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Characterization and Thermal Performance of a Compressed Earth Construction System for Improving Comfort and Achieving Energy Savings

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ABSTRACT: Earth has been used historically as a construction material in various regions and cultures for thousands of years. The primitive earth structures consisted mainly of simple wooden frames covered with mud. Earth constructions are usually built in locations where other construction materials are relatively scarce. The process of its fabrications consists of sun-dried mud or adobe bricks with organic material and sometimes require stabilization using lime, cement or sand. A variation of a typical adobe construction is by using compressed earth and straw, and this process can change the material´s nature and physical properties, among other features. The objective of this research is to characterize an experimental prototype built with a manually compressed poured earth construction system (MPE) and compared with a conventional industrialized system (CIS). The dimensions of the two prototypes are 3 meters length, 3 meters width, and 2.40 meters height Important advantages of the earth prototype investigated included its low ecological footprint, low embodied energy and low cost. Then results showed that the MPE presented better thermal performance than the CIS and the economic analysis proved that the MPE prototype has a low-cost to construct relative to the CIS. Likewise, the sustainable analysis realized demonstrated that MPE is a prototype with high potential for implementation in communities aimed at achieving a nearly zero environmental impact. It is expected that the results of this research can be served as a demonstrative example and be applied to generate a multiple effect in other similar regions and that this approach can improve the environment and the quality of living.

Keywords *Thermal comfort, low-cost housing, earth construction, energy savings, sustainability.*

1. INTRODUCTION

Earth has been used as building material since early times in history. Certainly, earth is one of man's oldest building materials and most ancient civilizations used it to some extent and in a wide variety of applications, frequently in relationship and harmony with the local climatic conditions. It is a construction material easily available, cheap, strong and required only simple technology. It also has a good thermal mass or thermal inertia properties, which makes it ideal to be used as modulator of the temperature differential between the exterior and interior of a building. For example, in Egypt the grain stores of Ramasseum built in adobe in 1300 BC still exist; the Great Wall of China has sections built in rammed earth constructed over 2000 years ago. Other successful examples of earth buildings can be found in Iran, India, Nepal, Yemen, Alhambra, among others, which have examples of ancient cities and large buildings built in various forms of earthen construction (Figures 1, 2). It is worth mentioning that earth wall constructions have more heat capacity and thermal inertia and lower conductivity than concrete walls. The earliest permanent dwellings yet discovered are found in the Middle East, China, and the Indus Valley. Jericho, which dates back from 8300 B.C., is the earliest city in the world with constructions made of earth. As early as 11, 000 year ago, the Jericho inhabitants built their dwellings made of oval, hand- formed, sun-dried brick using wooden moulds. Incidentally, the word "adobe" comes from the Arab word "toub", which means brick. Other historical application of rammed earth are found in Caral, Perú, the oldest city in America (3000 BJ); the Great Pyramid of Cholula, Puebla, Mexico (700 AJ), which is the world´s most voluminous pyramid; the Prehistoric City of Paquimé in Chihuahua, Mexico (1200 AJ) had up to four stories totally built of earth (Figures 3, 4 and 5). The Djenné Mesquite is the largest adobe building with its original use, built from 1180 to 1330) It was declared World Heritage by the UNESCO in 1988 (Figure 6).

Figure 1. Great Wall of China. Some sections Built of rammed earth. Construction began around 220 B

Figure 2. View of the City of Shibam Yemen. Multi-story natural earth high rise buildings 500 year old. The oldest skyscraper in the world. UNESCO World Heritage from 1982

It is noteworthy that the oldest remaining examples of this building form using earth as the main construction material are in located in hot arid areas of the world. The strength of unstabilised earth walls comes from the bonding effect of dried clay. If the structures don not have a suitable water protection systems integrated, they might be wet and the structural strength can be lost and the construction can be eroded and fail. However, different countries have approaches and corrective alternatives to solve and avoid this problem.

Figure 3. Caral City, Perú (3000 BJ).

