Totora: A Sustainable Insulation Material for the Andean Parts of Peru

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ABSTRACT: In the Andean areas of Peru (above 12,000 feet, 3,657 meters) altitude) rural communities are characterized by extreme poverty, precarious roads, and dwellings without heating systems nor the most common types of conventional construction materials that might provide thermal protection. In 2002, the weather in the Andes changed, generating temperatures as low as -16 degrees Fahrenheit (-26 degrees Celsius), creating major heating deficits in the majority of the adobe houses. “Totora” (Schoenoplectus Tatora), an aquatic plant that grows in Lake Titicaca at 12,500 ft (3,810 meters) above sea level, available in most rural areas in Puno, is sold as an inexpensive mattress. Samples of woven mats of Totora were exported from Peru and tested in a laboratory at the University of Minnesota following the ASTM Standard C1155 to find its R-value. The results indicate that the Totora ‘mattress’ has an R-value that is approximately eight times higher than adobe of the same thickness. Additionally, the findings show that Totora can be used as a sustainable insulation on walls, windows and doors by applying it as an external layer to new or existing houses. This solution could improve the interior comfort of the houses and the quality of life in the rural Andean communities of Peru.

Keywords: Comfort, Adobe, Insulation, Totora, Scirpus Californicus, Schoenoplectus Tatora.

INTRODUCTION
In the Andean parts of Peru the main system of housing construction is adobe. After 2002, there has been a shift in the temperature in the Andes generating temperatures as low as -16 degrees Fahrenheit (-26 degrees Celsius). Under these conditions conventional adobe is no longer able to protect its inhabitants. The most affected area in the Andes was Puno, specifically the rural communities that are in extreme poverty. The region of Puno is known to have the highest rates in children mortality in the country; children and elderly people represented the large group of the casualties caused by this temperature shift.

Most studies related to adobe houses in Peru focus on the structural resistance and construction improvements needed to make them structurally sound. Adobe construction regulations are included in the Peruvian “National Regulation of Construction” in the “Norm 080. Adobe”[1]. This standard sets the structural reinforcement for buildings according to the seismic zone the building is located in. However, there are no regulations directed towards insulating the adobe walls in the cold areas of Peru. Due to the fact that Puno is the most affected area in Peru in winter, it is important that the adobe houses have the appropriate insulation to resist cold temperatures.

Two communities were visited in Puno for this research in 2009: First: The rural community of Pacaje, located at 15,748 ft. (4,800 m) altitude in Macusani’s district, this is a typical rural community that build their houses entirely with adobe. The purpose of this visit was to measure the interior and exterior temperatures of the houses and characteristics (Fig. 1), identify commonly available materials, and interview the population to determine their capability to improve their houses and prepare a proposal that could be applied in similar rural communities in Puno. From this visit mattresses made of an aquatic plant named totora were found in most of the houses.

The second community visited was The Uros’ community located at 12,500 feet (3,810 m) altitude in
the middle of Lake Titicaca. They make their houses, boats and even their floating islands with an aquatic plant called totora that grows abundantly in Lake Titicaca. The purpose of this visit was to find out more about this material, their construction techniques, measure the temperatures of the houses, identify the endurance of the material, and interview the population about the use of this material.

Totora samples of 2” (5 cm) and 7/16” (1 cm) thick were brought to the U.S. from Peru and tested at steady state conditions at the University of Minnesota. The testing procedure followed the ASTM Standard C1155 to determine the R-value of the totora panels. The results show that a 2” (5 cm) totora panel has an average R-value of 2.11 (RSI 0.37) per inch, with R-value ranging between 2.07 (RSI 0.36) and 2.20 (RSI 0.39) per inch. This is approximately eight times higher than an inch of adobe.

The application of the totora can be added to the adobe walls and windows by using the same method that the Uros used to wrap the totora panel around a wood structure taking advantage of its rigidity. The application of totora mattresses can be added to the windows of the Pacaje houses as a curtain that can be rolled during the day and be covered during the night.

