

THERMAL PERFORMANCE OF THREE DIFFERENT STRAWBALE BUILDINGS AT THE KERKENES ECO-CENTER

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ABSTRACT

By and large, straw is not considered to be a building material, yet in comparison with traditional materials, building with straw bales is definitely more energy-efficient, eco-friendly, and low-cost; qualities that are desirable in sustainable buildings. This paper presents information on three different straw bales buildings at the Kerkenes Eco-Center, which is located in the village of Sahmuratli in central Anatolia, Turkey. The first of these was constructed with load-bearing straw bale walls; the second with straw bales as infill in a timber-frame structure; while the third utilized straw bales in combination with Autoclave Aerated Concrete (AAC) blocks. This last was a hybrid wall construction that has been tried for the first time to take advantage of the thermal-insulation property of straw combined with the humidity-regulating property of mud plaster inside and the weather-resistance property of AAC outside. These three buildings are being monitored for their temperature and humidity variances with the help of data loggers; this data is also presented herein.

KEYWORDS

strawbale building, eco-center, innovative wall, thermal comfort, greenhouse

1. INTRODUCTION: BUILDING WITH STRAWBALES

The mention of straw as a building material evokes images of fragility, instability and impermanence—a throwback to the childhood fairytale about the three little pigs and their house of straw. Yet straw bale buildings can last for a very long time if the right techniques are used in their construction; there are many examples of even century old straw bale houses that are still in use. For instance, the Burke home in Alliance, Nebraska was built in 1903 and though it was not maintained diligently after 1950, it was still in good condition when tested in 1993; other old straw bale houses, also from Nebraska, that are worth mentioning are the Simonton family home built in 1908, the Martin/Monhart house built in 1925 and the Scott house built in 1935 (Corum 2005). Despite these living examples, straw is still being wasted worldwide. In the USA alone 200 million tons of straw are either under-utilized or wasted, whereas this waste material can be used to construct 4 to 5 million houses every year, each measuring 2000 sq.ft (185 m²) (US DOE 1995).

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Straw bale buildings can be constructed in two ways: as load-bearing structures or non-load-bearing ones. In load-bearing structures, the stability of the straw bale walls is achieved by using vertical wooden stakes or iron rods pinned through the bales and aligning them between wooden floor- and roof-plates. In non-load bearing walls the bales are used as infill material in a timber frame structure. Chiras (2000) points out that load-bearing straw bale structures are extremely strong; they can support compressive loads of 10,000lbs/sq.ft (5.1 kg/cm²) and can resist lateral loads of 100 miles /hr wind forces, as well as earthquake loads.

Further, tests conducted on plastered straw bales have shown that nearly all types of bales tested had higher strengths than required in a typical residential construction (Vardy & MacDougall, 2006). A two-string bale wall which is usually 17" (43cm) thick can be built up to a height of 8'-4" (2.54m), while a three-string bale which is 23-24" (59-61cms) thick can be built up to a height of 10'-8" (3.25m). In order to increase the stability of the straw bale walls, the structure is composed of a braced wooden frame that is anchored to a stone, rubble, or concrete foundation while the bales are used as infill material (Chiras 2000).

Straw can also be used for roof cover, or as a thermal insulation material due to its high thermal resistance values. Lacinski and Bergeron (2000) inform us that tests conducted at the Oak Ridge National Lab of Tennessee have determined the R value of a bale laid flat to be 1.45 per inch, which translates into R-26 for a 2-string bale and R-33.5 for a 3-string bale. Similarly, tests conducted at the California Energy Commission facilities have determined the R-value of a bale laid on edge to be 2.06/inch, which is equivalent to R-29 for 2-string bales and R-33 for 3-string bales; while that for a plastered straw bale wall was found to be R-30 (Stone, 2003). On the other hand, the US Department of Energy (DOE 1995) gives the R-value of plastered straw-bale walls to be R-50 and the U-value of 23" straw bale as 0.014 to 0.023 BTU/hr ft² °F (0.08 to 0.13 W/m² °C). Naturally, the higher the thermal resistance of the building envelope the more energy efficient it will be.

Many authors (Ashour *et al.* 2011; Walker 2007; Wang and Zhang 2005; Gharaibeh *et al.* 2009; Garas *et al.* 2009b; Swan *et al.* 2011; Chiras 2000; and Corum 2005) agree that straw bale buildings are not only energy efficient due to the super insulating properties of this material; but they are also very low-cost to build. Garas *et al.* (2009b) compared the costs of a load bearing wall unit built with locally produced rice straw bales to one built with cement bricks, and found that not only does a straw bale house cost 40% less to construct, but it also generates further savings in terms of energy consumption and thermal insulation. Wang and Zhang (2005) have also found straw bale buildings to be more energy efficient than brick-masonry ones; they state that the energy required to heat a straw bale building is 60% less than that in a comparable brick-masonry building. Similarly, Gharaibeh *et al.* (2009) have conducted a comparative study in New Mexico, which shows that a straw bale house consumed 25% less energy compared to a conventional house in its neighborhood; this translates into a saving of \$194.28 per annum on the energy bills of each household. According to the authors, the amount of energy saved per annum is 5.868 million BTU (*i.e.* 1,720 kWh /year); hence, the cost of energy is calculated to be 0.113 \$/kWh.

Environmental sustainability is achieved not only by producing energy efficient buildings but also by using local and renewable materials. Buying locally manufactured material helps to reduce carbon emissions and the energy used in transportation while renewable materials are desirable from the life cycle point of view, as they do not cause pollution or hazards when they are disposed of (Goodhew *et al.* 2004). Sodagar *et al.* (2011) examined the role of straw bale as a construction material for reducing the life cycle impacts of housing, and found that

compared to conventional wall construction the whole-life embodied and operational CO₂ emissions are reduced by 61% over its 60-year design life. Another advantage is that the embodied energy required to produce 1 ton of straw is only 112,500 BTU (32.95 KW) as opposed to 5,800,000 BTU (1700 KW) for 1 ton of concrete; moreover, straw bale buildings need 30 times less energy than one using standard timber-frame drywall construction (Chiras 2000).

