elements, claddings, etc.).

The use of these materials was carried out with scarce knowledge but with the best of experience. Sometimes the real characteristics and performances of these materials were little known and for this reason their potentials and utilization were not often the best. The knowledge of the behavior of the material leads to designing and applying new and more efficient building solutions, with optimum use of the materials that come from agricultural wastes and residues

In this paper some test methods of building elements, made with giant reed and agglomerate cork which are two typical natural mate- rials of the Mediterranean area, are illustrated. Furthermore an innovative solution for new building components is proposed, which improves the performance of *Arundo donax* L. and cork.

2. Reuse of agriculture residues for building materials

The use and reuse of residues and wastes of the agriculture and forestry industry has always belonged to the traditional Mediterranean traditional rural culture. According to farmers, wastes do not exist but are only resources to recycle. Although the properties of natural material residues are characterized by a lot of environmental and producing factors such as weather conditions, soil contents, planting, harvesting, working methods of the main materials, there is a similar use of these materials in most of the Mediterranean countries. For example the stem of *Arundo donax* L. is used, in Italy as well as in Spain, to make the walls of a house or a shelter for animals.

2.1 Arundo donax L

Arundo donax L., commonly known as “giant reed”, is a potentially high yielding non-food crop with hollow stems. Giant reed is one of the most environmentally friendly cost effective crops and has a large prospective use in development so much as to be considered as the major biomass crop. It could meet market requirements for energy, paper pulp production and construction of building materials but it can also cause serious problems such as the outbreak of fires in the dry seasons and obstruct the free flow of rivers causing serious problems to structures and bridges (Fig. 1). However, giant reed has never been cultivated as a crop because there is yet no market for it.

In Mediterranean areas, giant reed grows widely naturally along stream and river banks. In good environmental conditions, the height can reach more than 10 m.. The nodes located along the stem, which are at a distance of about 20 cm from each other, give it a greater strength. The stem has a thickness of 0.2 cm–0.6 cm and an average external diameter of 2–3 cm or even 4 cm. The underground rhizomes of giant reeds are woody and fibrous and penetrate as much as one meter deep into the soil and allow the vegetative reproduction. The giant reed has been traditionally employed for building fences and temporary shelters for man and animals. They have also been used as props for plants, as windbreakers or as shading barriers. The use of giant reed as a construction material can be improved with our current technology and knowledge, which allow us to set behavior models, increase their resilience and improve safety. Although the mean tensile strength of the culm of giant reed (TS = 248 Mpa) is more than bamboo (TS = 230 Mpa) it is not used as a high performance structural material in the same wayas bamboo. In some countries with a hot dry climate the giant reed isused as building components. For example in the swamps of southern Iraq the traditional houses, called " Mudhif, were built with large and thick arches of giant reed culms. The arches built of giant reed were bundled into were by giant reed bundled into columns and then bent across and tied to form a curved geometrical shape. This building system creates a pre-stressing of the arches that are IS initially inserted into the soil at opposing angles (Fig. 2). The shape of the buildings is defined by the number and the diameter of the arches. For the Boom Festival 2010 in Idanha-a-Nova in Portugal, the architect Jonathan Cory-Wright, proposed a similar building system. The shelters were built joining together arches of giant reed, and it was the best example of modern architecture with giant reed, that highlighted the best performance of this vegetal material. In Italy and in Spain giant reed is used only insome parts of the buildings, for example for walls or for ceilings. Afterthe earthquake in 1908 in the southern part of Calabria, to take ad- vantage of the light weight of the culms, giant reed was used for cavity walls in the reconstruction of many buildings and refurbishments. In several Countries of Mediterranean areas, giant reed was also used with plaster in some structural elements (e.g. floor slabs and roof slabs) until around 1960, especially in rural buildings, but also in some buildings in the city. We can find them in interior elements and also in exteriors under cover (Fig. 3), but always with the cane protected from the water. This use has been supported by the practice of masonry, but not widely studied in theory to establish behavioral models.

Recently several authors have studied this behavior and others have tried modifications in the designs of the slabs, obtaining improvements in the resistant collaboration between the plaster and giant reed which increase the resistance to bending compared to that obtained with the traditional design.

