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Uku Thermal Performance Characteristics

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Abstract. The thermal performance characteristics of Uku, natural fibre reinforced earth composite, are reported in this paper along with earlier results from structural and social performance studies. Uku is a building material that is being developed by the University of Auckland as a durable, affordable and sustainable building solution for rural Maori communities in need of better housing. A construction trial has been conducted at Lake Rotoiti that allows the comparison of a conventional code compliant timber frame dwelling with an identical floor plan Uku dwelling. A prevalent low level of housing conditions within rural Maori communities around New Zealand inspired the conception of a new design of both building material and building method. Seismic and social aspects of Uku have been researched previously along with preliminary research into the thermal performance attributes of Uku. A need for further research into the thermal performance characteristics of Uku exists due to the Lake Rotoiti implemented design using wall thickness and thermal resistance values that fall short of New Zealand code defined minimum standards.

The two dwellings constructed on the shores of Lake Rotoiti are installed with thermal (temperature and humidity) measuring devices as well as having thermal comfort research platimber frameorms in place. Data has been collected from these two houses and their occupants for the past three years, and analysed against benchmarks provided by available literature on thermal performance of housing in New Zealand. Comparisons of results obtained show Uku walls of reduced thickness to perform to a thermal level that is just below that which is considered a requirement in New Zealand. When compared against the Timber frame designed house however they perform strongly. Thermal comfort analysis of the house depicts a level of thermal comfort that is satisfactory for the Uku house.

Introduction

Māori are the indigenous people of New Zealand and hold approximately 5% of the total land area. Most rural Māori communities are currently unable to utilise this land effectively leaving many rural Māori living in overcrowded and substandard dwellings. There are three major issues which prevent rural Māori from developing sufficient housing; financial barriers, legal issues and urbanization [1].

Figure 1 - Māori owned land trial site

Financial problems arise due to remote locations for the construction. Costs escalate rapidly due to the distances material and machinery must be transported, lack of access (infrastructure usually needs to be developed prior to construction) and limited availability of utilities such as water, electricity and telecommunications [1].

Māori land is owned collectively by many individuals who are related via a common ancestor four or five generations earlier. Reconnection with ancestral lands creates problems in managing building development, and is further complicated due to the government forced relocation of Māori to urban centres in the 1950s. Urbanised Māori can therefore lack the knowledge of genealogical links necessary for land development. In addition to this, urbanisation reduces the number of young rural Māori still resident within these rural communities. This creates a gap in the labour force whereby technical skills must be sourced from outside the local area to fill gaps [2].

In 2003 research into the development of a low-cost flax-fibre reinforced rammed earth (Uku) housing concept was commenced. The addition of flax fibre to the monolithic rammed earth walls facilitates enhanced structural performance allowing the adoption of reduced wall thicknesses in construction. The research set out to determine the suitability of the Uku construction system for Māori land development. It was hoped that the Uku construction system could address some of the barriers to Māori land development previously identified. The targeted solution meant that the acceptance of this technology by rural Māori communities was a crucial element in determining the success of the concept [3]. In 2008 research of structural properties was concluded and two houses were built at Lake Rotoiti, one with 150mm thick Uku walls, the other with conventional timber frame construction. Both houses have been continuously monitored for constructability, cost, and in-service performance in terms of temperature and relative humidity. Research commenced in 2009 that examines the thermal performance of the Uku house. Of particular interest is the longer term thermal properties of the Uku house. The Uku house has been awarded a temporary certificate of compliance requiring that the house performs to at least the standard of a regular timber frame house, against which its performance is being compared.

Overview of rammed earth walls

Earth is a natural resource which can be found locally to any typical building site. This produces a natural advantage in sustainability for rural Māori, as most of the required construction material can be sourced locally, minimising transportation costs of materials. With this in mind it is apparent that strength too will vary based on the locally available soil [4]. This will require a qualified person to assess the strength of the soil to be used in construction. Other advantages in rammed wall design include thermal comfort, local job creation, and conditional minimal environmental impact [5]. Obtaining the earth material on a larger commercial scale can cause various environmental problems. In Sri Lanka [4] suggests that the outcome for not filling clay mines correctly can lead to mosquitoes spawning in large numbers. Also extensive sand mining can lead to lowering of river beds causing salt water intrusions inland.