Straw bale construction is also seen as a fire hazard since straw is flammable; however, when it is baled and plastered it becomes fire resistant to a great extent. Lacinski and Bergeron (2000) have described an experiment that was carried out to establish the fire rating of straw bales in California. It was observed that when an un-plastered straw bale wall was exposed to fire on one side, the flames took 34 minutes to work through a seam between the bales. Hence, the fire-rating of these straw bales was declared to be half an hour at 921°C; even though it may be taken as 1 hour since the fire had not engulfed the bales. It was also observed that when the straw bale wall was protected with cement plaster on the inside and gypsum on the outside, the result was even more reassuring. After 2 hours of exposure to fire on the outside, the straw was charred to a depth of 5 cm only, and though the temperature on the outside surface had risen to 1060°C the inside surface temperature barely reached 21°C. This test underscores the high thermal insulation property of straw bales.

In experiments conducted by Garas *et al.* (2009a) plastered straw bales were subjected to direct flame for 2 hours but the bales resisted fire penetration and the amount of heat transferred to the other side raised the surface temperature by 5°C only. In another experiment, by Apte *et al.* (2008), plastered straw bales were subjected to radiant heat flux of 30kW/m² for 30 minutes but they remained unaffected. However, when the flux was increased to 50kW/m² for 40 minutes combustion started in the straw bale after 24 hours and it took 11 days to burn out the bale completely.

All the above mentioned studies have established the fact that houses made of straw bales are healthy; consume very little energy to build or to maintain thermal stability; use less timber and concrete than conventional timber/concrete structures; and if plastered and sealed against moisture and rodents, they are very durable and fireproof. Chiras (2000) summarizes the advantages of using straw bales, as follows:

- Straw bales are obtained from a renewable source;
- have low embodied energy and zero emissions;
- are bio-degradable and eco-friendly;
- do not require specialized labor or hi-tech machinery and equipment to build.

The main disadvantage of straw bale construction is that straw is highly susceptible to water and when exposed, it starts to deteriorate and rot. Consequently, keeping water off the surface of a straw bale wall and maintaining moisture control within the bales is very important. One way to provide a waterproof finish is to plaster the bales, as the plaster acts as a weather and air barrier and provides fire protection and rodent as well as insect control (Straube 2011).

However, the mud plaster that is conventionally used to render straw bale walls is susceptible to speedy deterioration in wet or humid weather conditions. Consequently, there arises the need to maintain such plaster diligently and periodically otherwise water seepage into the bales or moisture build-up will cause the straw to rot in the wall. The hazards of water-seepage and moisture-retention can also be overcome if the straw bale walls are protected further with overhangs; built higher than grade level; provided with waterproofing between the plinth and

the first course; plastered with material that can breathe; and the foundations are built with stone, rubble or concrete (Thomas 2008). If these preventive measures are taken right from the start, the moisture content in straw bales can be kept below the critical level of 15% of their weight; and they will not rot.

Straw bales are also associated with insects and rodents but these creatures need food grain to survive. Since the bales (especially of wheat straw) are made of the stalks left after threshing, no grains are left behind to attract insects or rodents.

Despite their many advantages straw bales are not widely accepted as an alternative building material because only select building codes in North America allow their use in building construction (Swan *et al.* 2011). On the other hand, Corum (2005) claims that straw bale construction is viable for code compliance in the USA. Similarly, Desborough and Samant (2009) point out that straw bale houses are feasible in terms of compliance with the UK building regulations and UK's climate; and that straw bale is also being promoted for compliance with the building codes in Canada. In Turkey, straw bale construction is a very new concept and the total number of known straw bale buildings in this country does not exceed eight, three of which are located at the Kerkenes Eco-center in Yozgat. The following sections present information on these three straw bale buildings.

2. STRAW BALE BUILDINGS AT THE KERKENES ECO-CENTRE

The Kerkenes Eco-Center is located near the Kerkenes Mountain at the edge of the village of Shahmuratli in central Anatolia, Turkey. The climate in this area is typical of semi-arid upland regions characterized by long severe winters, and hot and dry summers with considerable daily fluctuations in temperature. Winter temperatures are near or below freezing in December and January; and during summer, outdoor air temperatures rise to peaks above 30°C in July and August.

Three of the nine buildings at the Kerkenes Eco-Center have been built with straw bales as the main construction material. The first straw bale structure, a small greenhouse, was started in the summer of 2004 and completed within a few weeks time. The second, a small house, was also started at that same time but could not be completed until the following summer, for lack of funding. Construction of the third building, a conservation workshop for archaeological findings from the nearby iron-age city on the Kerkenes Mountain, was started in 2007. The cost of construction for the Strawbale Greenhouse and the Strawbale House together was approximately US\$15,000 and that of the Conservation Workshop is estimated to be about US\$20,000. Exact costing is difficult to calculate as some of the material was donated by project sponsors.

All three buildings are single storied with their front facades looking towards the south. The Strawbale House and the Conservation Workshop were built on sloping ground and have thus been provided with storage space under part of the concrete floor slab. Equipment as well as surplus material for recycling is kept there under cover. The design and construction of each of these buildings are described in the following sections.

The Greenhouse

The straw bale Greenhouse is a small building measuring 5 m by 3.75 m, built mostly with indigenous and waste material, such as straw, mud, discarded tires and glass bottles. The base of the straw bale walls was made of tires lined up on a concrete platform. The tires were

FIGURE 1. The Strawbale Greenhouse: [a] laying the foundations; [b] anchoring the first row of strawbales for the walls; [c] erecting the wooden structure; [d] roof insulation; [e] sewing on the chicken-wire before mud-rendering; [f] plastering the bales with mud and straw mixture; [g] plinth protection made of old tires, bottles and mud; [h] interior of the greenhouse.



filled with stones and a meter long rebar was anchored vertically in the centre of each, before pouring in the concrete mixture. A bituminous waterproofing membrane was then laid on top of the plinth and the first row was anchored down by impaling the bales on the rebar that had been embedded in the tire foundation. The subsequent rows were laid in a running bond and pinned down by driving rebar through them at regular intervals.

