The Potential for Light Straw Clay Construction in Japan: An Examination of the Building Method and Thermal Performance

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Abstract

Light straw clay is a mixture of straw and clay used as an infill in wood framed construction to create non-load bearing walls. Light straw clay has numerous advantages: Consisting of straw and clay, the raw materials are locally available throughout most of Japan. Light straw clay's relatively low thermal conductivity provides good thermal insulation, which reduces energy use and CO_2 emissions due to heating and cooling. The tools and technology needed to construct light straw clay walls are relatively simple and commonly available. And lastly, upon deconstruction, the walls can safely decompose without becoming landfill. There are relatively few non-commercial insulation materials consisting of renewable materials. The purpose of the present study is to evaluate the potential for light straw clay in Japan, including an investigation of the building method, thermal conductivity and overall heat transfer. The building method was found to take more time than conventional construction, which in turn increases labor costs. The mean thermal conductivity of the actual light straw clay insulation was 0.067W/mK. The heat transfer coefficient for a cross section of the insulated wall was 0.531W/m^{2}K.

Keywords: light straw clay; thermal conductivity; heat transfer

1. Introduction

Light straw clay is a mixture of straw and clay used as an infill in wood framed construction to create non-load bearing walls. Earth and straw have been used as infill in half-timber buildings throughout the world. In recent years light straw clay has gained international attention as an ecological building material (Baker-Laporte and Laporte, 2015). Light straw clay has numerous advantages: Consisting of straw and clay, the raw materials are locally available throughout most of Japan. Light straw clays' relatively low thermal conductivity provides good thermal insulation, which reduces energy use and CO_2 emissions due to heating and cooling. The tools and technology needed to construct light straw clay walls are relatively simple and commonly available. When designed and built correctly, protecting from moisture damage, light straw clay has proven to be durable and resistant to decay (Baker-Laporte and Laporte, 2015). And lastly, upon deconstruction, the walls can safely decompose without becoming landfill.

Currently, Japan has no mandatory thermal insulation standards for homes. According to the Ministry of Land, Infrastructure, Transport and Tourism, commercial and residential buildings in Japan are responsible for 33.8% of all final energy consumption (Mizutani, 2015), and account for 34% of Japan's CO_2 emissions (2007). In 2005, Residential homes alone produced 174 million tons of CO_2, of which approximately 25% was due to heating and cooling. The Ministry of Land, Infrastructure, Transport and Tourism estimates that energy efficiency improvements (not including water heating, lighting and appliances) such as improvements in thermal insulation could reduce 8.5 million tons of CO_2 emissions per year (2007).

In 2020, energy efficiency standards will be required of all new construction in Japan. There are relatively few insulation materials consisting of natural and renewable materials. Light straw clay is a natural, low embodied energy insulation material capable of meeting energy efficiency requirements.

With the author's assistance, in 2013, Japan's first fully-fledged light straw clay home was built in Nagano Prefecture (Fig.1.). The building was designed by Tadashi Ryoukawa and built by master carpenter Asao Tamai.

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Fig.1. Japan's First Light Straw Clay Home

The purpose of the present study is to evaluate the potential for light straw clay in Japan, including an investigation of the building method and thermal insulation.

2. Materials and Methods

2.1 An Examination of the Building Method

The building process of light straw clay insulation will be investigated, determining quantities of materials needed and time and labor requirements for construction.

The earth used for the project was sourced from an earthen plaster producer in Nagano City. The earth was originally produced as base coat plaster (Jp: *arakabe tsuchi*) (Fig.2.). During the initial production process in Nagano City, high clay content soil was mixed with chopped straw and allowed to ferment, breaking down the straw into thin fibers and creating an ideal mix for plastering.

Fig.2. Clayey Soil Sourced from Nagano City

However, there is no need to ferment clay for light straw clay. The higher the clay content, the less clay is needed to stabilize the light straw clay. The lower the clay content, the less dense the light straw clay and the lower the thermal conductivity, which, in turn, provides greater thermal resistance.

Additional water was added to the plaster and mixed in a vertical axis mortar mixer to create clay slip. Approximately 300 liters of water was added to 1.2 tons of delivered earthen plaster. The clay slip was then mixed with straw (Fig.3). The clay slip and straw were mixed like salad and salad dressing, turning the straw with a pitchfork.

Fig.3. Light Straw Clay Mixing Station

Light straw clay was used as thermal insulation in the walls, floor and roof (Fig.4.). In the walls, the thickness of the light-straw-clay insulation is 120mm. The thickness in the floor and roof is 100mm.

Fig.4. Light Straw Clay Thermal Insulation in Walls, Floor and Roof

In order to improve seismic stability, two additional measures were used:

1) 90mm x 45mm boards were toenailed at every 600mm of wall height as seen in Fig.5. Not only does this prevent the light straw clay infill from settling, it also prevents an entire wall system from failing at the same time by breaking the wall system into smaller compartments, similar to half-timber construction (Langenbach, 2010). Since the 90mm x 45mm boards are toenailed parallel to interior and exterior finishes and do not transverse the wall system, they do not act as thermal bridges.

