RESEARCH ON COMPOSITE RICE STRAW-CEMENT BRICK FOR HIGH-RISE BUILDING
/
适用于高层建筑的稻草秸秆-水泥复合墙砖研究

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ABSTRACT

The composite rice straw-cement brick is analysed with simulations and experiments using mechanical and heat transfer theory, and data demonstrate excellent characteristic of such brick including heat retaining, light weight and fire resistance, which is beneficial to save the precious clay resource, reduce energy consumption during production and enhance the safety and comfort of high-rise building. In the future, the processing of such brick should be optimized, and this new type of manufacturing apparatus is expected to be designed to satisfy the requirements of commercial application.

摘要

利用力学和热学的相关知识对秸秆-水泥复合墙砖的特性进行了仿真和实验研究，数据表明其既能节约宝贵的黏土资源和降低生产中的能量消耗，又在保温性、轻量化和耐火性方面具有突出的优点，显著提升了建筑物的舒适性和安全性。未来还应该在复合砖的生产工艺方面进行优化，以便设计出面向工业化生产的制造装备，使其能够大范围推广应用。

INTRODUCTION

It is well known that the traditional brick is the crucial material for the urban construction, but it has obvious drawbacks such as high rate of energy consumption, pollution and ruining the environment. Rice straw has been applied widely for thousands of years in China and other countries as shown in Figure 1, and it is proved to be eminent construction stuff for heat retention, sound insulation and light weight.

Fig. 1 – Straw house in foreign countries and in China

In China, rice straw yields 0.2 billion tons yearly, while it is always considered agricultural waste, lacking of effective processing technology. Considering the strong market demand for brick generated by urbanization, it is crucial to develop eco-friendly brick based on rice straw.

There are many studies on straw-brick published. A sort of rice straw-wood particle composite board with different parameters was researched for sound absorbing, and the most suitable specific gravity of the board could be determined (Yang *H.S. et al, 2003*). In order to reinforce performance such as sound absorption, electrical insulation, erosion-resisting for a type of rice straw composite board, waste tire particles were added (*Yang H.S. et al, 2004*). In Thailand, a light wall is designed using rice straw and maize husk, and its good properties are demonstrated (*Padkho N., 2012*).

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Similarly, an ECO-MDF board is manufactured with rice straw in Egypt, which can be used in furniture or hardscape (*Shehata S.M., 2016*). Obtaining morphological and mechanical performance about rice straw, wood and potato tuber, relevant tests are conducted to show that inherent characteristics of all the cellulose microfibrils exhibit the same characteristics in the dry state regardless of tissue functions (*Hiroyuki Y.K.A., 2009*). Rice straw contains high content of lignocellulose, and it is vital to be disposed through dilute acid and alkali enzymatic hydrolysis (*Li Y. et al, 2016; Hsu T.C., 2010*). Nowadays，two types of the most problematic wastes — rice straw, expanded polystyrene foam must be dealt with pressingly, and hard wood-composite can be made of them to replace the natural wood in many daily applications (*Tawfik M. E., 2017*). There are several published papers on mechanical investigation of bundled rice straw. Stephen conducted a vibration test of straw brick house in the University of Nevada, Pakistan, and it could resist 0.8g horizontal acceleration without collapse (*Yuan B., et al, 2014*). Heat retaining is critical to the building, and studies of this type were also done. A theoretical model of concrete block wall filled with compressed straw was created, and heat transfer coefficient was only 0.446 W/(m^2·k), which is far smaller than that of concrete wall (1.5 W/(m^2·k)) (*Hou S. D. et al, 2017*). Homogeneously, a type of cement-straw composite brick is manufactured in Southwest University, China and mechanical and heat transfer tests demonstrate that it satisfies requirements of residential building regulation (*Wang D., 2016*). Fire resistance is significant to the house as well, and the straw material is of excellent performance. Silicon and wax content are so high in straw that it is tough to be burnt in the sealed environment, and wiring inside straw walls can prevent fires effectively. In addition, poisonous gas hardly releases from straw even burning. (*Lin Y. T. et al, 2010*).

