Paper No 676: Analyzing environmental performance of AAC blocks, strawbales and mud-plaster in hybrid wall construction

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Abstract

This aim of this study was to compare the thermal performance of three buildings which are located at the Kerkenes Eco-center in Yozgat, Turkey. The first of these was constructed with strawbales rendered with mud plaster; the second with aerated autoclaved concrete (AAC) blocks and cement plaster; and the third with strawbales rendered with mud plaster inside and a layer of thin AAC blocks on the outside. The last type of hybrid wall construction has been tried for the first time, in order to take advantage of the thermal-insulation property of straw, combined with the humidity-regulating property of mud plaster inside and weather-resistance property of AAC outside. Temperature and humidity data were collected in these three buildings for certain time periods, concurrently. These data have been compared to elicit the degree of variance in the performance of the three types of constructions. Additionally, computer models of these buildings have also been simulated with Ecotect v5.5 for a comparison of their total energy loads.

Keywords: energy efficiency, Ecotect, strawbale, AAC, hybrid wall

1. Introduction

The Kerkenes Eco-center was established in the central Anatolian village of Sahmuratli in Yozgat, Turkey, in 2002. All buildings that have been constructed at this center uptill now, are being monitored continually for their thermal performance by recording temperature and humidity data at regular intervals. These buildings are constructed with a variety of materials, such as: mud-brick, strawbales, prefabricated concrete panels, extruded brick, Autoclaved aerated concrete (AAC) blocks, *etc. S*trawbale,however, is the most controversial of them all. The reason being that straw is considered to be a flimsy material which is not only susceptible to insects, rodents and rot attack; but also regarded as a fire hazard.

Experience has it otherwise, as strawbale buildings can last a long time if constructed with the right techniques. For example, the Burke home in Alliance, Nebraska, USA, which was built in 1903, is still standing, more than a century later [1]. Since straw bales (especially of wheat) are made with stalks, only after threshing, no grains are left behind to attract insects or rodents. Moreover, if water, which is the arch-enemy of most building material, is kept away from strawbales, they will not rot. Although, loose straw is flammable it gains fire resistant properties when compressed firmly into bales by baling machines.

As a result of a series of fire related experiments conducted in the USA [3] fire rating of standard un-plastered strawbales was declared to be at least half an hour, at temperatures up to 921°C. It was, however, argued that since the fire took as much as 34 minutes to work through a seam between the bales, fire rating of strawbales could easily be taken as one hour. Meanwhile, fire rating of plastered bales was found to be even better when they were protected with cement plaster on the inside and gypsum on the outside. It was observed that after 2 hours of exposure to fire on the outside the straw was charred to a depth of 5 cm only, even though the temperature of the external surface rose to 1060°C. On the other hand, the inside surface barely reached 21°C due to the high thermal insulation property of the strawbales.

A comparison of the recorded data has revealed that strawbale construction is advantageous with respect to thermal and sound insulation properties, embodied energy, and economy; when compared to contemporary building materials [2,4]. Although, from the point of view of thermal performance, AAC construction compares favourably with strawbale, it is not only more expensive but also less environmentally friendly than straw. Conversely, the disadvantage of strawbale construction is that the mud plaster that is conventionally used to render strawbale walls is susceptible to speedy deterioration in wet or humid weather conditions. Consequently, there arises the need to maintain such plaster diligently and periodically.

In order to overcome this drawback a hybrid external wall was designed and constructed with strawbales, which were protected from detrimental weather conditions by an external layer of 5cm thick AAC blocks instead of the traditional mud and straw rendering. Since the building was to be used for storage and analysis of archaeological findings from the nearby Iron-Age city of Kerkenes, it was necessary to prevent fluctuations in humidity levels within; therefore, the interior surfaces of the external walls were rendered with mud-plaster, which is known to possess the ability for regulating humidity levels within buildings. The photograph presented below shows the constructional configuration of the hybrid wall made of an external layer of AAC blocks, a middle layer of strawbales and an inner layer of mud plaster; as well as the timber roof structure, RCC tie-beams and AAC columns.

