PhD Synopsis: Quantifying and Evaluating the Risk Posed to Straw Bale Constructions from Moisture

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Abstract

This paper provides a synopsis of the PhD thesis titled 'Quantifying and Evaluating the Risk Posed to Straw Bale Constructions From Moisture'. The thesis reviews the potential for straw bale construction to aid the construction industry in reducing carbon emissions whilst promoting social and environmental values, and decreasing the reliance on non-renewable resources. Straw is however susceptible to degradation, under certain conditions. The thesis reviews different monitoring devices and the interaction of moisture with straw and presents a three part model aimed at promoting confidence in the construction method.

Key Words: *Straw Bale, Sustainable Construction, Moisture, Modeling.*

1. INTRODUCTION

The Kyoto Protocol, an international agreement adopted in 1997 by 37 countries committed to reducing greenhouse gas (GHG) emissions, has focused the world's attention on harmful atmosphere emissions. 47% of all carbon dioxide (CO_2) emissions in the UK are attributed to the construction industry (BIS 2010) and 27% originate from housing; 73% of which comes from heating space and water alone (Moore et al. 2007). Therefore, by designing housing to be more energy efficient, and striving to achieve greater sustainability in the construction industry, reductions in GHG emissions can be made.

Straw bales construction offers a means by which to provide energy efficient buildings whilst providing a sustainable method of construction; utilising a natural material that can be locally sourced, that has a low embodied energy, and a natural life cycle, combined with low thermal conductivity values of between 0.055-0.065 W/mK (Sutton et al. 2011).
The main concern regarding straw bale construction is with moisture ingress and the risk of microbial activity decomposing the material. This paper provides a synopsis of the Ph.D. thesis titled 'Quantifying and Evaluating the Risk Posed to Straw Bale Constructions from Moisture' (Robinson, 2014) which began by laying out aims and objectives:

- “To confirm the point at which moisture becomes an issue to the straw”, (Robinson, 2014)
- To assess different monitoring devices,
- To describe the interaction of moisture with straw, and
- To produce “a visual identification system and model to promote confidence in different monitoring techniques”.

2. POPULATION IMPACT

Human populations are set to rise, globally, from 6.1 billion in 2000 to 9.22 billion in 2075 (UN 2004), placing additional pressure on the built environment, ecosystem services, pollution reduction initiatives, and resource acquisition. Furedi (1997) suggests that vital resources will run out because at some point in the future technological improvements will be unable to support the growing population. The UK will require the construction of around 240,000 new houses per year until 2026 (NHPAU 2007) to house the increasing population, and new-build developments will also be required to be carbon zero from 2016 onward. Housing is therefore required to be more energy efficient, sustainable, adequate for future needs of the population, and rely less on non-renewable resources.

2.1 Straw as a resource

Straw is an annually grown renewable resource and a potential carbon store but is also seen as a byproduct of the agricultural industry. Harvested from rye, oats, barley, rice or wheat, straw has been used in construction as a thatching material, and as a composite to improve the tensile strengths of bricks and renders (Lacinski, 2000) for thousands of years. Yet, it is the grain that is the valuable resource and has, throughout human civilisation, been closely linked with nutrition (Evans et al. 1981, p.149). Watson (2010) estimates that the UK has a surplus four million tonnes of straw each year, enough to produce 450,000 new houses, of 150m^2 (Bigland-Pritchard and Pitts 2006). Baled straw's low thermal conductivity has the potential to increase energy efficiency of walls thereby reducing the dependence for space heating, and reducing the negative effects of transportation associated with the construction industry; if the material is locally sourced.

2.2 Straw Bale Construction

There are two basic forms of straw bale construction:

- 'Nebraskan style' involving the unsupported stacking of bales to form walls, developed in Nebraska, USA; also referred to as load-bearing, and
- Non-load bearing: a framework is constructed and the bales are used as an infill material.

In the construction of straw bale buildings, unskilled labour has been employed around the world, addressing social concerns through inclusion and participation, appealing to a “sense of belonging and a connection to place” (Bigland-Pritchard and Pitts 2006. pp. 374). The Ecovillages and Sustainable Communities Conference, 1994, concluded that communities require highly developed social skills, encompassing consideration for the ecosystem, built environment, economics and government, and group visions supporting the health of residents. Straw bale constructions can be erected with little prior construction knowledge or experience, although it is advised that at least one skilled person on-site. The construction method can also form part of an educational tool offering people a mechanism to reconnect with nature and decrease the impact of the negative influences of the built environment on fundamental ecosystem services.

