Experimental Research on the Indoor Environment Performance of Complex Natural Insulation Material: Carbonized Rice Hull and Rice Hull

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Abstract

This study investigated whether the combined use of rice hull and carbonized rice hull (CRH) can offset the negative aspects of each other, and can deliver an optimum indoor environment performance. To achieve this goal, the CO₂ emissions of rice hull and the economic feasibility of CRH were considered simultaneously to deliver a mix ratio, and the fundamental properties of the material were analyzed to verify its performance. Full-scale mockups were constructed, and the effect on the indoor environment was verified through monitoring and a comparative analysis. Analysis showed that the heat capacity of the experimental mockup was larger than that of the control, and therefore it was effective in controlling indoor temperature in winter. The application of complex insulation material is also effective in controlling indoor humidity in winter and spring, and a humidity control plan that follows either a moisture-proof plan or ventilation is required to control humidity in summer and autumn. The CO₂ level of the experimental mockup was high due to the anaerobic fermentation of the rice hull in the complex material. Therefore, a moisture prevention plan using water-proof and moisture-proof materials and a ventilation plan need to be considered in advance.

Keywords: natural insulation material; indoor environment; carbonized rice hull; rice hull; IEQ

1. Introduction

Since the implementation of the Kyoto protocol, many countries have endeavored to reduce greenhouse gas (GHG) emissions, and the domain of architecture has also made efforts to design environment-friendly buildings. The construction industry has a great impact on every nation's GDP and receives a large proportion of the general economy. In addition, it has a huge impact on the environment and society. In the United States, commercial and residential buildings produce 40% of GHG emissions, and buildings in Europe use 40% of the nation's total energy consumption and produce 36% of total GHG emissions⁵. Energy-efficient building designs have received considerable attention, and various research institutes and organizations are currently conducting related research, although a low energy building with high performance would imply high construction costs due to the inclusion of high performance organic compound materials⁶.

Modern people spend most of their time indoors, so the need for eco-friendly and natural construction materials is paramount⁷. Also, the number of people suffering from "new house syndrome" or atopic dermatitis (which are related to indoor air quality) has increased due to the use of high performance construction materials based on organic compounds⁸. Therefore, a number of studies are currently investigating designs focused on creating a comfortable and energy-efficient indoor environment with the use of natural construction materials. Natural construction materials can be defined as materials extracted from pure natural resources such as soil, wood, or stone, which can be used after cutting or grinding and have no chemical additives⁹. Using natural materials reduces carbon emissions and energy consumption in comparison with general construction materials, particularly in the production and transportation processes. In addition, such materials decompose naturally and produce no pollutants in the final stage of the life cycle⁹. Mostly, inorganic materials are used for insulation materials, but there has been a recent interest in the use of natural fiber as an insulation material⁹.

Rice hull can be used as a natural insulation material. It is harmless to the human body, and as a by-
showed a high insulation performance of the rice hull, temperature, humidity, and CO₂ at the insulation thickness. Lee et al. (October 2014) conducted using various perspectives in this domain and moisture content was investigated for its industrial use(11), and an insulation development study was conducted using a combination of rice hull and organic chemicals, thereby verifying its possible use(22).

Carbonized rice hull (CRH) is also a natural material derived as a by-product of rice, and is produced by carbonization of the rice hull. After carbonization, the hull maintains its original shape, but air permeability increases due to the low particle density(8,10). CRH has a pH at 8.5, a bulk density at 0.103, a particle density of 0.73, and a porosity of 86%(12). In addition, it is able to absorb moisture equal to 2.5 times of its dead load, which proves to be a good water holding capacity(14). Previous research on CRH has mostly focused on its application in water culture and as a horticultural bedding material, and considerable research has been conducted using various perspectives in this domain(4,19).