Although the giant reed was widely used in ancient times in many Mediterranean countries, as structures or components of a building, the mechanical and thermal characteristics of the material were not well known. Only recently some tests were done to study the real performance of this vegetal material, which is becoming a problem for agriculture and for the safety of the territory. The principal problems, in order to characterize the physical properties of the natural materials, derive from the lack of specific standard tests and from the irregularityand variability of the material. Several study and research were orientated to assess the thermal and mechanical characteristics of natural materials and of some agricultural by-products so as to be re-used or recycled in the building sector but in some cases they are limited to an experimental laboratory stage and the performance evaluations of these natural materials in a usage stage are neglected found out that the mean value of moisture of the plant of giant reed after being cut and naturally dried for 3 months was 12.11% and the mean value for water absorption was 52.6% after immersion in water for 24 h at room temperature of 23 °C. The author measured the mechanical properties of 21 samples of stems and obtained the mean value bending strength of 132.5 $N{\cdot}cm^{-2}$, a mean value of compressive strength of 67.8 $N{\cdot}cm^{-2}$ and a mean value of bearing strength of 27.2 $N{\cdot}cm^{-2}$.

Moreover, he found that by putting two layers of giant reed with a thickness of 4 cm perpendicular to each other, resulted in the best thermal insulation value ($K = 0.063\ W{\cdot}m^{-1}\ K^{-1}$). carried out an experiment to evaluate the thermal conductance of a panel of two crossed layers of giant reed, each of which were 2 cm thick. The panel was covered by two layers of plaster, 2 cm thick. The plaster was made of natural hydraulic lime, sifted lime, calcareous sandand a base inert material of silicate closed-cell. The thermal conductance of the plaster layers is certified by the producing company (0.76 $W{\cdot}m^{-1}\ K^{-1}$).

A specific measuring room equipped with instruments for the continuous measurement of microclimate values was made for this experiment, which was 2 m × 3 m in size and 3 m in height. It, above all during the night, was heated by a heater to ensure a proper thermal gradient between the indoor and outdoor environment and also to achieve a good stability of thermal conditions. The heat flow and the surface temperature of the panel were measured by means of a heat flowmeter and three temperature sensors, one of which was applied on the internal side.

The analyzed panel highlighted its good insulating properties in fact the conductance measured was of 1.31 $W{\cdot}m^{-2}\ K^{-1}$. The 8 cm-thick panel, made of giant reed and lime plaster, has a weight per unit of a surface area of only 240 $N{\cdot}m^{-2}$ but a thermal resistance ($Rad = 0.96\ m^2{\cdot}K{\cdot}W^{-1}$) three times more than that of a hollow brick wall and with the same thickness (Rb = 0.27 $m^2·K·W^{-1}$).

2.2 Cork

Cork is a natural material produced by Quercus suber, a tree wide- spread in North Africa and in a few areas of Portugal, Spain and Italy, the latter in Sardinia and Calabria (Modica et al., 2016). Its qualities have been known since ancient times and nowadays it is widely used in many fields. The presence of a large amount of gas in the cells of the cork makes it light, very elastic and waterproof to liquids and gases. It has a thermic and sound insulation and it is strong and resistant to the parasites because it contains suberin which is a resistant organic sub- stance (Franke and Schreiber, 2007). For this last reason, the best use of cork is as bottle stoppers but this produces more waste and residue. It was estimated than over 75% of cork used for stoppers becomes a waste product. Moreover, a large amount of cork waste comes from cleaned and pruned forests and also from urban wastes. These residual materials could be recycled and crushed to obtain cork granulate used in the building sector as insulation materials. The agglomerated cork boards have been introduced in the building sector for thermal insulation . The type of binder used to make the boards in- fluences their specific density and mechanical and thermal behavior . Various types of synthetic and natural binders were tested (urethane, melaminic and phenolic resins) in particular a special building method based on overheating granules (or using high- frequency ultrasounds) was used to soften the suberin and the lignin and to expand and bond together cork granules). carried out an experiment to evaluate the thermal characteristics of some agglomerate cork panels used in the insulation of buildings, the tests demonstrated that the average value of the cork agglomerate boards is 0.065 $W·m^{-1}·K^{-1}$ similar to those of natural cork . However, natural cork has a specific heat capacity definitely lower (350 $J·kg^{-1}·K^{-1}$) than the average value of agglomerate boards (3370 $J·kg^{-1}·K^{-1}$) and a value of thermal diffusivity (1.00·10^{-6} $m^2·s^{-1}$) higher than that of cork agglomerate boards (1.04·10^{-7} $m^2·s^{-1}$). The low thermal diffusivity value of an insulating material is one of the most important indicators of its thermal performance in particular for heat propagation under non-steady-state conditions. Therefore, in warm climate areas, it is very appreciated.

