Research on application and thermal performance of raw earth material in building envelope

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Abstract. Mainstream green has recently swept the construction industry throughout the world. Building envelope and material are two important aspects of green building evaluation. As the growing development of new green building concept "human-orientation design", raw earth, as a natural, locally sourced, minimally processed, and recyclable material that is very different from concrete, becomes one of the most attractive options. Most architects pay attention to the aesthetic design of the raw earth wall, while other researchers like civil engineers focus on the physical properties of raw earth material itself. Few studies discussed the effect of the raw earth wall in building a thermal environment. This paper firstly conducts a parametric study on the thermal performance of raw earth wall with the consideration of thermophysical properties of materials, application of thermal insulation layer in the wall, and design parameters, i.e. thickness, of each layer of the wall. A naturally ventilated public building in Shanghai is then simulated to discuss the feasibility and the most optimum strategy of raw earth wall applications as building envelope in the sub-tropical high-density cities. Based on comprehensive data analysis, four findings are identified: (1) Compared with common building materials like concrete, raw earth materials have significant advantages in two thermophysical parameters - thermal transmittance and thermal effusivity which directly influence the indoor air temperature; (2) Thickness and structure of both raw earth layer and insulation layer are two important design parameters to meet the requirements of the indoor thermal environment; (3) Raw earth wall performs better than the standardized “Green Wall” based on local green building standards; (4) In terms of thermal performance, “Raw Earth Wall with External Insulation” is more suitable in subtropics. However, “Raw Earth Wall with Sandwich Insulation” is more recommended if pursuing the beauty of raw earth materials, because the thermal performances of “Raw Earth Wall with Sandwich Insulation” and Raw Earth Wall with External Insulation” are almost the same in summer, and very close in winter.

1. Introduction
In recent decades, mainstream green has swept the construction industry in China and even the world. A review of representative green building rating systems reveals that envelope and material are two important aspects of green building evaluation [1-4]. The current trend of green building envelope research is mostly around modern technology, green elements added, and facilities, such as thermal insulation layer placed on the inner or outer side of the vertical wall [5-6], foam, granules or fibers injected into cavity of the wall [7], shading devices [8], window and glazing system [9-10], et.al. One of the major reasons for this situation is that the people involved in field of green envelope research are habitually engineers [6] and facility managers [6, 11] rather than architects. In contrast, the architect's
research is mostly morphology of the envelope and its opening, and material texture of the wall, i.e. architectural aesthetics [12-15]. Some architects conducted aesthetic research on modern technologies like shading devices [16], while another part of them prefers to use ancient wisdom (e.g. natural material application, passive design strategy, and other time-tested practices) to improve modern building. As the trend of green building development begins to shift from energy-oriented and active technology to human-oriented and passive architectural design [17-19], there is a revival of interest in natural material application in envelope design.

As we all know, concrete is major construction material and plays a vital role in building envelope. Worldwide, the total annual concrete production is more than 10 billion tons [20]. Yet such vast quantities of concrete used makes its production account for 5% of annual anthropogenic global carbon emissions [21-22]. And each ton of cement - concrete’s key ingredient - generates about one ton of CO2 [22-23]. Demolished concrete also faces with the problem of the waste recycling [24-25]. The above problems have triggered new interest in alternative and more environmentally-friendly methods [22]. Among these materials, raw earth becomes one of the most attractive options because it is natural, locally sourced, minimally processed and recyclable [22].