Rice hull can be obtained easily from rice mills in rural areas, which enables low transport costs. Although the price of the product varies between regions (the average price is $2.95 per 100 liters, it is cheaper in rural areas, which enables low transport costs. Although the price of the product varies between regions (the average price is $2.95 per 100 liters, it is cheaper in rural areas, which enables low transport costs. Although the price of the product varies between regions (the average price is $2.95 per 100 liters, it is cheaper in rural areas, which enables low transport costs. Although the price of the product varies between regions (the average price is $2.95 per 100 liters, it is cheaper in rural areas, which enables low transport costs. Although the price of the product varies between regions (the average price is $2.95 per 100 liters, it is cheaper in rural areas, which enables low transport costs.

A complex insulation material was developed initially from equal proportions of rice hull and CRH to analyze the basic material properties. The heat conductivity was calculated at 0.048 W/m·K, which is the same as that of rice hull, and indicated a higher thermal performance than CRH of 0.069 W/m·K. Usually, the heat in the carbonization process removes the minute hairs on the rice hull, and decreases the pore size between particles which increases the heat conductivity value. However, the newly developed complex insulation material was little affected by this effect.
Heat storage capacity of insulation materials were analyzed based on the calculated specific heat by the KS M 3049 method, and vapor resistance coefficient was also calculated. The equation (1) was used for the heat storage capacity calculation and the material properties are shown in Table 1.

Heat Storage Capacity (kJ²/m⁴h·K²) = Specific Heat (kJ/kg·K) × Density (kg/m³) × Thermal Conductivity (kJ/mh·K) …………. (1)

Table 1. Material Properties

| Material                  | Density (kg/m³) | Specific Heat (kJ/Kg·K) | Heat Conductivity (W/m·K) | Vapor Resistance Coefficient |
|---------------------------|-----------------|-------------------------|---------------------------|-----------------------------|
| Rice Hull and CRH Mix    | 100             | 4.812                   | 0.048                     | 2                           |
| EPS                       | 20              | 5.063                   | 0.036                     | 60                          |
| Glass Wool                |                 |                         |                           | 1.2                         |

A full-scale experimental mockup was constructed regarding these material properties. A mockup using the complex material as insulation (hereinafter referred to as “the experimental mockup”) and a mockup using EPS (Expanded Poly-Styrene) and glass wool as an insulation material were constructed as a control (hereinafter referred to as ”the control mockup”), and a comparative experiment was performed.

2.2 Mockup Plan and Monitoring Instruments

The ultimate purpose of this study is to verify the environmental performance of the new complex material for a low energy building. Therefore, the insulation performance of both mockups was based on the Design code for energy saving buildings from the Supportive law for green building construction. The insulation standard of a green home in Korea is presented in the Construction codes and performance for eco-friendly housing by the Ministry of Land, Infrastructure and Transport. Therefore, the outside wall of the mockup was designed to comply with the average heat transmission of the mid-region based on the Construction codes and performance for eco-friendly housing, and the roof, floor, and windows followed the passive house standard.

The size of the indoor area was designed identically (9 m²) to deliver the same experiment conditions (with the exception of the insulation material used) (Fig.1.). Both mockups were planned as column-beam structures, and the walls were made using SPF structural wood with the double stud method. The ceilings were insulated to prevent disconnection of the insulation line, and complex insulation was installed using a blow-in method to achieve a 100 kg/m³ density. In the control mockup, the first insulation layer containing EPS and glass wool was added to produce identical heat emissions with the experimental mockup. Windows in both mockups were produced exclusively in accordance with the requirements for a passive house, which is a heat transmission of 0.8 w/m²K, triple glazing, a low-E coating, Ar gas filling, airtightness, and a heat bridge prevention frame.

![Fig.1. Monitoring System and Sensor Placement](image-url)
Probe-type thermal and humidity sensors were installed to monitor the indoor environment of the mockups, and a NDIR-type CO₂ sensor was added regarding a previous study, which showed that rice hull produced CO₂. Weather data from the experimental site was recorded at a weather station placed within 25 m (in a straight line) of the mockups. The indoor sensors were installed at a height of 1.1 m from the center of the floor, and a monitoring program was used to measure and record changes. The insulation plan of the mockups is shown in Table 2, and the instrument accuracies of the sensors are shown in Table 3.