Briefly, researching on straw can be divided into mechanical, heat retaining, sound insulation and fire resistance fields. But several application problems regarding straw—whether such brick can be used in the high-rise building or not, and how to innovate the manufacture process achieved by the automatic equipment—are still unsolved. Hence, concerned researches should be conducted.

MATERIALS AND METHODS

Generally, the rice straw is applied in the construction domain under two forms: bundling and gelatinization. When the rice straw is used in bundling mode, the durability may be influenced by the insects. Besides, the challenge is to build the wall with a uniform density. Evidently, straw gelatinization can avoid these shortcomings (insects will be eliminated entirely by the chemical reagent). Instead, chemical reagent such as N_aOH and quicklime must be used to decompose straw cellulose, rising the manufacturing cost. For the sake of reliability and safety of straw buildings, it is wise to adopt the gelatinization mode for straw, which is also beneficial to make brick through automatic apparatus.

It must be pointed out that rice straw-brick cannot sustain the weight alone for high-rise building, and it should be combined with other stuff when using. Compared with other materials, the concrete hollow block has the following advantages: abundant raw stuff, low price, high compressive strength, good durability and simple production process, so it has been used as the main building material for the urban and rural houses (*Hou S. D. et al, 2017*). However, the high energy consumption for concrete hollow block cannot be neglected when it comes to its poor heat retention, which conflicts the increasingly strict construction code. As a result, rice straw-concrete composite brick may be a practicable way to improve the energy-saving effect of cement hollow block. Apparently, such a composite brick is eligible to be used in the high-rise building, particularly for the separating walls. The rice straw-cement compound brick is showed in Figure 2.

a) *b)*

Fig. 2 – Rice straw–cement compound brick

The manufacturing process of rice straw brick is described here. Firstly, the rice straw collected from the countryside in Chongqing is cut into small sections of a certain length. Secondly, the chemical reagent such as N_aOH or quicklime and the cut straw are stirred together for some minutes, which is useful to make the compound uniform. Thirdly, the mixture is put in a mould and then the mould is compressed by a press machine. Fourthly, the straw brick is maintained for some days to get uniform size, minimizing the bounce-back. After the assembling of rice-straw brick and hollow cement brick, the composite production can be obtained.

After manufacturing the composite brick, it is natural to research its properties such as thermal performance, mechanical performance and fire resistance, which are crucial to indicate its reliability. In this study moisture content, compressive strength and heat transfer coefficient or thermal conductivity of the composite brick will be illustrated gradually.

Moisture content will lead to mildew, so it is closely related to the brick life span—the higher the moisture content, the shorter the life span of brick is. Besides, moisture content can exert a negative impact on the heat transfer coefficient — the higher the moisture content, the higher the energy consumption is (*Kong F.H. et al, 2010*). Hence, the moisture content must be controlled within a certain range. Generally, it is can be denoted applying formula 1 below

$$h = \frac{m_w - m_d}{m_w} \tag{1}$$

where:

m_w is the mass of brick in the wet state, [g];

m_d - mass of the brick in the dry state, [g];

h - moisture content of the brick.

When the composite brick is used in the building construction, it must sustain the weight of upper stuff. This is the reason why the compressive strength of brick is compulsorily required to satisfy the corresponding norm. In engineering, it is always showed as formula 2. Of course, in most of the cases the compressive strength of the material can be predicted with formula 3 (*GB 25003-2011*) bellow.

$$f = \frac{P}{A} \tag{2}$$

where: f is the compressive strength,[MPa];

P - ultimate load, [N];

A - contact area, [mm^2].

$$f_m = k_1 f_1^{\alpha}\left(1 + 0.07 f_2\right) k_2 \tag{3}$$

where:

f_m is the average compressive strength of the brick, [MPa];

f_1 - strength level of the brick, [MPa];

f_2 - compressive strength of the mortar, [MPa];

α - constant, α=0.9;

k_1 - constant, k_1=0.46;

k_2 - constant, k_2=1.0.

