A Systematic Review Of Thermal And Moisture Performance Of Straw-Bale Houses In Hot And Humid Climates

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Abstract: As architects and home-owners look for innovative ways to help reduce their carbon footprint in the campaign against climate change, straw bale could become a new tool in the building industry's armory. In order to bring this form of building into the mainstream sector, as well as benefit from its inherent low carbon and high insulation characteristics, it is necessary to guarantee the long-term durability of the straw. Sources of data included extensive literature search of relevant English language articles and the results of literature search of Elsevier Science Direct, ISI Web of Knowledge, ProQuest Central, Scopus, and Google. This study strives to make an exhaustive review of straw-bale performance in different climates and respective improvements from an energy efficiency perspective. This research revealed that when straw-bale buildings are constructed using the correct and specific technique, moisture and thermal intrusion did not seem to be detrimental to the health of the building regardless of the climate. Furthermore, building with straw can lead to low thermal transfer, relatively high thermal inertia and high moisture regulation capacity. The study concluded that, at a time when the importance of building sustainably is widely accepted, it would seem imperative that the potential of building systems like this that use renewable resources, readily available, and have low embodied energy, is further studied.

Keywords: Energy efficiency, Moisture Performance, Sustainability, Straw-Bale buildings.

1.0 Introduction

Building with Straw bale is not new. Straw-bale construction dates back to the 18th century in Nebraska, U.S.A; where ingenious home-builders erected insulated walls for their houses. Straw bale construction uses an agricultural waste product of baled straw from wheat, oats, barley, rice etc. in walls covered by stucco (Wheeler et al. 2004). Many of these buildings were erected with straw bales in form of "large blocks" and then plastered with a variety of finish to weather proof the building. Over time this became known as the 'Nebraska style', such buildings still exist till to date (Faine & Zhang, 2001). This technique for constructing walls has been recently revived as a low cost alternative for building highly insulating walls (Memari et al. 2015). Straw is the structural material that supports a plant, this fiber structure is composed up of cellulose strands bound in a matrix of lignin and hemicellulose (Summers et. al, 2003). Straw is a natural fiber that can last many thousands of years under certain conditions. For instance, in dry Egyptian tombs straw were found and also buried in layers of frozen glacial ice. However, under typical conditions as do all natural fiber materials like wood, paper, cotton fabric, etc. straw will slowly degrade. The rate at which this deterioration occurs is largely dependent on the conditions of storage, mostly temperature and moisture content. A straw bale house can survive as long as any conventional wood framed home, if proper attention to moisture control is given (Summers et. al, 2003). The use of straw for construction declined drastically when people turned to bricks and mortar. Unlike hay, straw has no nutritional value for livestock, hence mostly burnt or sold as bedding for farm animals. Furthermore, straw bale can be used in its raw state which requires no further processing; in contrast to other recycled materials (e.g. recycled plastics or car tyres) currently used in the building industry. The use of straw in buildings is often carbon-neutral as well as carbon-negative. Straw bale can be broken up and will naturally bio-degrade once the building is no more needed. In developed nations, a momentous portion of the energy is consumed by buildings. For example, about 39% of the total United States primary energy is consumed by buildings (U.S. Department of Energy; 2009). Equally, the building industry accounts for about 41% of energy usage in the United States (EPA 2013); as shown in Fig. 1. Similarly, in European Union about 37% (Pérez-Lombard et. al., 2008). More than 80% of energy consumption used occur during the building's operating stage, and contributes to risks of global warming (Azar & Menassa, 2011).