Fig 1. A window is being installed in the under-construction hybrid wall of the Strawbale-cum-AAC building.

The thermal performance of these three buildings at the Kerkenes Eco-center, namely, the Strawbale building, the AAC building and the Strawbale-cum-AAC building is being monitored as part of the on-going research activities at the center. This paper reports on the findings of this research and the related simulation study, in the following sections.

2. Study Material and Method

All three buildings are single storied and face more or less southwards, with covered verandas in front to prevent direct solar gains during the hot summer months. Due to the sloping site, the space beneath the verandas and part of the building has been utilized to build storage spaces for various articles of use as well as surplus material for recycling. Of the three buildings, the Straw-bale house is the oldest structure and the hybrid wall (Strawbale-cum ACC) structure was the last to be built.

The Strawbale building has a net usable area of 54.4 m² and consists of a meeting room, a kitchen, a bathroom and an entrance vestibule. The foundation and semi-basement walls were constructed with stone masonry. The exterior walls of the Strawbale building were built with bales measuring 45cmx90cmx35cm, and were rendered with traditional mud plaster on both sides. The interior walls were constructed with sun-dried mud-brick, except for the party wall between the kitchen and the WC through which the plumbing pipes ran; this wall was made of factory-produced hollow-brick and rendered with cement plaster. The WC walls and floor are tiled to provide water proofing; while the rest of the floor in this building is of concrete. The pitched roof is of timber trusses, beams and rafters covered with heat and water proofing layers and protected with corrugated roofing sheets. All fenestration is wooden with double-glazed windows and solid-core timber doors.

The AAC building has a net usable area of 77.7 m² and consists of a meeting room, an office, a kitchen with storage, 2 WCs and an entrance corridor. The building has a reinforced concrete structure and walls of 30cm thick AAC blocks. The interior walls are of 20cm or 10cm thick AAC blocks, depending on their location. The ceiling is of AAC panels with a pitched timber roof as in the Strawbale building. The wet spaces are tiled while all other floors are of concrete terrazzo tiles. All fenestration is wooden with double-glazed windows and solid-core timber doors.

The Strawbale-cum-AAC building has a net usable area of 63.4 m² and consists of a large multi-purpose hall and an equally large covered veranda in front. The timber roof structure rests on 60cmx60cm columns made of 20cm thick AAC blocks laid side by side such that each layer was orthogonal to the next one. The walls are of 45cmx90cmx35cm strawbales resting on two parallel rows of AAC blocks with gravel in between and a layer of water-proofing on top. These walls were rendered inside with traditional mud-plaster, but on the outside, 5 cm thick AAC blocks were used for a more durable exterior finish (Fig. 1). The floor of the hall as well as the veranda is of cement concrete. All fenestration is wooden with double-glazed windows and solid-wood panel doors. Two of the three exterior doors have glass panels at the top.

Photographs of the three buildings are presented in Fig.2, which show the single storied structures and the storage spaces beneath.

The thermal behaviour of these buildings was studied in two ways: first by taking actual measurements on site, and then, by simulating thermal comfort conditions with the help of the energy simulation software Ecotect v5.2.

2.1 Measured- and Weather- Data

"Tinytag - Plus 2" data-loggers were placed in appropriate locations outside and inside the three buildings to record temperature and humidity levels. The plans of these buildings showing the location of the data loggers are presented in Fig.3.

Temperature and humidity readings were recorded at 15 minute intervals for a few days at a time, throughout the year. However, in this paper, data belonging to a 7 day period only, from the 7th to 13th of October 2007 has been evaluated to compare the thermal behaviour of the selected buildings.

