THERMAL PERFORMANCE OF PLASTERED RICE STRAW BALES AND WALLS: A CASE STUDY

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ABSTRACT

Straw, as a fiber, has been used as part of building materials for several years. A carefully constructed straw-bale building has excellent thermal performance because of the combination of the high isolative value of the bales and the thermal mass provided by the thick plaster coating of the interiors. This paper addresses the thermal performance of rice straw bales and walls plastered with different cement plaster mixes. The plaster mixes are applied on straw bales of thickness 45 cm. A fire resistance test is conducted for two complete h°urs on the bales using direct flame after which the flame was discontinued. According to the test results, the mix with equal parts of cement and lime showed acceptable mechanical properties. This mix is chosen to be applied on a prototype straw bale wall compartment with an aim to evaluate the thermal performance of the plastered straw bale walls in arid desert climate at the hottest month of the year in Egypt. The straw bale wall test is undertaken by collecting actual measurements on site. Thermal sensors are installed on both external and internal sides of the wall to record the heat transmission through the plastered walls. The results showed that all the plastered bales survived fire penetration for the life period of the test. Increasing the lime content and decreasing the cement content of the mix raises the possibility of weak areas in the plaster of straw bale walls causing cracks during direct fire exposure. Similar width and density of the bales for all the specimen mixes didn't affect the heat transmission through the bales, which did not exceed 5.3°C in all samples. The site readings on the straw bale walls showed high range of temperature fluctuation on the external wall sensor, while in the internal wall sensor the temperature fluctuation was kept to minimum values. It was concluded that due to their high thermal insulation, straw bale structures require comparatively less energy to sustain thermal comfort conditions.

Keywords: exposure period, heat transmission, straw bale cement plaster mixes, thermal comfort, thermal performance.

1 INTRODUCTION

Due to their inherent properties, different building materials respond differently to climatic conditions. The thermal properties of building components such as walls, ceilings and floors together determine the energy consumption patterns and comfort conditions in an enclosed space. As a result, researchers tend to resolve the problem of thermal comfort in buildings constructed using various building materials, each according to the local climatic conditions.

1.1 Thermal comfort in different regions

In China there are hot humid summers and cold winters causing a need for efficient thermal comfort. Energy conservation in relation to thermal comfort has become a large issue here in the last several decades due to rapid economic and population growth. Researchers are now looking into ways to heat and cool buildings in China for lower costs and also with less harm to the environment [1].

In tropical areas of Brazil, urbanization is causing a phenomenon called urban heat islands (UHIs). These are urban areas that have risen over the thermal comfort limits due to a large influx of people and only drop within the comfortable range occurs during the rainy season. UHIs are caused by surface and atmospheric modifications from the overcrowding of people in an already hot climate [2].

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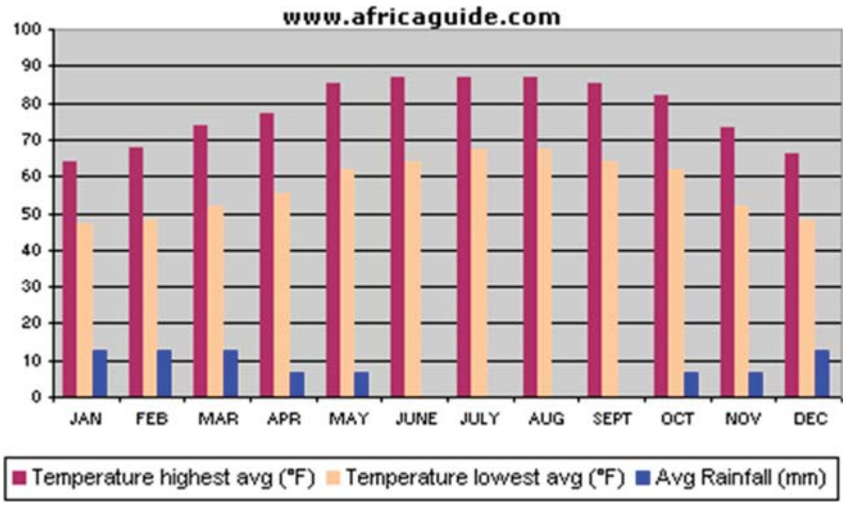

Figure 1: Climate chart for Cairo [4].