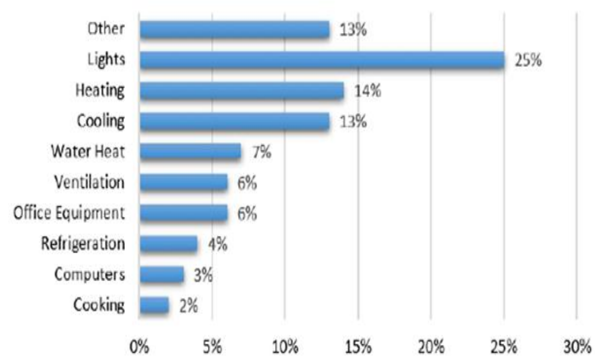

Fig. 1: *Buildings Share of U.S. Primary Energy Consumption (2006)*

These facts emphasizes on the imperative need for energy saving in buildings. Much of modern life is associated with buildings of some description; for living in, for working in, for cultural and sporting activities. The manner in which these buildings are constructed, the materials and processes that are used, and the resources that are required to keep them operating, has consequences for the sustainability of the environment. Straw-bale buildings are very demanding technically, and must be responsive to regional and local conditions, especially climatic ones. However, there are substantial environmental benefits in using non-toxic natural materials in creating highly insulated houses with low energy consumption.

1.2 Aim
The aim of this study is to review the performance of straw bale used as thermal and moisture insulation within the external envelope of buildings in different climates.

1.3 Research Question
1) Is there a future for 'natural' or 'alternative' building systems in the Construction Industry?
2) Do they have a role to play in the quest for more sustainable housing solutions?
3) Is straw-bale wall construction suitable for every climate?

1.4 Statement of Problem
The wasteful handling of straw not only deprives potential homeowners' access to affordable resources but also contributes to rising emission levels. In the 1990's in California for example, more than one million tonnes of rice straw was burned per year, producing an estimated 56,000 tonnes of carbon monoxide, which was twice as much that produced from all state powered plants. Similarly, in Australia, more than 600,000 tonnes of rice straw are burned each year; generating an estimated 30,000 tonnes of carbon monoxide and 2,000 PM into the atmosphere. However, straw bale buildings are proposed as one of the solutions to current building crisis; in the sense of adopting an agricultural waste material in providing affordable housing. Consequently, it is imperative to note that environmental and monetary costs would be largely reduced, not just by building with straw, but also creating an opportunity for low energy input, renewable, sustainable, non-toxic, re-used, recycled locally available products.

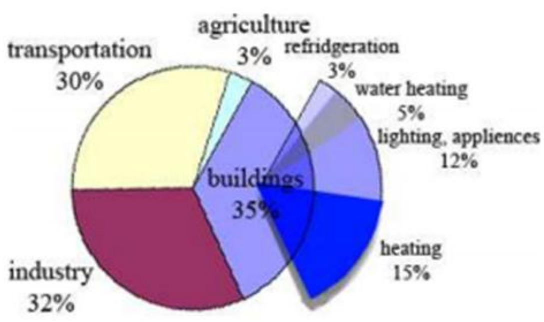

Fig. 2: *CO2 emissions generated by industrialized countries (Source: Price et al., 1999; Eia, 2005).*

The majority of carbon dioxide emitted by buildings comes from heating and cooling (Eia, 2005). Fig. 1 reveals that by changing existing building stock for highly insulated zero energy (passive) houses, a savings of about 15% of total CO2 emissions could be achieved.

1.5 Methodology
This review documents the thermal and moisture performance of straw-bale buildings in different climates with a particular focus on Hot and Humid Climates**.** To answer the research question under investigation, a review of literature was considered the appropriate method. In order to apply this technique, a review was undertaken between June, 2016 and December, 2016; which entailed searching many electronic databases. Sources of data comprised results from the literature search of Scopus, Elsevier Science Direct, Web of Knowledge, Google, and ProQuest Central using terms like 'straw-bale houses, affordable building materials, renewable building materials, performance of straw; as it relates to Hot and Humid climates as well as additional relevant terms adapted from the documents retrieved. Furthermore, reference lists of the retrieved articles were skimmed for further relevant materials and previous studies, which were significant in shaping the field under investigation. Reports of empirical studies from peer-reviewed journals were given priority. No form of restriction was given to article publication dates. In the analysis as suggested by several researchers, the data collection instrument utilizes criteria such as: authenticity; credibility; representativeness; and meaning; to appraise and elicit the eminence of the documents (Bryman, 2008; Macdonald, 2006; Mogalakwe, 2006; & Scott, 1990) Therefore, this paper used content analysis tools for qualitatively generated data, utilizing the four criteria of how: credible; authentic; meaningful; and representative; the various documents are in this study.

