Thermal performance evaluation of a low-cost housing ceiling prototype made with gypsum and sisal fibre panels.

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Abstract. Social housing needs and constructive demands required new constructive solutions based on the use of innovative materials, aiming energy efficiency, reducing waste, maintains of buildings and pollutants such as CO₂. The composites materials with a ceramic matrix and fibres as reinforcement originate materials widely used in building industry. However, the study of the thermal performance of these composites materials as a ceiling prototype panels contributes to the determination of the internal temperatures and thermal comfort achieve by the social house. The present research had the purpose of conceiving and evaluating the thermal performance of a low-cost ceiling prototype panels made of a gypsum composite reinforced with sisal nonwoven ("in nature"), located in Salvador, Napoli, Barcelona and Marseille, by means of computer simulations for testing the improvements of the original gypsum ceiling. Among the composites used in this study are the following conformations: gypsum-sisal-gypsum (GMG), gypsum-sisal-sisal-gypsum (GMMG), gypsum-sisal-gypsum-sisal-gypsum (GMGMG). From obtained results, general guidelines were drawn for improving indoor comfort condition for summer at each location.

1. Introduction

Environmental issues have increased global interest in sustainability and in the conduct required to protect the environment [12]. Currently, the construction industry faces a multi-dimensional environmental crisis, as buildings are considered a higher cause of pollution during their life cycle, using 40% of natural resources and energy and contributing with 67% of the solid urban areas [2]. Conventional materials used as thermal insulation in civil construction strongly contribute to this pollution, characterized by high energy consumption and CO₂ generation [6].

It should be emphasized that insulating materials should make it difficult to waste and gain heat, reducing the heat transfer between two environments, keeping the temperature of the built environment stable. At the same time, it is important that these materials are economical and reduce the energy consumption of complementary systems to achieve the thermal comfort of the built space such as air conditioning, fans or other active means of cooling.

The construction industry is concentrating on the creation of new solutions that protect the environment that guarantee the requirements of comfort, health and quality [12]. These new constructive solutions are based on the use of innovative materials, such as composites, that contribute to the advancement of civil construction, aiding in the evolution of conventional insulation materials.
The composite materials allow to combine the properties of two or more materials in order to improve the physical, mechanical, thermal and acoustic properties of each of them. The composites are formed by a matrix phase and a reinforcement phase, and the matrix phase acts as an envelope that will protect the reinforcement. However, the reinforcement will provide greater resistance to the matrix, avoiding the shattering and abrupt collapse of the material, allowing the perception of failures and decrease of its mechanical properties.

Currently, there are several investigations about the use and behavior of natural fibers as reinforcement for composites in order to replace the synthetic fibers used in construction, for instance nylon, polyester, polypropylene. This interest in the development of composites reinforced by natural fibers is due to the advantages presented by the fibers, as their lightness, origin in renewable sources, aesthetics, ease of handling, maintenance and versatility. Therefore, sisal fibers are used as a component for the thermal insulation material, benefiting from its flexibility, tensile strength, elasticity, density and high porosity, in order to improve the thermal behavior of the composite.

In this study, the chosen matrix was gypsum, used in the construction sector for its physical and chemical properties, acoustic and thermal performance. Gypsum applications have increased in recent years through panels, slabs, furniture and linings, but continue to be used as a coating material, not considering its structural properties.

Therefore, the conformation of this new composite of gypsum with sisal fiber allowed enhancing the structural characteristics of each of these materials with the intention of conforming a light composite for use internal ceilings in social housing as a lowcost solution and reducing the energy consumption of the buildings [5].

For the use of this new composite as an insulating material it is necessary to analyze the thermal properties of the composite material that will influence its behavior in order to meet the technical criteria to maintain the thermal comfort of the built environment and to determine the appropriate use in buildings.

