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Thermal performance and carbon emission of bio based buildings in severe cold area——Take " modular sustainable magic box" as an example

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Abstract. *Taking a small house as an example, the thermal performance and carbon emission of straw as building material in severe cold areas of China are examined in this paper. The house takes wood as the structural system and straw as the outer enclosure system. Through the thermal performance calculation, it is found that the heat transfer coefficient of the residential straw wall is lower than the external wall heat transfer coefficient standard in the severe cold area of Hebei Province, and can meet the requirements without using additional thermal insulation materials. This paper also calculates the carbon emission of straw 3000 * 3000mm unit wall in the production stage, and compares it with that of hollow clay brick, autoclaved aerated concrete blocks and gangue shale hollow brick wall. It is found that the carbon emission per unit straw wall is 18% less than that of hollow clay brick and 60% less than that of autoclaved aerated concrete blocks. Without considering the carbon sink, the carbon emission per unit straw wall is slightly higher than that of gangue shale hollow brick-wall.*

Keywords: Straw Bale，Thermal Performance，Carbon Emission，Low Carbon Building.

1 Introduction

Global climate change caused by CO_2 emissions has been an issue of great concern since the end of the 20th century. As one of the industries with a large carbon footprint, the building industry has been working hard to find carbon reduction solutions. In recent years, straw has gradually gained the attention of scholars as a low-carbon construction material.

Straw, the main agricultural waste, is mostly burned and returned to the field in China. Traffic accidents, fires, soil structure damage, toxic and harmful substances emission and other problems followed. In recent years, because energy conservation and low carbon have increasingly become the focus topic, straw has been widely concerned by scholars all over the world as a building material.

As a building material, straw bales perform good building performance. In recent years, the research mainly focuses on the structural form, structural performance, thermal insulation performance, durability, energy consumption and carbon emission of straw wall. T. Lecompte found that the ratio of straw bale density to bulk density and the shape of straw bale affect the stiffness of the straw load-bearing [1]. The durability of rice straw is closely related to the moisture content, so Yin found that the water absorption characteristics of rice straw and wheat straw are similar, and the balance between open ended straw with the environment is 25% faster than that of closed ended straw [2]. Different from building materials such as steel bars and concrete, straw absorbs CO_2 in the growth process. At the same time, using straw as building materials can also reduce or delay various hazards caused by incineration. In terms of energy conservation and carbon emission reduction, Yin also found that rural houses with straw wall in northern China consume less energy than conventional wall structure through computer simulation, and the use of coal is reduced by more than 40% [3]. Maryam conducted a comparative study on three different types of straw buildings and conventional buildings in four climatic regions of Iran. The results show that rice straw buildings have a strong potential to reduce energy consumption and carbon emission [4].

In this paper, a house named "Modular sustainable magic box" in Zhangbei is used as a research object to measure the thermal performance and carbon emission of straw walls. This paper compares the carbon emission with traditional wall materials to investigate whether straw has better thermal performance and carbon reduction potential in northeastern China.

2 Scope and Methodology

Firstly, in the aspect of the thermal performance of straw wall, this paper arranges the thermal conductivity of straw wall measured by scholars through experiments through literature, and then calculates the U-value of the straw wall through the structure of the " magic box". The results are compared with the design standard for energy efficiency of residential buildings in Hebei Province. So as to explore the thermal insulation performance of straw wall, and determine whether straw wall needs additional thermal insulation materials to meet the standard requirements.

Secondly, for the carbon emission of straw wall, this study mainly focuses on the production stage of building materials. In this paper, the carbon emission coefficient method is used to calculate the carbon emission of unit wall in the production stage according to the structural drawings of the " magic box". The carbon emission from material production can be calculated according to the formula specified in the Standard for Building Carbon Emission Calculation（GBT-51366-2019）:

$$Csc = \sum_{i=1}^{n} Mi \cdot Fi \tag{1}$$

Where: C_{SC} - carbon emission in the production stage of building materials（$kgCO_2e$）;

Mi -- consumption of the ith building material;

Fi - carbon emission factor of the ith building material ($kgCO_2e$ / quantity of building materials per unit).

As a comparison, this paper calculates several types of traditional material walls that meet the structural standard and the same thermal standard, so as to analyze the carbon emission characteristics of straw wall materials in the production stage and explore whether straw wall has carbon reduction potential. The carbon emission coefficient of this paper adopts the database in China's Standard for Building Carbon Emission Calculation （GBT-51366-2019）. The carbon emission coefficient of building materials not included in the standard, such as straw and wood, adopts the Bath University Inventory of Carbon and Energy (Bath ICE).