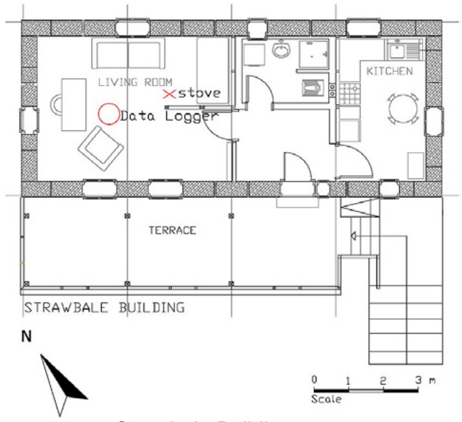
Strawbale Building

Strawbale-cum-AAC Building

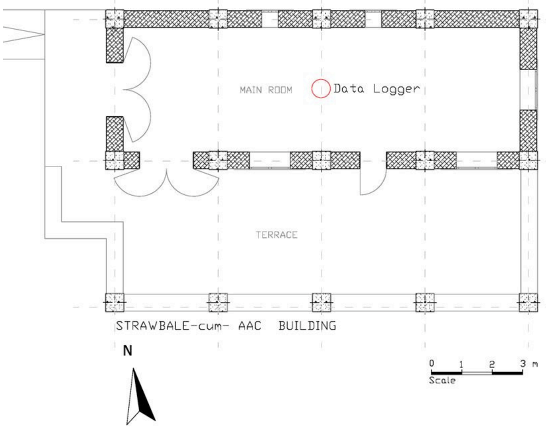
AAC Building

Fig 2. Exterior views of the three buildings studied at the Kerkenes Eco-Centre in the village of Sahmuratli, Yozgat, Turkey

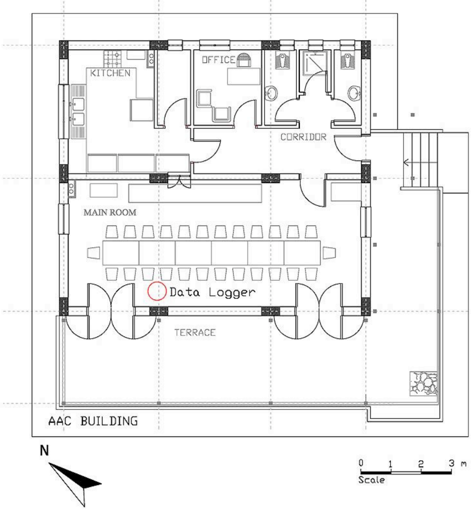
There was considerable diurnal fluctuation in external weather conditions but since the buildings were not in use during this period, there were no internal gains due to metabolic energy of occupants or machinery/equipment being operated. For the same reason they were neither heated nor cooled; nor were the doors or windows opened, therefore there was practically no ventilation. The temperature and humidity data that were recorded concurrently in all the buildings are presented graphically in Figures 6 and 7, respectively, in the following pages.



Strawbale Building



Strawbale-cum-AAC Building

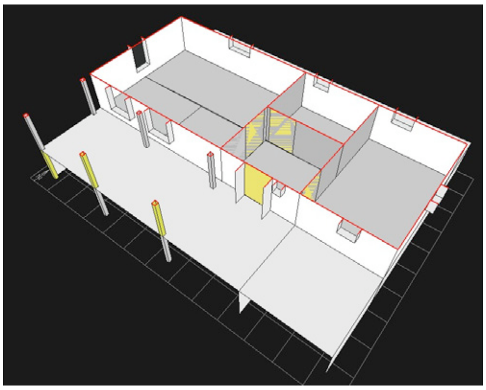


AAC Building

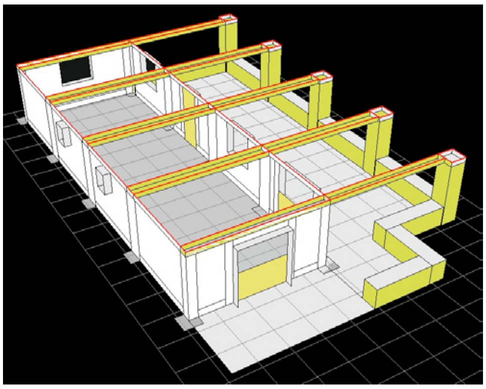
Fig 3. Floor plans of the three buildings showing the location of data loggers.