Several studies analyzed the impact of natural fibers in the thermal properties of composites, in order to achieve thermal comfort in buildings but it can be seen that there is a gap in the analyses of the thermal behavior of the composite materials al on-site simulations. Some studies, such as Krüger e Michaloski [8] evaluated different types of panels made with industrialized wood, concrete blocks and hard block sheet metal panels and epoxy waterproofing. It was evaluated the error range of the measurements by the correlation coefficient, R² and comfort in hours with a temperature reading with HOBO Data-loggers according to the clime for winter and summer (1 month each). The results of this articles showed that a a single panel configuration would yield a rather poor thermal performance in all wood-based panels, concluding that a double panel configuration could achieve a thermal performance comparable or even higher than conventional materials used in civil construction.

Baker [3] analyses an opaque homogeneous plywood panel for a period of time of eight days, estimating an error in the temperatures of 3% to 16%. The results of this researched allowed to conclude that the thermal transmittance and resistance of the material influence directly the internal temperature of the test-cell. Higher thermal transmittance of the material, higher internal temperatures in the test-cell.

Sp sosto et al. [13] evaluates a concrete block filled with rubble. The measurements were made with the temperatures by hour with thermogramar and calculated by the coefficient of correlation and comfort in degrees hours. The analysis period was of 15 days for each test-cell that allowed to evaluate the internal and external temperature of the test-cells (each test-cell had the modification of the thermal inertia of the fences) subsequently, simulations were performed to calibrate test-cell data and evaluate residence. The results show that the materials with higher inertia has more control of the internal temperatures of the test-cell.

The aim of the present paper is to characterize the thermal performance of gypsum-sisal fiber composite panels used in internal ceilings with 26% and 53% of sisal nonwoven by the measurement of the indoor temperatures with Energy plus. A simulation of the temperatures of a small-scale test-cell of 50x50x50cm under summer conditions in Salvador (Brazil), Marseille (France), Napoli (Italy) and Barcelona (Spain) was developed.
2. Climate Variables

2.1. Salvador
The city of Salvador is located at 12° 58’ 16”S, 38° 30’ 39”W and 8.3m above sea level. The climate type of Salvador is tropical rainforest with maximum summer temperatures of 30°C and minimum of 26.2°C, while in winter the maximum is 26.2°C and the minimum of 21°C, reaching a maximum insolation time in January of 245.6h. The region presents maximum precipitations of 295 mm and relative humidity without major variations during the year with a maximum of 83.1% and with a 4% oscillation. The dominant winds are in the southeast direction with a maximum average speed of 3.2m/s [1][12].

2.2. Marseille
The city of Marseille is located in 43° 17’ 48” N 5° 22’ 35” E and it’s characterized with a Mediterranean climate with mostly dry summers in the two months that are the warmer: July and August with maximum temperatures of 30°C average and 19°C minimum, achieving 2.900 hours of sunshine. December, January, and February are the coldest months in winter, averaging temperatures of 12°C maximum and 4°C minimum, with an average of 512mm precipitation annually, influenced by a cold, dry wind originating in the Rhône Valley [7][10].

The day considered to analyze the test-cells were the warmest day of the year according with the statistics for each day of the month, 21 of July, for a temperature of 32.7°C maximum and 10.3°C minimum.

2.3. Napoli
The city of Napoli is located at 40° 50’ N 14° 15’ E with a Mediterranean climate, characterized by rainy winters and dry summers, strongly influenced by the winds that come from the sea and a solar presence during 250 days of the year, with four warmer months: June, July, August and September. The climatic classification of these type of climate in the Italian communes is zone C, with an annual average temperature of 15.7°C and 23.6°C in the summer, considering an annual average precipitation of 147mm.

The day considered to analyze the test-cells were the warmest day of the year according with the statistics for each day of the month, 21 of July, for a temperature of 33.1°C maximum and 10.2°C minimum.

