ADOBE AS PHASE-CHANGE MATERIAL (PCM); Concerning a Proper Classification For Earthen Building Material

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ABSTACT

Latent heat is thermal energy released or absorbed during a phase-change of a chemical substance. *Latent heat of fusion* (*Lf*) is a phase-change from solid to liquid or liquid to solid; *latent heat of vaporization/condensation* (*Lv*) is a phase-change from a liquid to vapor or vapor to liquid. The reaction is exo- or endothermic depending on the direction of the phase-change. The building industry has long searched for phase-change materials (PCMs) that could be incorporated into a building's fabric to take advantage of latent heat flux. Such chemicals are intended to augment other means for maintaining moderate indoor temperature. To date, no PCMs have been developed for commercial use in the building industry.

Earthen building material, with unaltered clay, contains water as PCM. Clay, carrying a negative charge, draws water (a polar compound) from the atmosphere when relative humidity is highest, as in early morning. The resulting latent heat of condensation is endothermic thus rising the temperature of the earthen fabric. Conversely, a highly exothermic reaction occurs when the relative humidity is low, as in late afternoon, and liquid water vaporizes out of the adobe as latent heat of vaporization. The result is evaporative cooling that lowers the temperature of the building fabric.

Latent heat of vaporization of water is several folds greater than latent heat of fusion of any currently recognized PCMs of industry. There are thus two broad categories of PCMs. Those involving latent heat of vaporization, currently restricted to water and identified a *Lv*- or α-PCM, and PCMs associated with latent heat of fusion identified as *Lf*- or *β*-PCM.

Keywords: Phase-change material, latent heat, earthen building material

INTRODUCTION

The late Paul Graham McHenry, Jr., noted architect and earthen builder, has voiced the complaint of many respecting the low insulation values assigned to adobe by the American Society of Heating and Air Conditioning Engineers (ASHRAE 90-75). McHenry (1984, p. 154) commented that "Adobe is a traditional, successfully proven material with a good comfort factor, *so some element of measurement must not have been recognized in that test standard.*" (Emphases added). In a previous study, I identify the unrecognized factor with experimental data, demonstrating that traditional adobe, due to its water and clay content, is subject to latent heat flux (Morony 2005).

Phase-change of a material from solid/ liquid or liquid/vapor (and their reverses) results in the release or absorption of energy in a form known as latent (hidden) heat. A solid/liquid phase change involves *latent heat of fusion* (*L f*); a liquid/vapor phase change results in the *latent heat of vaporization* (*Lv*). Latent heat is thermal energy that is not sensible and thus not measurable by a thermometer. It is an elusive concept and little known or understood beyond those with need to know. An important phenomenon of nature, latent heat is manifested in highly varied forms acting as anything from the driving force of global climates to the cooling mechanism of plants and animals. For a conceptual analysis, see

Hewitt (1981) or any other physics textbook. In contrast, varied aspects of sensible heat in the form of conduction, convection, and radiation have long been of interest to the building industry. Such interest is manifested in an array of special building designs and materials that serve to retard or retain heat incorporating insulation, radiant barriers, and thermal mass. Sensible heat phenomenon alone is the basis for calculation of the R-value and U-factors of building materials, but such phenomena is of more limited interest to the analysis of PCM. If earthen building material is to be regarded as PCM, it differs profoundly from what it is considered to be in an industrial context; this difference constitutes the subject of this paper.

LATENT HEAT

The fundamental distinction of adobe as a PCM, due to variations in moisture content, is that it is subject to the latent heat of vaporization. All other forms of PCM in the building industry are restricted to latent heat of fusions of a varied assortment of chemicals that are intended for incorporation into some form of building material. There are two factors of significance: 1) For phase change of any chemical, the release of thermal energy of *Lv* is always significantly greater than that of *L f* and, 2) the thermal energy release of *Lv* of water is one of the highest known for any chemical substance. The two types of phase change with respect to the building industry may be designated *Lf*-PCM for latent heat of fusion and *Lv*-PCM for latent heat of vaporization /condensation. For simplicity, the latter may be referred to as *alpha*-PCM and the former as *beta*-PCM. Figure 1 is a graphic illustration of the two types of latent heat.

