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Earth Construction and the Meaning of Thermal Inertia

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In 1821, Joseph Fourier published *The Analytical Theory of Heat*, ten years after the presentation of his work on heat flow at the Academy of Science in Paris. This publication was the groundwork of what later became thermal analysis, used in every engineering field, and particularly in building design since then. In the preliminary discourse of this groundbreaking book, Fourier emphasizes the universality of thermal phenomena. Prigogine and Stengers state that the theory of heat of Fourier introduce “a new kind of science[1]”, as universal as the Newtonian system, but remarkably simpler and understandable. After Fourier, every thermal phenomenon will be explain in terms of gradient and irreversibility[2].

Following this intuition we want to develop the meaning of thermal analysis by studying an underrated thermal property of massive buildings called “thermal inertia”. In this paper, we will study earth as a construction material and try to define how this material illustrate thermal inertia property of a building structure. Nowadays, we tend to consider that a modern building needs to be strongly isolated from thermal variations of the environment, merely due to climate and temperature swings. However, as the architecture historian Kiel Moe explained recently, the idea that a building needs to be isolated can be historically explained as a result of a false analogy between a building and a refrigeration apparatus[3]. For him, refrigeration industry and contemporary building practice both illustrate “strategies that isolate interior from exterior through envelope design, coupled with a heat pump to manage internal convection[4].” As a matter of fact, isolated or not, a building continuously exchanges thermal energy through its surface and consider it as an isolated object is a huge simplification. Moe argues that buildings “are not thermos bottles[5]“ and “literal isolation is thermodynamically impossible to achieve in the context of buildings[6]”.

Earth couldn’t be define as an insulative material from thermal viewpoint but has multiple interesting thermal properties, the main one being thermal inertia. Earth also has the property to regulate the indoor humidity by absorbing and releasing moisture. In order to be used as a construction material, earth must be composed of fixed proportion of clay, sand and silt[7]. This mix

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[1] Ilya Prigogine and Isabelle Stengers, *Order out of Chaos: Man’s New Dialogue with Nature* (New York: Bantam Books, 1984), 104.

[2] *Ibid.*

[3] Kiel Moe, *Insulating Modernism: Isolated and Non-isolated Thermodynamics in Architecture* (Basel: Birkhäuser, 2014), 11-15.

[4] *Ibid.*, 38.

[5] *Ibid.*, 14.

[6] *Ibid.*

[7] Patrick Bardou and Varoujan Arzoumanian, *Archi de terre* (Roquevaire: Parenthèses, 1978), 5-6.

is called loam and needs to be mixed with other materials as straw or gravels to have mechanical strength. By adding water, this mix become plastic and can be processed using different techniques witch depend of the country and the locals traditions. It can be placed in wooden forms and pressed to form bricks (*adobe*) or directly tamped in a formwork to build a wall (rammed earth or "*pisé"* in France). With those techniques very thick earth walls can be made and there is examples of earth construction with nearly one meter (three feet) width walls in vernacular architecture. As we will see, traditional troglodyte buildings, made by digging in the lœss has much ticker wall. By contrast with those massive buildings techniques, with industrial processes and the adding of lime, earth can be form as thin board of about two centimetres (one inch). As it is still the cheapest raw material of construction, it seems like earth can now be used in massive buildings as well as light ones. Therefore it can illustrate a great variety of thermal behaviours when using in a building.

The "thermal behaviour" of a building expresses the way it looses and gains heat and therefore provides comfortable indoor temperature to the inhabitants. It represent the exchanges of thermal energy between indoor and outdoor, as a building is continuously expose to varying climate elements, the main one being sunlight intensity. As described by the architect Baruch Givoni, the propagation of a heat wave into a construction element can be easily represented by mentally slicing this element into smaller layers. When the temperature of one of the surface of this element rises, the thermal energy will flow and "fill" the first layer[8]. When this first layer is at the same temperature as the surface, the heat flow progresses to the adjacent layer and so on, as long as there is a thermal gradient between the two surfaces of this element[9]. The study of this type of heat flow called conduction occupied many scientists during the 18th century[10], and was clearly explained by Fourier at the beginning of the 19th century.