In the hot humid region of Saudi Arabia, the issue of thermal comfort has been important in mosques where people go to pray. There are very large open buildings that are used only intermittently making it hard to ventilate them properly. New designs have placed the ventilation systems lower in the buildings to provide more temperature control at ground level. Also new monitoring steps are being taken to improve the efficiency [3].

Most of Egypt is subtropical in nature, but the southern part of Upper Egypt is tropical. Northern winds temper the climate along the Mediterranean, but the interior areas are very hot. The temperature sinks quickly after sunset because of the high radiation rate under cloudless skies. Rainfall averages about 2 inches a year, but sudden storms sometimes cause devastating flash floods. Precipitation often approaches 8 inches annually on the Mediterranean coast. Hot dry sandstorms, known as Khamsin, come off the Western desert in spring. In Cairo (Fig. 1), average temperatures range from 7 to 29°C (45–85°F) in January, while July averages range from 21.6 to 35.5°C (71–96°F). Relative humidity varies from 68% in February to over 70 in August and 77 in December. The winter months are considered to be December, January and February [4].

Shebl [5] argued that the building performance in Egypt varies strongly with the outdoor climatic conditions because of the special impact of solar intensity, outdoor relative humidity and dry bulb temperature. Shebl investigated three different climatic conditions as representative of most Egyptian regions: Alexandria, situated at 31.12°N latitude and 29.53°E longitude; Cairo, situated at 30.13°N latitude and 31°E longitude; and Aswan, situated at 24°N latitude and 32.53°E longitude. These represent the climates of humid, hot dry and very hot dry regions, respectively.

1.2 Thermal performance of a material or building assembly

The U-value, or heat transmittance, of a material is the amount of heat transmitted per unit area of the material per unit temperature difference between inside and outside environments. The lower the U-value, the greater the insulation of the material. The inverse of U-factor is the R-value, which is the measure of how well a barrier resists the flow of heat. This is the unit we often use to represent the thermal performance of a material or a building assembly.

Several methods have been used to estimate the thermal performance, or R-value, of walls:

1. testing of walls using a hot-plate or thermal probe methodology;
2. testing of wall assemblies in a guarded hot-box facility;
3. monitoring of wall performance under ambient conditions;
4. modeling of wall performance using known or assumed physical properties of the materials; and
5. infrared thermo graphic imaging of in situ walls.

Researchers admitted that any of these approaches provide only an estimate. The actual R- value of wall systems vary with a number of factors. For straw bale walls these include the type of straw, the straw's moisture content, density and orientation of the fibers, the type and thickness of plaster applied and other factors [6].

Straw bales, because their width is around 450 mm, have a U-value of 0.13, which is considered a high insulation value [7].

1.3 Straw bale fire resistance rating

Building codes express the fire safety of walls as a function of fire *resistance*, meaning how long a conflagration can exist on one side of the wall in question before enough heat is transmitted through the wall to ignite materials on the other side, even if fire has not actually breached the wall. Fire requires high temperature, fuel and oxygen; compressing the straw into a dense block dramatically decreases the ability of oxygen to feed a fire at the straw. After the surface of a bale or bale wall has been charred (providing that the wall of exposed bales remains intact), the worst it will generally do is smolder. This resistance to rapid combustion has been observed during a few accidental fires during construction of bale buildings [8].

In general, most of the reported ASTM E-119 lab fire tests verified that once a bale wall has been plastered on both faces, the combination of an incombustible surface and an insulating interior that neither burns well nor melts makes a straw bale wall a very fire-resistive assembly [9].

Plastered straw bale walls have a 1-hour fire-resistance rating provided the components of the wall fit within the following parameters:

1. bales may be laid flat or on-edge;
2. the bale wall must have a minimum un-plastered thickness of 304 mm;
3. bales may be installed in a running bond or stack bond;
4. the wall must be finished on both sides with a plaster of any type allowed in the appendix of the California Building Codes draft [6].