2.4. Barcelona
The city of Barcelona is located at 41° 23’ N 2° 10’ E and is characterized by a Mediterranean climate, with mild and humid winters and hot, dry summers. Its average annual temperature is 21°C maximum and 14°C minimum. The coldest month of the year is January and the hottest month is August. In winter the average temperature is 15°C maximum and 9°C minimum and in the summer the maximum average can achieve 24.1°C. The region presents maximum precipitations of 95 mm and a mean annual relative humidity is 72%, with 2.524 hours of solar light per year [4][7][9].

The day considered to analyze the test-cells were the warmest day of the year according with the statistics for each day of the month, 21 of July, for a temperature of 30.2°C maximum and 7.7°C minimum.

3. Materials and methods

3.1. Materials
The composites are made with three different combinations: the gypsum used is a coating plaster from Araripe (Pernambuco), the sisal nonwoven was formed by the compression of the sisal fibers collected in Conceição do Coité (Brazil). The sisal nonwoven was provided by Hamilton Rios Ltda, characterized by a specific weigh of 1,36g/cm³ and a gram weight of 788,9m/m².
The mixture used to conform the coating plaster was made with a liquid superplasticizer additive that allows to increase the workability of the coating plaster, reducing the relation water-gypsum.

3.2. Samples preparation

3.2.1. Composite preparation. For the development of this research were made four types of samples: a sample of gypsum (called GP) prepared with 0.4 proportion of plaster/water and 1% of additive, a sample called GMG with one layer of gypsum, a layer of nonwoven in the middle and another layer of gypsum, a sample called GMMG with one layer of gypsum, two layers of nonwoven in the middle and another layer of gypsum, and a sample called GMGMG with one layer of gypsum, a layer of nonwoven, a layer of gypsum, and a layer of gypsum and sisal nonwovens. The samples were controlled by weight and the composite samples were prepared with a weight fraction of 26% and 53% of sisal nonwoven.

3.2.2. Test-cell configuration. For the measurement of the indoor temperatures in a small-scale prototype, five gypsum panels were fabricated to create the walls of the prototype, which is used as reference for comparisons of ceiling composite materials. As external ceiling of the prototypes are used an asbestos cement tile with a dimension of 50x50cm and as floor it’s also used a layer of Styrofoam (3cm), a layer of wood (5cm) and a layer of gypsum (1.5cm) to isolate the prototype of the ground. The final wall thickness was 1.5cm with an internal volume of 0.064m³ with 0.16m² walls on each side. The assembly of the test-cell is illustrated in Figure 1a-b.

![Figure 1. Assembly of the test-cell.](image)

The evaluation of the materials was made with the software Energyplus. The thermal properties used to evaluate the model are reported in Table 1.

| Material | Average density (kg/m³) | Thermal conductivity (W/m·K) | Specific Heat (J/kg·K) | Thermal Absorptance |
|----------|------------------------|-----------------------------|-----------------------|---------------------|
| Gypsum   | 1233.85                | 0.75                        | 886                   | 0.9                 |
| GMG      | 1180.44                | 0.539                       | 900                   | 0.9                 |
| GMMG     | 1029.67                | 0.845                       | 800                   | 0.9                 |
| GMGMG    | 1153.50                | 0.91                        | 820                   | 0.9                 |
4. Results

4.1. Thermal performance

The air temperature simulated inside the test-cell at Salvador, with an indoor ceiling made with a GMG panel, as compared with the test cell built entirely with gypsum, give the expected thermal behaviour of a gypsum-sisal panel, improving the temperatures, achieving a 31.17°C as a maximum and 20.17°C minimum, with 11.003°C of thermal oscillation. It’s important to consider the differences in the external temperature of the test-cells that explain the increases of the temperature in the interior of the test-cell. Indoor air temperatures during the summer are shown in Figure 2 and 3.