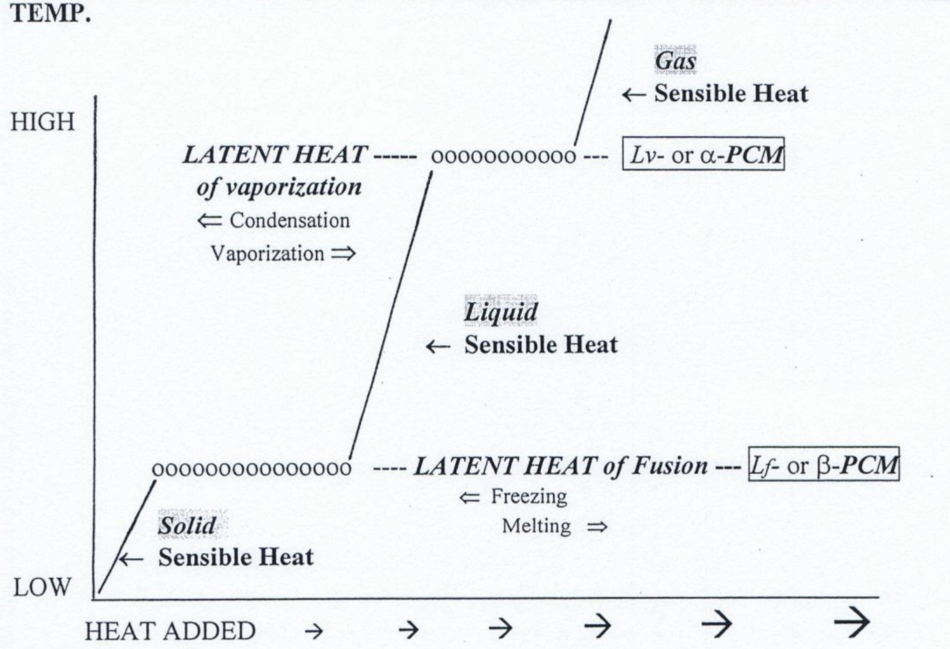

Figure 1. Thermal energy increases significantly in phase changes from solid to liquid to vapor. All PCM currently utilized in the building industry is restricted to *Lf* triggered by temperature changes and are thus *Lf*-PCM. Clay + water, associated with earthen material, constitute *Lv*-PCM at 2,258 kJ/kg and several fold higher than for the highest *Lf* –PCM. The latter is initiated by a difference in atmospheric moisture; not temperature *per se,* and thus it is restricted to earthen building material.

CONVENTIONAL PCM

Phase Change Material has been of interest to a select segment of the building industry since the 1940s creating an imposing corpus of technical studies over the years. Many, perhaps most, such studies have involved varieties of modeling and numerical simulation. A much-referenced study by Feuster *et al.* (1977, p. 1), at the Lawrence Berkeley National Laboratory, explains the use of phase change wall board for residential cooling applications: *Large thermal storage devices have been used in the past to overcome the shortcomings of alternative cooling sources, or to avoid high demand charges. The manufacturing of phase change material (PCM) implemented in gypsum wall board, plaster or other wall-covering material, would permit the thermal storage to become part of the building structure. PCM has two important advantages as storage media: they can offer an order-of-magnitude increase in thermal storage capacity, and their discharge is almost isothermal. This allows the storage of high amounts of energy without significantly changing the temperature of the room envelope. As heat storage takes place inside the building, where the loads occur, rather than externally, additional transport energy is not required.*

The authors conclude that PCM wallboard has the potential to convert light buildings, as often found in earthquake-prone regions, into "thermally heavy constructions." They note that where there are large diurnal swings, residences can be kept thermally comfortable by using night-time ventilation to disarge the latent heat storage of the wallboard. Mechanical cooling or evaporative cooling could be eliminated by applying PCM-treated wallboard.