2 METHODOLOGY AND SCOPE

This research is based on the results derived from a series of mechanical tests applied on cement plaster mixes of various proportions presented in Garas et al. 2008 [10] and 2009 [11]. The plaster mixes were tested to examine their performance in compression, modulus of elasticity (MOE) and modulus of rupture (MOR) as well as their resistance to fire exposure for 2 hours. According to the results of the lab tests the most appropriate mix was chosen to be applied on a full scale prototype straw bale building constructed on the 6th of October governorate to test its thermal performance under local climatic conditions. This area of Egypt represents the humid, very dry but stormy climate in New Cairo City.

2.1 Tests on cement plaster mixes

Structural tests were applied on standard cubes of four comparable plaster mixes as described in Garas et al. 2008 [10]. The samples of mixes tested included:

- Mix A. 1:3 Cement:Sand
- Mix B. 1:1:6 Cement:Lime:Sand
- Mix C. 1:2:9 Cement:Lime:Sand
- Mix D. 1:3 Lime:Sand

The study showed that by increasing the lime content for the same cement content in the mix the compression strength and the MOR decreases dramatically for all mixes cured after 28 days in water tanks. Also the mix containing sand and lime only (Mix D) with no cement showed very low results of compression; so it was excluded from further tests on cement plaster mixes.

The fire test on the three remaining cement plaster mixes provided a relative measure of the fire-test-response under the same fire exposure condition. The cement mixes described previously were applied to straw bale specimens using hand trowels in order to get a uniform thickness of 2.5 cm for each coat above the bale's skin. Samples were then cured by wetting twice daily for a period of 7 days after which they were covered with plastic sheets to maintain humidity. The samples were left to dry and sit for 36 days prior to testing. The cement mixes were applied with a constant layer of 5 cm thickness on all sides of the local rice straw bales of density 86 kg/cm^3 and moisture content of 19%. The straw bales (dimensions: 1.0 * 0.5 * 0.45 m, length * height * width) were prepared and tied with two polypropylene ties per bale. The samples were covered from all faces with galvanized reinforcing steel mesh with adequate overlap. The steel mesh was fastened to the bales' skin using curved steel pins. All the bales were local rice straw bales from the same supplier and were subjected to the same environmental conditions.

Fire exposure was maintained using a direct flame of the same source under atmospheric temperature. This exposure condition is not representative of all fire conditions applied in the standard fire tests because conditions vary with changes in the amount, nature and distribution of fire loading, ventilation, compartment size and configuration. Variation from the test conditions or specimen construction, such as size, materials, method of assembly, also affects the fire-test-response. The fire test was applied on single plastered bales under no compression and all specimens were tested for a complete 2-hours direct flame exposure after which the test was ended. The test standard does not provide information as to performance of specimens constructed with components or lengths other than those tested [11].

2.2 Thermal performance of rice straw bale plastered walls

Based on the results of the fire resistance test and the mechanical lab tests conducted by Garas [10, 11], mix C consisting two parts of lime and one part of cement that showed the appearance of weak points resulted in cracks under fire exposure and was excluded from field applications.

Figure 2: Sensor installed on the wall inside the building compartment.

Mix A also was excluded as it was uneconomic due to the high content of cement and could increase the possibility of cracking problems, although it passed all structural and fire tests. Mix B consisting of cement, lime and sand (1:1:6), which showed high workability performance as well as best economic indicators, is applied on the external and internal walls of a straw bale building erected in an arid desert area in Egypt. The plaster is applied on two coats of 2.5 cm each. The bales used in this research are rice straw bales of nearly similar dimensions – 1.0 m length, 0.45 m width and 0.5 m height – and were tied with two polypropylene strings. All specimens were laid flat and erected over each other in a running stacked bond, where each bale overlapped the two bales beneath it.

Two thermal sensors are stuck on the internal and external walls of each of the four main directions of the straw bale compartment (Fig. 2). The readings were recorded continuously for 12 executive days in the hottest month of the year (July).

The main aim was to measure the thermal performance of the plastered straw bale walls using the chosen plaster mix B under actual climatic conditions. It is out of the scope of this research to study the humidity of the plastered straw bale walls although it is recorded by the sensors and shown in all graphs.

3 RESULTS AND OBSERVATIONS

3.1 Fire test results

Garas et al. 2009 presented that the surface of all specimens that were directly exposed to the hose of the flame maintained the conflagration for the 2 hours without heat transmission through the wall to ignite the material on the other side.