The oldest city in America

Figure 4. The world´s most voluminous pyramid made of adobe. Cholula, Puebla, Mexico (700 AJ)

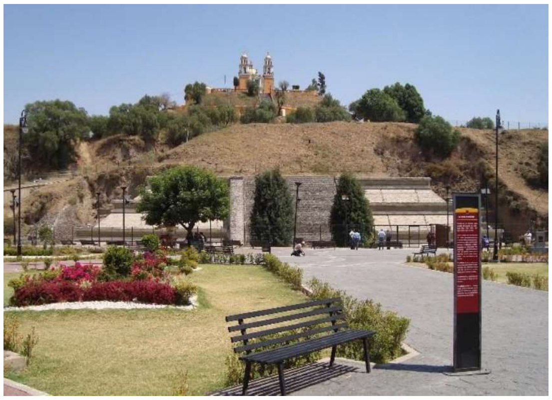


Figure 5. City of Paquimé. Chihuahua, Mexico. The world´s most voluminous (1200 AJ). Earth buildings up to five stories Made of earth

Figure 6. Djenné Mesquite, Mali. The largest building made of earth with its original use today (1240 AJ)

2. IMPORTANCE OF THERMO PHYSICAL PROPERTIES OF EARTH

The thermal-physical properties of earth are useful for application in buildings, particularly if they are located in climatic regions with large temperature swings. The time delay due to the thermal mass of the earth is known as a time lag. The thicker and more resistive the material, the longer it will take for heat waves to pass through. The reduction in cyclical temperature on the inside surface relative to the outside surface is known as the decrement factor, that is the ratio of maximum indoor temperature to maximum external temperature. Thus, a material with a decrement value of 0.5 which experiences a 20 K diurnal variation in external surface temperature would experience only a 10 K variation in internal surface temperature. Due to these properties, the use of earth is suitable alternative, particularly in climatic region which temperature swings are above 10K. Therefore, the use of the thermal properties of earth is a suitable passive cooling and heating strategy to contribute to provide thermal comfort conditions to building´s occupants (García Chávez, 2013, 2015)

3. USING EARTH AS SELF-CONSTRUCTION MATERIAL FOR LOW-COST HOUSING

Earth has been used as self-construction system through the empirical knowledge and technology transfer developed over generations in different climatic regions of the world.

In Mexico, the use of earth for self-construction has been a valuable approach to reduce the house deficit.

However, there have been a number of misconceptions that have prevented to widely promote and apply their advantages. At present 63% of dwelling are built with self- construction in the country. Nevertheless, most of the houses are built with cement and concrete as well as stainless steel bars, as the basic construction materials. Currently, 90% of housing construction in the country based its construction in cement and concrete, particularly in the walls, the use of concrete blocks is widely extended in the Mexico. Nonetheless, this use involves a high energy consumption and huge emission of CO2 and other greenhouse gasses (GHG) to the atmosphere, provoking a severe environmental damage at global levels and the distortion of our natural balance resulting in destructive effects in the planet such as the global warming and climate change, deforestation, ozone layer destruction, among others (IPCC, 2014). Therefore, it is important to find alternatives to this situation and the use of earth for the construction of houses and buildings becomes a promising alternative to solve this problem and its consequences.

3.1 The Role of the Building Envelope Relative to the Local Climate Conditions

Nowadays, most modern buildings incorporate architectural styles and materials that ignore the local climate as well as its cultural and traditional factors. This is the predominant case of many contemporary buildings located in different climate regions. As a result, such buildings are highly dependent on mechanical and electrical systems to control the indoor environment. This situation causes the consumption of large quantities of energy and thus high running costs for both artificial lighting and air-conditioning systems (AC), associated with problems of occupants' discomfort, both hygrothermal and visual, among others. Therefore, the climate plays an important role in the performance of a building and it is crucial the strategies selected from the conceptual stage of the design to the construction, such as orientation, solar control and natural ventilation, among others. Under this approach, the envelope of the buildings plays a fundamental role, and the use of earth in walls can provide significant benefits and advantages to achieve indoor hygrothermal comfort conditions of the occupants and to reduce the energy consumption for the climatization of the architectural spaces.

4. OBJECTIVE OF THIS RESEARCH

The objective of this research is to analyse, evaluate and characterize an experimental prototype built with a manually compressed poured earth construction system (MCE) and compared it with a conventional industrialized system (CIS), aimed at demonstrating that the utilization of MCE system can offer better thermal, economic and environmental conditions than CIS. Previous studies have reported the benefits of using compacted poured earth as the basic material for low-cost housing (Guerrero et al, 2015; Gernot, 2006, 2012).

5. CASE STUDY PROTOTYPES

The case study of this research is located in a typical rural community in the State of Puebla, Mexico. The climate in this location is temperate with high diurnal and seasonal temperature swings, and an annual mean dry bulb temperature (DBT) of 15.7 °C; an annual minimum DBT of 10.3 °C; an annual maximum DBT of 21.1 °C (Figures 7 and 8). Annual rainfall in the location is 727.9 mm. Average annual solar irradiation is 623 Watts/m^2.