Despite Fourier's work many engineers like Nessi and Nisolle in France or Mackey and Wright in the U.S.A. kept working on the mathematical analysis of the conduction of heat in a construction element during the first half of the 20th century, in order to define more accurately the thermal behaviour of building with massive materials. They were preoccupied by the fact that the temperature of the surfaces of an element is constantly varying throughout the time and consequently modifying the thermal gradient between the interior and the exterior surface as well as the heat flow between them. Mackey and Wright developed what they called the "sol-air temperature" in order to consider the thermal effects of surrounding environment (sun, ground reflection…) on a building element[11]. By introducing the "sol-air temperature" and the calculation of thermal inertia, Mackey and Wright mathematically explained that massive material like earth have the property to delay the conduction of heat flow but also to reduce the external thermal amplitude create on the outside surface due to sunshine exposure.

The thermal advantages of massive material like earth were intuitively known way before the birth of thermal analysis. In a temperate climate like France, the architect François Cointeraux (1740-1830) promoted the earth construction for its thermal and economic advantages. Vernacular and traditional Indian Pueblo architecture in New Mexico[12] or Nubian vaulted houses in Egypt[13]

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[8] Baruch Givoni, *L'Homme, l'architecture et le climat* (Paris: Le Moniteur, 1978), 140.

[9] *Ibid.*

[10] Gaston Bachelard, *Étude sur l'évolution d'un problème de physique : la propagation thermique dans les solides,* 3rd ed., Bibliothèque des textes philosophiques, (Paris : Vrin, 2016).

[11] Jacques Dreyfus, *Le Confort dans l'habitat en pays tropical. La Protection des constructions contre la chaleur. Problèmes de ventilation* (Paris: Eyrolles, 1960), 131-133.

[12] Patrick Bardou and Varoujan Arzoumanian, *Archi de terre,* 31-34.

[13] Hassan Fathy, *Architecture for the poor: An Experiment in Rural Egypt,* 4th ed., (Chicago: University of Chicago Press, 2000), 45-49.

provided a fair comfort in hot-arid climates because they were built with thick earth walls and roofs. Those climates are characterized by their great thermal amplitude: the diurnal thermal range can be as much as 22 °C[14] (40 °F). Massive earth walls helps damping those variations. The thickness of earth traditional walls, more than fifty centimetres (nearly 20"), allows the heat to be transmitted with a roughly twelve-hour delay, so the earth structure slowly conduct heat during the day and the cold nights. At sunrise, the structure is cool and has achieved thermal equilibrium, then it heats slowly during the whole day, providing cool interior temperatures for the inhabitants.

Although earth was widely used on intuitive basis, the work of Mackey and Wright and other engineers allowed to mathematically define the property of massive materials as earth, called thermal inertia. Their work was synthesize by thermal engineers and architects during the 1950s, like the French engineer Jacques Dreyfus who worked in tropical country in Africa in the middle of the 20th century. Dreyfus was a specialist of earth construction and has conducted many theoretical study on thermal inertia based on Mackey and Wright's work. He defines thermal inertia as the property of a material to slow down the transmission of the thermal wave through its thickness – thus creating what thermal engineers called a "thermal lag" or a "phase shift" – and to reduce inside temperature variations by damping the thermal wave[15]. Those two properties that characterize thermal inertia can be accurately estimate by the calculation of what engineers called "thermal diffusity[16]" which depends on the thermal conductivity of the material, its mass and its specific heat capacity. There's a robust analogy between the flow of heat through a massive wall and the flow of water through a dam: they both retain this flow and regulate its input variations so that it remains constant at the output[17]. As the architect Jean-Louis Izard states: "in the event of a flood, the dam fills up, thus reducing the downstream flow; if the flood follows a low flow (low water), the water stored by the dam is used to supply the downstream flow[18]." Like a dam, a massive wall regulate the diffusion of heat. Thus increasing thermal inertia of a building allows it to store a greater quantity of thermal energy.