2) Horizontal wood lath was applied to the exterior and interior of the light straw clay walls (Fig.6.). In order to save time, in some cases, the lath doubled as permanent formwork, but the authors found that the lath tended to bow outwards when the wall cavity was packed with light straw clay. In retrospect, we might consider not packing the cavity as densely.

Fig.5. 90mm x 45mm Boards Toenailed at Every 600mm

Fig.6. Wood Lath over Light Straw Clay Walls

A base coat of earth plaster was applied to the exterior and interior of all light straw clay walls. In order to protect the first story walls from rain erosion and moisture damage, wood siding (rain screen) was used (Fig.7.). The second story walls are finished with *Shikkui* lime plaster.

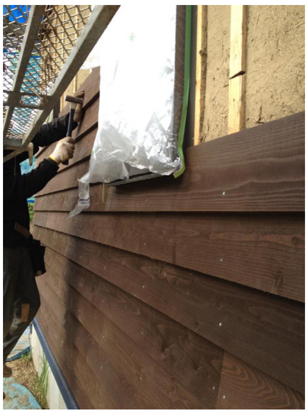


Fig.7. Wood Siding over Earthen Plastered Light Straw Clay Infill Walls

Through conversations with the architect and builder, the labor requirements of this building method are investigated.

2.2 Evaluation of Thermal Insulation

Since 2010, Nihon University's Architectural and Regional Ecological Design Studio has been researching the potential for light earth construction in Japan. Numerous samples using various lightweight aggregates, including straw, rice hulls and wood chips, have been made and the thermal conductivity measured.

The thermal conductivity of the in situ light straw clay wall is compared with laboratory samples. Two laboratory samples were made using the same light clay straw mix (clay slip and straw) as the actual wall in situ (Fig.8.).

Fig.8. Laboratory Samples

Fig.9. depicts the five testing locations of the in situ light straw clay wall. When testing in situ, locations 1 and 2 were finished with an earthen plaster. Locations 3-5 had not yet been plastered.

Fig.9. Testing in situ

An AINEX KD2 Pro Thermal Properties Analyzer was used to measure thermal conductivity of laboratory samples and the actual wall. The KD2 Pro Thermal Properties Analyzer is accurate to ±0.01W/mK between 0.02-0.2W/mK. The thermal conductivity of the laboratory samples will be compared to the in situ wall.

Moreover, the U-value and average heat transfer coefficient (W/m^2K) of the insulation layer will be calculated and compared to Japan's new energy efficiency standards.

In 2020, the 2013 Energy Efficiency Standards will become mandatory for all new construction in Japan. The 2013 Energy Efficiency Standards divide Japan into eight climate zones (Fig.10.).

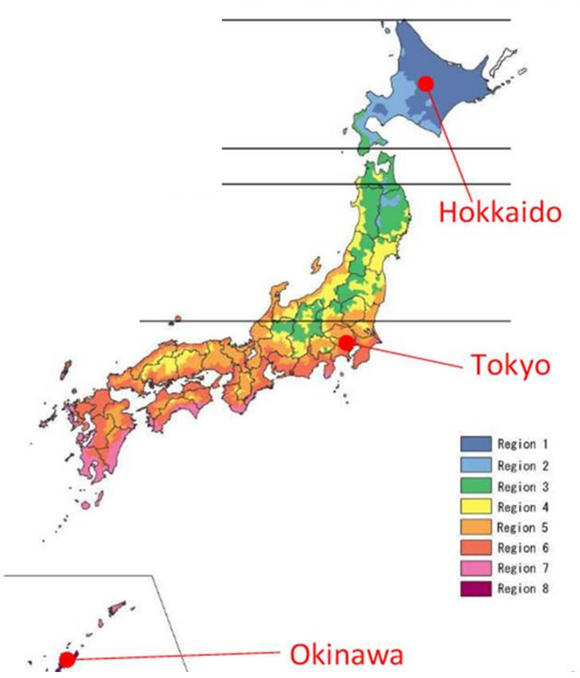


Fig.10. Eight Japanese Climate Zones [from Mizutani (2015)]

The 2013 energy efficiency standard's overall heat transfer coefficient for each climate zone is listed in Table 1. These values represent the envelope average thermal transmittance (U_A=W/m^{2}K), in other words, the area-weighted average U-values for the building envelope including every component. These values are calculated by averaging the thermal conductivity of all building components such as walls, roof, floor, windows and doors.

Table 1. 2013 Energy Efficiency Standard's Overall Heat Transfer Coefficient for Each Climate Zone

Climate Zone	1	2	3	4	5	6	7	8
Overall Heat Transfer Coefficient (W/m^{2}k)	0.46	0.46	0.56	0.75	0.87	0.87	0.87	na

In order to calculate the overall heat transfer coefficient for a wall section, the thermal conductivity and thickness of each element is needed. Since the present study does not examine the thermal conductivity of earthen plaster, the authors refer to the literature for such data. According to Horst Schroeder's Sustainable Building with Earth (2015), the thermal conductivity of earthen plaster is 0.65W/mK.