TOTORA
Totora is known with the scientific name of Schoenoplectus Tatora that forms the totorales of Lake Titicaca located in the heart of Puno, Peru. It is also an erect herbaceous plant that grows over flooded areas, streams, wetlands, and sandy areas. It belongs to the family Juncaceae. According to Monroy [2], totora first originated in Lake Titicaca and then propagated to the rest of South America and North America. In the U.S. it is known as Schoenoplectus Californicus or California bulrush [3]

Totora’s composition contains a high fraction of silica (SiO2), deposited in its roots, stems, and leaves. According to Piperno [4], silica is durable in soils and dry environments; Kaufman [5] stressed the fact that silica bodies serve a variety of purposes in plants, like giving them structural rigidity by supporting the shoot. Djamin [6] stated that silica bodies enhance the tolerance of the plant against fungal diseases. In conclusion, silica bodies help a plant to resist high and low temperatures, the attack of fungus and plant predators, and radiation or drought, causing the plant to last longer. The silica content in Totora (Schoenoplectus Tatora) may explain why it is one of the few plants in Puno that can resist drought periods and has structural rigidity. Sato’s thesis [7] stated that totora’s high tensile strength is due to a high content of cellulose in its composition.

Totora is composed of three parts: the stem, the root, and the inflorescence. The stem is covered by a wax surface. It does not have leaves or ramifications and it can reach a height of 13-feet depending on the ground, weather, and water conditions.

The Uros used this aquatic plant to build their houses. Because of Totora’s rigidity and its lightweight properties it only needs a wooden structure to wrap around to create a house. (Fig. 2)

The availability of totora in rural communities in Puno and its properties make it a good candidate for insulation, along with its porous stem section, and waxy surface. These qualities and the fact that totora contains silica were the main reasons why this material was selected to be researched as an intuitive solution for insulating adobe houses.

Figure 2. Uros’s totora house details

PACAJE HOUSES CHARACTERISTICS
Adobe walls in Puno are an earthen construction system used in the majority of rural areas for low-income families and made by local communities without the assistance of architects or engineers. The construction system in rural areas in Puno uses mostly adobe due to the availability of rocks, earth, and clay. In Puno the adobe construction represents approximately 80% of the total construction in rural areas [8].

Pacaje houses are formed by more than one building section, where the kitchen is usually separated in an isolated building from the living quarters. The local
people developed their social area around the kitchen, where they spend most of their time. Social activities are developed in the afternoon and no social activities take place in the winter nights.

The configuration of Pacaje houses is a quadrangular layout with a door and small windows. (Fig. 3) The single-floor houses vary in height with the eave and peak height between 7 to 9 ft (2.1 to 2.7m.) tall. Most houses have an average layout of 16’ by 10’ (4.87 m x 3.05 m) and they are around 7 feet (2.13 m) high, the number of windows varies from one to two in a small unit (162 ft2 or 15 m2) to three in a large unit (220 ft2 or 20 m2). Windows are made of glass; plastic bags, and recycled plastic bottles. The plastic bottles usually do not meet the edges of the window, which creates a source of leakage. The orientation of doors and windows in Pacaje houses are more influenced by the orientation of the street, rather than to the northern solar orientation.

Based on the measurement of temperatures in Pacaje houses, the range of temperatures in the interior of the houses was outside of the comfort conditions for the entire day in the winter, this means indoor temperatures range between 18F. to 43F. (-7 to 6 C.).

ESTIMATED R-VALUE OF ADOBE BRICK.
In order to make the tests with the totora panels it was necessary to find a material that can resemble the R-value of the adobe walls found in Pacaje adobe walls are 12” (30.48 cm) thick and have a density of approximately 100lb/ft³ (1,600 Kg/m3). The compositions of these walls are as follows: 10-20% clay, 55-70% sand, and 15-25% silt. Several adobe R-values were taken into consideration looking for one with a similar composition to the adobe brick found in Pacaje. The R-values of the adobe went from 0.236 to 0.28 (RSI 0.04 to 0.05) per inch. The value that was chosen was the R-value in John Morony’s paper “Adobe and Latent Heat: A Critical Connection, 2005” [9], which gives to adobe an R-value of 0.25 (RSI 0.04) per inch. Considering that adobe walls in Pacaje are 12 inches (30.48cm) thick, the total R-value is 3 (RSI 0.53). The material that was used to simulate the R-value of the adobe walls was an XPS panel of ½” (1.27 cm) which has a rated R-value of 3 (RSI 0.53). Because the test being used is at steady-state conditions, it was determined that the difference in the mass of the two materials is not critical.

TESTS PROCESS
The ASTM Standard, C1155 [10] was a guide to establish standards for the totora tests. The recommendations that were incorporated in the tests procedures were as follows: The recommended data collection interval for each sensor was at least every 5 minutes. The temperature output in the totora tests were recorded every 60 seconds. The temperature output was averaged and the value for temperature and heat flux was computed. Each value was recorded at intervals of 60 minutes or less as recommended.