Apart from the moisture content, heat transfer coefficient has decisive influence on the energy efficiency of the building. In theory, heat transfer coefficient is expressed by formula 4 (*Qiu S.J., 2012; Li A.J. et al, 2018*)

$$k = \frac{1}{\frac{1}{\alpha_{in}} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_{out}}} \tag{4}$$

where: α_{in} is the indoor convective heat transfer coefficient, [$W \cdot m^{-2} \cdot k^{-1}$];

α_{out} is the outdoor convective heat transfer coefficient, [$W \cdot m^{-2} \cdot k^{-1}$];

λ_i - heat conductivity coefficient of the i^{th} layer material, [$W \cdot m^{-1} \cdot k^{-1}$];

δ_i - thickness of the i^{th} layer material, [m].

If some parameters are difficult to measure when using formula 4, the heat transfer coefficient can be calculated in practice by formula 5 and 6 (*Hou S. D. et al, 2016*). In essence, formula 6 can be viewed as a rewrite of formula 4, using different parameters.

$$R = \frac{\sum_{i=1}^{n} \left(T_{1i} - T_{2i} \right)}{\sum_{i=1}^{n} q_i} \tag{5}$$

$$k = \frac{1}{R + R_i + R_o} \tag{6}$$

where:

R is the average heat resistance of material after multiple measurements, [$m^2 \cdot k \cdot W^{-1}$];

R_i - inner surface heat resistance, [$m^2 \cdot k \cdot W^{-1}$];

R_o - outer surface heat resistance, [$m^2 \cdot k \cdot W^{-1}$];

T_1 - inner surface temperature of material, [K];

T_2 - outer surface temperature of material, [K];

q - heat flux, [$W \cdot m^{-2}$].

RESULTS

Actually, the closed thin-walled hollow structure of rice straw can enable it to sustain pressure, and that is the reason why it has super sound insulation character — when the sound wave propagates, the air in the fibre gap inside the straw will vibrate, but the air near the surface will not be activated under the action of the viscous resistance of the fibre. Indicating the fine pressure resistance, stress experiments shown in Figure 3 have been accomplished based on the rice straw (shown in Figure 3a) and composite brick (shown in Figure 3b).

a) *b)*

Fig. 3 – Stress experiment of straw and composite bricks

In the experiment, the pressure machine is WAW-1000, produced by the Kexin Test Instrument Co. LTD, Changchun, China. The test data demonstrate that straw brick only has slight deformation if the stress is less than 15kN; the deformation will be more and more obvious with the stress increasing. Once the pressure disappears, the shape of straw brick will recover gradually. It is also indispensable to point out that the stress is an average value of different concentrations of N_aOH solution—2%, 3%, 4%, 5%, which is used in disposing the rice straw. Meanwhile, in order to verify the validity of formula 3, simulations have also been listed in Table 1(f_t is the test strength result of the brick, and f_m is the simulation result).

Table 1

Test data of rice-straw composite brick

Number	**Load** [**kN**]	f_t [**MPa**]	f_m [**MPa**]	f_t/f_m
1	218.55	5.95	6.21	0.96
2	220.70	6.01	6.21	0.97
3	223.06	6.04	6.21	0.97

According to the relevant construction regulation, this composite brick is allowed to be used in the bearing wall of village and town constructions, and it can be used in the separating wall of high-rise building incontrovertibly.

The experiment on the heat transfer of rice-straw brick is described here. The main instrument is DRCD-3030 intelligent thermal conductivity tester shown in Figure 4, made by Tianjin MEITESI Co., China, and the temperature of hot plate is set at 35ºC, while the temperature of cold plate is controlled at 15ºC. According to the operation manual of the instrument, heat transfer coefficient can be obtained. Similarly, the heat transfer coefficient of compound brick can be measured with such apparatus.

