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Adobe as a Sustainable Material: A Thermal Performance

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Abstract: Sustainable construction is achieved using natural resources, such as adobe, in such a way as to meet economic, social and cultural needs, but not depleting or degrading these resources to such an extent that they cannot meet these needs for future generations. Earth is a cheap, environmentally friendly and abundant building material and has been used extensively for construction around the world. Today the prevalence of earth as a building material may be attributed to its proven durability demonstrated by the number of ancient earthen buildings that remain standing today. Scientific work have demonstrated that adobe has low thermal conductivity and high heat capacity enabling earthen building thermal stability compared with concrete building. Computational fluid dynamics has been proposed as a new tool to study the thermal behavior of earthen building.

Key words: Adobe, low thermal conductivity, sustainability, earth building

INTRODUCTION

At the World Summit on Sustainable Development in Johannesburg, 2002, the world's nations reaffirmed their commitment to support sustainable development. Sustainability is not only satisfying present needs, but also ensure future generations can satisfy theirs. This includes socio-economic and environmental targets and is a concern to all sectors of human activity and development and housing is one of the more energy demanding sectors (Viviancos *et al*., 2009; Martin *et al*., 2010). Throughout a buildings lifetime (construction, use, dismantling), it has a direct impact on the environment through resource and energy consumptions. Some reasons for green building include reducing energy consumption, greenhouse gas emissions, water use, waste production and many more. The environmental impact of a building depends on the choices made during the different phases of a building's life, specifically; the choice of construction materials has a strong environmental impact. As mention above, selecting a material with a Low Life-Cycle Cost (LCC) and high technical performance reduces the building's impact on the environment (Collet *et al*., 2006).

Our ancestors had the same request for comfort that we have today, but without the availability of cheap plentiful energy resources that we now rely upon. Buildings and houses in particular, were constructed from locally available materials. Adobe bricks made from straw and unbaked clay were commonly used in many regions of the world. However, the use of the adobe bricks began to decline at the end of the 19th century, when the abundant supply of cheap manufactured construction materials began. A renewed interest in earth construction began during the oil crises of the 1970's, due to their lower demand for energy during fabrication and because in climatic regions where they had been traditionally used, provided a basic standard of thermal comfort (Alva-Balderrama, 2001; Parra-Saldivar and Batty, 2006). As a result, studies have been conducted to identify other factors that may explain adobe's excellent behavior as a heat moderator. In this study, some historic facts, concerning with earth construction, are presented along with scientific results on the matter. Finally some future trends to study thermal properties of earthen construction are proposed.

DEFINITION

Adobe is a common prehistoric building material, widely distributed in arid and semi-arid lands where other construction materials are scarce. Generally adobe is non-fired sun-dried mud bricks mixed with organic material and may be stabilized with lime or cement. A variation of adobe is the compressed earth which consists in monolithic masonry units made with earth and straw where consolidation is achieved by mechanic means without chemical processes that change the material's nature (Jimenez-Delgado and Canas-Gerrero, 2006).

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EARTH CONSTRUCTION AROUND THE WORLD