The test protocol recommends that the test continue for 24 hours or multiple of 24 hours, because 24 hours is the dominant temperature cycle. All of the tests lasted for 24 hours. The difference of temperature between the “inside” and “outside” area in the cold box was always greater than 75 degrees F (23.89 C). The calculations were taken after steady state was reached in every test. In order to report the results of the lab tests, it is required to record all ASTM practices used to obtain the temperature and heat flux data. For the lab test, ASTM Standard C1155-95 was used to set up the tests, and the formula to calculate the R-value was taken from the ASHRAE Handbook - Fundamentals [11].

The cold box, used to test the totora samples, was 16 feet (4.87 m) long, 9 feet (2.74 m) wide, and was divided into three different parts. (Fig. 4) [12].
The large space on the right is the cold side that houses the cooling units. The “outside,” the middle section is the smallest area, where the fan units are located blowing air parallel to the sample, producing winds of approximately 15 mph (24 km/h). This is the area that the outside air measurements are taken from for the R-Value formula. The “inside,” the space on the left of the cold box contains a heater and a small fan blowing on low to circulate the air creating a uniform temperature. The fan is pointed away from the test panels, and does not produce enough air movement to significantly impact the air film, so our interior air film will be factored with a wind speed of slightly above 0 mph (0 km/h). Two APT data loggers were used for capturing the data. Both APT boxes held 16 analog channels. These channels had thermocouples feeding temperature data back to the box that was connected to the computer, which recorded the data for each test specimen.

The thermocouples were located at 5” (12.7 cm) from the border of the window and one in each corner, and one in the middle of the panel. (Fig. 5) All the thermocouples were equally spaced so that they corresponded with the location of the thermocouples on the opposing side of the XPS. A gouge was cut into side of the XPS allowing the cables to go from the middle and outside layer of XPS back to the APT box. Two different thermocouples were also attached behind the wall on the “outside” and then two others on the “inside” so that they captured the temperatures internally and externally. After all the thermocouples were in place, the ½” (1.27 cm) plywood frame was set in against the XPS, wedging both of the pieces of XPS against the frame on the outside face of the window. All of the thermocouples were connected to the APT channels that they had been calibrated with, and the APT was connected to the computer. The software program, Teclog, was used to record 8 channels per APT unit. All of the results incorporate the calibration factor on the thermocouple readings to calculate the R-value of the XPS samples.

The formula used to calculate the R-value of the XPS panels is based on the principle that the temperature drops across any layer is proportional to the R-value of that layer compared to the total temperature drop and total R-value (page 27.9 in the 2009 ASHRAE Handbook of Fundamentals). The equation looks as follows:

$$t_i - t_o = \left( \frac{r_{iaf}}{r_{total}} \times (t_i - t_o) \right)$$

Where:
- $t_{r}$ = Temperature of outdoors
- $t_{o}$ = Temperature of interior surface of sample
- $t_{i}$ = Temperature of exterior

Assumptions: The velocity of the wind at 0 mph (0 km/h) has an R-value of 0.68 (RSI 0.12). With minimal wind movement impacting the interior air film, a riaf value of 0.60 (RSI0.11) was assumed. On the other hand the exterior film is impacted by a fan with the velocity of 15 mph creating an R-value of 0.17 (RSI 0.03).
TESTS RESULTS
Based on the existing mattresses found in rural communities nine tests were made to find the average R-value of a totora mattress 2” thick. The R-value results of the 2”(5.08 cm) totora panel after subtracting the R-value of the ½”(1.27 cm) XPS and the R-value of the interior and exterior air films (reaf + riaf) were much higher than expected. The combined average of the results of the 2”(5.08 cm) totora was generated, obtaining an R-value per inch of 2.11 (RSI 0.37). The R-values range between 2.07 (RSI 0.37) and 2.20 (RSI 0.39) (Fig. 6).

The conclusion is that a bunched weave of totora in a 2” (5.08 cm) thick panel has an R-value of at least 4.22 (RSI 0.74), although it is important to consider that not all totora mattresses have a uniform surface, and these results are approximate.[13]. Based on the results from the totora test protocols, it is possible to double the overall R-value of existing adobe walls by adding a 2” (5 cm) totora panel.

Figure 6. Totora R-value per inch results

TOTORAS APPLICATIONS IN THE ADOBE HOUSE
Using the available mattresses made of totora a proposal was made for the Pacaje houses. The configuration of Pacaje houses is a quadrangular layout with one door and small windows. The orientation of doors and windows in Pacaje houses are influenced by the orientation of the street, rather than the northern solar orientation. This is why a case-by-case proposal has to be developed in order to insulate the houses.