An inventory of PCMs is extensive and varied as to chemical composition and activity and are classed as either organic or inorganic chemicals. They are all likewise restricted to latent heat of fusion. Such chemicals are pure compounds with a range of associated heat of fusion and melting points. Kelly (1999, p.4) list five inorganic PCMs, all hydrate of salts, that are intended for use as insulation in dry wall installation. Of these Sodium orthophosphate dodecahydrate ($Na_2HPO\cdot 12H_2O$), had the highest heat of fusion at 281 kJ/kg and Glauber's salt, Zinc nitrate hexahydrate ($Zn(NO_3)_2.6H_20$), had the least at 147 kJ/kg. All hydrates of salt are restricted in use to solid/liquid phase change and require some form of specialized packaging before they can be inserted into a building fabric for use. None can be impregnated directly into porous building material. Other limitations are noted such being corrosiveness, a tendency to be instable, or they may not resolidify properly. Organic PCMs listed by Kelly (1999) are reported to be more stable than inorganic chemicals; melt congruently and do not readily super cool. Melting points range from 19° to 38°C. The highest heat of fusion is 140 kJ/kg for 1-tetradecanol. Other organic PCMs listed are Butyl stearate, I-dodecanol, 1-tetradecanol, paraffin, capriclauric acid, and propyl palmitate. Voigt and Zeng (2002), in a study of solid-liquid equilibriums noted thirty salt hydrates, the highest *Lf* (enthalpy of melting) was for $SrOH_2.8H_2O$ at 370 kJ/kg. As previously noted, the *Lv* of water is 2258 kJ/kg; a six-fold in-crease. No *Lf* of any commercial PCM approaches the energy field of *Lv* of water that constitutes the PCM of earthen material.

All phase-changes for conventional PCMs are restricted to the latent heat of fusion and are triggered by a change in temperature. None entail heat of vaporization for functional purposes. As the air temperature rises above the transition temperature (the point at which phases change occurs) the PCM absorbs heat and melts. As the air temperature lowers, the PCM releases stored heat and returns to a solid state. Such reversals of energy are described as latent heat flux. Besides use with building fabrics, other applications of PCM include, but are not limited to, biopharmaceutical systems, telecommunications, green-houses, heat sinks, and hot and cold storage facilities.

EQUILIBRIUM MOISTURE CONTENT

All porous material has characteristic specific moisture content known as *equilibrium moisture content* depending on the temperature and humidity of ambient air. Minke (2000, p. 1) duly stresses the importance of the equilibrium moisture content of clay of an earthen building fabric: *Loam [adobe] is able to absorb and desorb [release] humidity faster and to a higher extent than all other building materials. Therefore, it balances the indoor climate. Experiments at the Institute Florschungslabor fur Experimentelles Bauen (FEB, Builders Research Institute) at the University of Kassel, Germany, demonstrated that when the relative humidity in a room was suddenly raised from 50% to 80%, unburnt brick [adobes] were able to absorb 30 times more humidity than burnt brick in a period of 2 days. Even when standing in a climatic chamber at 95% humidity for 6 months, adobes do not get wet and lose stability; neither do they exceed their equilibrium moisture content, which is about 5%-7% by weight.* What is here described as absorption and release of moisture involves a phase change of water – liquid to vapor and the reverse.

Minke (2000) explains at length the characteristic of earthen building material (high in clay) to absorb and release moisture in response to changing ambient conditions of temperature and humidity. He notes an experiment in which the first 1.5 cm [0.7 inches] thick layer of earthen fabric was able to absorb 300 g [11 oz.] of water per m^2. This occurred when the humidity is raised from 50% to 80% over an extended time – a spectacular display of a phase change phenomena. The explanation is that clay carries a negative charge and is thus highly hygroscopic and captures water molecules in a vapor state. Water, being a polar compound, will adhere to a clay particle on the positive side of the molecule. The phase-change characteristic of adobe and like material is easily demonstrated. Samples of earthen building material can be exposed out of doors overnight when the humidity is likely to be the highest, and the weight may be recorded the following morning. The sample can then be reweighed at the end of the day when relative humidity will be at its lowest. There will be a loss of weight that is best explained by an evaporative loss (simple diffusion) of water absorbed the previous night.