Earth has been used as a construction material for thousands of years (Hall and Djerbib, 2004) with its most primitive form dating back to the nomadic years where humans lived a migratory life and often constructed temporary seasonal shelters from brush and wooden frames covered with mud (McHenry, 1984). The walls of Jericho in Palestine (9000 BCE) are evidence of sun-dried mud brick construction (Rodriguez and Saroza, 2006). The Egyptian civilization was the first to use the raw earth for building since the 10th Millennium BCE (Heathcote, 1995; Kemp, 1999; Atzeni *et al*,. 2007). Other constructions made with earthen blocks date from 8000 to 6000 BCE have been found in Turkestan, as well as blocks in Assyria date around 4000 BCE. Even today in Upper Egypt, monumental structures about 3200 years old remain visible, such as the huge earthen block fortification wall of Medinet Habu and the vaults of the storage rooms in the temple area of Ramses II near Gourna (Gernot, 2009). In Spain, the long-standing tradition of earth building is seen in monuments like the historic centre of the city of Córdoba and the Alhambra, Generalife and Albaicín in Granada (Jimenez-Delgado and Canas-Gerrero, 2006). The technique of constructing vaults and domes from earthen blocks without supports was known to many cultures. For centuries, Pueblo Indians in Taos, New Mexico, built their houses using mud and straw (Gernot, 2009). The historical core of the city of Shibam, Yemen, covering about 20,000 m^2 was accessible through a single gateway that was built entirely in adobe. Many houses resemble skyscrapers and date from the 15th century (Gernot, 2009). In Scandinavia and in England, sod (grass and the surface earth held together by its roots) construction was common in the 17th and 18th centuries. Houses were constructed from blocks cut from the top layer of loamy. The blocks were inverted and used as bricks to form walls without the need for mortar (Gernot, 2009). European immigrants then brought this technique to the United States of America (USA), where a large number of sod houses were built in the 18th and 19th centuries (Gernot, 2009). Some settlers also adapted the same concept from North American Indian nations such as the Omaha and Pawnee, who for centuries had used sod to cover their round huts (Gernot, 2009). In New Mexico, silty soil blocks were cut from riverbeds and used for building walls. These blocks, are called terronis or terrones, were also used in Mexico and Central America. It is interesting to note that the building codes in New Mexico still allow buildings to be constructed with terronis. In Germany, earthen block work was used in the 6th century BCE; adobe blocks 40×40 cm and 6 to 8 cm high were used in the fort of Heuneburg near Lake Constance. Around 140,000 blocks and 400 m^3 of mortar were used to construct the 3-m-high walls (Gernot, 2009).

Earth, is the most abundant resource in the central Mesaorian region of Cyprus. Sun dried earthen blocks are the most common walling material in the construction of load bearing walls. The original mixture is used as mortar and plaster. Earth is also used as a plastering material for the final layer of the roof (Dincyurek *et al*., 2003). The load bearing earthen walls support a timber roof frame cover with reeds, straw and sealed with mud. Timber is also used as door and window frames and panels (Dincyurek *et al*., 2003).

Earth has also been used as the raw basic building material throughout the history of Mexico. This has allowed expedient and efficient architectural development, while conserving natural resources and allowing a high degree of adaptation to varying climatic conditions (Rodriguez-Viqueira, 2001). The convergence of knowledge of pre-Hispanic civilizations with the building traditions brought from Europe during the colonial period has resulted in a vast array of earthen building types including farms, temples, monasteries, palaces, government buildings, prisons and residences (Guerrero-Baca, 2007).

Earth as a material construction came to be widely used due to its abundant availability, cost and simple construction techniques. One disadvantage of earthen construction is that the resistant to water damage is much lower than that of other building materials such as stone and terracotta. Yet, even when stone began to be used as a building material and as stone-working technology developed over the centuries, earth continued to be employed as mortar, sealer or plaster in stonework and had continued use in the construction of dwellings (Olotuah, 2002; Jimenez-Delgado and Canas-Gerrero, 2006).

Earth construction is still used extensively today (McHenry, 1984; Houben and Guillaud, 1994; Hall and Djerbid, 2004) and it has been estimated that over half of the world's current population reside in earthen based homes (Rodriguez and Saroza, 2006; Binici *et al*., 2009). Many of these people live in Less Economically Developed (LED) nations where other materials may be unavailable or deemed too expensive, the use of earth in construction is not limited to the LED world. The extent of earth construction in the More Economically Developed (MED) world is greater than one might expect. For example, it has been estimated that in Australia, approximately twenty percent of the new building market is occupied with earth based construction projects (Easton, 1996). The prevalence of earth as a construction material may be attributed to its proven durability demonstrated by the number of ancient earthen buildings that remain standing today (King, 1996).