2.0 Straw-bale Wall System
A straw bale wall system can be seen as a composite assembly of elements that work together to resist lateral and gravity forces. The walls are plastered with lime, cement or an earthen plaster, depending on the site's environment (King 2006). The outer layers on each side are called render with the straw bale center; reinforcement mesh can be used within the rendered surface in order to increase its strength (Jones, 2002; King, 2006). It was observed that load-bearing straw bale walls with unreinforced render failed at lower loads than those that were reinforced (Ash et al. 2003). Generally the thicker the render, the higher the load that can be carried and the greater the protection offered from lateral load inducing hazards (Ash et al. 2004). However, Faine & Zhang (2002) compared the load-bearing capacity of earth-plastered and cement plastered straw bale walls. It shows that stucco facings and earth-plaster are much firmer than the straw bales. Hence, if the compression struts in the bales are to be utilized, the facings would have to degrade significantly under load reversals as in earthquake conditions. Though limited studies are available to identify fire and flooding hazards, however, it is reasonable to project that due to the material composition the straw bale wall system does not fare well in these conditions.

2.1 Straw-bale Performance
Straw bales have been used in the construction of buildings since the late 19th century (Jones, 2002; King, 2002; Steen, et. al, 1994). Over the last 20 years interest in the use of straw in mainstream construction has developed for a number of reasons; Straw has excellent thermal insulation properties (Cripps, et.al, 2004); Straw has excellent sound insulation properties (Dalmeijer, 2006); The production of straw is a low energy process compared with other building materials (Cripps, et.al, 2004); Straw sequesters carbon dioxide (CO2) by photosynthesis, thereby reducing atmospheric CO2 (Lawrence et al, 2009). Some straws like rice have a significant amount (up to 20%) of inorganic compounds such as silica ash that serve a structural as well

as pest resistance. However, after harvesting is done and the plant is dried, the fiber structure remains intact unless it is decomposed by biological or chemical mechanisms. It is in the interest of all straw bale builders and homeowners to try to prevent such conditions (Summers, et.al, 2003). Reducing energy needs should not be the only concern of designers, the use of straw bale walls and inside earth plaster combines low heating load with high thermal inertia and thus high comfort in summer and winter (Evrard, 2013).

2.1.1 Straw Bale Characteristics

Straw-bales have a monolithic layer of straw that is usually covered with plaster on the inside and stucco on the outside unless straw is placed between posts and beams where sheathing is then applied. When designed and detailed properly, a monolithic bale wall will result in little air leakage. This is due to the cellulose form in the straw that has high-quality insulating qualities that makes the straw-bale wall thermally resistant. Based on ASTM Testing by the Department of Energy (1995), R-values for these bales come between R-2.4 and R-3.0 per inch. Between the bottom of the bale wall and the foundation, an adequate waterproof barrier is necessary to stop any unwanted moisture. Moisture control can be a concern and must be accounted for. To help stop water from leaking through at the foundations, the building should have a layer of pea gravel between wood plates along the inside and outside faces (Goodhew et al. 2004). Dry rot fungus in a straw-bale wall system will cause significant damage when they sustain high levels of moisture, usually with humidity of 70-80 % or having 20 % of dry weight as compared to moisture that comes and goes at different intervals. From experience and tests, the best way to control the moisture content, is to make sure the bales can transpire the moisture back into the atmosphere. An air barrier such as building paper applied on the exterior wall sheathing can help transpire the moisture content outside and create a surface where the moisture can be inhibited. However, this solution may not be applicable to straw bale (e.g. the plaster sheathed type); rather breathable sealers are usually the best because they do not allow the moisture to get in through the stucco and permits to transpire moisture out. A mistake that the building permit reviewers commonly make is on requiring barriers such as plastic or tar-impregnated paper cover the bales. This will not allow the straw bales to breathe, i.e. to release water vapor. Instead, it will be trapped against the straw-plaster interface, damaging it because the structure system depends on a thorough attachment of plaster and straw (King 2006).