3 Thermal Performance of Straw Wall

The thermal performance of straw wall is always one of the most popular problems in the research of straw as building materials. A large number of scholars have measured the thermal conductivity of straw in different regions through experiments. Maryam measured the thermal conductivity of straw bales with dimensions of 300 * 300 * 8.4mm and densities of 61kg / m^3 and 35kg / m^3 with a heat flow meter (HFM) respectively, which were 0.0465w / m · K and 0.0467w / m · K [4]. Cinzia Buratti measured the thermal conductivity of straw bales with a density of about 100 kg / m^3 when comparing the thermal performance of straw materials with other building materials, and the thermal conductivity was 0.065w / m · K [8]. Omar Douzane measured the thermal conductivity of straw bundle samples with 50 * 50 * 10cm^3 and average density of 80kg / m^3 in straw brick house by using guarded hot plate apparatus (GHP). When the fiber is parallel to the heat flow, the thermal conductivity is 0.067w / m · K; When the fiber is perpendicular to the heat flow, the thermal conductivity is 0.046w / m · K [9]. In order to determine the optimal direction of straw and produce straw bales more suitable for contemporary architectural practice, Shawn Platt measured straw bales with a density of 126kg / m3. The average thermal conductivity of the fiber direction parallel to the heat flow test sample is 0.078w / m · K, and the average thermal conductivity when the heat flow is perpendicular to the fiber is 0.056w

/ m · K, which is 28% lower than that in parallel [10]. Andy Shea explored the relationship between thermal conductivity and density, temperature and other related factors, and calculated the thermal conductivity of rice straw with different density from 63-123 [11]. Ricardo monitored the straw brick wall of a building in California, Mexico, and measured that the density was 115kg / m and the humidity was 10.50%. The thermal conductivity of straw brick was 0.0939 w / m · K [12]. The thermal conductivity of clay perforated brick is 0.58 w / m · K, and that of aerated concrete block brick is generally 0.11-0.18 w / m · K.
The u-value of the straw brick wall is calculated (as shown in Table 2) according to the structure of the " magic box" wall (as shown in Figure 1). The results show that the straw bale in this density range meets the standard of u-value of Hebei Province, which was lower than 0.3 W/m^2·K. The thermal conductivity of the straw wall of the " magic box" is taken as 0.065 W/ m · K, the u-value of the straw wall will be 0.156 W/m^2·K, which is not only 52% of the value in Design Standard for Energy Efficiency of Residential Buildings (energy saving 75%) (DB13 (J) 185-2020) of Hebei Province.

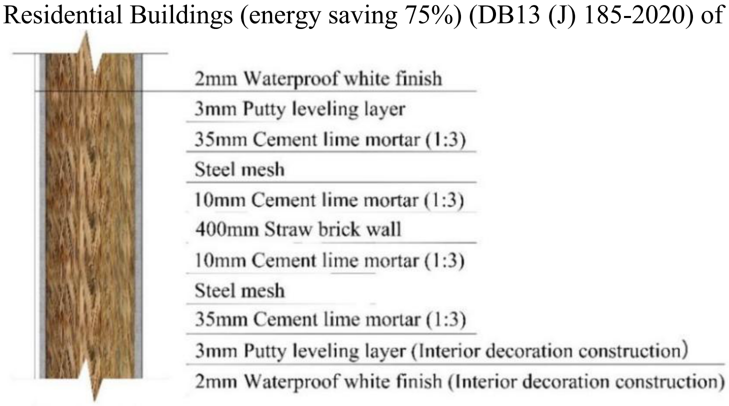

Fig. 4. Structural details of "modular sustainable magic box" wall.

Table 2. U-value of straw bale wall.

Scholar	Straw Density (kg/ m^3)	Thermal Conductivity of Straw (W/ m · K)		U-value (W/m^2·K)
Omar Douzane [9]	80	Parallel to heat flow	0.067	0.161
		Perpendicular to heat flow	0.046	0.112
Cinzia Buratti [8]	100	0.065		0.156
Andy Shea [11]	107	0.0642		0.155
	114	0.0642		0.155
Ricardo [12]	115	0.0939		0.222
Andy Shea [11]	123	0.0636		0.153
The Magic Box	110	0.065		0.156