ADOBE SUSTAINABILITY

Energy savings: Presently housing consists of, approximately, 40% of total energy demand in the European Union (EU) (Viviancos *et al*., 2009; Martin *et al*., 2010). Therefore, reducing energy consumption in heating and cooling of buildings is an issue of increasing interest, with multiple organizations conducting research into this area. EU Energy Performance of Buildings Directive (EPBD) was implemented in the legislation of Member States on January 4, 2006. This directive is an important step for the EU to decrease energy consumption (Viviancos *et al*., 2009).

Sustainable development includes socio-economic and environmental targets and concerns all sectors of human activity. The major reasons for green building are to reduce energy consumption, greenhouse gas emission, water use and waste production versus traditional building. The choice of materials used in the construction of a building has a direct impact on the environment (Collet *et al*., 2006; Goodman-Elgar, 2008). As the energy consumption of a building depends mainly on the building's construction and materials, building type, climatic conditions, occupancy behavior, insulation, heating, cooling, heating water and lighting (Viviancos *et al*., 2009).

Earthen housing appears to meet the requirements of green construction, Shukla *et al*. (2009) calculated the energy for construction and maintenance of an adobe house. The entire house was constructed materials such as soil, sand, cow dung and others that are not energy intensive. They found that approximately 370 GJ of energy can be saved per year using these construction materials. The energy payback time for the adobe house was 1.54 years. The mitigation of CO_2 in the environment was reduced by 101 tonnes per year. The adobe house was also more environmentally friendly compared to conventional buildings. Chel and Tiwari (2009) also found similar results for a mud-house construction.

Thermal behavior of adobe buildings: Adobe is able to absorb heat during the day keeping the house cool and then release this stored heat at night, warming the interior of the house. This behavior is due to the high specific heat capacity of adobe which is an important factor that allows this material to reduce the thermal gradient of earthen houses (Parra-Saldivar and Batty, 2006). On the other hand, the ability of adobe to conduct heat is highly dependent on its moisture content, with a strong relationship between water content and heat conduction (Rees *et al*., 2001). Table 1 shows some experimental results. Actual adobe constructions have wet-dry cycles due to rain and relative humidity that cause changes in its thermal behavior. The presence or absence of internal walls is another important factor that modifies room temperature and determines the thermal behavior of the internal space of the building. In terms of temperature attenuation the thickest internal wall shows the greatest effect for most climatic regions during the year (Parra-Saldivar and Batty, 2006).

Table 1: Adobe thermal conductivity from different sources

Type of adobe	Thermal conductivity (kW/m/K)
Fired adobe (Viviancos *et al*., 2009)	0.244
Concrete brick (Viviancos *et al*., 2009)	0.627
Adobe with straw (Goodhew and Griffiths, 2005)	0.180
Adobe (Goodhew and Griffiths, 2005)	0.240

Advantages and disadvantages: Adobe material has relatively high thermal conductivity (Parra-Saldivar and Batty, 2006). Even a poor insulating material can insulate effectively if it is large enough, which is the case of adobe construction (Baker, 1986; Martin *et al*., 2010). Another advantage of adobe is its sound insulation (Binici *et al*., 2009).

It is also mentioned that fiber reinforced mud brick houses have been found to be superior to concrete brick houses in reducing large fluctuations of indoor temperatures during the summer and winter (Martin *et al*., 2010; Binici *et al*., 2009).

Demir (2008) showed that sawdust, tobacco residues and grass can be used to improve the thermal and mechanical properties of adobe bricks. The insulation capacity of brick increases with the increasing porosity of the body clay. The organic residue additions were found to be effective for pore-forming in the clay body and the clay maintained acceptable mechanical properties.

Martin *et al*. (2010) conducted a field experiment to investigate the thermal behavior of existing housing in Spain. They compared, stone, adobe and wooden houses (modern). The results demonstrate better indoor conditions in the traditional houses. In summer, thermal comfort was achieved with no energy supply inside traditional houses but not inside the modern ones. In winter, the indoor environment was more stable inside the traditional houses; however no house was able to provide thermal comfort.