![Figure 2](image1.png)

**Figure 2.** Indoor temperatures for the gypsum indoor ceiling at the city of Salvador.

![Figure 3](image2.png)

**Figure 3.** Indoor temperatures for the GMG ceiling at the city of Salvador.

The air temperature simulated inside the test-cell with an indoor ceiling made with a GMMG and GMGMG panel, allows us to consider that the GMMG composite had higher internal temperature
achieving 32.329°C maximum and 21.104°C minimum. The GMGMG composite also presented more extreme temperatures than the GMG composite, achieving 31.896°C maximum and 20.857°C minimum. Indoor air temperatures during the summer monitoring periods are shown in Figure 4 and 5.

![Figure 4. Indoor temperatures for the GMMG ceiling at the city of Salvador.](image1)

![Figure 5. Indoor temperatures for the GMGMG ceiling at the city of Salvador.](image2)

When the European cities were analysed, it could be seen that the external temperatures had a thermal oscillation of 20°C or more, which doesn’t occur at the city of Salvador. This thermal oscillation contributes with a similar response of the composite, as shown in the Table 2.
Table 2. Thermal results of the composite for the European cities.

|            | Marseille |   | Barcelona |   | Napoli |   |
|------------|-----------|---|-----------|---|--------|---|
|            | Min. T°  | Max. T° | Min. T° | Max. T° | Min. T° | Max. T° |
| Gypsum     | 15.892   | 35.171 | 21.451   | 38.361 | 22.646 | 41.522 |
| GMG        | 14.926   | 34.195 | 20.485   | 37.395 | 20.653 | 39.501 |
| GMMG       | 14.932   | 34.223 | 20.486   | 37.433 | 20.791 | 37.211 |
| GMGGM      | 14.918   | 34.192 | 20.498   | 37.444 | 20.662 | 39.531 |

The air temperature simulated inside the test-cell, allows to determinate that the GMG composite always had a better thermal performance than the other three composite at Marseille and Barcelona, decreasing 1°C the internal temperature presented by the gypsum panel. At the city of Napoli, it can be seen that the GMMG composite decrease in 2°C the temperatures of the composite GMG and GMGGM, and 4°C the temperatures presented by the gypsum panels.

Figure 6. Indoor temperatures for all the cities.

The results presented in Figure 6 indicate that the city of Salvador has the highest internal temperatures in all the cities, followed by Barcelona, Napoli and Marseille, both in summer and winter. Being that the temperatures of Barcelona and Napoli are similar in the winter and with difference of 5 °C in the summer. However, the city of Marseille, the materials present the best thermal behaviour of all cities, both winter and summer.

In the cities of Marseille and Barcelona, all composite materials exhibit similar thermal performance for winter and summer. In the city of Napoli, in the winter the composite GMG and in the summer the composite GMMG has better performances. In Salvador, the GMG composite presents the best behaviour both in winter and in summer.

5. Conclusions

This paper presented the thermal performance of gypsum-sisal fiber composite panels for interior ceiling through the measurement of the indoor temperatures using a small-scale test-cell and the software Energy plus. Panels made with a gypsum ratio of 26% and 53% of sisal fiber. The thermal analysis of the indoor and outdoor temperatures of the test cell showed that the composite panel decrease the daily temperature and the average temperature swing inside the test cell, improving the results of the gypsum panel. In Salvador, it could be seen that the GMMG and GMGGM,
improved the internal temperature of the test-cell, but the cost of the material and the manufacturing are very high which allows concluding that the better composite to this type of climate is the GMG.

For the European Cities, the conclusion is that the composites don’t present a better performance because the results are very similar in Barcelona and Marseille but the composite GMG achieves a better performance than the gypsum panel. In Napoli it can be conclude that the composite GMMG achieves a better performance than the gypsum and the others composite.

In general, it is observed that the temperatures in summer for all composites exceed the thermal comfort temperatures appropriate for the building environment, reaching more than 24°C. Considering that all cities reach temperatures that surpass 30°C. However, the temperatures reached in winter allow us to reach the thermal comfort of the environment built in Salvador, Barcelona and Napoli.

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