ASSESSMENT OF STRAW DEGRADATION INSIDE STRAW BALE WALLS IN SEVERE COLD REGION OF CHINA

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Abstract

With the increasing concerns of low carbon development of building industry, the feasibility of using straw bale buildings has been widely discussed for the last decade in China. However, there are few studies focus on assessment of durability of this building type regarding the climatic features in China. This paper analyzes the features of straw degradation inside straw bale walls in the severe cold region in China. The analysis involves two parts of researches: The first part analyzes the degradation potential of straw inside straw bale walls in high humidity and high temperature conditions which was recorded in the summers in the climatic region; The following research examine straw conditions inside an experimental straw bale building in the region after one-year competition of the building. The results show that the straw inside straw bale walls have no concerns of degradation in the high hygrothermal environment in the severe cold region in China. The following inspections of straw conditions inside experimental building indicate that straw have moderate concerns of degradation in the area 2-3cm deep behind the lime render. The work of this research will help to build up models for predicting straw degradation levels inside straw bale building in severe cold region in China. This impact of this research will be the growth in low carbon energy efficient straw bale construction with confidence over its long-term durability characteristics in severe cold region in China.

Keywords:

Straw; Straw Bale building; Northern China; Durability; Degradation assessment; Experimental building

1 INTRODUCTION

Straw bale construction uses agricultural co-products in the construction of buildings (King, 2006). It was originally developed in Nebraska in late 19th century, due to shortage of building materials (King, 2006). This buildings type was replaced after achieving more industrialised building materials in the Middle West America in early 20th century (King, 2006). The oil crisis of the 1970s helped people to develop ideas of creating more energy efficient buildings. Straw bale buildings were characterised by combinations of low cost, quick construction process and high thermal insulation (Bergeron and Lacinski, 2000). The construction technique was re-introduced in the 1980s in west America and the construction method has become popular worldwide later on (Steen et al., 1994). Straw bale construction has now become more recognised globally and has developed into a contemporary building typology and construction method in the western world (King, 2006).

The construction technique was initially introduced to northern China by the Adventist Development and Relief Agency (ADRA) in 1998 ((ADRA), 2006). The project was funded by the ADRA/China, Central Government and Local Governments in northern China and more than 600 straw bale buildings had been finished by 2006 (Mantesi et al., 2018). However, recent research has shown degradation issues inside the straw bale walls in the project and the current status of the straw bale buildings are remain uncertain (Yin et al., 2018). To assess the durability issue of straw within the straw bale walling construction in the severe cold regions in China, this research analysis the straw degradation both though experiments of specimen of straw bale walls in climatic chamber and the visual inspection of the experimental building which constructed in the region.

2 LITERATURE REVIEW

2.1 Favourable environment for supporting straw degradation

There are two kinds of degradation processes within straw bale walls: aerobic degradation and anaerobic degradation (Summers et al., 2003). The oxygen availability of microorganisms inside straws decides what kind of degradation is triggered. The presence of oxygen is an accelerator of straw degradation. The suitable hygrothermal environment will lead to readily aerobic decomposition of straw (Zhu, 2007). However, straw bale walls are isolated from external environment by render layer and oxygen concentration can only support initial aerobic degradation of straw (Thomson and Walker, 2014).

The relative sealed environment within straw bale walls is mostly provided by rendering constructions. Even though different kinds of rendering constructions have various permeabilities for water and air transmittances, they all can provide relative sealed environment for straw bales (King, 2006). Even though relationships between properties of rendering construction and decomposition resistance of straw bales are not fully understood in current researches (Wihan, 2007), all rendering materials have ability in limiting moisture content and achieve similar air tightness inside straw bale walls (Bergeron and Lacinski, 2000). This property of rendering constructions can gradually reduce oxygen level inside straw bale walls and lead to anaerobic degradation (Summers et al., 2003).

In the process of anaerobic degradation, straw will have much longer decomposition process than the aerobic one. As most bacterial need oxygen to trigger the biological reaction which can transfer mineral nitrogen to proteins, the active microorganisms are in low quantity (Hopkins, 1999) in straw bale walls sealed by rendering constructions. As a result, the decomposition process of anaerobic is much longer than the aerobic one.