Porta-Gandara *et al*. (2002) carried out a study for La Paz, Baja California Sur, Mexico and found that vernacular wall adobe constructions have important energy savings compared to concrete housing. It is important to underline that adobe walls are about 5.1 times thicker than concrete block walls and this figure is very similar to the inverse ratio of energy requirements. Due to the thick exterior walls of high thermal inertia, the indoor environment inside them can be comfortable with less energy consumption than new buildings (Martin *et al*., 2010).

ADOBE TECHNOLOGY

Soils with a small clay component have been widely used as construction materials since the earliest times and continue to be used in some LED countries and in the so-called bioarchitecture (Atzeni *et al*., 2007).

The adobe production consists of molding a mixture of soil with 5 to 10% of straw (Binici *et al*., 2009; Demir, 2008). The necessary quantity of water is about one quarter of the dry earth volume. A soil will react very differently depending on the amount of water it absorbs. The four fundamentals states are: dry, humid, plastic and liquid. The adobe is produced at the plastic state which enables molding. When the soil goes back to the solid state it reduces its volume, resulting in cracks in the bricks. In order to stabilize the adobe, sand or straw are added to reduce the size of the cracks. Mixing by the feet of human's or animal's is the most common for small scale production. Sometimes the adobe is produced by using compressed soil in the humid stated to improve its mechanical behavior.

FUTURE TRENDS

The thermal conductivity of the external wall is an important parameter. Future research needs to be conducted concerning the amount of heat storage in an external adobe wall. It is known that the moisture content of adobe materials has a large effect on the thermal conductivity of adobe materials. Additionally, the water contained within adobe has latent heat effects, which modify both the thermal conductivity and thermal capacity of the material. Energy storage occurs through the heat of crystallization arising from salts within the clay structure of the adobe material. Consequently, the effects of rain wetting and the absorption and evaporation of water vapor due to changes in relative humidity should be investigated. Understanding the thermal behavior of phase change materials, such as salts contained within the wall, would increase the accuracy of predicting the performance of adobe structures (Parra-Saldivar and Batty, 2006).

On the other hand, in order to decrease thermal gradients between day and night some passive elements can be added, like bodies of water or gravel (Mier-Chaplea *et al*., 2010; Alatorre-Jacome and Rico-García, 2009; Soto-Zarazua *et al*., 2009) and then evaluate their effect on the thermal behavior of earth housing or even any type of housing.

Computational Fluid Dynamics (CFD) is a sophisticated design and analysis tool that uses computers to simulate fluid flow, heat and mass transfer, phase change, chemical reaction, mechanical movement and solid and fluid interaction. The technique enables a computational model of a physical system to be studied under many different design constraints. The quality of a CFD study is a function of not only the physics available in the software to model the system, but also the understanding that the CFD modeler has of both the numeric's and physics contained in the software package. If used correctly CFD can provide an understanding of the physics of a flow system in detail and does so through non-intrusive flow, thermal and concentration field predictions (Norton *et al*., 2007).

CFD represents another interesting tool to evaluate the thermal behavior of adobe houses. This software allows the user to address the complicated geometry and also evaluate the change in the rate of air exchange due to wind or thermal buoyancy effect (Rico-Garcia *et al*., 2006, 2007, 2008). Therefore, it is necessary to utilize the power of CFD to better understanding of the thermal behavior of earthen construction.

CONCLUSIONS

The worldwide tradition of earth construction has shown that it is possible to achieve long lasting and majestic buildings from single to multi storey.

One of the main advantages of adobe is that the raw materials are locally available. In fact adobe may be produced from the soil excavated from the building site reducing transportation and other energy intensive processes.

Adobe low thermal conductivity provides a more stable temperature behavior inside a house and reduces heat losses.

Moisture content in adobe and CFD have been proposed as new trends to gain fundamental knowledge about the thermal behavior of earth building.

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