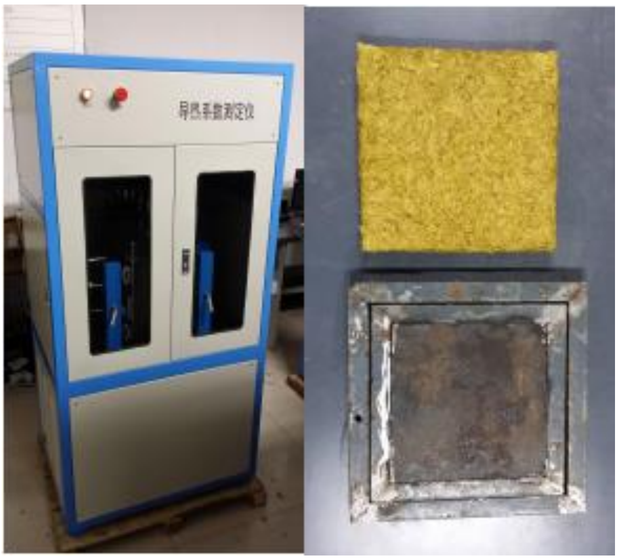
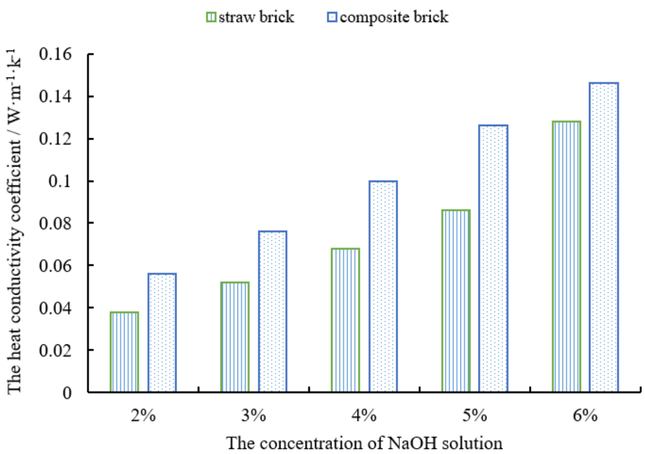


Fig. 4 – The instrument of heat transfer experiment

The NaOH solution plays a final role in disposing the rice straw fibre, and different concentrations of the solution have obvious impact on the density and heat conductivity of rice-straw and composite brick. Test data are illustrated in Figure 5 and Figure 6. It is not difficult to draw two conclusions —the heat conductivity coefficient of compound brick is higher than that of rice-straw brick, and high concentration of solution would give rise to large heat conductivity coefficient. For the straw brick, heat is transferred mainly by the air, so it indicates small heat conductivity coefficient, determined by the air property. But for the composite brick, the voidage of concrete stuff can be neglected and heat is transferred easily, so its heat conductivity coefficient keeps big. The moisture content is decisive to heat conductivity coefficient as well (*Huang J. E. et al*, 2015; *Bao Y. et al, 2018*). The bigger concentration of solution is, the higher moisture content keeps. Moreover, the heat conductivity of water is much bigger than that of the air, and this is the cause why the heat conductivity coefficient of brick becomes bigger with the moisture content increasing.



Fi g. 5– The comparison of two types of bricks

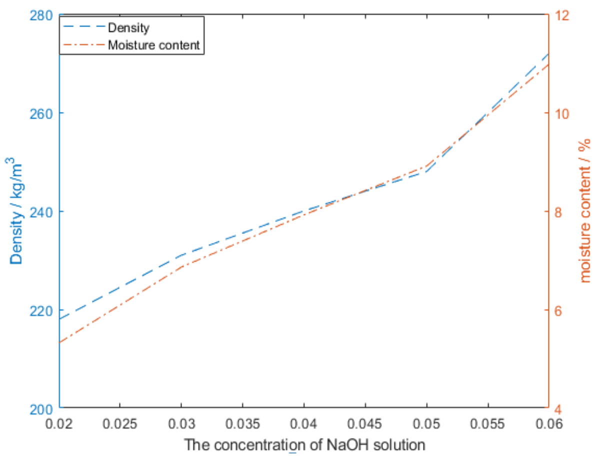


Fig. 6– The property of straw brick

Except for the moisture content, the concentrations of the N_aOH solution are also crucial to the shrinkage rate of rice straw brick, influencing on the assembling of two sorts of bricks and the uniformity of composite brick. Test data have been list in Table 2, and it is not hard to find some rules. The concentration of N_aOH solution is in direct proportion to the shrinkage rate of rice brick, similarly to the moisture content rate of rice brick. The conclusion can be explained as follow. The lignin and hemicellulose of rice straw may be degraded by the N_aOH solution, and the resilience force of compressed rice straw will lose, so the rice brick disposed by high concentration N_aOH solution has big shrinkage rate.

