Development and performance evaluation of natural building materials with pyrolyzed agricultural by-products for carbon reduction and energy saving

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Abstract. Hwangtoh (Korean red clay) and Biochar were used to develop building materials for sustainable and energy-efficient buildings and propose environmentally and thermally superior materials. Rice husk, coconut shell, and bamboo were made of biochar through pyrolysis with complete oxygen limitation. The compressive strength test was carried out to analyze the thermal performance and the mechanical performance, and the thermal conductivity measurement was conducted in order to derive the physical property information for the thermal performance of the material. The microporous structure affecting the thermal conductivity and mechanical performance. Through the dynamic heat transfer experiment, the temperature changes of the biochar mixed specimens in the same heating environment were analyzed. Comprehensive considerations have shown that bamboo biochar is replaced by 10% by weight.

1. Introduction
Hwangtoh is a building material that has been continuously used and studied in Korea because of its beneficial functions such as far infrared ray emission, moisture control capability, air purification. Sustainable architecture and methods to reduce internal energy used for cement production have been adopted as a method for reducing carbon emissions. One of the proposed methods is replacing cement with loess [1]. This method is based on the discovery of the possibility of a pozzolanic substance as a pozzolanic reaction in the cement hydration reaction mechanism [2]. However, it is a disadvantage that it is difficult to handle in the construction stage and physical and mechanical performance degradation such as cracking and strength reduction as the building material. Therefore, a methodology for improving mechanical performance must be developed. The solution proposed by the present study as a concrete method for improving the strength and weakness of loess is biochar. Biochar is a biomass-based substance, a compound word in which 'char', meaning charcoal, is synthesized with the bio. Biochar is a substance modified by carbon-based materials, which removes unnecessary substances by pyrolyzing bio-based materials under oxygen control [3]. By using such a method, it is possible to control the performance such as the change in the performance of conduction, heat conduction, and the like and the specific surface area to be widened and is usefully used in the development of new materials [4]. In this study, we aimed to develop Hwangtoh based building material which is eco-friendly, improved thermal and mechanical performance by using biochar and Hwangtoh.

2. Experimental
2.1. Materials and preparation
The Hwangtoh binder consisted of 25% anhydrous gypsum, 35% pure Hwangtoh and 40% silicon oxide.
The three biochar materials used in this study were produced at different pyrolysis temperatures, with or without steam activation. For removal of impurities, rice husk, coconut shell, and bamboo were washed with deionized water. For drying in an appropriate condition, they were dried at room temperature, and pulverized to a size of 5.0 mm or less before pyrolysis. The reason for crushing before thermal decomposition is to increase the pyrolysis area sufficiently to obtain biochar. Then the biomass was heated at a heating rate of 7 °C/min for 2 h under limited oxygen conditions. For steam activation, the biochar was treated with 5 ml/min steam for an additional 45 min at the peak temperature. To obtain a reasonable yield according to the characteristics of each feedstock, the rice husks were treated at 450 °C, the coconut shells at 800 °C, and the bamboo at 1000 °C peaks [23-25]. The thermal decomposition temperature is an important factor in determining the ratio of pore to carbon material and is optimized for each crop.

2.2. Preparing specimens for experiment

Table 1 shows the definitions and mixing ratios of the different weight ratios for the experiment. For the preparation of the specimen, the biochar should be dried again and dried at 60 °C for 48 hours. The binder was mixed on the basis of 23.5% by weight of the loess powder. Water characterization was reduced by biochar, and water was added if additional water was deemed necessary. For the dynamic heat transfer experiment, specimens were fabricated with dimensions of 100mm width, 100mm length, and 20mm height. Specimens for compressive strength test were made with 50mm width, 50mm length, and 50mm height. After curing for 6 hours in the mold, all specimens were cured at 60 °C for 48 hours and cured at room temperature for 28 days. RB, BB, and CB mean rice husk biochar, bamboo biochar, and coconut shell biochar, respectively.

| Weight ratio | H   | RB2.5 | RB5  | RB7.5 | RB10 | BB2.5 | BB5  | BB7.5 | BB10 | CB2.5 | CB5  | CB7.5 | CB10 |
|--------------|-----|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|
| Loess (g)    | 400 | 400   | 400  | 400   | 400  | 400   | 400  | 400   | 400  | 400   | 400  | 400   | 400  |
| Water (g)    | 92  | 92(+20)| 92   | 92(+20)| 92(+20)| 92   | 92   | 92   | 92   | 92   | 92   | 92   | 92(+20) |
| Biochar (g)  | 0   | 10    | 20   | 30    | 40   | 10    | 20   | 30    | 40   | 10    | 20   | 30    | 40    |
| W/H (%)      | 23  | 23(+2)| 23(+2)| 23(+2)| 23(+4)| 23   | 23   | 23    | 23   | 23    | 23   | 23    | 23(+2) |
| Biochar/H (%)| 0   | 2.5   | 5    | 7.5   | 10   | 2.5   | 5    | 7.5   | 10   | 2.5   | 5    | 7.5   | 10    |

2.3. Characterization techniques

2.3.1. Thermal conductivity measurement. The thermal conductivity was measured using a TCi thermal conductivity meter from C-Therm. The surface was smoothly ground to make the roughness of the surface homogeneous, and a weight of 2000 g was applied to ensure that all surface areas were in close contact. In the case of thermal conductivity measurement, five different parts of the specimen were measured as a method to obtain homogeneous data and the mean value was derived.