The application of raw earth was common in rural habitats and military citadels originally [22]. During the late 18th century, Cointeraux defined construction technique about raw earth as the terminology “rammed earth” in his publication “Ecole d’Architecture Rurale” [22, 26]. After a period of neglect after World War II, the “rammed earth” has been refocused in recent years [22]. In the discipline of architecture, the application of raw earth materials is mainly divided into three categories - “load-bearing structure”, “building envelope”, and “landscape and decoration”. Typical cases are the utility building sports facility “Sihlhölzli” designed by Architect Roger Boltshauser in 2002 (Figure.1) and the “Visitor Centre at the Swiss Ornithological Institute” designed by studio MLZD in 2015 (Figure.2).
2. Among them, raw earth as “building envelope” is the most main application and also the mainstream research recently. Some architects also summarized the traditional production process and aesthetic design of raw earth wall [27]. In the scientific research field, most research of raw earth studied by disciplinary of engineering and building focuses on the material itself, such as ageing and creep [28], durability [29] or reliability [30] along with mechanical and thermal capacities, dynamic characteristics along with earthquake capacities [31], Hydro-thermo-mechanical properties[22], thermal mass and time lag [26, 32] of raw earth. Only a few studies have discussed the research on raw earth wall to improve the indoor thermal environment, such as the sandwiched raw earth wall studied in hot arid, warm temperate, cool temperate climate [33], and the internal raw earth wall studied in hot dry climate [34]. The study presented in this paper investigated the effects of different types of raw earth wall as building envelope on the thermal environment of naturally ventilated space, so as to identify the most optimum wall strategy which is suitable for sub-tropical climates with the consideration of both thermophysical properties and aesthetics of raw earth material.

2. Parametric study on thermal performance of raw earth wall

2.1. Thermophysical properties of raw earth material

The thermophysical index of raw earth includes thermal effusivity, specific heat capacity, thermal diffusivity and so on [35]. Among these parameters, thermal effusivity is one of the most important factors that affect thermal performance of raw earth material. It increases with the increase of density and water content.

\[ e = (\lambda \rho c_p)^{\frac{1}{2}} \]  \hspace{1cm} (1)

where

- \( e \): thermal effusivity
- \( \lambda \): thermal conductivity
- \( \rho \): density
- \( c_p \): specific heat capacity

As shown in Formula 1, thermal effusivity is defined as the square root of the product of the material's thermal conductivity, its density and specific heat capacity. It is a measure of its ability to exchange thermal energy with its surroundings. It is also a characteristic index that shows the sensitivity of the surface directly affected by heat to the harmonic heat reaction [36]. The larger the value, the better the thermal stability of a material. The thermal effusivity of a material is related to its thermophysical properties (dry density of material, thermal conductivity). The greater the density of the material, the greater the thermal conductivity and the greater the thermal effusivity of the material layer. The thermal effusivity indicates the sensitivity of the external protection system to harmonic heat. Thermal inertia index is an index that indicates the degree of temperature fluctuations on the surface after the material layer is subjected to fluctuating heat [37]. That is to say, a characteristic index of the ability of the bright material layer to resist temperature fluctuations, its value depends on the thermal resistance of the material layer and the thermal effusivity of the material. When the thermal resistance of the material layer is constant, the greater the thermal effusivity of the material, the greater its thermal inertia index, the greater the attenuation of the temperature wave across the material layer. When the outdoor temperature wave passes through the layer-by-layer envelope structure, temperature wave attenuation will occur and the total phase delay will occur when the maximum temperature of the inner surface of the outer envelope occurs. It is caused by the heat capacity of the material and the thermal resistance of the material layer in the heat transfer during the heating and cooling process. Dividing a homogeneous solid flat structure into four thin layers of the same thickness can help understand how heat flow is transferred from the outer surface that has increased temperature through the entire wall. When the heat storage becomes larger in the layer, the excess heat is transferred to the adjacent cooler layer in turn, which causes the heat flow through every layers and thus increasing their temperature. Therefore, each layer receives only a small amount of heat, and its temperature increase is lower than the adjacent outer layer. When the temperature of the outer surface reaches its maximum value, it begins to cool, and then
begins to hot when the temperature drops to the lowest value \([38]\). This process of heating and cooling occurs in turn. It can be seen that any section of the wall body undergoes a cyclical change process of heating and cooling. The fluctuation amplitude of the inner surface temperature is lower than that of the outer surface. The maximum temperature appears on the inner surface later than the maximum temperature appears on the outer surface. The temperature difference between the inner surface and the outer surface depends on the thermophysical properties of the material and thickness of the wall. When the heat capacity and thickness of the wall increase and the thermal conductivity of the material decreases, there are two results: a) the amplitude of the fluctuation of the inner surface decreases; b) wall can provide a thermal time lag.