The walls on three sides are load-bearing and support the timber structure for the sloping straw bale roof; which is also held up in the middle by timber posts. The bales placed on the

roof were covered with a waterproofing membrane and bituminous corrugated roofing sheets for protection from rain and snow. The entrance door was inserted in the side wall between two posts. Bale needles were used to secure the chicken wire net to both sides of the straw bale walls and the ceiling, in order to bind the mud and straw plaster to the bales. Two layers of plaster were applied: first a rough coat by hand and then a second coat with hawk and trowel. After the plaster had dried completely, lime wash was applied to the walls and wooden planks were nailed on the ceiling to support the weight of the straw bales. The sloping southern façade was covered with a thick transparent nylon sheet, instead of glazing. Car tires and discarded glass bottles were used to build a protective bench around the greenhouse. The straw bale greenhouse and its construction stages are shown in Figure 1.

The Strawbale House

The Strawbale House is a single-storey building with a total covered area of 96m², including the terrace; and a net usable area of 54.4 m². It consists of a living room, a kitchen, a bathroom and an entrance vestibule. The sloping ground permitted the provision of an open storage space under a part of the floor slab. The floor plan and the construction stages of the Strawbale House are shown in Figures 2 and 3 below.

The foundations and above grade walls of the house were built with stone masonry and concrete mortar, up to plinth level. Tires filled with rubble and concrete were placed, one on top of the other, to form columns that supported the terrace deck. Water proofing was applied to the foundations and below-grade walls. Reinforced concrete tie beams were poured at the plinth level, and the ground floor slab was made by pouring concrete over a bed of rubble stone. A water proofing membrane was laid down on the tie-beams and the timber frame structure was erected on these beams. The foot-plate of the timber frame was fixed to the concrete plinth by means of rebar that had been anchored into the concrete at regular intervals. Glass wool was laid between the two parallel timbers components of the foot-plate before constructing the straw bale infill walls. Half a meter high rebar had been embedded into the tie beams before pouring the concrete and the first layer of straw bales was anchored to the beams by

FIGURE 2. Floor plan and sections of the Strawbale House, showing location of the datalogger.

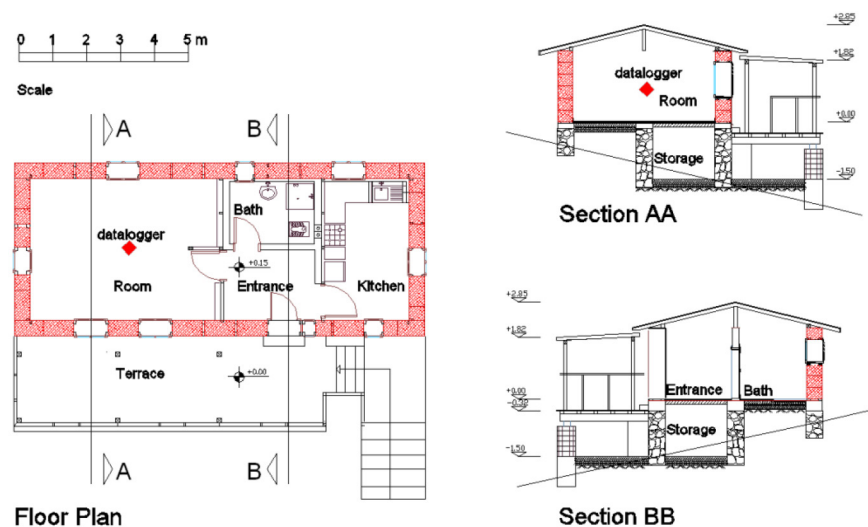


FIGURE 3. The Strawbale House: [a] Timber structure on stone foundations; [b] erecting the roof structure; [c] finishing the roof; [d] trimming the straw; [e] applying mud-plaster on the walls. [f] The kitchen; [g] bathroom; [h] and interior of the strawbale house.



impaling them on these bars. Bales measuring $45 \times 90 \times 35$ centimeters were stacked plumb and level in a running bond, while smaller gaps were stuffed with loose straw. In this way the external straw bale walls were built up to the timber roof-plates, which provided rigidity to the timber structure and also helped to contain and stabilize the stacked up straw bales.

A timber truss supported by the walls and posts ran along the centre of the building to hold up the roof ridge. Rafters spanning the distance between the central truss and the peripheral roof plates supported the timber roof decking, which in turn was covered with a waterproofing membrane, 5 cm thick glass wool insulation bats and bituminous corrugated roofing

sheets. The door and window frames were secured to the wooden structure before trimming and plastering the straw bale walls.

The partition wall between the entrance and living room was constructed with sun-dried mud brick; and timber bracing placed diagonally within this wall contributed to the lateral stability of the structure. The partition walls in the wet spaces, *i.e.* kitchen and bathroom, were built with factory-produced hollow clay bricks. Such brick was also used as a protective layer on the inner face of the external straw bale walls in wet spaces. The bathroom walls and floor were tiled to provide water proofing; while the rest of the floors in this building have a cement concrete finish. Conduits for electrical wiring were embedded in the straw bale walls before plastering. Chicken wire was fixed on to the inside surface of the strawbale walls with wire clips. Two coats of mud-cum-straw plaster were applied to these walls; a rough coat by hand and then a second one with hawk and trowel. The walls were then finished with plaster of Paris inside and lime wash outside.

The Conservation Workshop

The Conservation Workshop has a net usable area of 63.4 m² and consists of a large multi-purpose hall with an equally large covered veranda in front. As this building was also constructed on a sloping site, storage space could be provided under the floor slab of the veranda (Figs 4 and 5). Since the building was built for conservation of stone elements from the nearby archaeological site, it was necessary to minimize fluctuations in humidity levels as well as prevent winter minimum temperatures to drop below frost level even during the winter season when the building is neither used nor heated. The innovative combination of straw bale and AAC blocks provided a very high level of heat insulation while the internal mud plaster rendering helps regulating humidity levels within the building. Details of the construction process are given below.

Just like the Strawbale House, the foundations and above grade walls of this building were also built with stone masonry up to plinth level. However, the superstructure was very different; the structural system was composed of Autoclaved Aerated Concrete (AAC) piers (columns) and reinforced concrete beams instead of a timber frame structure. The 60 × 60cm piers were fashioned out of three 20 cm-thick AAC blocks laid side by side, each course being perpendicular to the previous one. The concrete tie beams were anchored to these piers and

FIGURE 4. Floor plan and sections of the Strawbale Conservation Workshop showing location of the datalogger.