The specimen with the highest lime content, Mix C with cement:lime:sand in the ratio of 1:2:9, developed a visible crack at the specimen highest corner above the exposed area after 25 minutes (Fig. 3). The crack increased in size by the time and smoke was visible coming out of it (Fig. 4). Hair cracks appeared on the exposed side of the specimen after about 90 minutes of the continuous flame

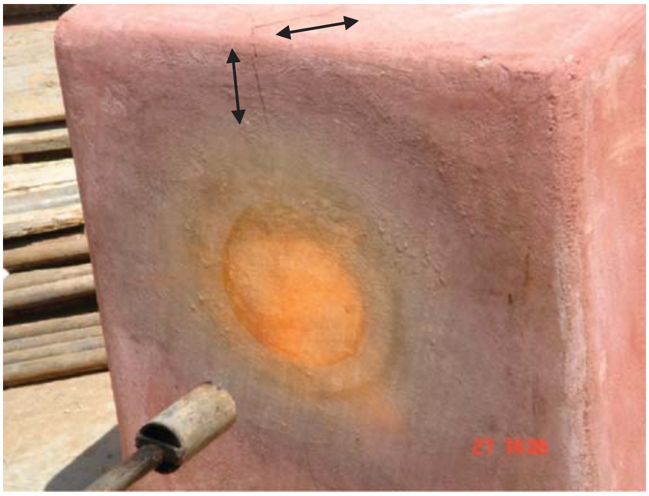

Figure 3: The appearance of a narrow crack on Specimen Mix C after 25 minutes.

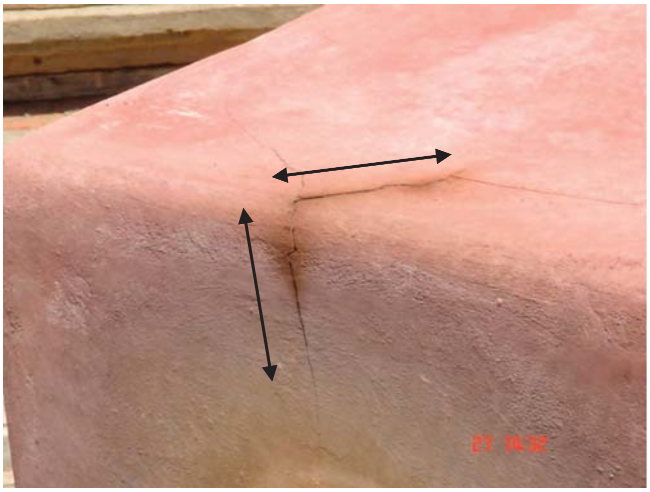

Figure 4: The increase in the crack width in specimen of Mix C after 1 hour.

exposure (Fig. 5). The smoke coming out of the upper crack was extinguished with water at the end of the test (Fig. 6). After 9 hours of the test completion the specimen was still smoking, which required complete soaking down of the specimen.

The atmospheric temperature at the beginning of the test for specimen one was 33°C and ended at 38°C as recorded by the sensor on the opposite side of the flame on specimen Mix C. The temperature increased gradually during the total life time of the test to record a total increase of 5.3°C.

The specimen of Mix B, with a lime content half that of Mix C, continued for the two hours of the test and no cracks were noticed till the end. The maximum temperature increase transferred through the specimen width was about 5.3°C during the two hours. The specimen Mix A, without

Figure 5: The cracks of the exposed area of specimen Mix C after 90 minutes.

Figure 6: The specimen Mix C after 2 hours.

any lime content, showed no signs of minute change during the overall life of the test. The sensor showed the same amount of temperature increase throughout the total exposure of specimen Mix A. However, some fluctuation in the sensor readings were recorded after one and a half hour of the test life time due to the increase in wind speed and lasted for about ten minutes.