Figure 7. Annual Dry Bulb Temperatures

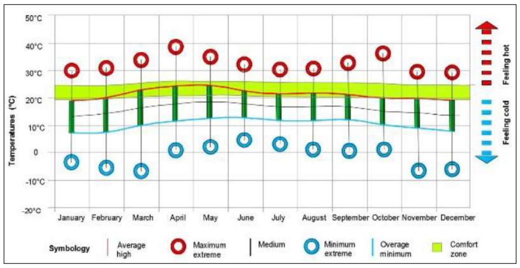
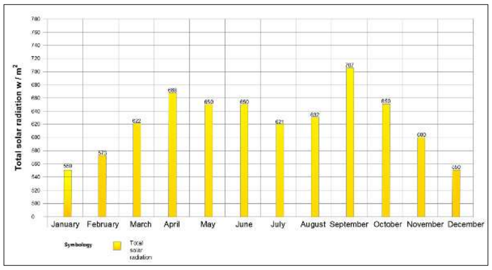


Figure 8. Annual Solar Irradiation



5.1 Construction Process of the Prototypes

The construction configuration of each the two prototypes consisted of the following dimensions: 3 meters long by 3 meters wide and 2.4 meters high. The aim was to evaluate the thermal performance of the MCE system relative to the CIS system. Both prototypes were made with the same thickness in walls (0.23 meters), same thickness in roofs (see construction system in Figures 11 and 12), with the same interior air volume; doors and windows. Therefore, the geometry and dimensions, position and materials were the same on both prototypes but the walls, which for the MCE were made of manually compressed poured earth and for the CIS, walls of conventional concrete blocks. Therefore, the only variable in both prototypes was the material of the walls. The construction process is shown in Figures 9, 10, 11, 12 and 13)

Figure 9. Construction process of the walls of concrete blocks

Figure 10. Construction process of the prototype with with walls of manually compressed poured earth

Figure11. Roof detail of CIS

Figure 12. Roof detail of MCE

Figure 13. View of the two prototypes completed

The construction of both prototypes was made with materials from the region, based on earth, and wood in roofs; and doors and windows, were also made of typical local materials, characterized to be very economical with important sustainable advantages and low energy embedded properties.

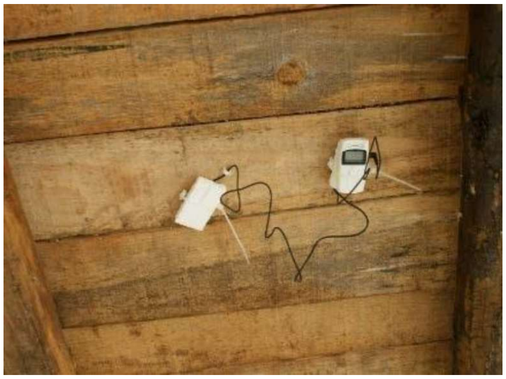
6. METHODOLOGY AND DEVELOPMENT OF THE EXPERIMENTAL WORK

The methodology of this work consisted of construction of the two prototypes with highly controlled procedure so that both had the same physical characteristics with the only variable being the wall. The monitoring of the internal temperatures and relative humidities took place after one month so that the two prototypes were completely dry. There were two representative monitoring periods, during the underheating, from April 10 to April 29, 2016 and the overheating, from May 29 to June 3, 2016. Six data loggers were placed in each of the two prototypes, five to register surface temperatures of each orientation (north, east, south and west), and the ceiling, and one for ambient temperatures in the middle of the experimental spaces. Intervals were at 30 minutes. During these monitoring periods the two prototypes were closed with practically no air changes (Figures 14 and 15). External temperatures were also recorded concurrently with the monitoring of the two prototypes.

Furthermore, questionnaires were applied to a representative group of people to determine their perception of the thermal comfort conditions inside the two prototypes.

Figure 14. View of data logger to measure surface surface temperatures

Figure 15. View of data logger to temperatures measure on the timber ceiling



7. ANALYSIS OF RESULTS AND INTERPRETATION

During a typical overheating day (April 12, 2016) with a maximum external temperature of 28.5°C and a minimal external temperature of 18.5°C, that is a 10 K temperature swings, the MCE had a minimum dry bulb temperature (DBT) of 20°C and a maximum of 26°C, then the time lag was 3.5 hours, with a decrement factor of 0.91, whereas the CIS had a minimum DBT of 20.5°C and a maximum DBT of 26°C (Figure 16). Although the time lag of both prototypes was similar during the hours of lower external temperatures, the ambient temperature in the MCE were higher than in the CIS and lower during the hours with higher temperatures.