2.2. The application of thermal insulation layer in raw earth wall

The external wall of the building plays an important role in stabilizing the indoor thermal environment and saving energy. Although raw earth materials have advantages in terms of thermal inertia index, the thermal resistance of raw earth material does not have an advantage compared to other conventional building materials \([39]\). Therefore, the raw earth wall needs to be matched with thermal insulation materials in order to be able to meet the relevant requirements for thermal insulation of the external wall of the building. Therefore, the thermal performance of the raw earth wall is not only related to the thermophysical properties of raw earth material, but also related to design parameters of the wall.

Although architects did not set up external wall insulation for economic reasons in some examples of raw earth construction, it is essential for public modern buildings in cities to design the external wall of the raw earth to meet the requirements of building insulation via adding thermal insulation layers. The composite wall combining raw earth and thermal insulation layer mainly has the following two forms.

One is to place the thermal insulation layer in the raw earth wall to form a sandwich form. This practice is common in buildings that want to see the texture of raw earth both inside and outside the building. The advantage is that it meets the user’s visual aesthetic needs, while the disadvantage is that thermal insulation layer divides the raw earth wall into two parts, thus weakening the integrity of the wall. Moreover, this approach is difficult to avoid the generation of cold bridges on the exterior wall of the building.

The other is to place the thermal insulation layer on one side of (mostly outside) the raw earth wall, and set the decorative layer on the other side. This form makes the functions of each level of the building’s exterior wall relatively single. Each material performs its own duties, and the construction operation is relatively simple. This approach is adopted by many of the newly-built modern building.

2.3. Relationship between thickness and thermal performance of the wall

The thickness of raw earth layer and thermal insulation layer, and structural measures directly affect the thermal performance of the wall. The thickness of raw earth wall also depends on the requirements of its bearing capacity. From the perspective of structural stress and wall stability, the thickness of raw earth wall should not be less than 250mm. The study of this section discusses the effect of thickness of the raw earth wall and thermal insulation layer on thermal performance. The formulas involved areas follows \([40]\).

\[
U = \frac{1}{R_{\text{tot}}} \tag{2}
\]

where

- \(U\) is the thermal transmittance, in W/(m\(^2\)·K);
- \(R_{\text{tot}}\) is the total thermal resistance, in m\(^2\)·K/W.

\[
R = \frac{d}{\lambda} \tag{3}
\]

where

- \(R\) is the thermal resistance of homogeneous layers, in m\(^2\)·K/W;
- \(d\) is the thickness of the material layer in the component, in m;
- \(\lambda\) is the design thermal conductivity of the material, in W/(m·K).
2.3.1. **Thickness of raw earth wall.** The thermophysical index of single-layer raw earth wall can be calculated according to its thickness. The thermal resistance of raw earth wall is proportional to the wall thickness. Therefore, thermal insulation effect of raw earth wall becomes better with the increasing of its thickness.

2.3.2. **Thickness of thermal insulation layer.** When the thickness of raw earth layer is fixed, the thermal transmittance of the wall will be reduced accordingly with the increasing of the thickness of the thermal insulation layer. It means that the thickness of thermal insulation layer is inversely proportional to thermal transmittance of the wall. To sum up, increasing the thickness of thermal insulation layer can not only reduce the thermal transmittance of the wall, but also increase the thermal inertia index of the wall, thus saving heat in during winter and emitting heat out during summer.

3. **Methodology**
Research methods of this study mainly include literature review (thermophysical properties of materials, thermal performance of the wall, building design files, local building standards, et.al), field study, floor plan drawing and building modeling (software: Rhinoceros), simulation test (software: Ladybug Tools series of EnergyPlus) and data analysis.