4 Low Carbon Advantage of Straw Wall

According to the structure of straw wall, sort out the list of material consumption required for 3m-by-3m dimension wall which is a typical prefabricated modular of the straw bale wall.. According to the calculation, the carbon emission per unit straw wall is 530.329643 kgCO_2e.
After replacing the enclosure material of straw wall with hollow clay brick and autoclaved aerated concrete blocks, the required thickness of thermal insulation material is calculated by the standard of u-value in severe cold area of Hebei Province.. The carbon emission of unit hollow clay brick wall is 651.7684 kgCO_2e, and that of unit aerated concrete block brick wall is 1343.5084 kgCO_2e.
It is shown in the results, in the production stage, the carbon emission per unit straw wall is 18% less than that of hollow clay brick wall and 60% less than that of autoclaved aerated concrete blocks wall. Compared with clay hollow brick and concrete aerated brick, the disadvantage of straw bale wall is that it needs more steel parts, and the carbon emission coefficient of steel is relatively high. Because of its relatively excellent thermal insulation performance, straw wall does not need additional thermal insulation treatment. Polystyrene foam board commonly used in building thermal insulation in severe cold areas also has a high carbon emission factor.
Gangue shale hollow brick is originally made of industrial waste materials, so the carbon emission of gangue shale hollow brick in the material production stage is far lower than that of traditional building materials. Due to the reuse of waste, gangue shale hollow brick is a commonly used environmental protection building material in China. Through calculation, the carbon emission per unit wall of gangue shale hollow brick meeting the same building standards in cold areas is 251.6284 kgCO_2e.

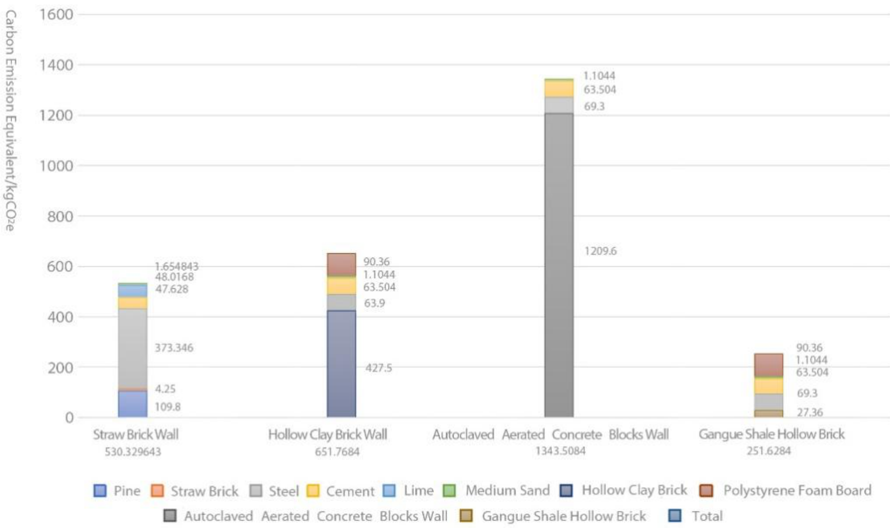

Fig. 5. Carbon emission in the production stage of each unit wall of different materials.

The thermal insulation performance of gangue shale hollow brick is lower than that of straw material. If it reaches the same wall U-value as straw wall, gangue shale hollow brick needs more polystyrene foam board. In this case, the carbon emission from material production is 372.1084kgCO_2e, as shown in Table 2. Although it is less than the straw wall, the carbon sink of straw and wood in the growth stage is not taken into account in this paper. If carbon sequestration is taken into account, straw wall may become an environmental protection building material comparable to gangue shale hollow brick.

Table 2. Carbon emission of coal gangue hollow brick wall with similar U-value as straw bale wall modular.

Component Name	Size	Density (t/m3)	Density (t/m3)	Quality (t)	Carbon Emission Factor	Carbon Emission Equivalent （kgCO2e）
Gangue Shale Hollow Brick	290*190*90mm	1.71	——	——	16	27.36
Polystyrene Foam Board	—	2.1	0.02	0.042	5020	210.84
Steel Mesh	—	——	——	0.03	2310	69.3
Cement	From JGJ98-2000	0.36	0.24	0.0864	735	63.504
Medium Sand	From JGJ98-2000	0.36	1.221	0.44	2.51	1.1044
Total						372.1084

5 Conclusion

Compared with hollow clay brick wall and autoclaved aerated concrete blocks wall, straw bale has better thermal insulation performance. The 400mm thick straw bale wall with a density of 90-110kg / m^3 can meet the requirements of building wall heat transfer coefficient in severe cold areas of Hebei Province without laying additional thermal insulation materials and it can maintain good thermal insulation performance at low temperature.

In the production stage, the carbon emission of 3000 * 3000mm wall straw bale is more than 800 kgCO_2e less than that of autoclaved aerated concrete blocks wall and 121 kgCO_2e less than that of hollow clay brick wall. In this paper, without considering carbon sink, the carbon emission per unit wall is slightly higher than that of gangue shale hollow brick, which shows the development prospect of straw wall.

Therefore, the "modular sustainable magic box" can meet the thermal design requirements of residential buildings in severe cold areas of Hebei Province without using additional thermal insulation materials. At the same time, the straw bale wall has good carbon reduction ability, which can fix the carbon absorbed in the growth of straw and wood in the building for a period of time. It can be seen that straw has a certain value of continuous research, application and popularization in severe cold areas of China.

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