Figure 16. Thermal performance of MCE and CIS prototypes

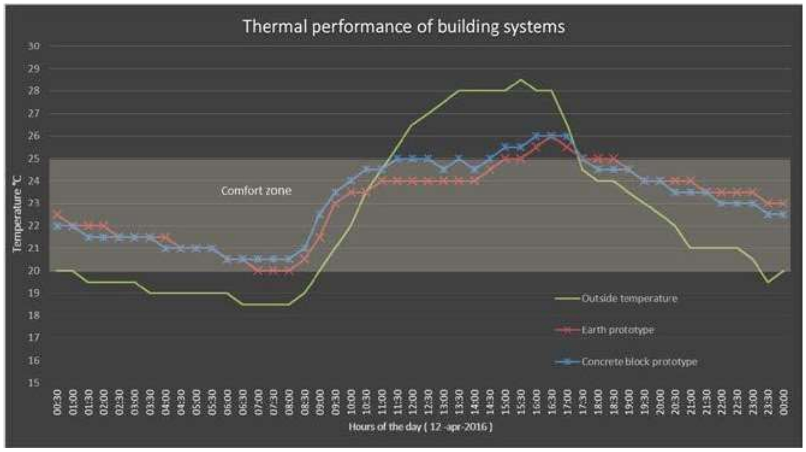
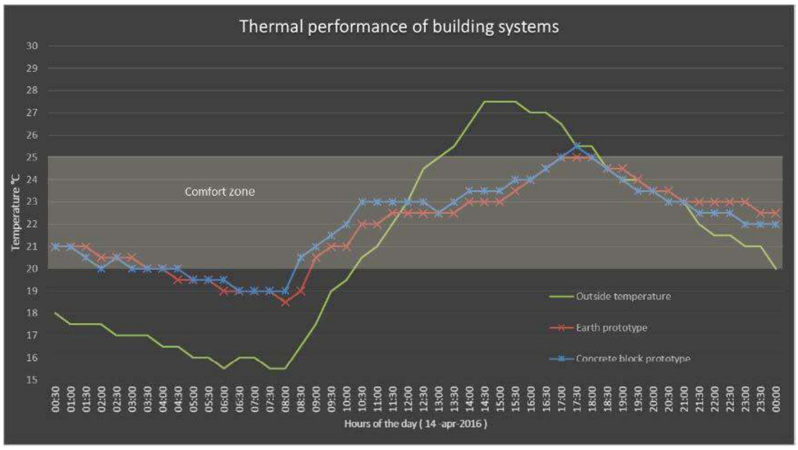
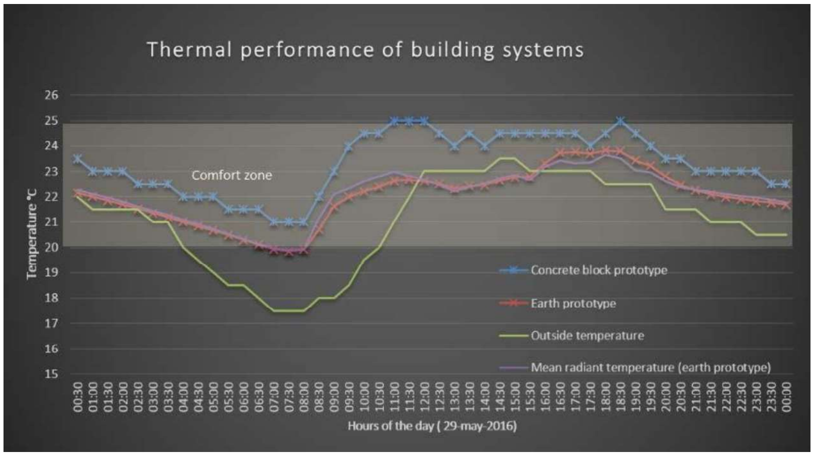


Figure 17. Thermal performance of MCE and CIS prototypes



The thermal performance of the MCE relative to CIS systems is shown in Figure 17, with a maximum external temperature of 27.5°C and a minimal external temperature of 15.5°C, that is a 12 K temperature swings, the MCE had a minimum DBT temperature of 18.5°C and a maximum DBT of 25°C, then the time lag was 3.5 hours, with a decrement factor of 0.90, whereas the CIS had a minimum DBT of 19°C and a maximum DBT of 25.5°C (Figure 17). In this case, the same situation as in the previous case can be observed as the time lag of both prototypes was rather similar during the hours of lower external temperatures, the ambient temperature in the MCE were higher than in the CIS and lower during the hours with higher temperatures. This situation reveals that the MCE prototype has a better thermal comfort than CIS system. It is worth mentioning that the application of questionnaires has shown that most of the thirty people who participated entering in both prototypes perceived the indoor conditions of the MCE experimental prototype as more comfortable under overheating and underheating conditions relative to the CIS prototype.