Table 3. Monitoring System Accuracy

| Monitoring | Accuracy |
|------------|----------|
| Temperature | ±0.6 between −40 °C and 375 °C |
| Humidity | ±2% (20–80%), ±3% (<20%, >80%) |
| CO₂ | ±50 ppm, ±3% of reading |

2.3 Monitoring Plan

The construction of mockups was completed in July 2013. The mockups were stabilized without any residents or use before the experiment, and a monitoring system was initially installed and tested. Monitoring experiments were conducted from August 2013 to April 2014 in the summer, autumn, winter, and spring to verify the seasonal environmental performance. Seven days of data was collected and analyzed from the series which shows clear seasonal characteristics.

Data was recorded every ten minutes. Every window and door was opened 30 minutes before each experiment series for ventilation, and the experiments were conducted in a sealed condition (there were no doors or windows open during monitoring and neither heating nor air-conditioning was supplied). In addition, entering or use of the mockups were also prohibited between seasonal monitoring periods to keep the indoor environment in a similar condition.

3. Results

3.1 Results of Temperature Monitoring

The temperature monitoring results are shown in Table 4. The PHPP (Passive House Planning Package / German passive house design and simulation program) analysis results demonstrated that the heat gain during daylight through windows was 95 kWh/a from the south and 10 kWh/a from the north. The heat loss from windows was 97 kWh/a in the south and 60 kWh/a in the north: thus, the annual heat loss was a little higher than the annual heat gain.

There was little variation in temperature in all seasons for both mockups, in comparison with outdoor variations. The average temperature in summer in both mockups was the same (30 °C), and the average temperature in both mockups appeared also the same in autumn and spring. However, the average temperature in winter of the control mockup was 1.8 °C and that of the experimental mockup was 2.5 °C, which demonstrated a significant difference.

The average outdoor temperature was 26.8 °C in summer, and the average temperature in both mockups was 30 °C, which was higher than that of the thermal comfort range. The maximum temperature of the control mockup was 32.2 °C, and that of the experimental mockup 31.7 °C: both indicated similar temperatures to the outdoor maximum temperature. A similar pattern also appeared in winter and spring, which demonstrated uncomfortable temperatures ranges in both mockups. There were no significant differences between mockups except in winter.

Table 4. Temperature Monitoring Results

|          | Summer (August 16~23) | Autumn (October 05~12) | Winter (December 10~17) | Early Spring (February 21~28) | Spring (April 01~08) |
|----------|-----------------------|------------------------|-------------------------|-------------------------------|---------------------|
| Temp. Avg. (°C) | G 30.0 | 21.8 | 1.8 | 7.8 | 13.5 |
| Variation (°C) | G 5.4 | 7.4 | 8 | 10 | 11.9 |
| St. Dev. | N 4.5 | 5.9 | 7.4 | 8.8 | 10.5 |
| Max. (°C) | N 31.7 | 24.5 | 6.6 | 11.8 | 18.6 |
| Min. (°C) | G 26.8 | 17.2 | -2.0 | 2.6 | 7.2 |

Index: G-General Insulation (Glass wool + Eps), N-Natural Insulation (Rice Hull and CRH Mix), O-Outdoor

3.2 Results of Humidity Monitoring

In the humidity monitoring result (Table 5.), the standard deviation of the humidity in both mockups appeared stable at 0.8–2.1 compared with the outdoor humidity, which changed rapidly by the precipitation. The average relative humidity of the control mockup was 51.3–69.3%; however, that of the experimental mockup appeared as 66.1–79.3%, which was therefore 10–14.8% higher than that of the outdoor relative humidity. The humidity in both mockups was higher than the comfort range (40–60%) in summer and autumn due to the high outdoor humidity (74.4–74.6%). The average humidity in the control mockup was 62.8% in winter and 51.8% in spring, which is close to the comfort range. However, the average humidity in the experimental mockup was 66.1% in winter, which was higher than the comfort range, and it also indicated similar humidity at 68.2% in spring. In general, both mockups showed similar tendencies followed by the outdoor humidity; however, the humidity in the experimental mockup was consistently higher than that of the control mockup.
3.3 Results of CO₂ Monitoring