2.2 Simulated Models

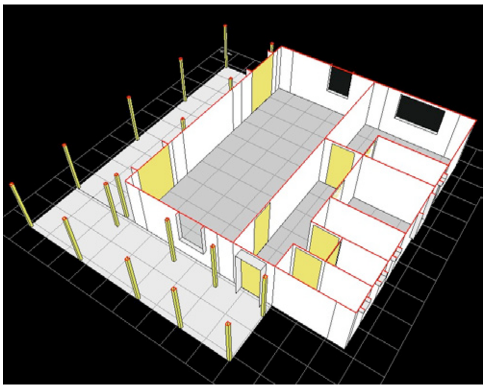
All three buildings were first modelled in Ecotect v5.5 and then simulated for their annual heating and cooling loads under local weather conditions, *i.e.* cold winters and warm summers. The site is located in the village of Sahmuratli in Yozgat, Turkey (Latitude: 38.5^{o}, Longitude: 35.3^{o}, +2 GMT) and the weather data for this area was obtained from the Turkish Meteorological Institute (TMI) and reformatted as input for the software. Fig.4 shows the three 3-dimensional models.



Strawbale building



Strawbale-cum-AAC building



AAC building

Fig 4. Three-dimensional models of the three buildings studied at the Eco-Center, generated with the simulation software Ecotect V5.5

In order to simulate the buildings, full air conditioning (heating and cooling) was assumed in the rooms during weekdays such that the thermostat set-point temperature upper-band limit was fixed at 26.0°C and the lower band limit at 18.0°C, in order to maintain thermal comfort conditions.

Air infiltration rates were taken as 1.0 ac/h for all models as they were considered average construction in terms of air leakages through joints *etc*. Wind sensitivity is given as 0.75 for rural areas which indicates exposed building surfaces [5]. However, the buildings being studied are reasonably protected due to the covered verandas and proximity to other buildings; hence this value was taken an as 0.25 ac/h.

All input variables for software Ecotect v.5.5 are given in Table 1 below, for each of the three simulated building models.

Table 1: Input values of variables for the as-built simulation models in Ecotect v5.5.

Input Variables	**Straw bales**	**Straw bales + AAC**	**AAC**
Area	Rural	Rural	Rural
Location	Turkey	Turkey	Turkey
Latitude	38.5°	38.5°	38.5°
Longitude	35.3°	35.3°	35.3°
Time Zone	+2 GMT	+2 GMT	+2 GMT
Orientation	SSW	South	SW
Net Usable Floor Area (m^2)	54.39	63.4	77.7
Bldg. Material attributes	As-built	As-built	As-built
Building Envelope U-Values in W/m^2K:			
RCC LB elements	n/a	3.01	3.01
AAC LB elements	n/a	0.33	0.33
AAC Base walls + gravel in-fill	n/a	0.32	n/a
Stone Basement Wall	2.03	2.03	2.03
Strawbale	0.11		
Strawbale + AAC hybrid w	n/a	0.12	n/a
Mudbrick interior walls	2.78	n/a	n/a
Hollow brick interior wall	1.66	n/a	n/a
AAC Exterior Walls	n/a	n/a	0.56
AAC Interior Walls 20 cm	n/a	n/a	0.87
AAC Interior Walls 10cm	n/a	n/a	1.19
Pitched Roof structure	0.90	0.90	2.62
AAC Panel Ceiling	n/a	n/a	0.57
Floor	0.73	0.93	0.66
Windows	2.9	2.9	2.9
Doors	2.26	2.26	2.26
Total Conductance (W/K)	98	128	471
Total Admittance (W/K)	1907	714	2585
Operational Profiles:			
HVAC System	full AC	full AC	full AC
Operation Schedule:	24hrs	24hrs	24hrs
TST Upper Band Limit	26.0°C	26.0°C	26.0°C
TST Lower Band Limit	18.0°C	18.0°C	18.0°C
Occupancy	None	None	None
Heat Gains	None	None	None
Air Infiltration Rate	1.0 ac/h	1.0 ac/h	1.0 ac/h
Wind Sensitivity ac/h	0.25	0.25	0.25
Building Thermal Zones			
AC	1	1	2
Non-AC	5	0	6
Thermal Simulation Results:			
Annual Heating Load	5239.5	16026.1	14646.2
Heating Load / NUFA	96.31	252.77	188.49
Annual Cooling Load	20.7	115.4	52.6
Cooling Load / NUFA	0.38	1.82	0.67
Total Energy Load	5260.2	16141.5	14698.8
Total Energy Load/ NUFA	96.69	254.59	189.16