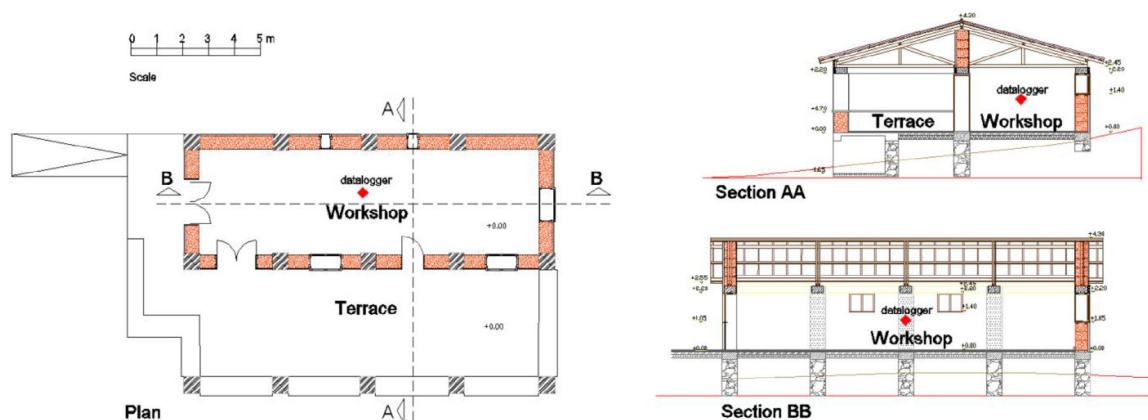


FIGURE 5. The Strawbale Conservation Workshop: [a] timber roof structure, concrete lintels and AAC piers on stone foundations; [b] laying layers of insulation on the roof; [c] wall composed of strawbales and AAC blocks; [d] installing a re-used door; [e] installing a re-used door; [f] interior view of external layer of AAC blocks; [g] trimming the straw bales; [h] plastering interior wall surface with mud and straw mixture.



in turn supported the timber roof structure composed of wooden trusses, rafters and battens; while waterproofing, thermal insulation bats and corrugated roofing sheets finished off the roof.

Straw bale buildings are conventionally plastered with mud and perform well in dry climates. But in areas where there is plenty of rain and snowfall, such as the central Anatolian region where the Eco-Center is located; it is not the most appropriate finishing material; hence, an innovative wall composition was experimented with to combat this problem. The non-bearing straw bale infill walls are comprised of an external layer of 5 cm thick AAC

blocks, a middle layer of 45 cm thick straw bales and an inner layer of mud plaster. The external layer of thin AAC blocks was finished off with a 3:1 lime and cement plaster; thus rendering the building envelope weather proof and hence eliminating the need for constant maintenance and repair work. On the other hand, since the building interior is not exposed to weathering it is appropriate to use a mud plaster rendering over the internal surface of the straw bale walls as this helps regulate the humidity inside the building.

The first course of straw bales was placed on two parallel rows of AAC blocks with gravel in between so that the bales would not be affected by rising damp. The floor of the hall as well as that of the veranda is of cement concrete. All fenestration is wooden with double-glazed windows and wood panel doors. Two of the three exterior doors have glass panels at the top. All doors and windows as well as all timber roofing material had been salvaged from demolished buildings and re-used after necessary repair work.

3. DATA COLLECTION AND ANALYSIS

The thermal performance of buildings at the Kerkenes Eco-Center is being monitored as part of an on-going research program. Tinytag and Hobo data loggers placed in appropriate locations inside and outside the buildings record temperature and humidity levels concurrently. Data is collected during summer and winter months under occupied and unoccupied conditions and has been analyzed and presented at international conferences (Elias-Ozkan *et al.*, 2006 & 2008).

In this paper, first the data from the Strawbale Greenhouse at Kerkenes, in Yozgat, is compared to that from a conventional greenhouse at Güneşköy, in Balaban. Although the locations of the two greenhouses are some distance apart, they lie within the Central Anatolian Plateau region and have a similar climate. In order to record the temperature and humidity values at these locations a Tinytag datalogger that saved data at 15 minute intervals, was suspended from the ceiling in the centre of the greenhouse; while another one was placed outside the building at a height of 2m (7ft) from the ground, at a location protected from precipitations and direct solar gains. Due to a limited number of dataloggers at that time, the data were first recorded at Kerkens and downloaded to the computer before moving them to Güneşköy.

The second set of data discussed here illustrates the thermal behavior of the two straw-bale buildings during summer and winter months. Temperature and humidity values were recorded at 15 minute intervals throughout the year with three Tinytag dataloggers. One was placed inside the Strawbale House, on a wooden desk at the center of the main room; another was placed at the center of the Workshop on a wooden stool, and a third was hung outside at a height of 2.5m (8ft) from the ground, under the eaves of a nearby building in the Eco-center. The locations of data loggers inside the Strawbale House and the Workshop are shown in Figures 2 and 4, respectively.

Although annual data are available, this paper deliberately presents data only for periods when the buildings were unoccupied so that the influence of occupant behavior and related internal loads may be disregarded. Hence, data belonging to four weeks during summer, i.e. 3,075 readings from 20th July to 21st August; and another four weeks during winter, i.e. 2,240 readings from 18th February to 20th March, have been evaluated and presented in the following sections. Since the buildings were not in use they were neither heated nor cooled; nor were the doors or windows opened, therefore there was practically no natural ventilation; while any

air change was due to infiltration. In other words, apart from the temperature and humidity data the thermal behavior of these buildings cannot be attributed to any other factor; such as: heating, cooling, ventilation, lighting, and machine or occupant related internal gains.