Any insulation proposal takes into account all typical cases to adjust to any design. According to David Easton[14], in regions where temperatures are extreme, the addition of supplemental insulation may be required to counteract excessive heat loss during the winter. Insulation either embedded within the wall or applied to the outside surface of the walls and protected with stucco or panelling is economically justifiable. Based on Easton’s recommendation and, the interviews with the Pacaje population, the insulation will be best located on the outside surface of the adobe walls and protected with a layer of 1” (2.5 cm) mud.

A previous research project that sought to structurally reinforce adobe houses with a wire mesh was used as a guide for adding totora panels to the walls. The wire mesh was added to the walls with nails every 9 3/16” (25 cm), and embedded into adobe bricks and not the adobe joints in the corner of the adobe houses.[15]. (Fig. 7)

Figure 7: Addition of wired mesh to the adobe walls. Source: Chuquimia. E. Manual earthquake resistant adobe construction

The wire mesh concept can be applied to the totora wrap for the adobe walls. The totora mattresses will need to be pegged to the adobe walls every two feet (0.61 m) across, and 15 inches (38.1 cm) apart vertically. The wooden pegs are five inches (12.7 cm) long, embedded four inches (10.2 cm) into the adobe wall. To vertically stack the panels it is necessary to interweave the end of both panels (Fig. 8)

Figure 8: Wall section with totora addition.
The totora mattresses are sold as a twin and a full sized mattress. Most houses have an average layout dimension of (16' by 10') and they are around 7 feet high. To cover one of the sides of the house it is necessary to use four panels for the wall and one additional panel for the gable on the side of the house. (Fig. 9) In total, ten panels will be used to insulate the adobe walls as a minimal approach with a total material cost of approximately $50.

The triangular panel of totora covering the gable of the adobe house will sit on top of the first layer of totora. It will also be attached to the adobe wall by wooden pegs. Applying a 1” (2.5 cm) layer of mud over the totora panels will enhance the durability of the totora for more than 3 years; it is also a traditional technique on adobe walls.

The windows will be covered with a 2” (5 cm) panel of totora, nailed from the top part of the window, rolled up during the day and kept tied to the upper part of the window and extended during the night. (See Fig. 10) In the case of the door, a 1” (2.5 cm) totora panel will be embedded to the interior of the door frame; finally a 1” (2.5 cm) totora panel will be attached to the door overlapping the exterior wooden door frame reducing air leakage. The original window and door will be kept in their original place; this addition is added over the existing elements to enhance the insulation of the total envelope.

The window and door panels will not be covered with a layer of mud and could be coloured according to the taste of the owner. Figure 11 shows the construction process of the window. Once the totora insulation is added to the rest of the walls, the window will be embedded diminishing the chances for air leakage. This would increase the insulation in one of the most vulnerable parts of the house “the window” that is covered with plastic most of the time because glass is expensive and transportation is difficult due to precarious roads.

One more recommendation is that any area causing heat loss should be sealed. If not, the insulation proposal will be compromised. Based on the Pacaje house tests, most of the heat loss was attributed to the walls, windows, doors, and roof.
CONCLUSION
Totora can be used as a sustainable insulation on adobe walls by applying it to new or existing houses as an external layer covered with mud keeping the house protected from the sun and bugs. This new use of totora will increase the market for this local, sustainable material and will have a positive impact upon the local economy.

The future demand of totora panels for use on adobe structures would increase the commerce and production of this product. It may make it necessary to expand growing areas and implement existing recommended methods [16] in totora agricultural production to grow and harvest totora properly without jeopardizing totora’s annual production. By following these recommendations the economic situation of rural areas in Puno could improve.

The high silica and cellulose contents of totora make it resistant to the conditions found at high altitude and could also provide structural benefits to the adobe construction. In conclusion, a further benefit is that the addition of 2” (5 cm) totora panels at the corners of the buildings not only improves the thermal behaviour of the adobe walls, but might also improve the structural stability of adobe construction. However, further research is needed to test this theory.

Totora may be used as a composition material for prefabricated panels that could be used in urban houses and added to the roof and doors of the Pacaje houses.

Based on the average indoor - outdoor temperature difference in Pacaje houses, adding only ten panels of totora to the adobe walls might double the thermal properties of the adobe structure. The proposal will also take advantage of Uro’s ancestral construction techniques with totora, which has been used for over 500 years by adding it to the adobe walls in nearby Puno.

Totora can be used in different parts of the house in order to increase the interior temperature of the house and most importantly to improve the quality of life of the people in the Andean parts of Peru.

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REFERENCES