A convenient way to understand thermal inertia is to calculate or measure the thermal lag in hours. Dreyfus proposed many charts in order to design a structure with a proper thermal lag in tropical arid climates. Choosing the proper thermal lag imply anticipating when the outdoor thermal energy will be beneficial to the indoor comfort. Dreyfus give the following values: with a 10 centimetres (4") thick earth wall, this thermal lag will be of 2h40, with 20 centimetres (8") of 5h25, with 30 centimetres (12") it would attain 8h10[19] and so on. But designing by considering thermal lag could be tricky because the sol-air temperature of the different façades and the roof is varying throughout the day. If you plan a bedroom behind a west wall with a 6 hour time lag, it would radiates its thermal energy in the middle of the night, at the most inappropriate moment[20]. The simplest solution is to increase the thickness of this west wall in order to expand the thermal lag and delay the heat transmission. This imply designing a construction with different materials and thickness for each facade.

After the work of Wright, Mackey and Dreyfus the importance of thermal inertia was widely accepted by architects who worked in hot-arid climates. The famous Egyptian architect Hassan

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[14] Otto Koenigsberger *et. al., Manual of Tropical Housing and Building. Part 1: Climatic Design*, (Londres: Longman, 1974), 27.

[15] Jacques Dreyfus, *Le Confort dans l'habitat en pays tropical*, 77-80.

[16] *Ibid.*, 80-83.

[17] Jean-Louis Izard and Alain Guyot, *Archi bio*, (Roquevaire: Parenthèses, 1979), 16.

[18] *Ibid.*

[19] Jacques Dreyfus, *Le Confort dans l'habitat en pays tropical*, 83.

[20] *Ibid.*, 142.

Fathy conducted experiments on earth construction techniques in Egypt and promoted those techniques in his book called *Architecture for the Poor* published in 1969. He emphasized the thermal qualities of earth in the Egyptian climate compared to much more expensive materials like concrete[21]. The main difference between earth and other massive materials like concrete or stone is that there's theoretically no limitation of earth wall thickness because earth is a very cheap raw material. Increasing the thickness of earth wall can add more and more thermal inertia and therefore reduce indoor thermal amplitude to a point where isothermal conditions can occur. In theory, infinite thickness earth wall can be made.

In practice, increasing the thickness of an earth wall up to the infinite can be made by digging in loess soils[22], which is a soft sedimentary rock made of silt, one of a three basic component of loam. There is plenty example of very thick loess walls and roofs in troglodyte houses and underground vernacular architecture (Tunisia, Spain…). In China, in the Shaanxi province, troglodyte houses made by digging in the loess soil have at least three meters thick roofs and walls with an unmeasurable thickness, with infinite thermal inertia[23]. At this depth very little temperature variations can be felt. Although outside temperature can be as low as –20 °C (–4 °F) with a diurnal thermal range of more than 20 °C (36 °F), the temperature inside the troglodyte houses remains close to 9 °C (48 °F) throughout the year and can be easily warmed by a small furnace[24].

Those thermal performances of underground building can be calculated with the methods of thermal engineers. Like a wall, the temperature of the earth's surface is subjected to diurnal and seasonal variations due to the heat balance between inflow and outflow radiations. If we consider those variations as sinusoidal to simplify, it is possible to calculate at which depth those seasonal thermal variations are unnoticeable. In a book about insulative materials, Claude Huraux made some of those calculations[25]. He found that if you consider the thermal diffusivity of the ground, at a depth of about nine meters (approximately thirty feet) the temperature is higher in winter than in summer[26]. It means that at this depth there is a six month phase shift (or thermal lag) of the thermal wave as well as a reduction of the annual temperature range. At a depth of about twenty meters (approximately sixty-five feet) those seasonal variations become unnoticeable and the temperature is in a steady-state throughout the year. In architectural terms, this calculation means that the temperature inside an underground house with twenty meters thick walls will remain the same independently of the temperature variations of the outside. In practice, very little temperature variations occurs in underground or troglodyte vernacular buildings with thinner earth roofs and walls. Measures show that at a depth of five meters (approximately sixteen feet) in temperate climates only very little temperature of 1 or 2 °C (2 or 4 °F) variations occurs that remain practically unnoticeable[27].