The temperature and humidity data are downloaded on a regular basis from the dataloggers to the computer using proprietary software and then exported to Excel as tables, in order to produce comparison graphs. These graphs showing diurnal fluctuations in the data are presented in Figures 6 to 11. Additionally, in Figures 8 to 10 the graphs have been overlaid with the thermal comfort bands, for which the minimum and maximum temperature and humidity values have been taken from the limits set by the Canadian Center for Occupational Health and Safety (CCOHS) in accordance with the 2010 ASHRAE-55 thermal comfort standards. The blue region on the temperature graphs represents cold temperatures, white is neutral (or comfortable) and red represents heat (see Figures 8 and 9). In the humidity graphs (Figures 10 and 11) green represents humidity, white is neutral and purple means dry weather.

Three qualities are important when evaluating comparative temperature and humidity charts: fluctuation, trend and time-lag. Any difference observed between the building's interior and the exterior with respect to any of these three indicators is instrumental in illustrating its thermal behavior.

Thermal Behavior of the Strawbale Greenhouse

Comparison of data from the Kerkenes Strawbale Greenhouse and the Balaban Conventional Greenhouse clearly illustrates the difference in the behavior of the two structures even if the data could not be collected simultaneously. Temperature and humidity data were recorded, first in the straw bale greenhouse, from 10th to 25th April 2006, and then in the conventional greenhouse, from 7th to 28th May 2006. In order to compare the thermal behavior of the two greenhouses, charts prepared for a week long data set from each greenhouse are presented side by side in Figures 6 and 7.

As seen from the charts below, solar gains led to much higher daytime temperatures within the greenhouses except for the days when solar radiation was reduced due to cloud cover; *e.g.* the fifth day in the Strawbale Greenhouse location. On the other hand, night time

FIGURE 6. Indoor temperature readings collected during a week in spring from the Strawbale Greenhouse and the Conventional Greenhouse, as well as the external temperatures at their locations.

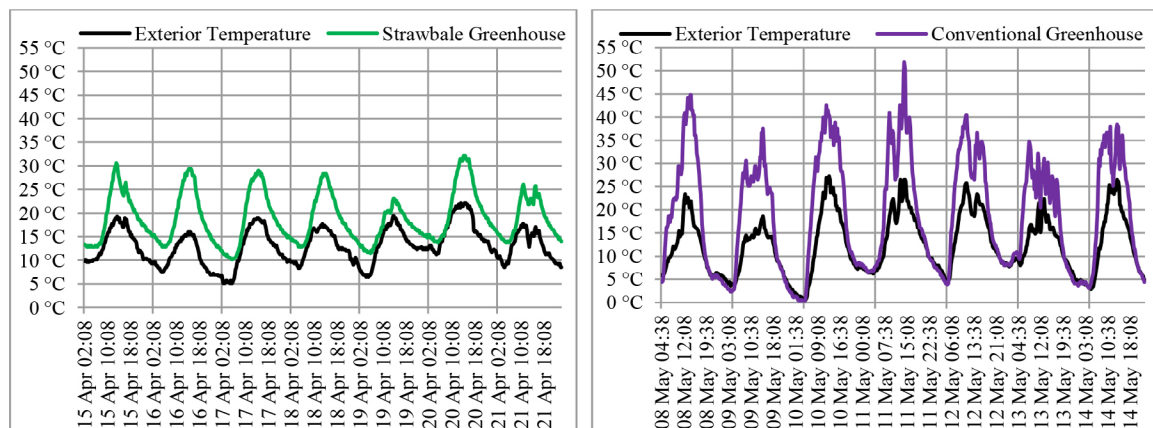
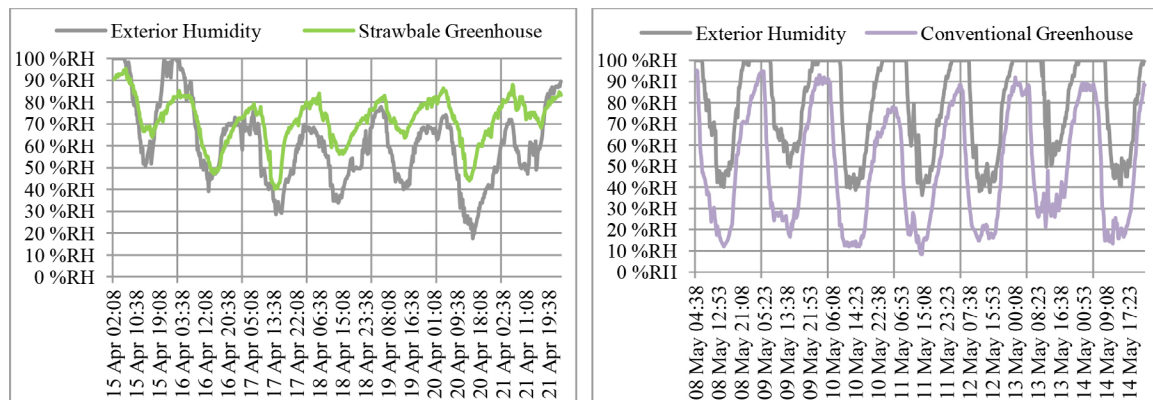


FIGURE 7. Humidity readings from the two greenhouses and the two locations during a 7 day period in spring.



temperatures dropped to the level of exterior temperatures in the conventional greenhouse, leading to a daily fluctuation from 35 to 40 °C; while in the Strawbale Greenhouse the night time temperature never went as low as the exterior, thus maintaining a 15 °C fluctuation (see Fig. 6). This phenomenon was also observed during winter months when incident solar energy was low due to snowfall, yet interior daytime temperatures in the straw bale greenhouse remained higher than the exterior. Similarly, during the night, when temperatures dropped below freezing, the nighttime temperature remained above 0 °C due to the high thermal-insulation properties of the strawbale walls.

The relative humidity charts show how the levels fluctuate within a 30% range in the straw bale greenhouse even when outside weather fluctuations are up to 60%; but the fluctuations in the conventional greenhouse are observed to be much higher, to the order of 70% (see Fig. 7). Since higher temperature in winter season and stable humidity levels are desirable in a greenhouse the straw bale greenhouse can be declared as superior to a conventional one. These attributes were seen to extend the harvesting season at Kerkenes well into the winter months.