2.3.2. Compressive strength measurement. The compressive strength test was carried out according to the ISO 679 test method [5]. Compressive strength tests were carried out on the specimens cured for 28 days, and the specimens were smoothly polished to maintain the level. Three specimens were produced
for each case, and the compressive strengths were based on three average values. The load was set at 20 kN / min and the pressure was applied.

2.3.3. Microstructure analysis. A morphological analysis was conducted to fully explain the thermal conductivity and compressive strength measurement results. Microstructures are worthy of analysis because they are useful in interpreting the thermal conductivity and compressive strength that can change due to pores. Scanning Electron Microscope (SEM) equipment was used to analyze the microstructure to obtain 500 × and 1000 × magnification images. In order to discuss based on consistent results, SEM analysis was performed with the fragments obtained from the compressive strength test.

2.3.4. Dynamic thermal experiment. The experimental setup for the dynamic heat transfer experiment is shown in Figure 1. The experimental device is divided into an upper cell and a lower cell, and in the middle of the two boxes, there is an insulating layer with a place where the sample can be placed. An infrared ray irradiating device is provided on the upper part of the apparatus, and the upper surface of the specimen is irradiated with infrared rays. Due to the difference in the insulation performance, the heat transferred to the upper part moves to the lower part of the specimen, and the temperature varies depending on the heat transferred according to the performance of the specimen. The infrared irradiation device uses a 250 W infrared bulb, and the upper surface is defined as 'US' and the lower surface as 'LS' as shown in the figure. Infrared rays were applied to the specimen for a total of 2 hours and cooling was observed for 3 hours after the lamp was turned off. The temperature was measured with a thermocouple K type temperature sensor installed at the top and bottom of the specimen and stored every second.

![Figure 1. Set up for thermal performance evaluation](image)

3. Results and discussion

3.1. Thermal conductivity

The H corresponding to the reference group had a thermal conductivity of 0.244 W / mK. As a result of adding each biochar, the thermal conductivity of all specimens decreased. The RB2.5, RB5, RB7.5 and RB10 showed thermal conductivity of 0.143, 0.184, 0.137 and 0.123 W / mK, respectively, although the apparent tendency of RB was not significant. As the rice husk biochar addition increased, the thermal conductivity decreased, but slightly increased water was found.

In the case of CB, the lowest value was 0.162 W / mK in CB 7.5 and decreased by 33.1% compared with the reference group. For BB, BB10 was the lowest at 0.143 W / mK.
3.2. Mechanical performance
For compressive strength, different tendencies were derived depending on the type of biochar. For reference group H, the average compressive strength was 5.91 MPa. RB2.5, RB5, RB7.5 and RB10 were 5.18, 4.99, 4.36 and 2.35 MPa, respectively, and the maximum compressive strength was decreased by 60% compared to H. RB showed a tendency to be pronounced, and a decrease in strength with weight increase was found. The CB specimens tended to increase slightly when the addition rate was low, but increased when the CB was mixed more than 5%. The compressive strength increased by 51% at the maximum CB10, and the compressive strength tended to increase with increasing mixing amount. In case of BB, the compressive strength was increased in all specimens, and in BB10, the maximum compressive strength was 8.21 MPa.

3.3. Morphological analysis
In Figure 2, the result of SEM images a) by 500 and 1000 X microstructure images of H shows that the typical hexagonal particles of CH from the hydration reaction of loess binder and C-S-H GEL. This is judged that the strength of the loess binder is expressed by the hydration reaction. (b) shows the microstructure of the specimen to which RB is added, revealing the structure of the micropores supporting the result of decreasing the thermal conductivity of RB. These results can be supplemented by the results of the tendency of strength reduction in terms of strength. C) shows the microstructure of the specimen mixed with BB, and shows a slight tightening of the voids but shows a closer connection between the particles. It can be seen that the thermal conductivity decreased in association with the pores inside the bio-car, but the tightness between the particles increased and the strength increased.

3.4. Thermal performance
The temperature ratio of TLS, which is the LS temperature defined by the temperature TUS of the US defined as the upper temperature and the lower temperature of the sample, is shown in Fig. 3. The lower temperature was lower than the relative temperature due to factors such as temperature transfer performance and heat storage. The value of TLS tends to become constant after about 0.5 hours. This means maintaining a constant temperature for the upper temperature, which is reasonable considering that it is in the infrared situation for two hours. RB2.5 and RB10 delivered the lowest temperature to the lower surface in the case of the upper-temperature rise. In addition, BB10 and R7.5 delivered a relatively small amount of heat energy to the bottom. The decrease of the initial temperature ratio and the immediately rising temperature transfer rate are judged to be influenced by the abrupt temperature at the top and the validity of the experiment can be proven by judging from the similar tendency observed in all the specimens.
Figure 3. Dynamic heat transfer of each specimen

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