2.2 Thermal comfort in different climates

Urbanization is creating a phenomenon known as urban heat islands (UHIs) in tropical areas of Brazil. These are urban areas that has risen over the thermal comfort thresholds due to a large influx of people and comfortable drop range occurs during the rainy season. UHIs are caused by atmospheric and surface modifications from the overcrowding of people in an already hot climate (Da Silva, & de Azevedo, 2009). The issue of thermal comfort has been of great concern for people using mosques, in the hot humid region of Saudi Arabia. There are very large open buildings that are used only intermittently making it difficult to properly ventilate them. In new designs, ventilation systems have been placed lower in the buildings to provide for more temperature control at ground level. In addition, new monitoring measures are being taken to enhance its efficiency (Al-Homoud, et.al, 2009). The cold winters and hot humid summers experienced in China are causing a demand for more efficient thermal comfort. In the last decade, energy conservation in relation to thermal comfort has become a big issue there due to rapid population and economic growth. Several researches are seeking alternative ways to heat and cool buildings for affordable costs as well as zero harm to the environment (Yu, & Changzhi, 2009).

2.3 Improving indoor climate

Individuals generally spend most of their time in enclosed spaces in moderate to cold climates (EPA 2009). Hence, indoor climate becomes a crucial element in general well-being. Comfort determined by the radiation, humidity, movement, temperature to and from surrounding objects as well as pollution content of the air in a given indoor environment. Inhabitants express concerns when room temperature becomes too low or too high. However, the negative implications of excessively reduced or elevated humidity levels are not common knowledge. Air humidity in in-door environments has a substantial impact on the health of occupants (Minke, 2012).

2.3.1 Air humidity and health

According to Grandjean (1972) and Becker (1986) a relative humidity lower than 40% within a long period of time can dry out the mucous membrane, as well as reduce resistance to colds and related illnesses. This happens primarily because the mucous membrane of the epithelial tissue within the trachea absorbs bacteria, viruses, dust, etc. and transmits them to the mouth by the wavelike movement of the epithelial hair. Consequently, if this transportation and absorption system is altered by drying, then foreign bodies could get to the lungs and create health challenges. However, an elevated relative humidity around 70% has several positive benefits such as; it lowers the fine dust content of the air; triggers the protection mechanisms against microbes by the skin; shrinks the life of many viruses and bacteria; and decreases odour and static charge on the surfaces of objects in the contained space. Relative humidity of above 70% is usually deemed as unpleasant, possibly because of the reduced oxygen intake by the blood in warm-humid environments. Increased rheumatic pains are experienced in cold humid air. Formation of fungus increases significantly in enclosed spaces when the humidity rises more than 70% or 80%. Similarly, various kinds of pain and allergies are observed when fungus spores in large quantities. Consequently, it follows that the humidity content of a room should range between 40% and 70%.

2.3.2 Effect of air exchange on air humidity

In cold and moderate climates, at periods when the indoor temperatures are much higher than outdoor temperatures, the higher degree of fresh air exchange could make indoor air so dry resulting in negative health effects. For instance, the outdoor air with a temperature of let's say between 0°C and 60% relative humidity finds its way into a room and is heated to 20°C, its relative humidity reduces lower than

20%. Moreover, if the outdoor air (temperature 0°C) has 100% humidity level and is heated up to about 20°C, its relative humidity would also reduce to less than 30%. Therefore, in both instances, it is of importance to raise the humidity in order to achieve comfortable and healthy conditions. This can be achieved by regulating the humidity that is released by ceilings, walls, furniture and floors (Minke, 2012).

2.4 Moisture and Temperature Testing

The amount of nutrients and the availability of oxygen are not parameters that will change once a straw bale has been placed inside a wall. However, depending on the outdoor climate temperature and moisture of indoor conditions will fluctuate, as well as accidental entry of liquid moisture. Of key interest to straw bale builders is what effect different moisture and temperature regimes will have on the degradation of straw contained within a wall (Summers, et.al, 2003).