2.3 Problems with Straw

Straw bales are not standardised and can vary by up to ±7.2% in size, ±25.1% in weight and ±21% in density (Carfrae et al. 2011) leading to the analogical term 'fuzzy building blocks'.

The lack of standardisation is not generally an issue as the material is easy to work with and can be shaped using rudimentary tools; hedge trimmers and mallets for example. The presence of moisture in elevated levels however, is a problem; given the correct conditions micro-organism will break organic material down. Other issues including fire resistance, vermin resistance and structural performance are reviewed by Lawrence et al. (2009). Moisture together with optimum temperatures between 20^{o}C and 28^{o}C (Jolly, 2000) are required for the degradation yet, if the straw is protected from moisture, by render, cladding or topography, the risk of decay can be decreased. A potential question is therefore; at what moisture content is straw susceptible to decay?

Figure 5 illustrates the uncertainty surrounding the issue of moisture and temperature; the majority of the literature agree that moisture contents of 15% and below render the straw safe from decay. Straw with moisture contents exceeding 25%, Lawrence (2009) suggests, are at risk of degradation, with Goodhew (2010) providing evidence to suggest straw held at up to 37% for short periods of time was undamaged. Moisture contents between 20 and 25% are rarely commented on in literature but, under certain conditions may be assumed to be at risk.

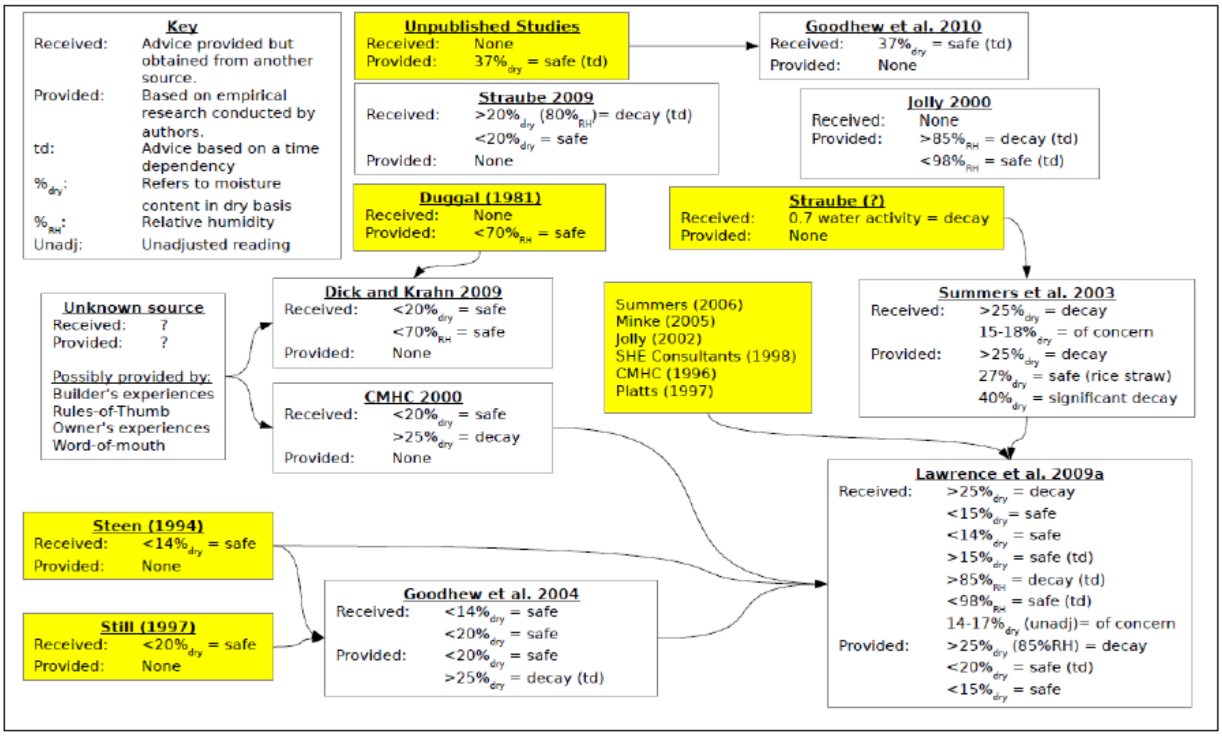

Figure 5. Risks posed to straw from moisture and temperature (Robinson, 2014)

In conclusion the literature is unclear, different experiments and observation providing differing results. The thesis identified the issue of uncertainty and sought to provide a model to address it.