3. Innovative use of residues deriving from agricultural production for building components

The major problem in Mediterranean housing is to insulate the in- door environment from high temperature. To reach this aim, using only high thermal resistance materials is not enough but it is also necessary to design and build efficient component solutions to bring out and optimize the thermal properties of the materials.

3.1. Innovative panels in giant reed for buildings in Mediterranean area

In Barreca and Fichera (2013) a new solution to build thermal ef- ficient wall partitions in Mediterranean areas was proposed. This paper analyzed a cavity wall panel made with a wood skeleton on which two double crossed layers of giant reed stems were fiXed. The panel was finished on both sides with two layers of cement plaster of 1 cm each. The two double layers of giant reed stems formed an internal air space of about 20 cm (Fig. 4) trough holes located at the top and bottom of the panels. The cavity was then linked to an outside environment to gen- erate an ascendant area flow called "chimney effect". The authors car- ried out a steady-state thermal analysis to evaluate the heat transfer through the panel. They considered a typical Mediterranean tempera- ture gradient, which is 35 °C outdoor temperature and 20 °C indoor temperature. The results of the analysis showed a heat flow entering inside the environment of about 4.5 $W·m^{-2}$, a limited value that allows one to obtain a comfortable environment also in a warm climate. For the author, this building solution is better than a traditional masonry wall, 30 cm thick, which allows a thermal flow rate of 23 $W·m^{-2}$ as for the previous indoor and outdoor temperatures. This solution is suitable for animal stalls, temporary buildings, buildings used for the pre- servation of agricultural products and also for the restoration of existing buildings in the Mediterranean area. The lightness of the building components allows an easier transport and assembly by anyone and not only by specialized workers.
Another innovative use of giant reed in buildings is for roof slabs in green buildings. For this purpose, a lot of

solutions were developed. Some of these designs, such as that of the slotted reed (Fig. 5), also improve the breaking mechanism of traditional slabs, by preventing the collapse of the piece after the appearance of the first crack. The increase in flexural strength, for this case, is 116.2%, reaching 5.34 N·mm−2 compared to 2.47 N·mm−2 in the traditional design.

The consequence of the increase in flexural strength is that we can build plaster and giant reed slabs with beams separated 70 cm and thicknesses from 7.50 cm (Fig. 6) fulfilling the requirements of fiXed loads in the Spanish code, with environmentally friendly mate- rials more sustainable than those conventionally used, steel and re- inforced concrete. For the case of 75 mm specimens, if we consider a coefficient of reduction of the properties of the gypsum material Yc = 1.5, the average values of the reduced fracture load obtained are 1275.58 N, 1452.51 N and 1334.76 N respectively, according to the diameter of cane used (9–13 mm, 12–16 mm, 15–18 mm), which are far above the require-
ments of the Spanish code (220%, 250% and 230% approXi- mately), and therefore the validity of the designs tested for structural use in floor and roof slabs is demonstrated.

On the other hand, some investigations (Flores et al., 2011a,b) are based on the use of crushed cane fiber, with several sizes of fiber (< 8 mm), for the manufacture of boards for indoor use (Fig. 7), using urea formaldehyde resin as binder (as in the industry of the wood boards) obtaining similar results as those obtained in boards made with wood fibers, in terms of Modulus of Rupture values (MoR = 15.98 N·mm−2).

When we use high pressure in the manufacture of the boards (up to 25 N·mm−2), according to the UNE EN 310 standard, the results, for particles of size < 4 mm, meet the requirements to be considered par- ticle boards for indoor use, according to the UNE EN 312-4 standard, although the results decrease when we use particles up to 8 mm (Flores et al., 2011a,b).