Figure 18. Thermal performance of MCE and CIS prototypes with radiant temperatures



During the last stage of the experimental work, the indoor radiant globe temperatures (RGT) were recorded concurrently with the ambient dry bulb temperature in the MCE prototype, using a digital globe thermometer. Figure 18 shows that a maximum external temperature of 23.5 °C and a minimal external temperature of 17.5°C, that is a 6 K temperature swings, the MCE had a minimum DBT temperature of 18.5°C and a maximum DBT of 25°C, then the time lag was 6 hours, with a decrement factor of 1, whereas the CIS had a minimum DBT of 21°C and a maximum DBT of 25°C (Figure 17). In this case, the same situation as in the previous case can be observed as the time lag of both prototypes was rather similar during the hours of lower external temperatures, the ambient temperature in the MCE were higher than in the CIS and lower during the hours with higher temperatures. However, it is significant to notice that the RGT recorded followed the DBT during the hours after midnight up to 8 am when the later increased until midday, then both temperatures were similar until 3:30 pm where RGT started to be lower until 5 hours later, that is, 8:30 pm, then both temperatures had similar behavior until midnight. It is important to clarify that the civil time in the location is 1 hour and 36 minutes ahead the solar time, this is the reason why the occurrence of the maximum and minimum temperature conditions reported in both prototypes have a time offset of that period of time.

As to the results of the RGT relative to the DBT in the MCE prototype, it is clear that the radiant temperature is more closely related to the perception of occupant's thermal comfort in the MCE relative to the CIS prototype. Other studies have shown that human body is more sensible to mean radiant temperature than to dry bulb temperatures. This situation also demonstrated that the MCE prototype has a better thermal comfort perception than the CIS prototype. Furthermore, the application of the questionnaires has also shown that, most of the thirty people who participated entering in both prototypes perceived the indoor conditions of the MCE experimental prototype as more comfortable under overheating and underheating conditions relative to the CIS prototype.

8. ECONOMICAL ADVANTAGES AND BENEFITS OF THE MCE SYSTEM RELATIVE TO THE CIS

A cost analysis carried out for both prototypes have shown that the MCE is 40% cheaper than the CIS system, this is because the earth with which it is made was taken from the same construction place, therefore, had practically no cost, unlike the CIS, where the cost of each block carries the cost of manufacture, storage, transport and sale of each piece. Other items that increase the cost of CIS and make it more expensive compared to MCE, are the materials used for bonding the blocks and, besides, the construction time of this later is longer. It is also important to note that in this cost analysis the price of natural paint that was applied to both prototypes, was very low as the materials used included natural lime, nopal mucilage and water, widely abundant in the location. Furthermore, the expected better thermal performance and low environmental impact of MCE using earth, make it a more suitable bioclimatic and sustainable building alternative (Guerrero, 2014; Hall et al, 2012; Kwok et al, 2014). Besides, the by using the new available technology and optimized materials based on earth properly treated, modern buildings can be better built with a sustainable approach.

9. CONCLUSIONS

The earth used for the construction of the MCE prototype was taken directly from the same site where it was built, thus reducing the environmental impact and the ecological footprint relative to the CIS. From the economical point of view, the MCE prototype was 40 cheaper than the CIS one. Furthermore, earth is 100% recyclable and concrete used in blocks for the walls is not. Even though the thermal advantages of MCE compared to CIS prototype was not significant, its lower cost and environmental attributes make it a more suitable sustainable alternative. It is also important to mention that the position and thickness of the blocks used in the walls of prototype CIS are not found in most housing units in the country and these conditions were chosen to have the same dimensions as the MCE prototype. It is expected that the results of this research work can be applied in locations either with temperate or with hot arid climate conditions as the larger the temperature swings of the site the more evident the benefits of utilizing the earth with its implicit thermal properties aimed at improving the indoor comfort conditions of building occupants as well as the environment, the economy and the quality of living.

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