Figure 2 - Example of conventional rammed earth wall (Piripono Kura Construction Trial 2004)

Rammed earth walls have some characteristics that are undesirable properties.

1) Loss of strength when saturated in water
2) Erosion due to wind and/or driving rain
3) Poor dimensional stability
4) Low seismic strength [6]

Properties one to three are mitigated by adding stabilising agents such as cement which can significantly increase the dimensional stability of an earth wall. Even so rammed earth structures are not suitable for very tall structures, but can be used for structures of 2-3 storeys. This will not present a problem as the Uku houses are a single storey design. Due to the seismic nature of New Zealand three standards were created in 1998 [7] to regulate construction of earth houses:

NZS 4297 Engineering Design of Earth Buildings
NZS 4298 Materials and Workmanship for Earth Buildings
NZS 4299 Earth Buildings Not Requiring Specific Design

These codes provide a streamlined approach to building consent for earth structures, but still require iinput from a professional engineer for non-specific design to certify the soil properties and methods of construction. The lack of professional engineers in rural Māori communities is another barrier to Māori communities from using earth construction technologies. The Uku project aims to produce a construction system and design guide that can provide rural Māori communities with access to Uku technology without the reliance on external input into design and construction [2]**.**

Thermal Properties and values

Rammed earth walls have the inherent capacity of their thermal mass to store heat, providing a form of passive thermal regulation for the dwelling [8]. This functions by storing/absorbing heat energy during the day when the outside ambient temperature is greater than the wall temperature and releasing the stored heat when the outside ambient temperature is lower than the wall. Rammed earth is found to have a low R value (measure of thermal resistivity) per unit mass [9], however rammed earth walls can actually perform very well due to the large mass of the walls [10]. The New Zealand code NZS 4297 (3.5.2) contains an empirical formula for estimating the R of a simple earth wall.

Where t is the wall thickness in metres
[7]

Using this formula and the Uku house's wall thickness of 150mm R = 0.426 . The minimum thermal resistivity for a single skin normal weight masonry based wall is 0.6 as given in The New Zealand Building Code, 2004. 1.1.1 E3/AS1. Rammed earth used in adobe was researched in China [11]. Thermal conductivity (opposite of R) was found to increase with moisture content, however no empirical correlation could be determined. It is expected that over time the walls will become drier. This will increase the R value over its design life, however by how much remains unknown.

Thermal performance and comfort are measured in terms of ambient temperature and relative humidity within the dwelling. Guidelines are provided by the Department of Building and Housing New Zealand [12] states that humidity should be within the range of 30 and 80 percent provided the temperature remains within the range of 18-24 °C. These guidelines are for both comfort and health and safety reasons. Very high humidity can promote an increase in growth of harmful bacteria, fungi and mould.

Methodology

Two houses, one Uku (Figure 3) and the other of conventional timber frame, were constructed at Rotoiti in 2008 and are used to collect data to decide the level of thermal comfort of Uku design. These houses are of identical size and orientation, and are constructed in close proximity of each other. Both have concrete foundations, timber frame roofs and double glazed window joinery. The Uku house is monitored quantitatively and qualitatively for thermal comfort. The quantified measurements of the Uku house are temperature and relative humidity which are readily comparable to building standards and/or that of a similar timber frame house meeting current standards of compliance. The qualitative data is a survey of perceived thermal comfort by the occupants of the Uku house.