The environment inside straw bale walls can protect straw from hostile activities of microorganisms. Bacteria and yeasts can only duplicate in high moisture condition and other than this, yeasts also need light to process the biochemical reactions which are essential for growth of microorganisms (Dresbøll and Magid, 2006). Considering the environment inside a straw bale wall, rendering construction (lime, cement, earth and etc.) form a barrier between straw bales inside walls and atmosphere. As a result, relatively dry and completely no light conditions can be achieved and the environment in straw bale walls will not accommodate growth of the microorganisms. However, there may be some issues for straw bale walls in the situations with presence of liquid water between rendering constructions and straw bales. The straw bale walls which are exposed to high humidity and great differential temperature on both sides may lead condensation in the straw bales. Straw will be degraded by long time exposure to liquid water.

Favourable temperature is important in the process of anaerobic straw decomposition (Bergeron and Lacinski, 2000). There are two major ranges of temperatures in the digestion process (Bergeron and Lacinski, 2000). The mesophilic digestion is triggered between 30 °C to 38°C and the thermophilic decomposition occurs around 49°C - 57°C (Song et al., 2004). When temperature drop lower than freezing point, because water transform from liquid to ice, decomposition will not happen due to frozen water (Summers et al., 2003). Also, bacteria and fungi cannot survive in temperatures which are above 65°C (Summers and Beall, 2000).

2.2 Climatic condition of examined area

The climate in China encompasses a wide range of air temperatures and humidity. MOHURD published the national code for thermal designs of civil buildings which identifies a number of different climatic regions (Development, 1994). The design and construction of buildings in China is informed by five climate regions differentiated by the climatic characteristics of the regions (Figure1). Northern China is in the climatic areas of 'Severe Cold' and 'Cold'. In these two areas, the primary energy consumption of buildings is that of winter heating energy (Development, 1994).

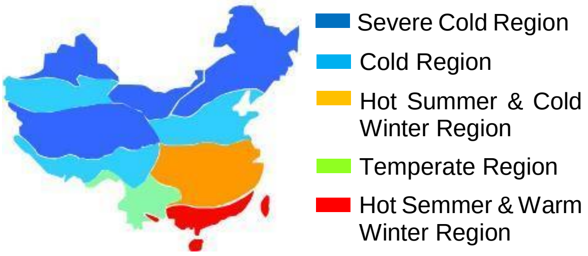

Figure 1. Climatic regionalization in the GB50178-93. (reproduced from. (Development, 1994).

The experimental straw bale building was constructed in Changchun, in the Jilin province of northeast China (Figure 2). Changchun is subject to a typical temperate monsoon climate. In the national thermal design code of civil buildings (Development, 1994), the area is identified in the severe cold climate zone which is part of the temperate monsoon climate zone. Temperature peaks at around 30℃ in the area from June to August and drops to below freezing after late October annually (Figure 2). The highest monthly air humidity level is 88% and it appears in January (Figure 3). The monthly humidity levels are from 63% to 72% in summer during which the highest temperature appears.

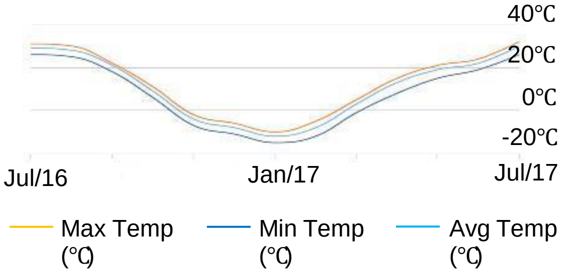

Figure 2. Average monthly maximum temperature, minimum temperature and average temperature in Changchun from July 2016 to June 2017.