In most geographic regions the higher the temperature is during the course of the day the lower the atmospheric humidity. As relative humidity declines moisture within the building fabric diffuses into the atmosphere resulting in latent heat of vaporization. Thus, as a phase change material, earthen building material is unique in responding to humidity by way of simple diffusion of water into and out of an adobe fabric; not temperature *per se*. The role of temperature is indirect in the sense that atmospheric humidity varies with respect to temperature fluctuations to and from the dew point.

EARTHEN MATERIAL AS PCM

As water is the PCM of earthen building material, a brief review of water and latent heat flux is provided. Interestingly, water was the basis for the discovery of latent heat by Joseph Black (1728-1799). It came relatively late in the history of science. In the years between 1759 and 1763, the Scottish physician and chemist noted that melting ice does not change in temperature as long as ice remains; an example of solid/liquid phase change. The other phase change is liquid/vapor that occurs when water is heated to boiling temperature. During the boiling and vaporizing process, the temperature of the liquid water remains the same. Where, then, is the heat going? It is incorporated as internal energy of the water molecules that are vaporized during the phase change. However, it is important to realize that a reverse phase change from vapor to liquid or liquid to solid constitutes the same quantity of thermal energy being released by the water as had been absorbed initially. Such energy changes of heat content or enthalpy is designated ΔH. The change of enthalpy, ΔH, is defined as the quantity of heat absorbed when a reaction takes place at constant pressure. The reaction is *exothermic* if it evolves (contributes) thermal energy to the atmosphere (the surroundings) thus lowering the temperature of the adobe, *i.e.* evaporative cooling results. When water vapor condenses back to liquid within the adobe (when atmospheric humidity is high) the reaction is *endothermic* as heat energy is absorbed back by the system (earthen material) and the temperature of the adobe rises. In contrast, by definition, there is not a separation of molecules in the latent heat of fusion and thus there is always a lower ΔH. Heat content associated with phase changes of water are as follows:

- L_f of water = 334 kJ/kg; 80 cal/g, or 144 Btu/lb water
- L_v of water = 2258 kJ/kg; 540 cal/g at 100°, or and 970/lb Btu

Understanding latent heat phenomena requires that a distinction be made between temperature and heat. Temperature is a measure of the average kinetic energy per molecule or atomic constituent of a substance. It is what is recorded by a thermometer. Heat is the special manifestation of thermal energy derived from the energy of a quantity of matter. When heat enters a system, it causes an increase in the speed at which particles in the system move. Heat is thus said to be a form of energy associated with the random motion of atoms and molecules. Although the two phases, water and steam, both register a temperature of 100° C, the heat content of the two is different. The water molecule present as steam has a much higher internal energy. A burn caused by steam at 100 °C is more severe than a burn caused by boiling water.

In summary while latent heat of fusion with PCMs, utilized by the building industry, is a direct consequence of temperature changes, it is otherwise for latent heat of vaporization of water-clay PCM. Water-clay PCM responds to ambient temperature *decrease* as follows; 1) internal energy of water molecules in the atmosphere declines as ambient temperature declines and approaches dew point; 2) as dew point is approached relative humidity increases; 3) as water vapor, in a lesser energy state, contract the surface of earthen fabric they are readily captured by clay particles and condense as liquid. The result is a phase change of a latent heat of condensation that is highly *endothermic*, i.e., the earthen fabric warms; 4) as water is taken on at the surface of the fabric it moves to the interior of the earthen material *via* capillary action and attraction of water to interior clay particles. With a *rise* in ambient temperature there is: 1) a lowering of relative humidity accompanied by an increase of the internal energy of water molecules within the earthen fabric; 2) hydrogen bonds, as the inter-molecular bonds of water molecules, weaken with a rise in temperature and diffusion accelerates from a high concentration in the interior of an earthen fabric to a lower concentration at its surface; 4) as the surface is reached, molecular (hydrogen) bonds sever as a phase change occurs from liquid to vapor resulting in a highly *exothermic* reaction and thus lowering the temperature of the earthen fabric. In both types of phase change the enthalpy, or heat content, is 2258 kj/kg.