3. METHODOLOGICAL APPROACH

The thesis identified six main research questions based upon the literature review concerning the interpretation of monitoring device measurements, risk posed to straw from moisture, definition of the term 'risk', defining moisture's interaction with straw, and describing the way in which moisture is transferred through a bale. This sections reviews the main findings and observations concerning monitoring methods together with the development of the model.

3.1 Monitoring Methods

In order to gauge the moisture content of straw established monitoring methods were tested, assessing limitations and accuracy of the data.

3.2 **Gravimetric Analysis**

A destructive form of analysis in the field; involving the removal and weighing of a sample of straw from a wall, placing it in an oven at 105°C until a constant mass is achieved. The difference between the masses equates to the moisture content.

3.2.1 Resistance Meters

Resistance meters convert the resistance of a material to an equivalent moisture reading, but results vary in accordance with the material's dialetric properties and temperature.

Figure 6 Timbermaster, Balemaster, Balemaster Probe, Digital Thermometer and Thermocouple (Robinson, 2014)

Figure 2 illustrates the Timbermater and Balemaster meters with the Bale master probe which is inserted into a bale and linked to either of the meters to provide a moisture reading. During the study it was discovered that the meters relay the straw surface moisture level only, and require additional compensation for density and temperature. The thesis provides equations to correct for errors concerning straw.

3.2.2 Wood-Block Probes

Wood-block probes (Figure 3) offer a simple, cheap and robust method of monitoring the moisture content of straw and can be used in conjunction with resistance meters. However, using wood-block probes assumes that timber reflects the same moisture values as straw due to the organic nature.

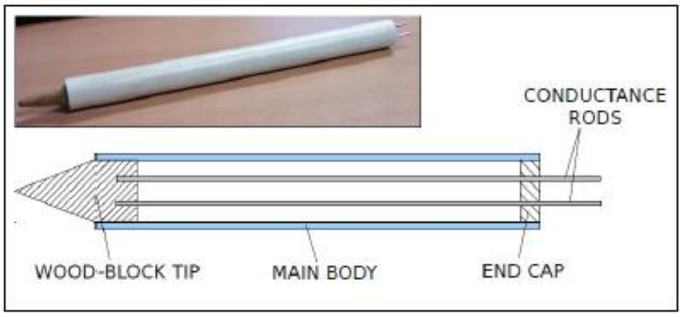

Figure 7 Wood-Block Probe (Robinson, 2014)

Laboratory experiments and field trials, conducted during the research programme, demonstrated a time lag under rapidly rising moisture regimes when compared to straw. Other identified issues included maintaining effective electrical contact between the wood-block tip and the conductance rods, and correcting the resistance meter reading for temperature.

3.2.3 Relative Humidity Sensors and Isothermal Studies

Relative humidity sensors analyse the amount of moisture in the surrounding atmosphere for a given temperature. In conjunction with Isothermal Studies, a relative humidity reading can be converted into an equivalent moisture content. Field trials and laboratory experiments conducted during the research programme demonstrated that in dynamic environment's however, the relative humidity of a bale is not directly related to the moisture content of the straw.

3.2.4 Isopleth Studies

Humidity sensors can also be used in conjunction with Isopleth Studies. Isopleth Studies use the relationship between temperature and humidity to predict mycellium growth (Figure 4) and spore germination times (Figure 5) of mould species.