3.2. Innovative walls in agglomerated cork for buildings in Mediterranean areas

Barreca and Fichera (2013) proposed a multilayer agglomerated cork wall with a double cavity multilayer, characterized by two layers of 6.5 cm thick agglomerate cork placed at the two ends of the panel having an overall thickness of 20 cm and a periodic thermal transmit- tance value lower than 0.12 W·m−2 K-1. Between the two layers, two 3 cm thick air cavities were planned, separated by an OSB load-bearing layer (Fig. 8).

This structure enables one to exploit the breathability of the ag- glomerated cork panels and to let out condensation or water vapors, which may form inside the environment. Moreover, the presence of cavities limits the heat transfer by solar radiation, since the faces of the OSB have a lower emissivity value than those of cork panels. The dy- namic thermal performances and characteristics of the wall were cal- culated by means of the method proposed by the ISO (2007), con- sidering a horizontal heat flow passing through the wall. In particular, this method takes into account the dynamic behavior of building components undergoing a sinusoidal temporal temperature variation.

Such characteristics make the wall particularly suitable to hot and wet climate areas. The walls characterized by a low thermal diffusivity value allow one to obtain a time delay peak of the external thermal stresses therefore, mitigating internal microclimate conditions. The same performances can be obtained from hollow brick walls with a width of at least 50 cm, and insulation with no less than 5 cm of rock wool, with an overall weight per unit area more than 20 times higher. The proposed cork wall shows high performances in hot climate areas, high environmental sustainability and, thanks to its low weight, it can be easily transported and installed.

4. Energy performance assessment of the innovative walls

To evaluate the energy performances of the innovative walls pro- posed, a dynamic thermal analysis of a hypothetic one floor Mediterranean house with three different wall solutions was conducted. It was carried out by EnergyPlus™ which is a building energy simulation program to model energy consumption for heating and cooling the in- door environment of a house. The first analysed solution was depicted by the typical Mediterranean brick walls, the second by the proposed walls in agglomerated cork and the third by the proposed walls in giant reed. The hypothetic house analysed was located in Reggio Calabria which is a city in southern

Italy. The weather of the site was characterized by summer temperatures close to 30 °C and winter temperatures higher Than 5 °C (Fig. 9)
The analysed house had a regular plan with dimensions of 12 × 6 m on a surface of 72 m2 and a height of 3 m below the roof eaves. It had 6 windows and one door (Fig. 10). The indoor temperature, for the en- ergy performance evaluation, was maintained in a range between 18–25 °C. The thermal characteristics of the different analysed walls are reported in Tables 1–3.
Fig. 11 illustrates, for the three different wall solutions, the result of a monthly energy to heat and cool the indoor environment necessary to maintain the temperature within the fiXed range.
The total yearly energy demand for heating and cooling the fol- lowing houses was: 4154 kWh for brick walls, 1028 kWh for agglom- erated cork walls and 1807 kWh for giant reed walls.
In particular the saved energy by the use of agglomerated cork walls for the envelope of buildings is more than 75% of the energy spent for building with brick walls. The saving is not only economic but also environmental. In fact the yearly estimated production of CO_2 for heating and cooling the following houses was: 2517 kg for brick walls, 623 kg for agglomerated cork walls and 1905 kg for giant reed walls.

5.Conclusion

The present paper reports on an up-to-date review of some in- novative uses of wastes deriving from agricultural production in order to build walls and partitions for Mediterranean houses.
The report is about two materials coming from giant reed and cork residues, whose plants are widely found in a lot of Mediterranean countries.
The agricultural residues are often a problem for farmers or in- dustries because the organic wastes are considered dangerous and the disposal of such material is very expensive.
They are often good natural insulation materials and their use is an excellent solution to reduce agricultural waste.
The use of these materials produces different benefits to the en- vironment which could be synthesized in the points below:

- To dispose of agricultural residues from the environment and to give farms an extra income, in such a way that this waste becomes a product (e.g. building components).
- To improve the indoor environmental quality of the buildings and human health. These materials do not release toXic substances as do some petrochemical insulation materials, which are widely used in modern houses.
- These natural materials have a good thermal insulation perfor- mance. Their application allows a significant energy saving and consequently lower CO_2 emissions in the environment for indoor climate control and for the comfort of the occupants. In this paper the dynamic thermal analysis carried out for the houses with the proposed walls, highlights a better environmental performance of buildings with agglomerated cork and with giant reed walls rather than brick walls. In fact the production of CO_2 for the indoor en- vironmental thermal control of the house with giant reed walls is less than 1/2 and for the house with agglomerated cork walls is less than 1/4 compared to the brick wall house.
- The easy recycling of these natural materials at the end of the life cycle of the buildings does not require much energy or work, and the recycled material could be used in other applications for example for packaging, as a growing medium for plants, miXing it with concrete to enable it to become lighter, etc.
- The environmental effects of the disposed wastes are lower than other building materials. The giant reed is a biodegradable material and could be burnt to produce thermal energy. In agriculture cork is a good material to improve the performance of crop soil such as improving air exchange and humidity control.

Thanks to research the natural materials could be used in a better way than in the past with the reproposal of traditional Mediterranean architecture principles.

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Fig. 2. Arches in giant reed for Mudhif house.

Fig. 1. Culm of *Arundo donax* L.

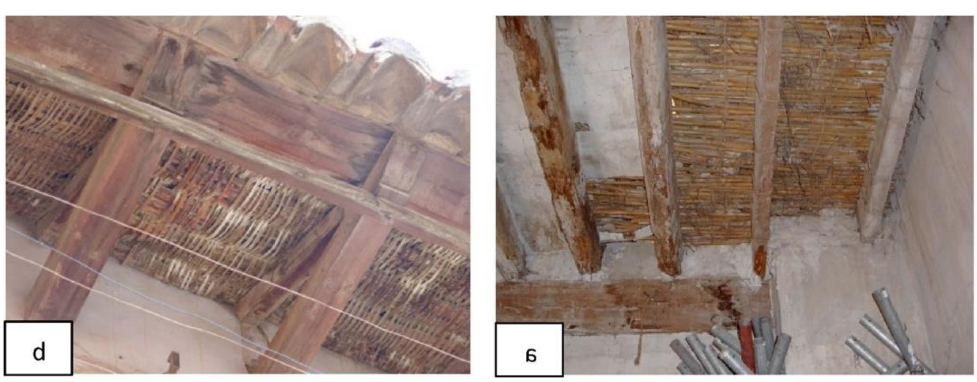


Fig. 3. Interior floor slab (a) and exterior roof slab (b).

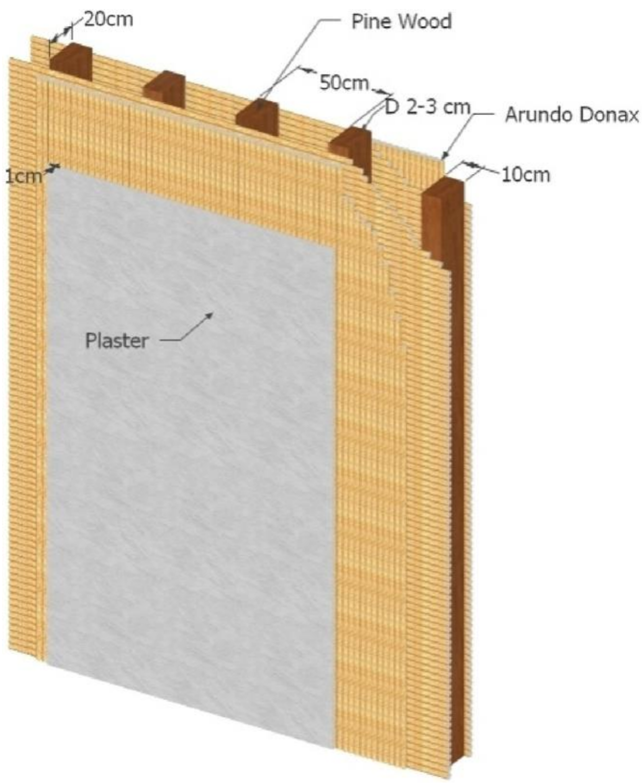


Fig. 4. Innovative wall in giant reed.