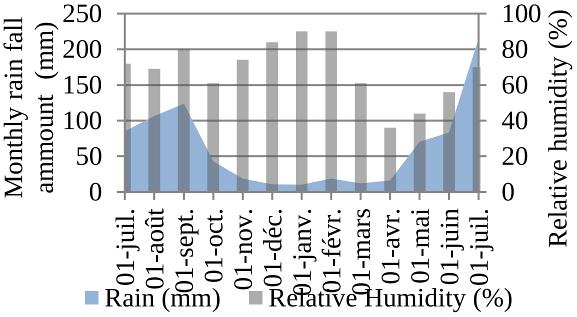

Figure 3. Average monthly Humidity and rain fall in Changchun from July 2016 to June 2017.

The climatic features of Changchun represent three typical climatic characteristics in northern China: Firstly, both the air temperature and humidity are at high levels in summer months. The daily high temperatures are around 30℃ in summer months. Due to the features of template monsoon climate, rainfalls are expected mostly in summer months which lead to the high air humidity. Secondly, as lowest rain potentials and air humidity are expected in spring months in template monsoon climate areas, the spring can be identified as a "dry" season in northern China. However, as air temperatures begin to rise up above freezing in March, melting snow increases humidity levels in northern China. Comparing the air humidity levels in April and May, the monthly average humidity of March is significantly higher than the one in April and May in Figure 3. Thirdly, the air temperatures in northern China are expected below freezing during the whole winter months and highest monthly air humidity levels present during the same period of time. However, the high air humidity levels do not result in humid environment inside and outside buildings. As the low temperatures decrease absolute water vapour pressures in the air, the relative humidity levels in winter months are significantly higher than other months annually in northern China. As a result, the winter months in norther China are featured cold and dry (Development, 1994).

3 RESEARCH METHOD

To assess the possibility of degradation induced by the high RH and high temperature conditions, an experimental investigation was designed to represent a typical wall build-up. There are no published methods for the tests. The experimental results will be compared with onsite visits of the experimental building to access degradation potential of straw within straw bale walls.

3.1 Laboratorial Experiment

The investigation of degradation potential of straw uses a climatic chamber to replicate the environment in Changchun. The climatic chamber was manufactured by ACS and the model is DY 110 (C). Concluding from the monitoring research, the conditions of climatic chamber is set up at 95% RH and 35℃ to represent the potential peak daily mean temperature and peak daily mean RH. The duration of the experiment was designed to be slightly longer than the summer months would be encountered in the monitoring research. The duration of the degradation experiment was designed to be 12 weeks. The duration includes an allowance for an initial 2 weeks for moisture build up within the sealed straw bales and the following 10 weeks which represent typical summer months in northern China.

Straw bales and lime render were constructed in three transparent boxes to represent walling constructions of straw bale buildings (Figure 4). Both rice straw and wheat straw were used in different wall constructions. The straw was baled in small bundles and placed both parallel and perpendicular to the lime render to represent the laid flat stacking method and the laid on-edge stacking method in typical construction of straw bale buildings. A RH/T sensor was installed in the straw bundles in each specimen (Figure 5). The thickness of lime render was 50mm in the construction of specimen. The adjacent area between the lime render and the transparent boxes were sealed by wax to avoid direct pass of environmental RH to travel into the straw in the specimen. The transparent boxes of the walling constructions were labelled into small rectangle to identify possible area of straw degradation in the research. The specimens were placed in controlled climatic room (80% RH and 20℃) for one week to cure the lime render. The cured specimens were then placed in low temperature (40℃) oven for one week to reach lower than 85% initial RH @ 30℃ before placing specimens in climatic chamber. During the 12week experimental period, the conditions of straw were visually checked once a week, and at the beginning of week 4, once a day for the following 8 weeks.

Figure 4. Section of walling construction in the degradation potential experiment.

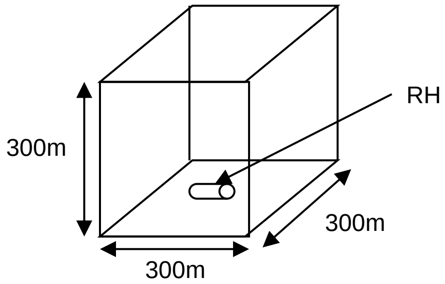

Figure 5. Diagram of experiment specimen and sensor set up.