TST = Thermostat Set-point Temperatures
NUFA= Net Usable Floor Area

3. Thermal Behaviour

The thermal behaviour of the three buildings was analysed both by evaluating the real-time temperature and humidity readings obtained from the data loggers and that generated by Ecotect v5.5 software through the simulated building models. Results of these evaluations are discussed in the following sections.

3.1 Temperature and Humidity Data

The temperature data, and also the humidity data, for all the three buildings were combined and presented in a single chart in order to visually compare their thermal performance (Figs. 5 and 6).

Three qualities are important when evaluating comparative temperature and humidity charts: fluctuation, trend and time-lag. Any difference observed amongst the buildings with respect to any of these three indicators is instrumental in illustrating the variance between their thermal behaviour.

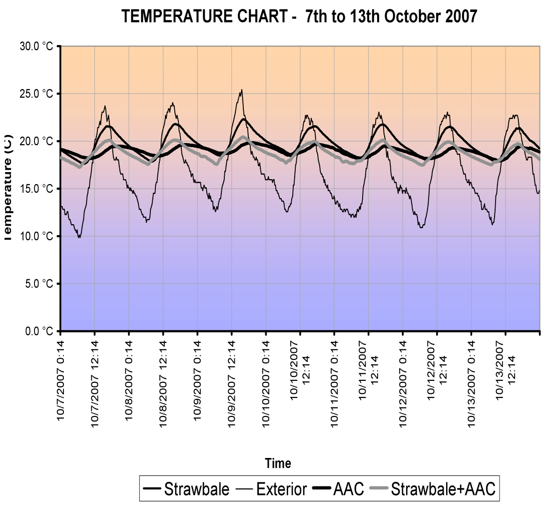


Fig 5. Air temperature readings from the three buildings and external air temperature during a 7 day period in October 2007

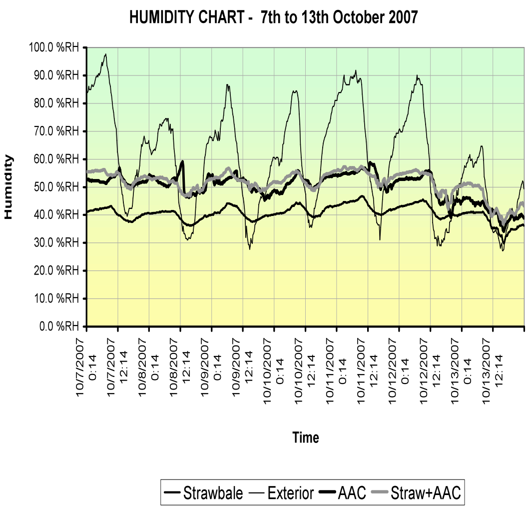


Fig 6. Humidity readings from the three buildings and external humidity levels during a 7 day period in October 2007

From the comparative temperature chart above, it is clear that as the outside temperature fluctuates (approximately 13 ºC) so does the temperature within the three buildings. However, the amount of fluctuation is quite low in the AAC building (approximately 1 ºC to 1.5 ºC), higher in the Strawbale-cum-AAC building (approximately 2 ºC to 2.5 ºC), and highest in the Strawbale building (approximately 3 ºC to 3.5 ºC). This means that the thermal capacity of the AAC building is adequate in providing an interim heat sink which helps to keep temperatures stable and prevents them from rising to discomfort levels. Although strawbale does not have enough thermal mass, its higher thermal insulation counteracts this drawback. Since all the buildings face more or less in the south direction, passive solar gains would have been high in all three during summer months also, but the presence of covered verandas prevents overheating by protecting them.