Lastly, through conversations with the homeowner, the indoor thermal environment is subjectively evaluated.

3. Results and Discussion

3.1 The Building Method

Table 2. lists the materials and quantities used to construct the light straw clay walls, roof and floor.

For every 1m^3 of earth, approximately 4.3m^3 of straw was used.

Table 2. Light Straw Clay Materials and Quantities

Material	Quantity (m^3)
Straw	44.8
Earth	10.5

The volume of light straw clay used in walls, floor and roof is listed in Table 3.

Table 3. Volume of Light Straw Clay

Location	Quantity (m^3)
Walls	16.77
Floor	5.23
Roof	5.26

The total volume of light straw clay insulation is 27.26m^3. Thus, for every 1m^3 of light straw clay insulation, 1.64m^3 of straw and 0.39m^3 of clay was needed.

According to the builder, approximately 60% of total building labor was used to construct the light straw clay walls, including finish plastering. For every 3.3m^2 of floor space (*Tsubo* in Japanese), in total approximately 7-8 labor days were required for construction. Of those 7-8 days, 4 days were spent on the light straw clay walls including plastering.

The walls specifically required 60 people-days to fill with light straw clay. At a volume of 16.77m^3, the rate of mixing and packing is 3.58m^3/person/day.

The *Tsubo* (3.3m^2) unit cost of the building increased by 15,000JPY compared to commercial insulation consisting of 85% wool.

3.2 Thermal Insulation

The thermal conductivity of the laboratory samples (Table 4.) and actual in situ wall (Table 5.) was measured using an AINEX KD2 Pro Thermal Properties Analyzer.

The mean thermal conductivity of the actual light straw clay wall was 0.067W/mK. For comparison, the thermal conductivity of concrete is 0.8 W/mK (Young, 1992). Fig.11. outlines a thermal analysis of a cross section of the light straw clay wall. The thermal resistance (R-value) at 120mm is 1.791m^{2}K/W. According to Schroeder (2015), the R-value of 30mm of earthen plaster is 0.046m^{2}K/W. Thus, the heat transfer coefficient for a cross section of the light straw clay wall, including insulation layer and interior and exterior finishes, is 0.531W/m^{2}K. For comparison, the heat transfer coefficient for 180mm of concrete is 4.444 W/m^{2}K.

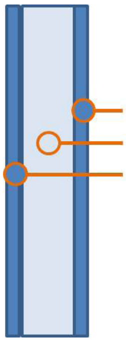
Table 4. Density and Thermal Conductivity of Laboratory Samples

Sample No.	Density (kg/m^3)	Thermal Conductivity (W/mK)
1	343.145	0.060
2	369.395	0.083
Mean	356.270	0.072

A complete thermal analysis of the home is beyond the scope of the current study, and therefore only a cross section of the light straw clay wall is compared

Table 5. Thermal Conductivity of the in situ Wall

Location No.	Thermal Conductivity (W/mK)
1	0.076
2	0.072
3	0.082
4	0.042
5	0.061
Mean	0.067



Material	Thickness (mm)	Thermal Conductivity (W/mK)	R-value (m^2K/W)
Earth Plaster	30	0.650	0.046
Light Straw Clay	120	0.067	1.791
Earth Plaster	30	0.650	0.046
R-value sum (m^2K/W)			1.883
Heat Transfer Coefficient (W/m^2K)			0.531

Fig.11. Thermal Analysis of a Cross Section of the Insulated Wall

to Japan's new energy efficiency standards. At 0.531 W/m^2K, the cross section of the wall is permitted in climate zones 3-8. In climate zones 1 and 2, additional insulation is required.

In order to meet energy efficiency standards for zones 1 and 2, the light straw clay wall can be made (1) thicker than 120mm and/or (2) the density can be decreased. If the density of the light straw clay is decreased, which would in turn decrease thermal conductivity and increase thermal resistance, 120mm of light straw clay insulation may pass the heat transfer coefficient for zones 1 and 2. In practical application, in order to decrease density, purer and stronger clay is needed.

Lastly, through conversations with the homeowner, the home seems to be performing well thermally. With passive solar design, the masonry rocket stove heater only needs firing for roughly 30 minutes a day to keep interior temperatures comfortable in winter.

4. Conclusion

In 2020, energy efficiency standards will be required of all new construction in Japan. There are relatively few insulation materials consisting of natural and renewable materials. Light straw clay is a natural, low embodied energy insulation material capable of meeting energy efficiency requirements. The purpose of the present study was to evaluate the potential for light straw clay in Japan, including an investigation of the building method and thermal insulation. The building method was found to take more time than conventional construction, which in turn increases labor costs. The mean thermal conductivity of the actual light straw clay insulation was 0.067W/mK. The heat transfer coefficient for a cross section of the insulated wall was 0.531W/m^2K, which met the energy efficiency requirements in climate zones 3-8, but at t=120mm, light straw clay insulation failed to meet the requirements for zones 1-2. In order to meet energy efficiency standards for zones 1 and 2, the light straw clay wall can be made (1) thicker than 120mm and/or (2) the density can be decreased which would also decrease thermal conductivity.

Acknowledgments

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