DISCUSSION

As a rule, temperature is lowest and humidity is highest at dawn and reversed at the end of the day. The result is that adobe will rise in temperature at dawn due to moisture absorption and lower in the late afternoon when temperatures are actually highest and moisture is released. In large measure, this accounts for the adage that "adobe is cooler in the summer and warmer in the winter" relative to other building fabrics. There are profound differences between an earthen building fabric and conventional material due to the magnitude of energy involved and the nature of the triggering mechanisms for phasechange. Such explains, in part, why the utilization of latent heat flux in earthen buildings may render the use of moisture barriers a detriment rather than an asset. Moisture barriers in an earthen building fabric would, in some instances, impede latent heat phenomena, but such is otherwise with convent-ional building material where moisture barriers are generally considered a necessity. Other differences between PCMs of current interest to the building industry (L_f-PCM) and earthen building materials (L_v-PCM) follow:

MATERIALS

L_f-PCM	L_v-PCM
• Pure organic or inorganic molecules;	Clay and water interaction associated with earthen building material.
• Maximum $L_f = 370$ kJ/kg	L_v of water = 2260 kJ/kg
• Restricted to L_f	L_v and possibly L_f.
• PCM is encapsulated or packaged for insertion into the building fabric or applied to porous building materials such as dry wall.	Entire building fabric is phase-change material.
• Phase change promoted by temperature.	Phase change promoted by differential atmospheric moisture.
• Can only store energy; not remove it.	Removes and stores energy.
• High-tech production.	Low tech material.

While masonry units have been the choice for building in general, and on a global basis, it is otherwise for home dwellings in some geographical regions. It must be stressed that consideration of earthen building material as PCM, as here presented, is primarily in the context of rather low elevations in the arid and semiarid regions of the world where high, unremitting heat during most of the year is the primary comfort concern. Such is the location of the Gulf coastal plain in Texas and Mexico where much of the research of this report has been conducted. Thus, much of what is said in this report may be irrelevant to geographic regions of upper latitudes and high elevation. In such regions, the comfort concern for dwellings and buildings is prolonged, subfreezing temperature in winter and mild summer temperatures.

A successful development of phase change drywall for ceiling and wall insulation long has been sought by the building industry to moderate thermal extremes within a building – a focus of interest to the Department of Energy's various National Laboratories of Research and other research agencies. It is readily recognized that the use of PCM drywall may be potentially effective, less costly, and less bulky than the use of thermal mass material. Salt hydrates, paraffin, and even fatty acids have been considered as PCMs. However, it appears at this point that nothing of commercial interest in the way of PCMs has been developed for general home construction. Furthermore, a review of current literature suggests a lack of consensus of opinion as to the most appropriate phase change chemicals. Each of the various types exhibits advantages and disadvantages. The National Association of Home Builders Research Center, in an internet article on home construction, summarized PCM by noting that such material is not yet commercially available for residential construction and thus there is currently no code or regulatory requirements pertaining to PCMs.

Adobe, earth blocks, and rammed earth, etc., all originate as soil and essentially remain soil as a building fabric and, with unaltered clay, they should be considered as phase-change materials. However, they differ profoundly from what are currently considered PCMs; a difference rendering them unsurpassed as phase change material especially when considered in respect to their other attributes.

- Soil saves energy: "To prepare, transport and handle loam on site, only about 1% of the energy needed for production, transport and handling of burnt bricks or reinforced concrete is used" (Minke, 2000, p. 13).
- Soil balances air humidity (an important attribute recognized by Europeans).

- Suitable soil is generally locally available.
- No toxic waste or air pollution is released to the environment during production.
- Generally no special skill is required in block and adobe manufacturing.
- The price of soil is not tied to the price of oil.
- Material is readily biodegradable.
- Steel reinforcement is not generally required in construction except in high seismic zones.
- Moisture is an asset and not a liability as with conventional building material.
- In hot climates, insulation, save for the roof, is a liability and not an asset.
- Solid earthen walls are fireproof and may be made vermin proof.

One may well wonder if there is anything of such plebeian origin as the soil that can be found to possess such an exalted quality as building material. Appropriate soil must be recognized as it has been in the past; it is superb building material for use in many parts of the world by the rich and poor.

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