Figure 3 - Uku house at Lake Rotoiti

Temperature and humidity monitoring (iButtons)

The Uku and conventional timber frame houses are equipped with Hygrochron iButtons (figure 4) at the locations are shown in Figure 5. In the Uku house there are 16 iButtons in total; 5 on the ceiling rafters, 3 sets of 3 buttons (total of 9 buttons) are positioned on 3 walls, the buttons are placed on the interior surface, exterior surface, and within the wall itself and 2 buttons are located on exterior eaves to monitor ambient external air temperature and relative humidity. In the timber frame house there are 9 buttons, 2 on the interior wall surface, 5 on the ceiling and 2 located on exterior eaves.

The iButtons are set on 11-bit (0.0625°C) resolution recording temperature and relative humidity at 20 minute intervals. At this rate the iButtons store up to 7 weeks of continuous data. The data is retrieved by downloading to a laptop computer at 6 week intervals.

Figure 4 - Hygrochron iButton and reader

Figure 5 - Position of thermal iButtons

Method of analysis - quantitative

During 2009 data was collected for the seasons of summer autumn and winter. The initial focus was on the room temperatures within each house to determine whether the Uku house is providing acceptable living conditions. The first comparison is for a typical 24-hour period of the months January and June to understand diurnal variation between the seasons of summer and winter. This was achieved by averaging the daily data over the entire month (31 and 30 days respectively). The second comparison is an annual overview of the temperature of the two houses. This was produced by smoothing the data over a month (30 days). Final comparison is of the relative humidity data which is shown in table format.

Performance requirements.

Criteria for thermal performance vary internationally. The New Zealand Building code requires a minimum average temperature of 16°C measured at 750mm above the ground for retirement houses and early childhood centers [10]. While this does not apply to residential buildings it provides a benchmark value which is consistent with the World Health Organisation (WHO) recommended lower limit which is also 16°C [13]**.** The provisions of the Temporary Certificate of Completion state that the Uku house at Rotoiti is to demonstrate thermal properties and performance at least as good as that of a conventional timber frame house.

Thermal comfort recordings.

Thermal comfort of a person is a highly subjective assessment; however it is a so-called 'true' measurement of comfort as the satisfaction is measured by the end user. It is defined [14] as the "condition of mind that expresses satisfaction with the thermal environment". It can be considered as any person's perception of the thermal ambiance. This can be influenced by more than just the actual temperature and humidity and includes the colour of the room, the effect of lighting, the room's use and the occupant's general state of mind/mood.

The data for thermal comfort of the Uku house are recorded as the personal assessment of the occupants. The occupants complete a daily comfort survey by completing a regular questionnaire about the level relative thermal comfort experienced. This is accomplished by assessing thermal comfort in the range of cold (-3) to hot (3), zero being neutral, and asking the number of items of clothing worn by the occupants (1-4). Finally the use of a heater is also recorded as a yes or no. An example of the questionnaire is shown in Figure 6.

Figure 6 - Example daily questionnaire

Uku thermal properties.

Analysis of the 2009 data found that the temperature of the Uku house is lower during the summer (Uku mean of 22.78°C to timber frame mean of 23.80°C) and higher during the winter (Uku mean of 14.80°C to timber frame mean of 13.36°C). The Uku mean is 1.2°C lower than the 16°C desired minimum. The Uku house out-performed the timber frame house which complies with current standards.

Research completed by HEEP of houses constructed before 1978 had a mean of 16.2°C in the upper North Island and a mean of 15.9°C in the lower North Island during the winter months. The low value of 13.36°C for the timber frame house may be a result of less than full-time occupancy. The Uku house mean is expected to improve as the moisture content of the walls was very high when the house was 'closed in' and the moisture content will require several years to attain a constant moisture content.

The 2009 relative humidity data showed that the Uku house performed within the 30-80% limits for the majority of the time, on rare occasions the RH% would increase beyond 80% very briefly. The timber house exhibited similar trends with a slightly lower average.

Qualitative analysis suggested that the comfort levels were above average during summer and only satisfactory in winter with the use of a portable gas heater required in winter.