3.2 Examination of straw condition within experimental building

The experimental building was a single-story bungalow with pitched roof (Figure 6). The layout of the building was similar to the existing residential building in rural area of severe cold region of China. The structural frames and foundation of the experimental building were made of cast concrete reinforced by steel rebar, being the construction technique with which the builders used in this project were familiar. For the same reason, the building was designed to have a cold roof, thus the insulation layer in the roof was laid beneath above the ceiling. The experimental building was constructed in an open field in the campus of Jilin Jianzhu University. The building was orientated on cardinal directions and there was no structure and obstruction around the building.

Figure 6. Perspective of the experimental building with laid flat straw bales (light yellow) and on edge straw bales (dark yellow).

There were two stacking methods in the experimental building to examine the effects of local climate on the straw bales. The west flank of the building had stacking of laid-flat straw bales and the on-edge bales were used in the east flank. Comparing with the laid flat straw bale walls, the laid on-edge walls had one less level of bales. To minimise thermal bridging of the concrete structure, EPS insulation boards were used between the concrete frames and between straw bales and frame in the east gable wall and the west gable wall. The experimental building was constructed from April 2016 and finished in July 2016. The processes of visual inspection of the straw condition were conducted one year after the completion of the experimental building (19th June 2017). During the onsite research, lime render layer was opened up to check straw status within straw bale walls. Moisture contents of the straw within walls are measured directly using a HF-LM9 moisture content meter

4 RESULTS

4.1 Laboratorial results

Due to the construction, the lime render introduces different amount of water in each specimen, the initial RH readings are different. The initial RH readings of the specimens were 52% RH for the specimen with parallel placed rice straw, 77% for the specimen perpendicular placing of rice straw and 55% for the specimen with perpendicular placed wheat straw. The effects of the different humidity levels inside the specimen are effects of different adsorption process through external surface and cutting end of straw. Despite the notable difference of initial RH in the straw bundles, the specimens reach 95% RH relative in similar period of time in the climatic chamber. The specimens of perpendicular placing straw reached the environmental RH after 9 days and 12 days for rice straw and wheat straw respectively. The specimen of parallel placed rice straw has slightly longer time to reach 95% RH and the period of time is 15 days.

The visual checks of the specimens does not identify any recognisable straw degradation both in the experimental process and at the end of the experiments. Comparisons of the specimens of the straw status before experiment and after experiment are shown in Figure 7, Figure 8 and Figure 9. Existing research on sorption isotherm of straw have identified that straw would have serious degradation after more than 4 weeks exposure in the environment of 95% RH and 22℃ (Carfrae, 2011, Lawrence et al., 2009). The straw in typical lime rendered construction becomes protected.

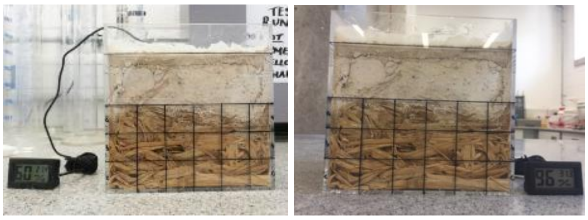

Figure 7. Specimen of rice straw with parallel placing before the degradation research (left) and after 12 weeks in climatic chamber (right).

Figure 8. Specimen of rice straw with perpendicular placing before the degradation research (left) and after 12 weeks in climatic chamber (right).

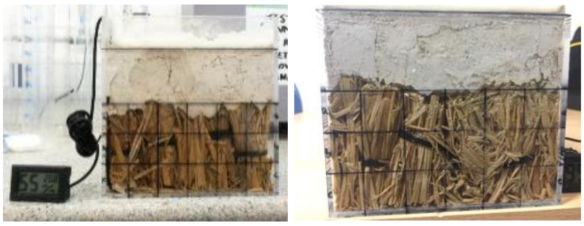

Figure 9. Specimen of wheat straw with perpendicular placing before the degradation research (left) and after 12 weeks in climatic chamber (right).