Fig. 5. Slotted reed inside the specimen mold.

Fig. 6. Specimen series with 100 and 75 mm thickness in real size.

Fig. 7. Common reed particleboards test developed.

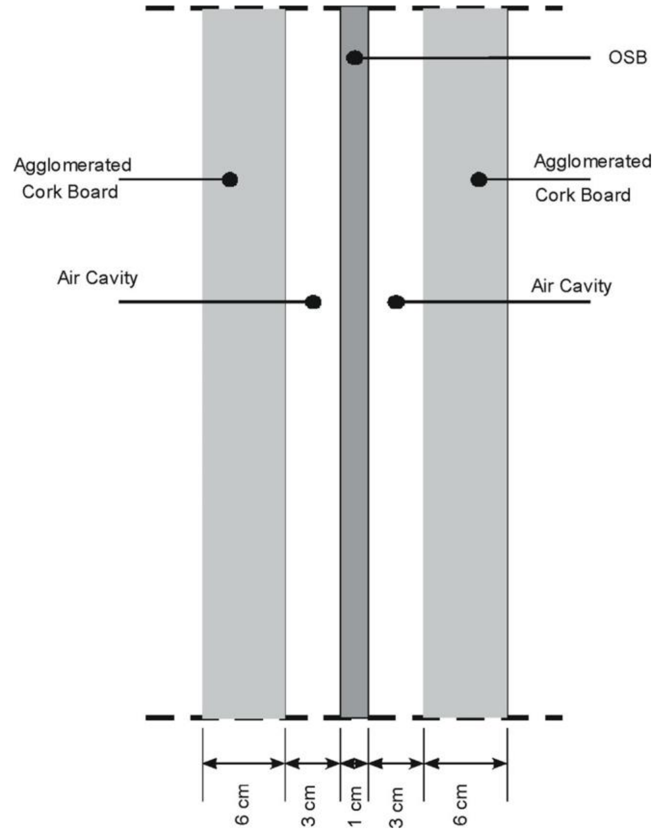


Fig. 8. Double cavity multilayer proposed.

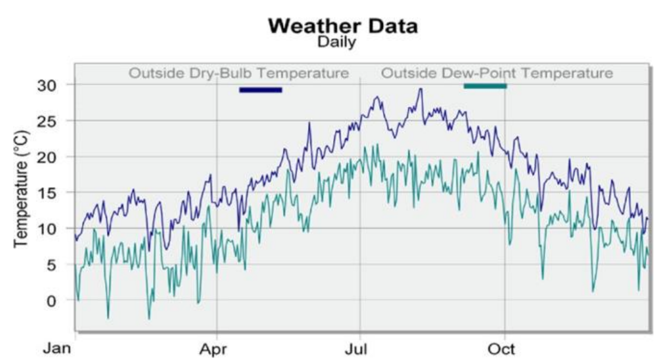


Fig. 9. Daily weather dry-bulb and dew-point temperatures of the site of the analysed house.