Thermal Behavior of Straw Bale Buildings

Although strawbales do not have enough thermal mass to provide an interim heat sink that helps to keep temperatures stable and prevents them from rising to discomfort levels, its higher thermal insulation overcomes this drawback. This is evident from the comparative temperature charts prepared from data collected in both summer and winter months (Figs. 8 and 9). There was considerable diurnal fluctuation in external weather conditions and though the temperature within the buildings fluctuated parallel to outside temperature fluctuations, this amount was significantly lower in the strawbale buildings. For example during summer time when the difference in external diurnal temperatures is to the order of 15 °C the interior temperature fluctuates by about 3°C only. For this reason even when external temperature rises to 35 °C the internal temperatures do not exceed 27 °C. The Workshop is seen to be one degree cooler during the day as compared to the Strawbale house, due to the deep covered verandah along its southern façade, which prevents solar gains.

Similarly, during winter time, the diurnal fluctuations outside are around 7 to 8 °C while those inside the buildings are barely 1 to 2 °C; i.e. the conditions within remain fairly stable. On the other hand the temperature within the Strawbale House is slightly lower than that in

FIGURE 8. Temperature data from the exterior and interior of the two strawbale buildings at the Kerkenes EcoCenter during four weeks in summer; the graph shows diurnal fluctuations as well as the thermal comfort band.

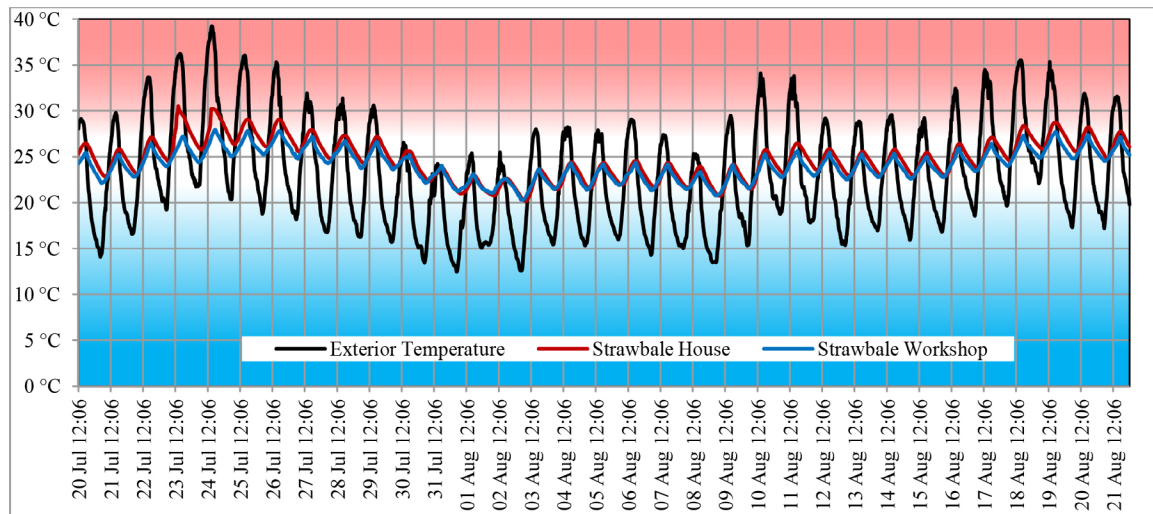
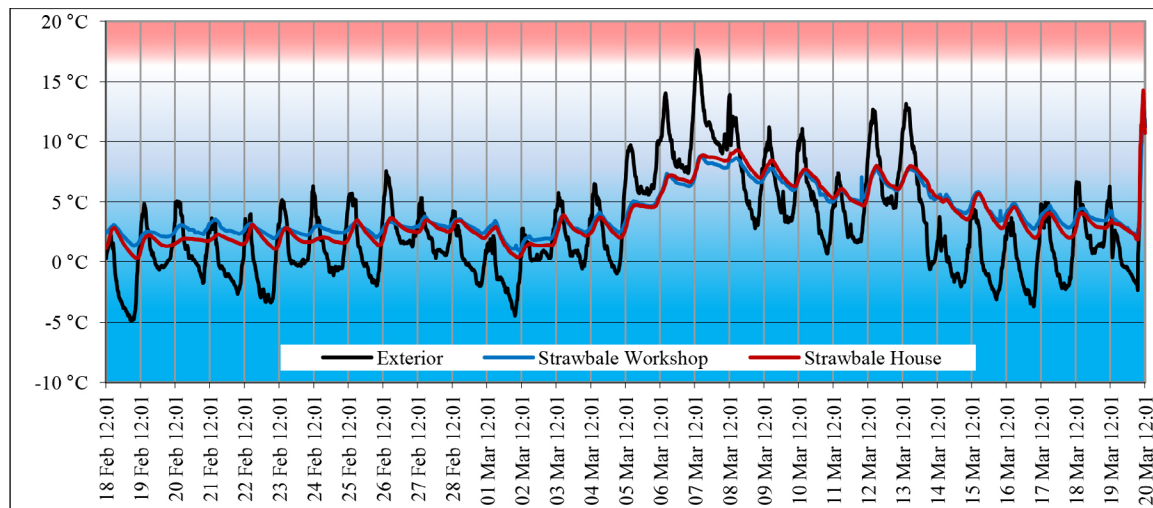


FIGURE 9. Temperature data from the exterior and interior of the two strawbale buildings at the Kerkenes EcoCenter, during four weeks in winter; the graph shows diurnal fluctuations as well as the thermal comfort band.



the Workshop. However, both buildings show parallel trends in their graphs, which means that they respond in the same way to external weather conditions. And though the response time-lag is also similar, the Workshop building is slightly faster than the House in responding to external weather conditions.

The comparative charts (Figs. 10 and 11) for relative humidity data collected inside and outside of the buildings show that humidity levels in the straw bale building remain pretty stable even when outside fluctuations are high. This is due to the humidity regulating properties of the mud plaster on the interior, thus ensuring that relative humidity remains within the comfort range.

On clear sunny days during the summer months when outside humidity levels may change by 60%, for example on 26th July when minimum and maximum levels were recorded to be 20 and 80%, the variations within the two buildings are limited to 10% only and the minimum and maximum levels were within the comfort range (40% and 50%). Despite comparable temperatures inside the two buildings (as shown in Fig.8) humidity in the strawbale house is a little less than in the Workshop because the external walls in the former are rendered on both sides by mud-plaster whereas the external finish in the latter is AAC blocks.