Simultaneously, the moisture content rate of rice brick is affected as well. The bigger the shrinkage rate is, the harder the moisture evaporates, which is stated that the air circulation is blocked in a compact structure obviously. In a word, the concentration of N_aOH solution exerts a vital impact on the physical performance of rice brick, and thus selecting the most appropriate concentration of N_aOH solution is a challenging task, obtaining the satisfying the properties of rice brick.

Table 2

The physical properties of rice brick regarding different concentrations of N_aOH solution

The concentration of N_aOH solution	The shrinkage rate of rice brick	The moisture content rate of rice brick
2%	2.84%	5.32%
3%	3.76%	6.86%
4%	4.48%	7.92%
5%	5.34%	8.91%
6%	7.41%	10.98%
7%	9.45%	12.13%

When heat transfer coefficient is not convenient to calculate, it is wise to use another terminology — heat conductivity coefficient. Although there is a small difference between the two parameters such as unit (heat transfer coefficient is generally for the convective case, while heat conductivity coefficient is invariably for heat conduction), they can both give expression to the heat retention capacity of the material. Compared with other material, the composite brick is still an excellent construction stuff as shown in Table 3. Remarkably, the mechanical property of rice-straw brick has been improved greatly so that it can be used for high-rise building.

Table 3

Comparison of heat properties of different materials

Material	Density [$kg \cdot m^{-3}$]	Heat conductivity coefficient [$W \cdot m^{-1} \cdot k^{-1}$]
Clay brick	800~1000	0.45~0.81
Rice straw brick	218~248	0.038~0.08
Concrete	1413~1900	1.51
Expanded perlite	2200~2400	0.021~0.062
Composite brick	1142~1413	0.056~0.126

It is important to underline two points resulting from the Table 2. Firstly, the heat conductivity coefficient of rice straw brick is the smallest, determined by the closed thin-walled hollow structure, which is a poor heat conductor. Although the heat transfer factor of expanded perlite is similar to the rice straw, its density is far larger than that of rice straw brick, which is crucial to the safety of high-rise building. Secondly, the density of composite brick is a little different compared to concrete density, while the heat transfer coefficient is very different due to the unique structure of rice straw.

Fire resistance of material is vital to the urban construction, particularly to the skyscraper (*Wu W. et al, 2015*). It is well known that the yield strength and ultimate strength of the steel structure are degenerated sharply with temperature rising. If the temperature is above 600℃, the steel structure will even lose bearing capacity, as demonstrated by the collapse of New York World Trade Centre Towers. The compressive strength of brick applied in the separating wall is expected to be larger than $5MPa$, the composite brick fits the bill definitely. In addition, the density of composite brick is about 24%-35% smaller than that of concrete as shown in Table 2, which is beneficial to satisfy the requirement of structure's light weight. If a good fire resistance can be demonstrated in the case of the composite brick, it will be an excellent stuff for building skyscrapers. Just like it is used, the top surface of composite brick shown in Figure 2b is sealed with cement at first. Then the sealed brick is put into a test stove.

After burning for three hours, the fire resistance test has been completed. The experimental scene is shown in Figure 7.

a) b)

Fig. 7 – Fire resistance of composite brick

As it can be seen in Figure 7a, it is hard to find distinct change on the surface of compound brick after burning for three hours, while some variation appeared inside the compound brick in Figure 7b—merely the top of rice straw has become carbonized, but the other parts remained unchanged. There are two reasons for this. One is that the rice straw has a high content of silicon, which is an excellent material of fire resistance; The other is the lack of oxygen in such environment, which makes the fire stops inevitably. Moreover, the rice straw cannot give off any poisonous gas even if it can be ignited, and there is no fireproofing agent added except for the reagent. Briefly, the safety of high-rise building has been enhanced greatly after using concrete-rice brick.

CONCLUSIONS

- Test data indicate eminent advantages of compound brick including heat retention, mechanical performance and fire resistance, and it is feasible to be used in the high-rise building.
- The composite brick is made by hand in this study, and efforts are made to optimize this process and develop new apparatus to implement industrial production of the brick.

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