The experimental results show that straw does not exhibit signs of notable degradation in high humidity and high temperature environment. The property of low degradation potential of straw at high temperature has specific importance in building straw bale constructions in severe cold region of China. The potential self-builders of straw bale buildings are local farmers in the region. Because of extensive farming activities in spring and autumn, the group of self-builders are available for construction activities merely in summer. Due to the low degradation of straw in high RH and high temperature environment in the region, the straw bales in the buildings constructed in the summer months would have as little chance of degradation in other months in the climatic region.

The reason for the lack of degradation maybe due to the effect of oxygen availability and presence of lime render. The lime rendering provides a sealed environment which can limit the fungi and bacteria activity in the form of anaerobic degradation (Summers et al., 2003). The anaerobic activity of fungi and bacteria can have slow degradation effects on the straw bales. Available free moisture is a crucial factor on anaerobic activity of microorganisms inside straw bale walls (Clynes, 2009). The lime in the form of lime wash is widely used in preventing mould growth on walling surface in conventional buildings in China (Liu, 2015). The use of lime rendering on straw bale walls may prevent mould growth in the straw bale walls.

4.2 Results of the experimental building

To examine the straw conditions behind rendering layer, rendering layer of 8 positions (Table 1) were removed to expose the straw inside the bale walls in the second onsite visit after 11 months monitoring research on 19th June 2017. The straw was visually checked onsite. There was limited degradation of straw at the interface between straw bales and external rendering for all opened positions (Figure 10). The degradation appears on the interface of lime render and straw bales and penetrated 2-3 cm deep into the straw bales. The straw behind the interface remains golden colour inside the walls. The site visit confirms that the straw was in good condition inside the straw bale walls for one year. Unlike the limited straw degradation on the interface between straw bales and the lime render layers, the straw was in good condition with mixture of lime render (Figure 11).

Figure 10. Opening of external render (left) and straw adjacent rendering layer (right) of low position of laid flat bale wall.

Figure 11. Mixture of straw and lime stucco outside the high position of laid flat bale wall.

The thickness of lime rendering varies significantly from the design thickness (Figure 12). The thickness variations of lime rendering was between 40mm to 105mm in the experimental building (Table1). The thicker lime rendering layers may provide more moisture buffering to straw bales and introduce more initial moisture in the straw bales at the drying stage of lime rendering. The bales behind the thicker lime rendering would have higher initial moisture content and have longer drying period than the one behind thinner lime rendering. However, the thicker lime render layers do not have significant effect on straw degradation from visually inspection.

Figure 12. Straw conditions behind opening locations with thin rendering thickness (left) and thick rendering thickness (right).

4.3 Assessment of straw degradation regarding climatic feature of the experimental building

During the onsite visit, the straw outside the high position of on-edge bale wall show insignificant decolourisation and no notable mould growth are identified on the straw surface by visual inspection through the drilled opining outside the monitoring location (Figure 12). Even though straw degradation is identified behind the render layer outside the low position of laid flat bale wall, the situations are not as severe as the prediction of the isopleth model. The limited straw degradation only appears on the surface of straw bale stacking and the straw remain unchanged inside the bales.

The overestimation of straw degradation has been discussed in other research (Thomson and Walker, 2014), however, there is no proper explanations for the inaccurate prediction of isopleth (Thomson and Walker, 2014). The presence of the lime render significantly increase durability of straw both in the laboratorial experiment and the on-site visit. Even though there is limited scientific evidence on the connection of anaerobic decomposition of straw and the material of rendering constructions, application of lime based rendering constructions may have effects on limiting anaerobic decomposition of straw in straw bale walls. During the anaerobic digestion process, carbohydrates in straw is initially converted into sugars in the hydrolysis stage (Mussoline et al., 2013). The sugar is later broken down to intermediates (acetic acid, hydrogen and carbo dioxide) by acidogenic and acetogenic bacteria (Mussoline et al., 2013). The methanogenic bacteria convert the intermediates into methane and carbon dioxide at the final stage of the anaerobic decomposition of straw (Mussoline et al., 2013). The active PH range of the acidogenic and acetogenic bacteria is 6-10 and the methanogens has smaller range of allowable pH range (7.5-8) (Athienitis et al., 1997).