3.2 Thermal performance of the straw bale walls.

The field in situ temperature readings in each couple of sensors installed internally and externally in the four main directions of the plastered straw bale compartment showed comparatively similar

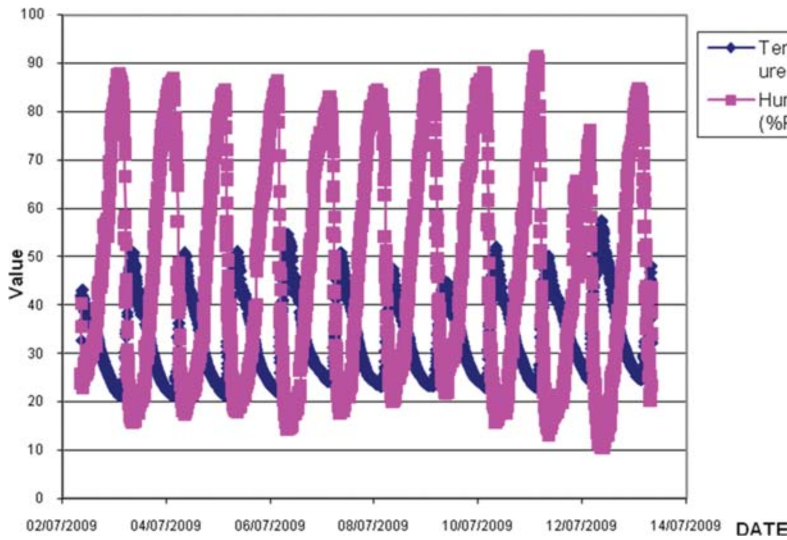

Figure 7: External eastern wall temperature results.

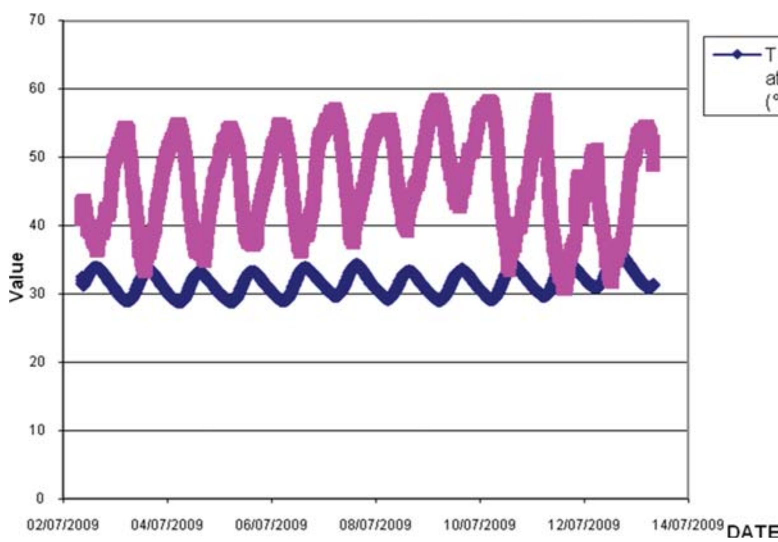

Figure 8: Internal eastern wall temperature results.

results. The recorded readings of the internal and external sensors are represented in Figs 7–10, for the 12 days at the eastern and western directions, respectively. The daily external temperature readings showed great difference between day and night: the minimum difference was 20 degrees while the maximum was 33 degrees. For the same days, the minimum difference in recorded temperature readings for the internal wall was 3 degrees and the maximum was 5 degrees only.

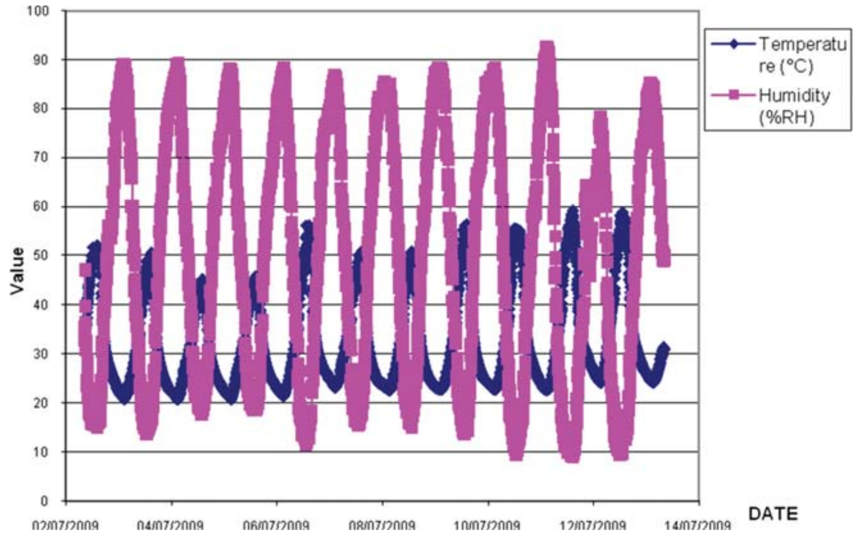

Figure 9: External western wall temperature results.