2.4.1 Moisture Management in Straw Bale Houses

One major challenge for straw bale builders is; what moisture levels should be of concern, and in addition, how should it be handled when detected. However, all sources of moisture must be put into consideration be it external such as flood, rain, fog, humidity, mist, etc, in addition to internally generated moisture from bathing, cooking, condensation, respiration, washing, etc), as well as the dynamic movement of water vapour within and through the straw-bale wall, cladding system and surface coatings. Furthermore, bales with bulk moisture content less than 25% dry basis (20% wet basis) should be used in wall systems. Conversely, this measure would help ensure that no free moisture is added to the system and the moisture levels are less than necessary for microorganism growth. However, if bales get wet during transportation or storage, it must be ensured that they are dried out sufficiently before using them in walls. Moreover, it requires the use of a testing core samples or moisture probe, because bale surface can appear dry while significant moisture level is still contained in it. When placed in the wall, drying will be inhibited by the wall treatments.

2.5 Impact of Climate on a Bale House

Inarguably, local climates have large effects on buildings, irrespective of bale house or concrete block. In fact, the climate is often a driving force in people's decision to build with bales. House owners often complain about how hot their climate is or how cold it is and how if they only had a more efficient home, they could better stand the extremes. Unfortunately, some people decide to build a straw bale house before they consider the potential affects that their climate could have on it. It's important to understand the Impact of climate on bale walls.

2.5.1 Rain

This can saturate walls if they are not properly protected. A good roof overhang and a large raised foundation are two very good ideas in areas with high rainfalls. In addition, using a waterproof membrane above the bales, just below the bale stop or box beam. The challenge is in avoiding punctures of this membrane during construction. Hence, ensuring it laps over the edge of the bales a couple inches because too little overlap would allow water to penetrate into the bales.

2.5.2 Humidity

In contrast to rain, humidity permeates everywhere and it can cause moisture to build up in the walls if not properly handled. Hygroscopic plaster such as earth or lime can naturally keep a constant moisture level in the wall. If there is excess moisture in the air, absorption takes place until it reaches saturation. As soon as the air dries below the level of what the plaster is holding, the plaster releases the excess moisture back into the air.

2.5.3 Cold

Weather has several types of impacts. Many are often overlooked like the condensation of moisture in the walls. Cold climates require the heating of the indoor air space to sustain warm, thereby, creating uneven climates from one side of a wall to the other that are quite drastic. When the warm and moisture laden air in the house pushes into the center of the bale wall where everything is cold, the moisture condenses on the straw. The best approach to this predicament is to seal any penetrations into the wall and seams between the wall and other surfaces. The most observed areas are around plumbing and electrical installations as well as the wall to ceiling and floor to wall transitions.

2.5.4 Hot

Hot climates that are associated with high humidity and should be approached in line with humid conditions as explained above. Nevertheless, dry climates have a different set of concerns. The life of the plaster is often not considered. Moreover, natural plasters are not built with chemicals designed to help them resist cracking and thus must be installed carefully. Hence, plastering should be carried out only when the house is protected.

3.0 Findings and Discussions

3.1 Moisture Performance and Durability

Moisture seems to be one of the major factors affecting building enclosure performance and durability. Moisture encourages most common performance problems such as dissolution, rot, staining, corrosion, mould growth, freeze-thaw damage, swelling and cracking. In straw-bale buildings the potential moisture-related concerns are rot of the wood components, mould growth, and corrosion of steel. Different materials have different moisture performance thresholds, for instance, steel corrosion occurs as a function of its time of wetness that is the number of hours per year is it damp and the acid content of the vapour (from industry), the salt content of the vapour (e.g. from the ocean or deicing salts), and the temperature (the warmer the faster corrosion occurs). Corrosion starts at a surface relative humidity above 80%RH. Similarly, mould growth on straw and wood occurs when exposed to prolonged periods of over 80%RH (about 20% moisture content). Wood can rot when exposed to over 95%RH or liquid water for several months at warm temperatures. It is common knowledge that wood cannot rot below 28 to 30% moisture content. Equally, it is supposed that straw cannot rot at slightly lower moisture content due to its much higher surface area. Furthermore, for a moisture-based problem to occur at least the following four conditions must be met, such as; there must exist a moisture source; there must be a channel for moisture to permeate; there must be a driving force to cause moisture movement, and finally, the materials must be vulnerable to moisture harm. However, in theory to avoid moisture problems eliminate any one of these four conditions. Though, in reality, it is not practically and/or economically possible to eliminate all sources of moisture. Hence, moisture control and plummeting the risk of failure by judicious design, assembly and choice of material should be an approach taken in the design of durable building enclosures.