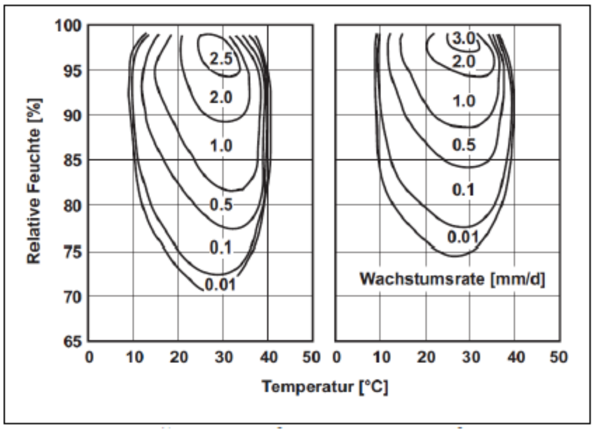

Figure 8 Mycelium development (Wieland 2004)

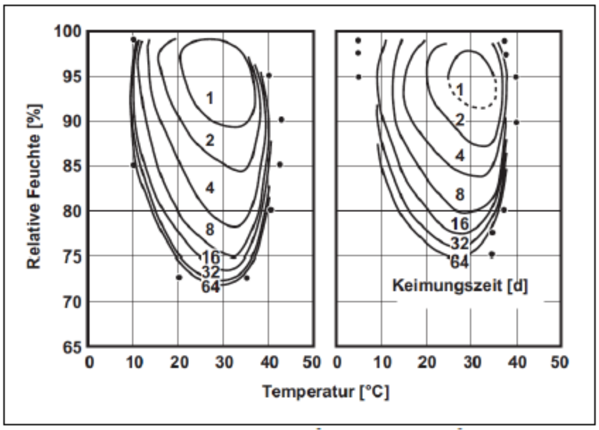

Figure 9 Germination of spores (Wieland 2004)

The isopleth diagrams can be used to predict the development of mould, but it is important to note that Figure 8 and 3 were produced with two highly xerophilic moulds. Isopleth studies "overpredict mould growth" (Bronsema, 2010, pp.45) and therefore, offer a worst case scenario yet, the diagrams and data can be used as an early warning system within a model.

3.2.5 Compressed Straw Probes

The Compressed Straw Probe (Figure 6) was designed to address the weaknesses inherent in other monitoring methods and aimed to be a “cheap, robust, easy to use and install, reliable and accurate way to assess the moisture content of a bale” (Robinson, 2014).

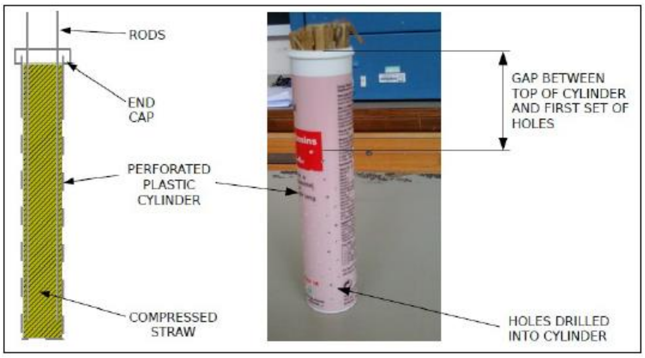

Figure 10 Compressed straw probe Prototype 01 (Robinson, 2014)

The benefit of the compressed straw probe was in the ability to obtain a moisture content results based on multiple measurement methods; gravimetric analysis, and resistance meter readings. The probe also has the advantage of visual and olfactory inspection of the straw, as the probe can be removed from the wall and inspected for signs of degradation; noting changes in colour and smell.

3.3 Models

To quantify and evaluate the risk posed to a straw bale construction from moisture the development of a model was required.

3.3.1 Contour Plots

In order to portray the results of the moisture monitoring devices used during the experimentation phases, a contour plot was developed (Figure 7).