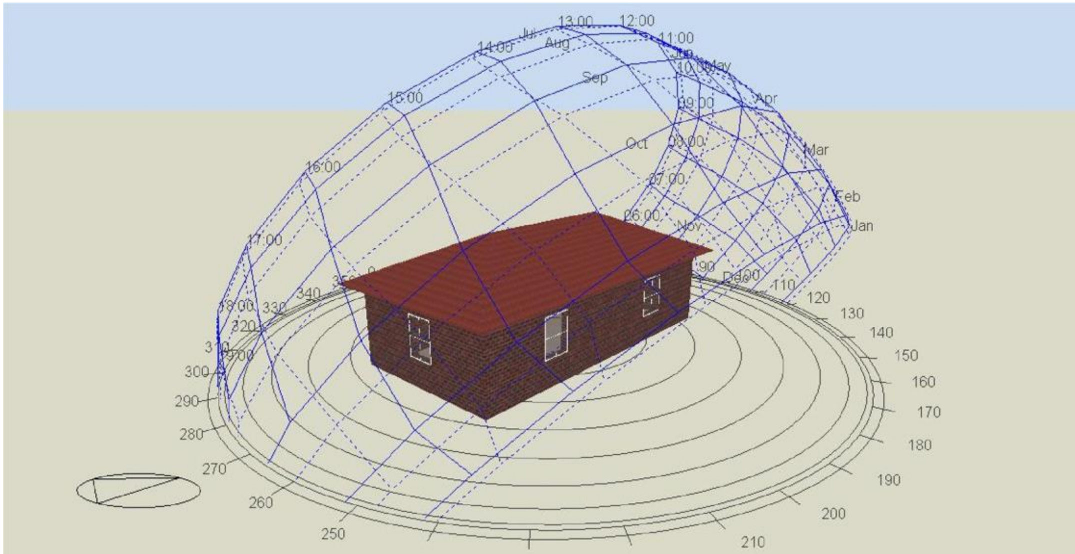


Fig. 10. Model for thermal dynamic analysis of a brick walls house.

Table 1
Brick wall thermal properties.

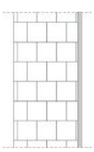
	Layers (from inside to outside)	Thickness (cm)	Mass density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Specific heat (J kg^{-1} K^{-1})	Transmittance (W m^{-2} K^{-1})
	Plaster	1	950.00	0.35	840.00	
	Brick	20	1700	0.84	800.00	
						2.450

Table 2
Cork agglomerated wall thermal properties.

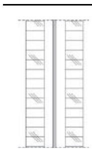
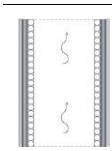
	Layers (from inside to outside)	Thickness (cm)	Mass density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Specific heat (J kg^{-1} K^{-1})	Transmittance (W m^{-2} K^{-1})
	Agglomerated cork	6	160	0.0400	1888	
	Air gap	3				
	OSB	1	650.00	0.13	1700	
	Air gap	3				
	Agglomerated cork	6	160	0.0400	1888	
						0.279

Table 3
Giant reed wall thermal properties.

	Layers (from inside to outside)	Thickness (cm)	Mass density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Specific heat (J kg^{-1} K^{-1})	Transmittance (W m^{-2} K^{-1})
	Plaster	1	600	0.16	1000	
	Arundo donax	4	510	0.0630	1000	
	Ventilated cavity	20				
	Arundo donax	4	510	0.0630	1000	
	Plaster	1	600	0.16	1000	
						0.604

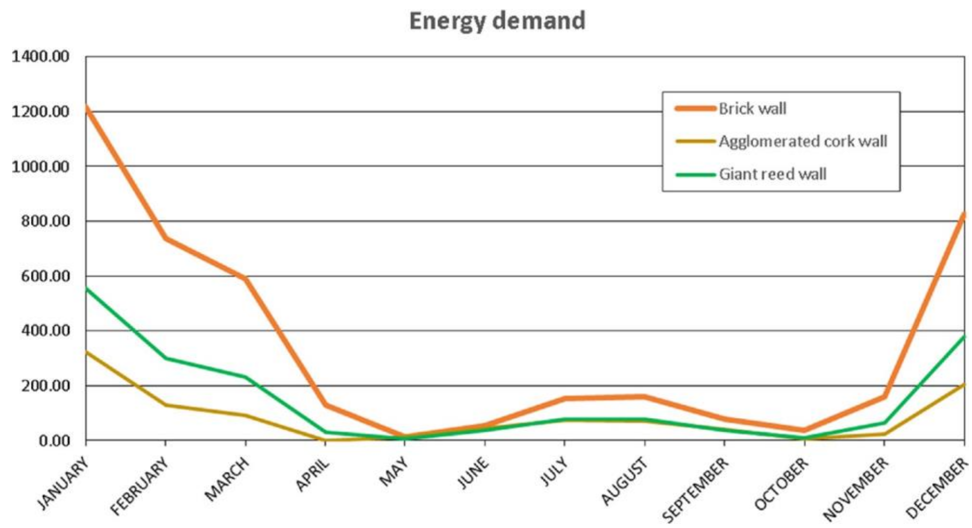


Fig. 11. Energy demand for indoor thermal control of the analysed houses.