3.2 The Moisture Balance

Moisture-related problems are unlikely if a balance between wetting and drying is achieved, moisture cannot accumulate over time. A summary of the main sources and sinks of moisture and the transport mechanisms associated with moisture movement in straw-bale walls (Fig 3 & 4) are as follows;

Wetting: The three main moisture source for straw-bale buildings are; condensation of water vapour transported by air movement and/or diffusion through the wall; precipitation, particularly driving rain, both by capillary absorption and penetration; built-in and stored moisture.

Condensation: Condensation of the water vapour in infiltrating air during hot-humid conditions or exfiltrating air during cold weather can deposit substantial amount of water within a wall. Although diffusion wetting is not a powerful wetting mechanism, nevertheless, diffusion is a major means of moisture movement between stucco layers and straw in straw-bale walls.

Wicking and splashing: from the ground can be a problem for walls close to grade. However, it can be controlled with the use of flashing, good eaves trough, well-drained soils, and site drainage, etc.

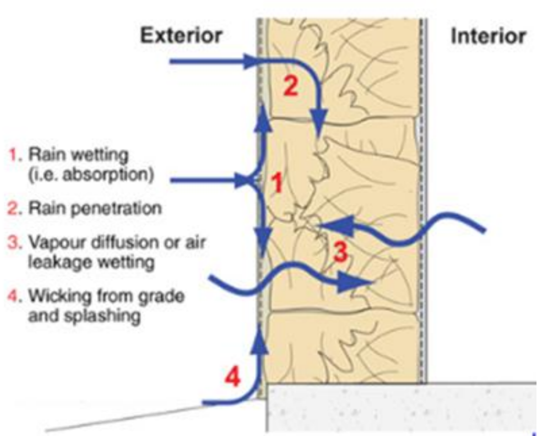

Fig 3: *Wetting mechanisms in straw-bale walls*

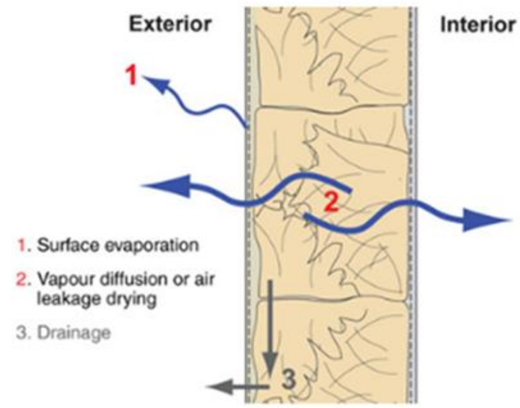

Fig 4: *Drying mechanisms in straw-bale walls*

4.0 Conclusion

Moisture-based concerns (e.g. the need for air, vapour, and rain control) can be satisfied. This in no way implies that all straw-bale houses are necessarily performing and durable. High performance and durability is very much dependent on the construction details deployed and the exposure of the environment. In cold or hot-humid climates, rain control is of major concern; hence air barrier systems must be put in place. Furthermore, vapour diffusion control can be achieved in cold climate walls of a standard cement-stucco straw-bale house with interior painted stucco (with a permeance of no more than about 300 metric perms). Conversely, insulation seems to be an energetically cost-effective approach for the provision of thermal comfort with a minimal investment of total non-renewable energy. In summary, ecological and sustainability issues are increasingly at the forefront of discussions in the context of architecture. The use of straw-bale as a building material in the industrial age has never been widely seen to represent progress. Haven studied the relevant performance criteria of straw-bale houses as well as bale as a building material. Hence, I assert that straw-bale wall systems can provide high thermal insulation, air tightness, moisture control, indoor air quality and durability as well as load bearing strength in any climate zone. If no mechanical devices and few rendering are used, straw-bale offers the lowest embodied energy construction. Newly developed and successfully tested straw-bale construction techniques are being exploited, adapted and implemented in the developed nations.

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