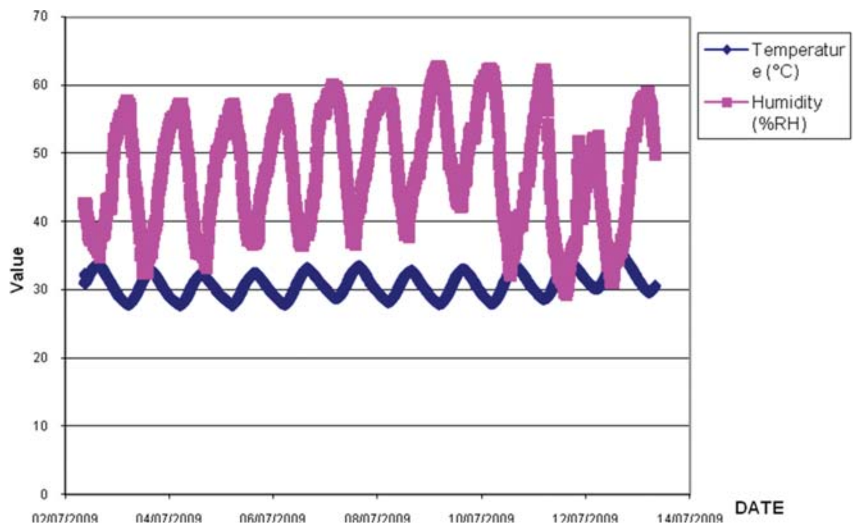

Figure 10: Internal western wall temperature results.

Table 1 presents the readings of the sensors installed in the east direction of the compartment wall recorded for 7 executive days from the 3rd of July till the 9th of July as a sample of the 12 days' readings.The data presented in Table 1 represents the readings at 6.00 am, 6.00 pm, 12.00 am and 12.00 pm. Also the maximum temperatures plotted by the sensors internally and externally for the 7 days under study were presented although these readings were taken at various times of the day. The difference between the maximum temperatures externally and internally ranged between 11 and 18°C.

Table 1: The temperature readings of the sensors for seven consecutive days.

Internal wall	External wall	Difference	Date	Time	Remarks
33.6	31.7	–1.9	7/3/2009	0:00	Max external temp. = 50.9
31.1	24.2	–6.9	7/3/2009	6:00	
29	26.7	–2.3	7/3/2009	12:00	Max internal temp. = 33.6
31.5	41	9.5	7/3/2009	18:00	Difference = 17.3
33.6	31.6	–2	7/4/2009	0:00	Max external temp. = 50.8
30.6	23.3	–7.3	7/4/2009	6:00	
28.8	25.6	–3.2	7/4/2009	12:00	Max internal temp. = 33.2
31.6	42.9	11.3	7/4/2009	18:00	Difference = 17.6
32.8	31.1	–1.7	7/5/2009	0:00	Max external temp. = 51.0
30.4	23.8	–6.6	7/5/2009	6:00	
28.8	38.1	9.3	7/5/2009	12:00	Max internal temp. = 33.3
31.7	43.3	11.6	7/5/2009	18:00	Difference = 16.7
33	32	–1	7/6/2009	0:00	Max external temp. = 52.8
30.7	24.6	–6.1	7/6/2009	6:00	
29	36.2	7.2	7/6/2009	12:00	Max internal temp. = 33.9
32.3	44.9	12.6	7/6/2009	18:00	Difference = 16.7
33.5	32.1	–1.4	7/7/2009	0:00	Max external temp. = 50.9
31.5	26.7	–4.8	7/7/2009	6:00	
29.8	26.6	–3.2	7/7/2009	12:00	Max internal temp. = 34.2
31.6	43.7	12.1	7/7/2009	18:00	Difference = 16.7
33.8	31.6	–2.2	7/8/2009	0:00	Max external temp. = 47.4
31.1	24.6	–6.5	7/8/2009	6:00	
29.3	26.7	–2.6	7/8/2009	12:00	Max internal temp. = 33.4
31.6	39.7	8.1	7/8/2009	18:00	Difference = 14.0
33.1	30.6	–2.5	7/9/2009	0:00	Max external temp. = 44.9
30.7	24.4	–6.3	7/9/2009	6:00	
29.1	30.7	1.6	7/9/2009	12:00	Max internal temp. = 33.5
32.1	40.1	8	7/9/2009	18:00	Difference = 11.4