With presence of lime-based rendering constructions, reaction would be limited for two reasons: Firstly, the lime-based rendering constructions would provide unfavourable environment for anaerobic decomposition of straw. The major content of lime is the calcium hydroxide which is a high alkaline pH standard (Rijal et al., 2008). The pH of calcium hydroxide is over 12 which is notably over the active range of the acidogenic and acetogenic bacteria. During the curing stage of lime-based rendering constructions, calcium hydroxide provides long-term alkaline environment for straw within straw bale walls and therefore limit the decomposition of straw. In the second, the calcium hydroxide react with the intermediates of the anaerobic digestion of straw. Calcium hydroxide require carbon dioxide in the chemical reaction of achieving calcium carbonate during curing stage of lime based rendering and acetic acid is also neutralised by the high pH environment provided by the calcium hydroxide. As a result, the lime based rendering construction reduce the intermediates of the anaerobic decomposition of straw and increasing durability of straw bale walls. However, the effect of lime rendering on limiting anaerobic digestion are limited understood in current research (Wihan, 2007), the effectiveness of lime rendering in increasing durability of straw bale walls against anaerobic degradation remain uncertain.

The degradation between the lime render and the straw bales indicate the effect of aerobic degradation of straw and therefore the isopleth successfully predicts the straw degradation.

Tab.1: Rending thickness of opening locations and measured moisture.

Monitoring location	Inner actual moisture content	Outer actual moisture content	Render thickness
High position of west gable wall	20.3%	28%	75mm
Low position of west gable wall	15.3%	24%	65mm
High position of laid on-edge bale wall	12.8%	14.6%	50mm
Low position of laid on-edge bale wall	17.3%	21.0%	70mm
High position of east gable wall	18.0%	23.0%	105mm
Low position of east gable wall	28.6%	33.0%	40mm
High position of laid flat bale wall	17.0%	14.0%	50mm
Low position of laid flat bale wall	24.0%	16.0%	100mm

Due to breathability of the lime render, the oxygen condensation behind the lime render would not be as low as the one in the straw bales. As a result, the aerobic degradation happens at the area behind the lime render in straw bales. However, due to alkaline environment provided by the lime render, the degradation of straw is not serious with mix of lime render. The degradation of straw was identified 2-3cm behind the lime render. Because of the oxygen inside straw bales are much lower than the adjacent area of lime render and the straw bales, the degradation does not penetrate into straw bales (Figure 13). However, if straw experiences serious degradation behind the lime render, hollows and cavity would likely form. Without support of straw behind lime render, the render may have cracking issues and lead to water penetration into straw bales.

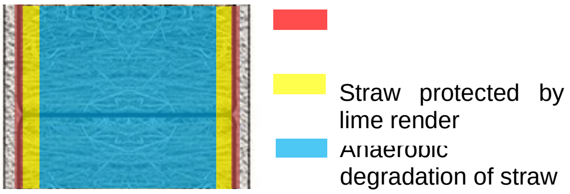

Figure 13. Analysis of straw degradation inside straw.

5 CONCLUSION

The results of this research show moderate concerns of straw degradation between straw bales and the lime render regarding the climatic features in northern China. The experimental show that the hot and humid summer have insignificant impact on durability of straw bales within straw bale walls, whereas due to relative high oxygen levels behind the lime render. Due to the aerobic degradation is far more rapid than the anerobic degradation, the straw condition behind the lime render would be a concern of the durability of straw bale walls in the northern China.

The following inspections of straw conditions inside experimental building indicate that straw have moderate concerns of degradation in the area 2-3cm deep behind the lime render. The work of this research will help to build up models for predicting straw degradation levels inside straw bale building in severe cold region in China.