3.1. **Climate zone, typical summer day and typical winter day**
Shanghai is selected because it is a typical city located in sub-tropical climate. Compared with other regions located at the same latitude in China, the outdoor climatic condition of Shanghai is poor because of the climatic features and Urban Heat Island effect. In such an urban environment, the thermal performance of building envelope has become an important factor. Its humidity is high throughout the year due to large average annual precipitation. The temperature is very high in summer (the hottest month: August) and very low in winter (the coldest month: January) because of sufficient summer sunshine, and lack of winter sunshine. According to the China National Meteorological Science Data Center, 15 August and 31 January are the typical summer day and typical winter day respectively in Shanghai. Subsequent research will discuss thermal environment of the building under the circumstance of the hottest month, the coldest month, typical summer day and typical winter day.

3.2. **Case selection, field study and modeling**
A second-level primary school in Shanghai is selected as a sample building for simulation test. After consulting the design data and conducting on-site investigations, the wall materials of sample building are concrete (200mm thickness) and additional external EPS insulation board (30mm thickness). After on-site testing, it can be found that the indoor thermal environment is not comfortable. According to questionnaire survey, building occupants responded that the main reason for the discomfort is few HVAC systems in Shanghai. They have to endure extreme heat and cold in such naturally ventilated room.

Rhinoceros, commonly abbreviated Rhino, is a commercial 3D computer graphics and computer-aided design (CAD) application software. Based on the data of field investigation and building design documents, the study firstly draws the plan of building (Figure. 3) and then establishes modeling (Figure. 4) via using Rhinoceros.
Figure 3. Building plan.

Figure 4. Building modelling.
3.3. Simulation tools
Building modelling is then imported into simulation tool - Ladybug Tools series of plug-ins. It is an energy consumption simulation software based on EnergyPlus funded by the U.S. Department of Energy Building Technologies Office. EnergyPlus is a whole-building energy simulation program that can be used by engineers, architects, and researchers to model both water use in buildings and energy consumption for heating, cooling, ventilation, lighting, and process and plug loads. EnergyPlus is a console-based program that reads input and writes output to text files. Several comprehensive graphical interfaces for EnergyPlus are also available [41-42].

3.4. Preliminary simulation of building thermal environment and zone selection
Each room of sample building is labelled. Naturally ventilated spaces where occupants stay for a long time are zone 0, 1, 4, 6, 7, 8, and 12. Through simulating the thermal environments of the building with “Original Wall”, it can be obtained that “Zone 4” is the hottest space in the hottest month (Figure.5); “Zone 8” is the coldest space in the coldest month (Figure.6) These two zones, as the most uncomfortable spaces, are identified as sample zones for further discussion and analysis in the following chapter.

Figure 5. Different average air temperatures of zones in building in August.

Figure 6. Different average air temperatures of zones in building in January.
3.5. Wall type
In this study, there are five simulated scenarios that have five different wall types of building envelope (as shown in Figure 7).

- “Original Wall” (A) is the existing wall of sample building.
- “Green Wall” (B) is formed by increasing the thickness of thermal insulation layer on the basis of “Original Wall”. It is a standardized wall that meets local green building standard.
- Raw earth wall is divided into “Raw Earth Wall with External Insulation” (C), “Raw Earth Wall with Internal Insulation” (C1) and “Raw Earth Wall with Sandwich Insulation” (C2) according to study in chapter 2.2.

Figure 7. Five wall types.

4. Simulation results and data analysis
This section will firstly explore the feasibility of applying the raw earth wall in naturally ventilated environments in hot summer and cold winter regions. In addition to “Original Wall” and “Raw Earth Wall with External Insulation”, “Green Wall” is used as a comparison object to analyse the thermal performance difference between the refocused raw earth wall and the popular green standardized wall. Their insulation forms are all external insulation. After that, there are analysis of thermal performance of different raw earth walls so as to identify the most optimum strategy of raw earth wall.