As can be seen from the data for winter, during wet or snowy winter days when the humidity levels rise to 100%, the internal levels rarely exceed 80% within the two buildings

FIGURE 10. Humidity data from the exterior and interior of the two strawbale buildings at the Kerkenes Ecocenter, during four weeks in summer; the graph shows diurnal fluctuations as well as the humidity comfort band.

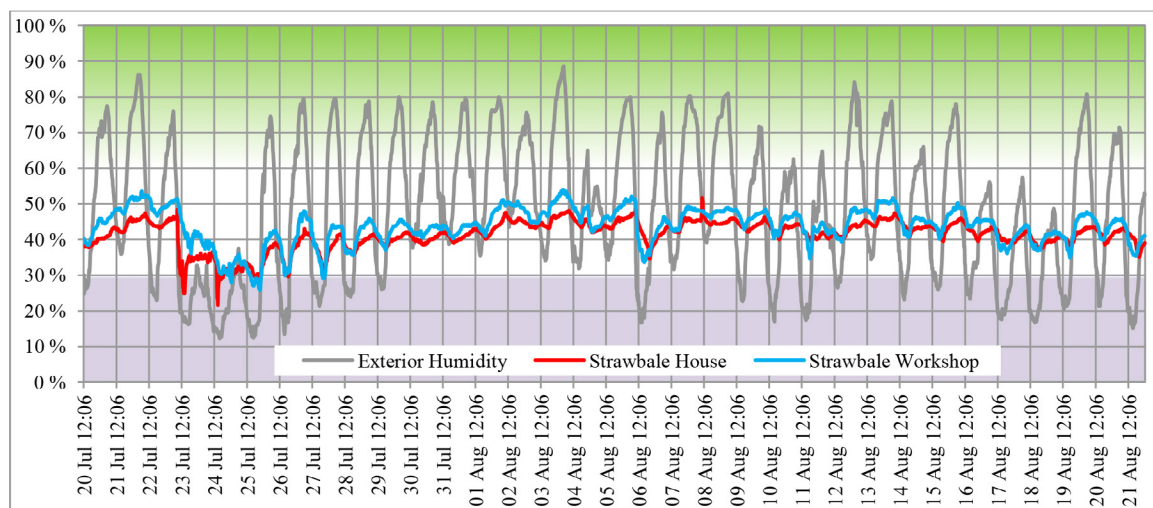
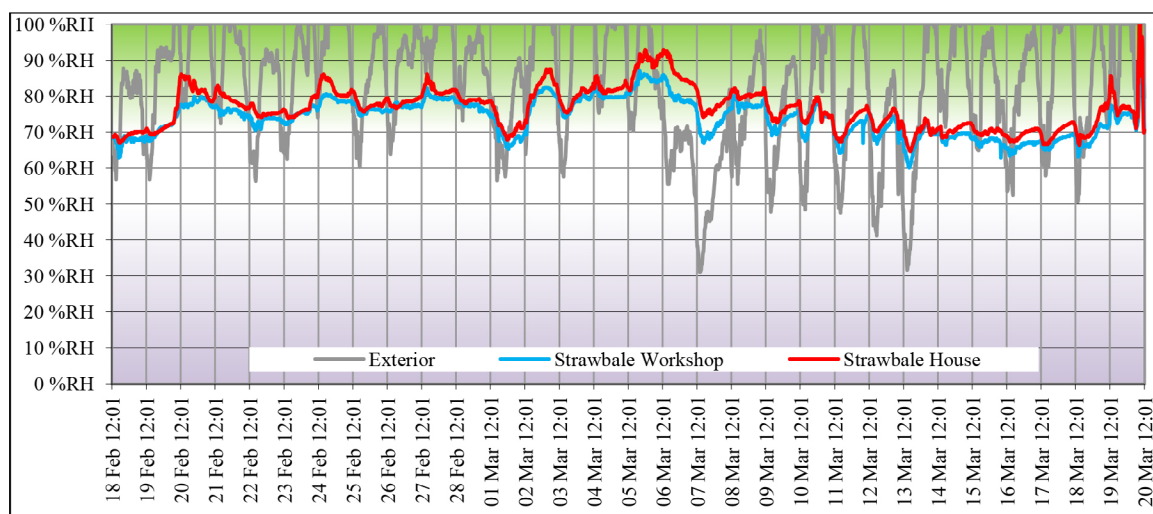


FIGURE 11. Humidity data from the exterior and interior of the two strawbale buildings at the Kerkenes Ecocenter, during four weeks in winter; the graph shows diurnal fluctuations as well as the humidity comfort band.



(Fig. 11). Additionally, the absence of a covered verandah in the strawbale House also allows the winter sun to keep the walls dryer. On 7th March (see Fig. 9) when the external temperature rose unexpectedly to almost 18°C as compared to only 2°C in the week before, and the humidity level dropped to 30% (see Fig. 11) the relative humidity went down to only 67% in the strawbale workshop and 76% in the strawbale house.

Although, it is possible to read fluctuations, trend and time-lag from thermal graphs it is difficult to pinpoint the behaviour of the buildings on average as well as under extreme conditions. To this end, Figures 12 and 13 were prepared to compare the minimum and maximum readings recorded outside and inside the buildings during hot and cold seasons and average values for temperature and humidity data recorded during the summer and winter weeks. These bar charts give a fair picture of the conditions within as compared to those without, regardless of the location of the strawbale buildings.

The “Thermal Comfort Tool for ASHRAE-55” developed at UC Berkley by Hoyt *et al.* (2012) was used to input temperature extremes and averages to calculate thermal neutralities. When the adaptive method was used to determine indoor operative temperatures within 90% acceptability limits, the range was calculated to be 27.5 to 32.5°C for maximum outdoor temperature of 39.2°C. As shown in Figure 12, the maximum temperatures in both the strawbale buildings are within this range. Similarly, the buildings were comfortable even when the minimum outdoor temperature fell to 12.5°C in summer as the indoor temperatures were within the 90% acceptable range of 19.2 to 24.2°C (see Figure 12). In other words, during summer time the buildings were comfortable even without ventilation. On the other hand,

FIGURE 12. Bar chart showing differences in outdoor and indoor temperatures during hot and cold weather conditions.