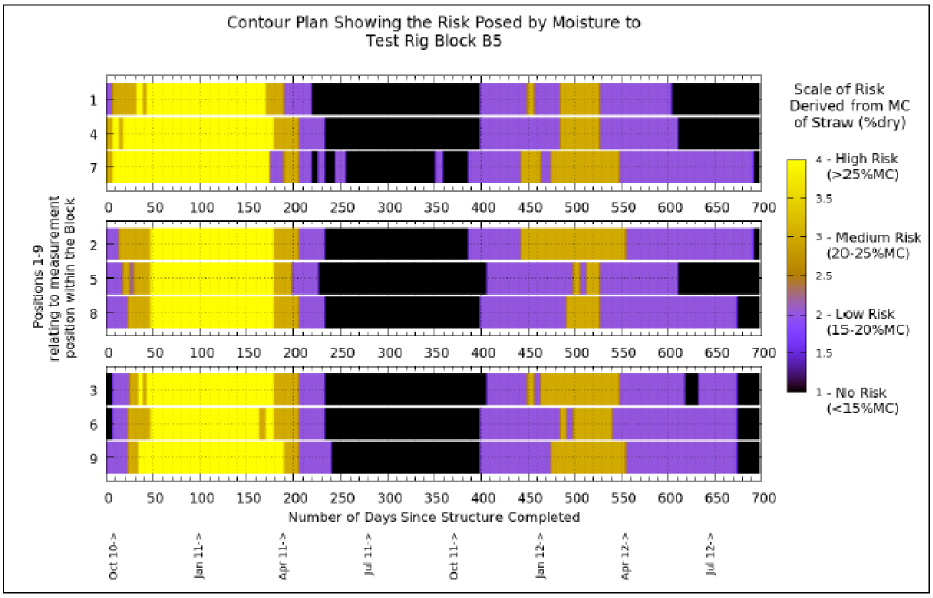

Figure 11 Contour plot showing Test Rig results (Robinson, 2014)

The plot utilises a simple traffic light system as a visual indicator to the risk posed to the straw in a wall. The plot illustrates three sections of wall, each with three monitoring devices along the y-axis. The x-axis shows the date, the z-axis represents associated risk. From Figure 7 it is possible to evaluate the risk posed to the straw; in January 2011 (day 100) all positions show high moisture values which drop to safe values (No Risk) in June 2011 (day 250). The plot provides a quick visual representation of the risk however, it does not provide detailed analysis of the wall as the traffic light system is too simplistic.

3.3.2 Fuzzy Risk Assessment

In developing a model to describe the risk posed to straw from moisture a simple traffic light system combined with fuzzy logic was devised (Figure 8).

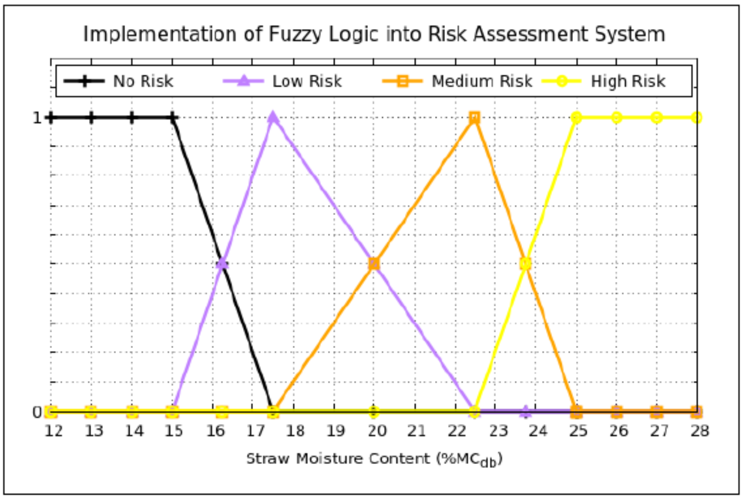

Figure 12 Implementing Fuzzy Risk Assessment System (Robinson, 2014)

The graph shows moisture content along the x-axis and a probability decision along the y-axis. The graph allows a more informed judgment to be made by utilising descriptive language (where 'MC' relates to moisture content); “It is generally accepted that readings of below 15%MC are safe from decay, but it is more informative to say that a reading of 19%MC is quite concerning (70% Low Risk) and a little unsafe (30% Medium Risk).” (Robinson, 2014). The fuzzy risk assessment system and contour plot form only two parts of an overall model, as no provision for temperature is given.

3.3.3 **Main Model**

The main model (Figure 9) relies on the collection and correct interpretation of data from single or multiple monitoring devices to make an informed decision as to the risk posed to straw. The flow diagram offers advise based on the associated risk.