The CO₂ monitoring results are shown in Table 6.

| Table 6. CO₂ Level Monitoring Results |
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humidity, and the indoor humidity of the mockup increased because of the absorption effect of the rice hull to maintain the equilibrium humidity.

\[ S_d = \mu \times t \] \hspace{1cm} (4)

The sd-value of the experimental mockup was 0.55 m, which indicated that the complex insulation material delivered a good moisture permeability. For the control mockup, the glass wool showed a good sd-value of 0.168 m, but that of EPS was 5.4 m, which therefore showed very unfavorable moisture permeability.

The indoor and outdoor moisture partial pressure of each mockup was calculated using the sd-value, indoor/outdoor temperature, and relative humidity of the mockups. Based on the calculation, the moisture content (per 1 m²) penetrating the wall in a one-hour period was deducted by the equation (5) which was based on ASTM E96, and the results are shown in Table 8. and in Fig.3.

\[ MVTR = \frac{(P_{ai} - P_{ao})}{(S_d \times 5.1) \times t [S] \times A} \] \hspace{1cm} (5)

**Table 7. sd-Value of Materials**

| #  | Material                      | Thickness | \( \mu \) Value | sd-Value (m) |
|----|-------------------------------|-----------|-----------------|--------------|
| 1  | Hwangtoh Wall Exterior Finish | 20 mm     | 10              | 0.2          |
| 2  | Plywood Board                 | 19 mm     | 50              | 0.95         |
| 3  | Rice Hull and CRH Mix         | 275 mm    | 2               | 0.55         |
| 4  | Nonwoven                     | 0.5 mm    | 1               | 0.02         |
| 5  | Vertical Squared Timber       | 20 mm     | 1               | 0.02         |
| 6  | Gypsum Board                 | 15 mm     | 8               | 0.12         |

**Table 8. Vapor Pressure and Transmission**

|                          | Indoor Vapor Pressure (pa) | Outdoor Vapor Pressure (pa) | Transmission of Vapor/h (g) |
|--------------------------|---------------------------|-----------------------------|-----------------------------|
| General A.H              |                          |                             |                            |
| Summer                   | 2929.45                   | 3396.46                     | 2487.50                     |
| Autumn                   | 1665.46                   | 2061.41                     | 1625.04                     |
| Winter                   | 388.21                    | 557.56                      | 140 mm                      |
| Early Spring             | 557.56                    | 608.98                      | 497.12                      |
| Spring                   | 763.29                    | 1017.72                     | 655.90                      |

**Fig.2. Absolute Humidity \([\text{g/m}^2]\)**

In addition, moisture penetrates the walls within the mockups due to the absolute humidity difference between the indoor and outdoor. If the outside finishing material is moisture permeable, it absorbs moisture until the humidity level equals that of the surroundings\(^{20}\). For a further analysis of the moisture permeability, the thickness of the equivalence air layer (sd-value) was calculated with the vapor resistance coefficient (\( \mu \)). The calculation of the sd-value was based on the ISO 10456: 2007 (Permeability measurement method for construction material), and the \( \mu \) value of each material was based on the ISO 10456: 2007. The equation (4) was used, and the results are shown in Table 7.

The complex insulation material was composed of a natural material, and this showed a good moisture permeable performance compared with the insulation material in the control mockup. The results demonstrated that a relatively large amount of the moisture content penetrated into the experimental mockup due to the outdoor absolute humidity changes, and this caused high relative humidity in the experimental mockup. Thus, a large amount of moisture was able to penetrate into the experimental mockup through the complex insulation material, which was not advantageous for controlling indoor humidity. Therefore, a careful water-proof design and specific moisture permeability plan are required to use the combined material of rice hull and CRH.