4.1. Comparison between different wall types
By comparing the difference between “Original Wall” (Line A) and "Green Wall"(Line B) on typical summer day, it can be found that two lines almost overlap before 10:00. From 11:00, the rising rate of "Green Wall" is slightly larger than that of "Original Wall". Both of them reach a peak around 17:00, and then decline and get closer to each other. It means that thermal performance of both walls almost the same before 10:00. After 11:00, the thickened thermal insulation layer of "Green Wall" contributes to more difficult dissipation from the indoor to the outdoor, which causes its indoor air temperature is slightly higher than that of “Original Wall”. The relationship between line A and line C is different from that between line A and line B. They appear to cross. The intersection occurs at 15:00. Before it, data of “Raw Earth Wall with External” Insulation is higher than that of “Original Wall”. After that, data of “Raw Earth Wall with External” is obviously lower than that of “Original Wall”. Based on the study in chapter 2.1 and 2.3.1, raw earth wall can store more heat due to thermophysical properties of its material, which results in slow decrease (before 15:00) and slow increase (after 15:00) of indoor air temperature.
In typical winter day of Figure 8, three lines do not cross. Line A and line B are parallel. Line of "Green Wall" in is slightly higher than line of "Original Wall", which means that there is very little indoor air temperature difference between buildings with two wall types in a typical winter day. In contrast, line C is significantly higher than both line A and line B before 16:00. After that, line C is closer to line B but still slightly higher than it.

In summary, increasing the thickness of thermal insulation layer can make the envelope better prevent outdoor heat from entering the room in summer and reduce the loss of indoor heat in winter. Raw earth can also improve the thermal stability of the indoor environment and effectively avoid the sudden change of indoor air temperature within a day. The application of raw earth in Shanghai is feasible and worthy of further research.

4.2. Comparison between different wall insulation types of raw earth wall

Following the above research, further studies are conducted focusing on raw earth wall itself. Three types of walls with different forms of insulation are shown in Figure 9.
In typical summer day, line C and line C2 almost coincide. And there is a cross phenomenon between them and line C1. From 00:00 to 11:00, indoor air temperature of the building with “Raw Earth Wall with Internal Thermal Insulation” is lower than that of the building using other two raw earth wall types. After 12:00, indoor air temperature of the building with “Raw Earth Wall with Internal Thermal Insulation” is significantly higher than others, and reaches the highest value at 17:00. The reason why “Raw Earth Wall with Internal Thermal Insulation” is clearly different from the other two is mainly due to the nature of insulation material and the position of insulation layer. Insulation material suppresses the heat dissipation from the indoor to the outdoor in summer; its own temperature also rises faster. Such two natures combined with its position (internal insulation) lead to the phenomenon as described before.

In winter, line C is a little above line C2; Line C1 crosses with them. The intersection appears around 14:00. It means that before 14:00, indoor air temperature of the building with “Raw Earth Wall with Internal Thermal Insulation” is significantly lower than other two wall types. After 14:00, there is no obvious difference in indoor air temperature between these three scenarios. But from beginning to end of the day, line C is always at a higher position, showing good thermal performance of “Raw Earth Wall with External Insulation” in winter.

In conclusion, the position of thermal insulation layer has a certain influence on the thermal performance of building envelope. Since the raw earth layer of “Raw Earth Wall with Internal Thermal Insulation” does not directly contact the indoor air, the temperature adjustment function of raw earth material cannot directly affect the indoor air. To some extent, the internal thermal insulation structure will lead to poor stability of indoor air temperature. Therefore, it is recommended to prefer to use the forms of external insulation and sandwich insulation.
Table 1. Minimum and Maximum indoor air temperature in typical winter day.

| Structure | Minimum temperature | Maximum temperature |
|-----------|---------------------|---------------------|
| Structure A | 6.55575(7:00) | 19.844295(16:00) |
| Structure B | 6.932854(7:00) | 20.318179(16:00) |
| Structure C | 8.710246(7:00) | 20.533478(16:00) |
| Structure C1 | 7.100327(7:00) | 20.709184(16:00) |
| Structure C2 | 8.52739(7:00) | 20.245805(16:00) |

Table 2. Minimum and Maximum indoor air temperature in typical summer day.