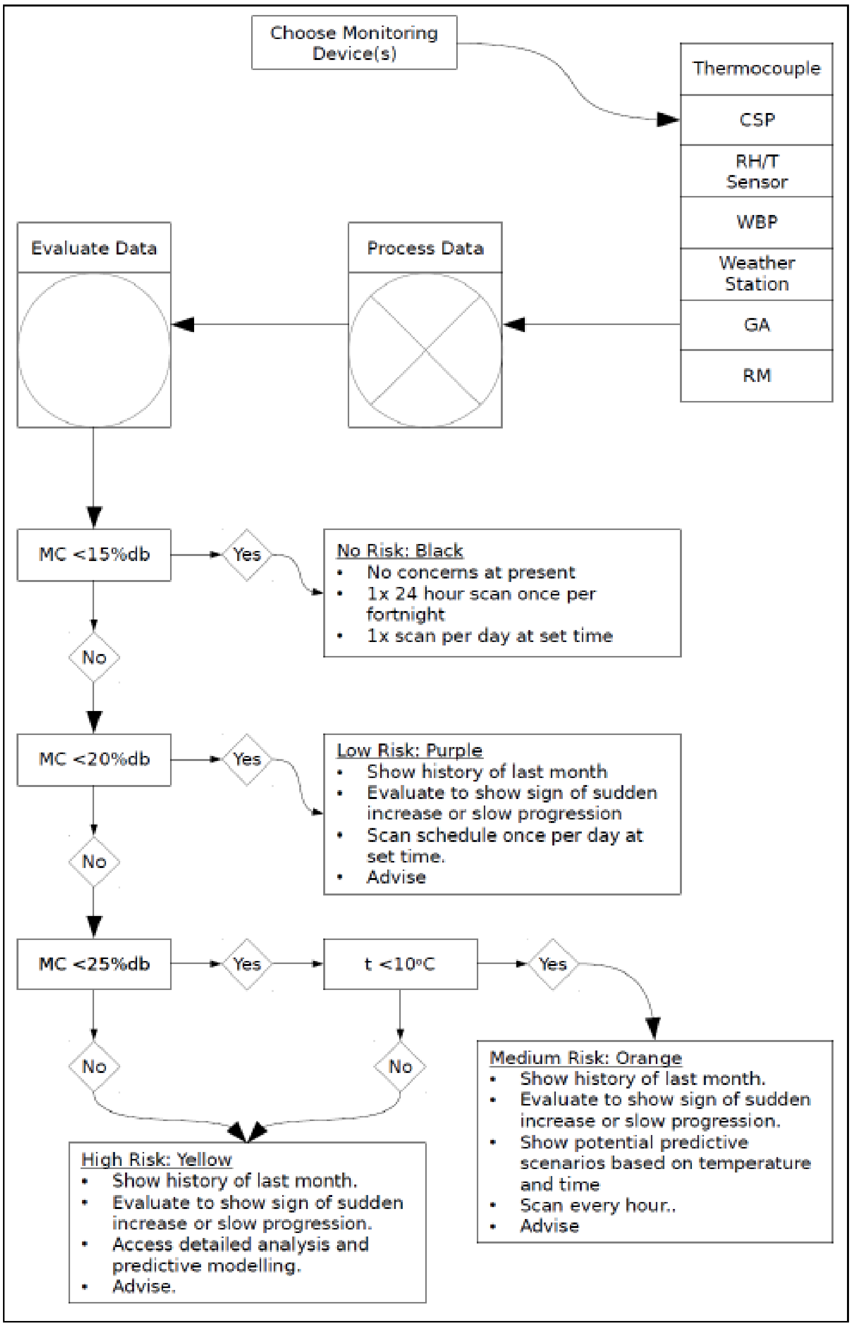

Figure 13 Main Model (Robinson, 2014)

4. CONCLUSIONS AND RECOMMENDATIONS

The Ph.D. research sought to "Quantify and Evaluate the Risk Posed to Straw Bale Construction from moisture". The thesis provides a model to explain the risk posed to straw from moisture by way of the Fuzzy Risk Assessment System (Figure 8) and evaluates the strengths of each monitoring device leading to the development of the Compressed Straw Probe (Figure 6). The interaction of moisture with straw is explained within the thesis and is based on field and laboratory experiments. Finally the contour plot and main model offer a visual identification system, and utilising descriptive terminology can advise on the risk posed to a construction.

The thesis concludes, stating that although straw bale construction is not an established method of construction, it is sustainable, provides a method of carbon capture, can reduce the negative impact of material transportation, contains no inherent toxic elements, is widely available, and has a low thermal conductivity. Therefore, the model and definition of the monitoring methods promote confidence in the construction method and if straw bale construction was to be accepted as a main stream method it would help increase building energy efficiencies and therefore reduce CO_2 emissions.

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