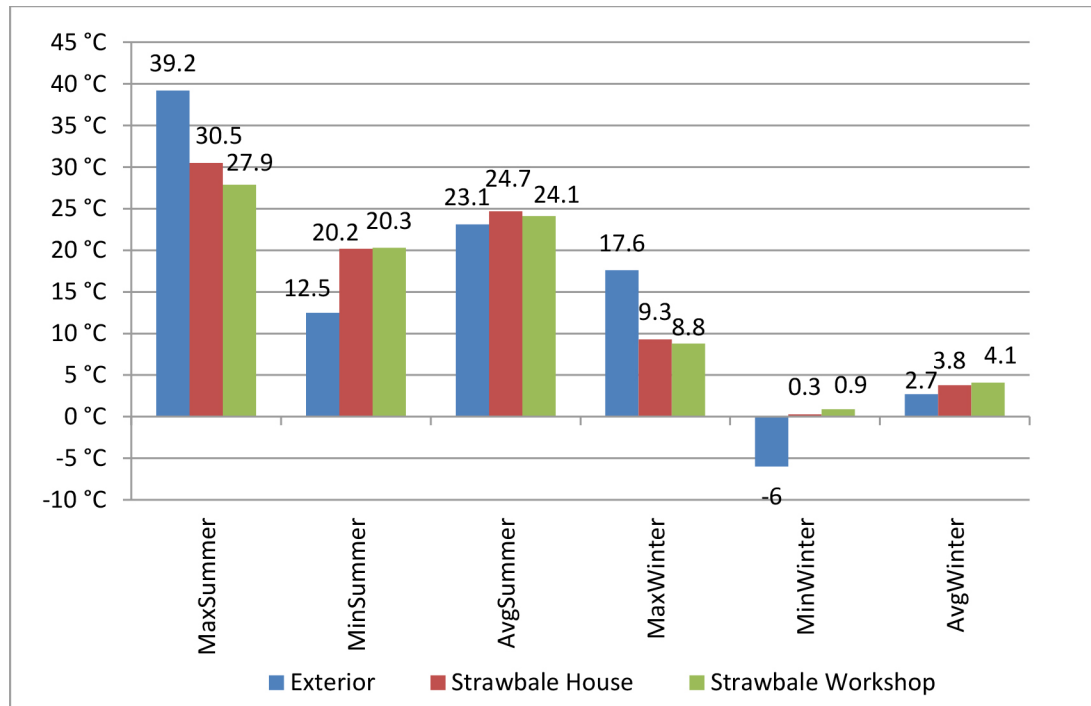
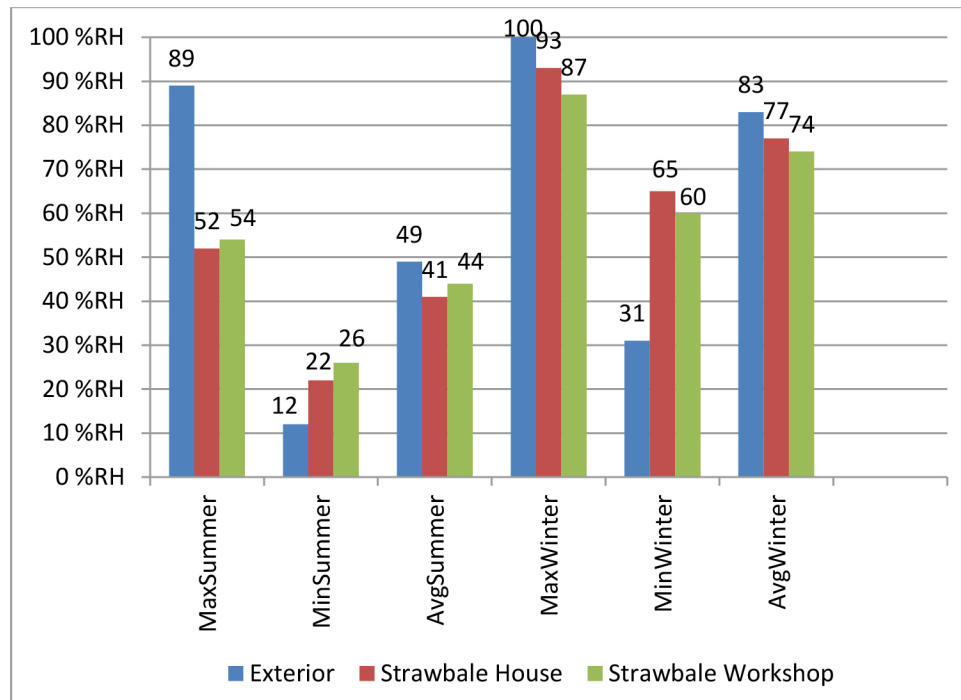


FIGURE 13. Bar chart showing differences in outdoor and indoor humidity levels during hot and cold weather conditions.



during winter when the outside temperatures were below freezing point the temperatures inside, though uncomfortable, remained above 0°C even when the building had not been heated for weeks on end. Yet, due to the super insulating properties of strawbale walls it is possible to keep the buildings warm with very little heating for a few hours a day (Elias-Ozkan *et al.*, 2006 & 2008).

4. CONCLUSION

A comparison of recorded data has revealed that straw bale construction is advantageous with respect to thermal insulation properties, in addition to embodied energy and economy; when compared to contemporary building materials. Another aspect worth mentioning is that contrary to popular belief strawbale walls could be made rodent-proof by plastering them properly. This was important because there are a multitude of insects and field mice in the area but none have been detected so far in the strawbale buildings at the Eco-center.

This paper has also illustrated how a hybrid wall construction can take advantage of the various desirable properties of different materials in order to improve its over-all performance. Combining the high thermal insulation property of straw bales with the weather proofing property of AAC blocks and the humidity regulating property of mud plaster in hybrid wall constructions helps to produce buildings that are more thermally comfortable, cheaper to build and easier to maintain than conventional structures. However, due to the considerable wall thickness such construction would be more suitable for rural or sub-urban areas where building plots are not limited in size and where high-rise construction is not desirable.

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