4 DISCUSSION

4.1 The experimental tests on plastered bales

The fire experimental test was conducted to monitor and describe the behavior of various cement plaster mixes applied as a layer of 5 cm thickness on rice straw bales after exposure to heat and flame under controlled conditions. The results of this test are one factor of several others used in assessing predicted performance of actual cement plastered straw bale walls.

Cracks initially appeared at the weak corner of specimen C with highest lime content while by decreasing this component and increasing the amount of cement in the mix no cracks were noticed.

Although smoke was emitted from the crack of the weak point in mix C no heat transmission adequate to ignite materials on the opposite side of the straw bales was noticed throughout the total life time of the test. The test is regarded successful as all specimens sustained the two hour direct fire exposure without passage of the flame or even gases hot enough to ignite the internal straw to reach the opposite side of the plastered bale.

Transmission of heat throughout the width of the specimens with three different mixes did not exceed 5.3°C above its initial temperature when measured from the unexposed surface opposite to the flame. This indicates that the components of the plaster mixes do not affect the transmission of heat through the bale. The width and density of the bales, which remained constant for all the specimens, is considered to be the main guiding factor for heat transmission.

4.2 In situ thermal performance tests on the plastered straw bale walls

The great fluctuation in the daily readings of the external sensors between morning and nights indicates that the location chosen to undertake this experiment presents one of the toughest climatic conditions that a straw bale building can undergo. The difference in the readings of the external and internal sensors at the same specific time highlights the great insulation performance of the plastered rice straw bale walls. This means that the temperature gained by the walls from the hot medium outside the compartment to the cool medium where the occupant lives requires a period of time long enough to provide thermal comfort. On the contrary, the slow loss of the temperature gained by the internal walls is considered a disadvantage of the straw bale building in summer while it's an advantage in winter. This fact is expressed by the negative results presented in Table 1. The maximum temperatures recorded by the external sensors were noticed between 3.30 and 4.00 pm, while the maximum recorded data by the internal sensors took place between 9.30 and 11.00 pm. During the afternoon when the atmospheric temperature reaches its maximum values the external walls gain this heat. However, due to the high insulation performance of the 0.45 m plastered straw bale walls this heat takes a long time to be partially transmitted to the internal face of the wall. The heat transmission reaches its maximum at night, after which the walls begin to transmit the heat gained back to the outer medium.

5 CONCLUSIONS

1. Increasing the lime content and decreasing the cement content of the mix raises the possibility of weak areas in the plaster of straw bale walls causing cracks during direct fire exposure.
2. The variance in plaster mix components does not greatly affect the heat transmission through the bale and accordingly throughout the wall constructed using straw.
3. The width and density of the bales for all the specimen mixes are responsible for the high insulation performance of those bales.
4. The fire test results on the plastered bales meet the conditions of acceptance of the ASTM E119 for testing bearing walls and partitions taking into consideration that the test was applied on single cement plastered bales. Previous tests conducted by Garas et al. 2008, on the same group of mixes to examine its compressive strength, MOR and MOE were in favor of mixes A and B indicating higher efficiency by increasing the cement content and decreasing the amount of lime in the mix [10].
5. The great insulation performance of the plastered rice straw bale walls was emphasized by a homogenous flow for the internal temperature readings throughout the whole 24 hours, while for the external temperature flow, the readings showed a wide range that reached up to a 30 degree difference during the same days.
6. In arid desert areas (such as the 6th of October Governorate-New Cairo City), the slow loss of the heat gained during winter mornings by the internal straw bale walls is considered to be of great advantage for the occupants of plastered rice straw bale houses, whereas in summer times,

the slow gain of the heat from the outer environment during morning time is also considered an advantage to these buildings and vice versa.

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