| Structure | Minimum temperature | Maximum temperature |
|-----------|---------------------|---------------------|
| Structure A | 28.01295(7:00) | 36.279309(17:00) |
| Structure B | 28.049973(7:00) | 37.10195(17:00) |
| Structure C | 28.943824(6:00) | 35.190579(16:00) |
| Structure C1 | 27.957392(6:00) | 37.096753(17:00) |
| Structure C2 | 28.928082(6:00) | 35.117181(16:00) |

5. Conclusions

The building should meet the needs of people at different levels and different dimensions. With the deepening of research, the research on materials has also shown a multi-dimensional trend. Raw earth material has been favored by architects due to their unique material texture and expressiveness. In recent years, it has been partly used as envelopes in modern buildings. As people's demand for the indoor thermal environment is getting higher and higher, it is necessary to conduct corresponding research on the thermal performance of building envelope system of raw earth material to meet people's demand. This paper explores the application strategies of raw earth for hot summer and cold winter regions by studying the thermal performance of different wall types as a building envelope.

Compared with common building materials, raw earth materials have significant advantages in thermal transmittance, thermal effusivity, et.al. In buildings, thermal transmittance of the envelope directly determines the amount of heat exchange between indoor and outdoor; thermal effusivity has a direct impact on the stability of indoor air temperature. This shows that the material itself has good thermal performance and has great application potential in the construction industry.

The raw earth wall needs to be combined with thermal insulation materials to form a composite wall to meet the requirements of the indoor thermal environment. In addition to the thermophysical properties of the material itself, the thermal performance of the envelope structure is also closely related to the design parameters and structure. Firstly, the thickness of both raw earth layer and insulation layer has a direct influence on the thermophysical properties of the raw earth wall. The thermal resistance of the wall increases as its thickness increases. Secondly, the structural form of the wall also has an important influence on the thermal performance of the wall. The main structural forms of raw earth wall are roughly divided into three types: sandwich insulation formed by placing the insulation layer between raw earth layers, and one-side insulation that includes external insulation layer and internal insulation layer.

In order to study the impact of different types of raw earth wall on the indoor thermal environment in sub-tropical regions, a second-level primary school in Shanghai was simulated and tested. Through simulation tests, it is known that thanks to the relatively high thermal effusivity of the raw earth material, indoor air temperature of the building using “Raw Earth Wall with External Insulation” in summer has obvious advantages in thermal stability, compared with “Original Wall” and “Green Wall”. In the typical summer day, although the minimum indoor temperature of “Raw Earth Wall with External Insulation” during the whole day is slightly higher than that of the other two wall types (temperature difference is 0.9-0.93℃), its maximum indoor temperature is much lower (temperature difference is 1.09-2℃). “Raw Earth Wall with External Insulation” has better thermal insulation performance in winter, especially at night and in the early morning.
After that, three different types of raw earth walls are horizontally compared. Comparative analysis shows that the thermal stability of “Raw Earth Wall with Internal Insulation” is relatively poor because its raw earth layer does not directly contact with indoor air. In summer, the insulations of “Raw Earth Wall with Sandwich Insulation” and “Raw Earth Wall with External Insulation” are almost the same, while “Raw Earth Wall with Internal Insulation” demonstrates a large fluctuation range. In winter, the raw earth layer on the inside of “Raw Earth Wall with External Insulation” (400mm thickness) is thicker than that of “Raw Earth Wall with Sandwich Insulation” (200mm thickness) and “Raw Earth Wall with Internal Insulation” (0mm thickness), which makes its indoor heat loss is slower in winter night and early morning. Therefore, in terms of thermal performance, the “Raw Earth Wall with External Insulation” is more suitable in winter in subtropics.

But as mentioned above, the building should meet the needs of people at different levels and different dimensions. Besides the thermal performance of the raw earth wall, its aesthetics is also an important level or dimension. “Raw Earth Wall with External Insulation”, to a certain extent, influences the expressiveness of raw earth material itself with a unique texture since it is installed an additional insulation layer outside. So, it is more recommended to use “Raw Earth Wall with Sandwich Insulation” if the building design pursues the natural beauty of raw earth materials. Therefore, appropriate wall types should be selected according to different needs in practical applications.

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