### 4.3 Results of \( \text{CO}_2 \) Monitoring

In the experimental mockup, the correlation coefficient of temperature and \( \text{CO}_2 \) was 0.845, and that of humidity and \( \text{CO}_2 \) was 0.891, which indicates a high correlation. The previous study verified that CRH does not produce \( \text{CO}_2 \) by fermentation\(^{23}\), and it was also presented that temperature and humidity were correlated to increases in \( \text{CO}_2 \). When temperature and humidity rise to a certain level, anaerobic fermentation occurs based on the starch of the rice hull in the complex insulation material. It produced a large
amount of CO₂ emission, and increased indoor CO₂ level.

Fermentation requires humidity, an oxygen supply, nutrition, and a particular temperature, and the growth of fungus becomes active when these conditions are satisfied\(^3\), \(^23\). In addition, rice hull is known for its ventilation via minute hairs\(^3\), \(^24\). Despite the equal proportions of rice hull and CRH, there was evidently adequate room for oxygen to permeate, which is essential for the growth of fungus. In summer and autumn, where there was an average outdoor temperature of over 20 °C (Fig.4.), the fermentation requirements were satisfied, and thus the CO₂ level increased. It also showed that as the average temperature dropped to under 20 °C after autumn, the temperature was not sufficient to promote fermentation, and therefore the CO₂ level decreased rapidly during this time.

In Korea, the Indoor air quality standard for multiple use facilities currently stipulates that the indoor CO₂ level should be under 1,000 ppm. Although the indoor CO₂ level of the experimental mockup was not exceeded, it was relatively higher than that of the control mockup. It is therefore expected that a higher CO₂ level would occur in a real building due to the increased amount of rice hull used for insulation. Thus, fermentation control plans such as extra ventilation or an indoor moisture-proof layer are required if any amount of rice hull is to be used.

5. Conclusion

This study investigated the effect of a complex insulation material composed of equal proportions of rice hull and CRH on the indoor environment. To achieve this goal, a complex insulation mockup and a control mockup using a general insulation were constructed on a full-scale, and monitored in every season. A comparative analysis was conducted, and the results are presented as follows:

1. There were no significant differences in the average temperature between the mockups in spring, summer, and autumn, and the temperature of the experimental mockup appeared to be relatively high in winter. Analysis showed that the heat capacity of the experimental mockup was larger than that of the control mockup, and therefore the experimental mockup was more effective in controlling indoor temperature than the control mockup in winter.

2. Both mockups indicated a stable humidity variation compared with that of outdoor humidity. The experimental mockup sustained a relatively high humidity due to the absorption effect of the rice hull in addition to the relatively low sd-value. It was thus concluded that the correct amount of complex insulation material is effective in controlling indoor humidity in winter and spring, and a humidity control plan such as a moisture-proof plan or ventilation is still required to control indoor humidity in summer and autumn.

3. The CO₂ level of the control mockup was maintained at a stable level during the monitoring experiment. However, the CO₂ level of the experimental mockup appeared high (an average of...
were below the standard specified for the indoor CO$_2$ emission. These CO$_2$ levels were below the standard specified for the indoor CO$_2$ levels of the building, but it is considered that these levels would rise by the increasing size of the building. Therefore, a careful moisture control design such as using water- and moisture-proof materials and a ventilation plan need to be considered in advance if any amount of rice hull is to be used as an insulation material.

This study verified the significant possibility of using a complex insulation material by the analysis of the temperature, humidity, and CO$_2$ of the full-scale experimental mockup in four seasons. The results can be used as a valuable reference when choosing natural materials in building construction. Further studies on the long-term changes, durability, and various complex ratios are required in the future.

Acknowledgement

This research was a part of the project titled "Development of zero energy smart aquaculture system", funded by the Ministry of Oceans and Fisheries, Korea.

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