This impact of this research will be the growth in low carbon energy efficient straw bale construction with confidence over its long-term durability characteristics in severe cold region in China.

6 REFERENCES

(ADRA), A. D. A. R. A. 2006. What is a Straw Bales Building? [Online]. http://www.adrachina.org/site/program_details.php?ID=26. [Accessed 3rd July 2014].

ATHIENITIS, A. K., LIU, C., HAWES, D., BANU, D. & FELDMAN, D. 1997. Investigation of the thermal performance of a passive solar test-room with wall latent heat storage. Building and Environment, 32, 405-410.

BERGERON, M. & LACINSKI, P. 2000. Serious Straw Bale, A home construction guide for all climates. Chelsea Green Publishing Company, Vermont.

CARFRAE, J. 2011. The Moisture performance of Straw Bale Construction in a Temperate Maritime Climate. Doctor of Philosophy, University of Plymouth.

CLYNES, J. 2009. Decay Characteristics of Different Types of Straw Used in Straw Bale Building. London: sn.

DEVELOPMENT, M. O. H. A. R. U. 1994. Standard of climatic regionalization for architecture. Ministry of Housing and Rural Urban Development.

DRESBøLL, D. B. & MAGID, J. 2006. Structural changes of plant residues during decomposition in a compost environment. Bioresource Technology, 97, 973-981.

HOPKINS, W. G. 1999. Introduction to plant physiology, John Wiley and Sons.

KING, B. 2006. Design of straw bale buildings : the state of the art, San Rafael, Calif., San Rafael, Calif. : Green Building.

LAWRENCE, M., HEATH, A. & WALKER, P. 2009. Determining moisture levels in straw bale construction. Construction and Building Materials, 23, 2763-2768.

LIU, X. 2015. 中国传统灰浆的化学组成特征及粘结机理研究 (in Chinese). PhD Thesis, Zhejiang University.

MANTESI, E., HOPFE, C. J., COOK, M. J., GLASS, J. & STRACHAN, P. 2018. The modelling gap: Quantifying the discrepancy in the representation of thermal mass in building simulation. Building and Environment, 131, 74-98.

MUSSOLINE, W., ESPOSITO, G., GIORDANO, A. & LENS, P. 2013. The Anaerobic Digestion of Rice Straw: A Review. Critical Reviews in Environmental Science and Technology, 43, 895-915.

ONLINE, W. W. 2017. Changchun, Jilin Monthly Climate Average, China [Online]. Available: https://zh.worldweatheronline.com/changchun-weather-averages/jilin/cn.aspx [Accessed 7th/May 2017].

RIJAL, H. B., TUOHY, P., NICOL, F., HUMPHREYS, M. A., SAMUEL, A. & CLARKE, J. 2008. Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. Journal of Building Performance Simulation, 1, 17-30.

SONG, Y. C., KWON, S. J. & WOO, J. H. 2004. Mesophilic and thermophilic temperature co-phase anaerobic digestion compared with single-stage mesophilic- and thermophilic digestion of sewage sludge. Water Research, 38, 1653-1662.

STEEN, A. S., STEEN, B. & BAINBRIDGE, D. 1994. The straw bale house, Chelsea Green Publishing.

SUMMERS, M. D. & BEALL, F. 2000. Fundamental properties of rice straw in comparison with softwoods.

SUMMERS, M. D., BLUNK, S. L. & JENKINS, B. M. 2003. How straw decomposes: Implications for straw bale construction. Ecological Building Network.

THOMSON, A. & WALKER, P. 2014. Durability characteristics of straw bales in building envelopes. Construction and Building Materials, 68, 135-141.

WIHAN, J. 2007. Humidity in straw bale walls and its effect on the decomposition of straw.

YIN, X., LAWRENCE, M. & MASKELL, D. 2018. Straw bale construction in northern China – Analysis of existing practices and recommendations for future development. Journal of Building Engineering, 18, 408-417.

ZHU, N. 2007. Effect of low initial C/N ratio on aerobic composting of swine manure with rice straw. Bioresource Technology, 98, 9-13.