All three buildings also show parallel trends in their graphs, which means that all three respond more or less in the same way to external weather conditions. Although, response lag-time is also similar, the Strawbale-cum-AAC building is slightly faster in responding to external weather conditions, while the AAC building is comparatively slower. Hence the AAC building can be said to possess higher thermal inertia in addition to high thermal insulation values. On the other hand strawbales have lower thermal transmittance (U) values; these lower U values also mean lower heating loads; this conclusion can also be arrived at from the results of the simulated heating/ cooling loads obtained for the 'as-built' Ecotect models (Fig. 7).

The humidity chart shows humidity levels in the Strawbale building to be lower than those in the AAC and Strawbale-cum-AAC buildings; both of which seem to have almost the same humidity levels within. In fact humidity levels in the Strawbale building correspond to the lowest levels outside during the night. These almost stable humidity conditions in this building are due to the humidity regulating property of the mud plaster on both the interior and exterior surfaces of its walls. On the other hand the AAC and the Strawbale-cum-AAC buildings fluctuate around the mid-points of the external humidity levels.

3.2 Simulated Heating and Cooling Loads

The total heating and cooling loads for a typical year were obtained for the 'as-built' simulated models of the three buildings, three-dimensional plans of which are shown in Fig.4 above. The buildings were simulated with HVAC set-points for heating as 18ºC and cooling as 26 ºC. The results of Ecotect v5.5 simulations under Yozgat weather conditions were then transferred into Microsoft Excel format and then combined as a single data set for the sake of comparison. These data were then used to prepare a comparative chart for the monthly heating/ cooling-loads per usable floor area of all the three buildings. This bar-chart is presented in Fig. 7 below.

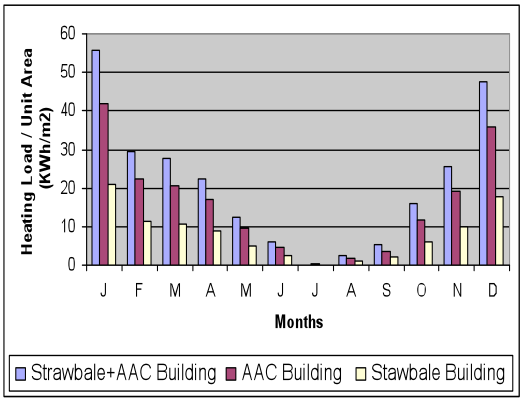


Fig 7. Comparing simulated monthly heating/ cooling loads for the three buildings shows strawbale to be the most energy-efficient building material.

As can be seen from the bar chart above, the monthly heating loads per square meter (kWh/m²) are lowest for the Strawbale building and highest for the Strawbale+AAC building; while those for the AAC building are in the middle. Additionally, the measured data charts show Strawbale to be the warmest building, followed by AAC; while the Strawbale-cum-AAC building is the coolest.

Since all three buildings have the same type of timber pitched roofs, the thermal behaviour of the hybrid-wall structure (where strawbale is combined with AAC) can be expected to be somewhere between the other two *i.e.* a strawbale structure and an AAC structure. The heating loads per unit area for the Strawbale building are lowest, which is expected from the temperature graphs for actual data as shown in Fig. 5. However, the loads for the other two building deviate from expectations in that the heating loads of the AAC structure are seen to be less than the hybrid one (Strawbale-cum-AAC). This can be explained simply by the fact that the AAC building had an additional layer of insulation in the form of AAC slabs under the pitched timber roof. This extra insulation has apparently contributed to lowering the annual heating loads for this building below expectations. Also, since the Strawbale-cum-AAC does not have any partition walls in the single space within that may contribute to its thermal mass, since the external wall composed mostly of strawbales does not contribute much in terms of thermal sink, heat retention is lesser in this building than the AAC one.

4. Conclusion

This paper has 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 strawbales with the weather proofing property of AAC blocks and the humidity regulating property of mud plaster in hybrid wall constructions can help us to produce buildings that are more thermally comfortable, cheaper to build and easier to maintain. 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.

5. References

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