By considering thermal inertia, a built structure can be define by the thermal lag it produces. Rather than seeing a massive structure as a static element, it appears that it has a thermal function which is to delay and reduce indoor thermal variations. The engineer Dreyfus considers thermal inertia as a form of "memory[28]". He states that a massive construction "records everything it

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[21] Hassan Fathy, *Architecture for the poor: An Experiment in Rural Egypt*, 45-46.

[22] Jean-Paul Loubes, *Archi troglo*, (Roquevaire: Parenthèses, 1984), 17.

[23] *Ibid.*, 70.

[24] *Ibid.*, 69.

[25] Claude Huraux, *Les Isolants*, Que-sais je? (Paris: PUF, 1968), 70-71.

[26] *Ibid.*, 71.

[27] Jean-Paul Loubes, *Archi troglo*, 117.

[28] Jacques Dreyfus, *Le Confort dans l'habitat en pays tropical*, 179.

receives” and “any amount of heat absorbed by the walls will influence comfort for the next 10 hours or more[29].” Following this metaphor, massive earth walls have greater thermal memory than light ones. Other thermal engineers, like Gilles Olive, talk about the “thermal past[30]” of the massive structure and the way this “past” influences thermal present state of a structure. All those metaphors have a profound meaning as they insist on temporal dimension of thermal phenomena.

But understanding thermal inertia is not the privilege of thermal engineers and architects because our touch give a sense of that phenomenon. We commonly think that air temperature expresses accurately the thermal comfort zone. But our body is very sensitive to the temperature of surfaces that surround us (ground, wall…). As a first approximation, those surfaces radiate thermal energy when they are hotter than our skin and absorb our body thermal energy when they are colder[31]. Therefore, indoor thermal comfort depends greatly on the temperature of those surfaces, that’s why we feel cold in a room with a very acceptable air temperature if we are surrounded by colder surfaces, like single glass window in winter for instance. In fact, our skin can’t measure temperature. It can only measure very accurately the rate at which our body loses or gains thermal energy[32]. Physiologist found that this measure could be very precise[33]. The faster we loose thermal energy the colder we feel, and the faster we gain it the hotter we have. All those energy exchanges depends greatly on the materials of the surrounding surfaces witch have a certain thermal inertia, emissivity and effusivity. The fact that our body measures the rate of inflow or outflow of heat means that we intuitively understand thermal phenomenon in a time perspective.

Moreover, by considering the relation between thermal comfort and thermal inertia, we also want to stress that choosing the right materials in architecture and urbanism would be decisive in a global warmed world. The urban heat island effect, known since the 19th century, is principally caused by the thermal inertia of all the building materials and their impermeability. Therefore that thermal property that can be very beneficial has disastrous consequences on urban thermal comfort during a growing period each year. Every urban inhabitant has felt the warm mineral surfaces that radiate heat at the beginning of the summer nights. But urban heat island effect isn’t a fatality, it forces urbanists, architects and thermal engineers to consider and tackle this phenomenon by choosing more porous and reflexive materials. For them, as for all urban inhabitants, understanding thermal inertia means learning the active role of surfaces and materials by feeling the different thermal lags it produces. Those thermal lags are time signals, they illustrate the near past and the future thermal behaviour of a material. By considering the meaning of thermal inertia, we wanted to show that thermal phenomena could be precisely explain in sensible terms without using complex mathematical calculation and that they have direct influence on our daily living. As there is a “poetic of space[34]”, we think that there is also a poetic of time in thermal phenomena.

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[29] *Ibid.*

[30] Gilles Olive, « Hygrothermique des enveloppes », *Techniques & Architecture*, n° 315 (1977): 50-51.

[31] André Missenard, *La Chaleur animale*, Que sais-je? (Paris : PUF, 1969), 13.

[32] *Ibid.*, 49.

[33] *Ibid.*

[34] Gaston Bachelard, *The Poetic of Space*, 2nd ed., trans. Maria Jolas (Boston: Beacon Press, 1994).

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