Thermal performance modeling carried out for the Uku house for different locations in New Zealand's North Island concluded that to maintain higher temperatures the 150mm walls would need to be thicker. Increasing the wall thickness increases the amount of material used and therefore cost. Modeling suggests that the nominal 300mm wall thickness in houses compliant with the New Zealand code could be reduced and that a wall of 150mm-200m would be satisfactory in most regions similar to Lake Rotoiti. The additional wall thickness of a 200mm wall, increases the thermal mass, and therefore is expected to raise the minimum temperatures experienced in winter.

Figure 7 - 48h temperature simulation for Uku house at Lake Rotoiti

Figure 7 shows that at 6:00am the temperature for July could be as low as 14°C however for the majority of the time the temperature would be greater than 15°C.

Method of analysis – qualitative.

The qualitative data is analysed to understand seasonal comfort based on perceived thermal comfort, the number of clothes worn and percentage of heater usage over time increments of a month. Data of this kind provides a better understanding of the actual thermal performance of the Uku house for habitation. That is heater use and clothing layers provide a correlation between the actual temperature data and the occupants' preferred temperature rather than relying solely on a relatively universal indicator such as the WHO minimum temperature of 16°C.

Temperature analysis

A complete data set for 2010 initially provided options to examine a very broad range of attributes of the temperature records. The 2010 data is used here to compare the two performance of the two houses to verify the suitability of the Uku house living conditions. During 2010 a hard drive failure resulted in the loss of various channels of data for periods of time. This especially affected the Uku data over the month of April and the timber frame data over the months February to April in which all data was lost. To provide a continuous analysis the data was backfilled from the 2009 data, adjusted slightly to fit the 2010 initial and final temperatures for the sequences of lost data. The relevance is assumed on the basis of the same location, there were no significant changes in the recorded local weather conditions, no extreme weather events occurred in either of the time periods affected, and the purpose and use of the houses remained similar over the affected timeframes.

Figure 8 shows the average outdoor and indoor temperatures of the Uku and timber frame houses with the back filled data included. This graph was produced by averaging the indoor room centre buttons and the outside buttons. The data averages are smoothed over a month (30 day period). The smoothed values are then plotted against the actual time they were recorded.

Over the summer months the temperature in the timber frame house is on average warmer by 0.73°C. Before the month of May the average temperatures converge and the Uku house remains up to 2°C warmer than the timber frame house until June. At this point the average temperatures converge until September. The 2010 data suggests that the Uku house achieves a similar level of performance to 2009 when measured against the range of recorded temperatures for the timber frame house. The consistent trend is that the thermal mass of the Uku house moderates the indoor temperature providing a more stable temperature over the year.

Figure 8 - Edited annual temperature graph (see appendix for larger graph)

Table 1 - Seasonal Temperature Summary

(°C)	Uku Min	Uku Mean	Uku Max	timber Min	timber Mean	timber Max
Summer						
Inside	17.31	22.80	28.64	17.83	23.53	29.40
Outside	8.63	19.62	29.91	7.84	19.07	30.04
Autumn						
Inside	12.03	19.23	26.65	11.15	19.48	30.10
Outside	3.11	14.83	30.91	2.31	14.63	31.35
Winter						
Inside	9.12	13.75	21.31	8.14	13.36	19.83
Outside	0.11	9.49	20.90	0.06	9.63	19.86
Spring						
Inside	11.15	15.48	27.64	10.15	15.80	24.00
Outside	2.36	11.67	23.91	2.31	11.41	24.14

Table 1 gives a summary of the unsmoothed indoor temperature averages over four seasonal periods. The important figures are the lowest winter values. The winter indoor average of the Uku house is 13.75°C 2.25°C below the desirable minimum. Interestingly the Uku house outperforms the timber frame house average winter temperature of 13.36°C. These results require verification against the thermal comfort data to determine whether house temperatures drop over-night when the occupants are in bed asleep. Typical automated domestic heat-pumps are pre-set to maintain a minimum indoor temperature of 10°C in New Zealand. If house temperatures dropped to 10°C for a six hour period at night, this would have the effect of reducing the average daily temperature by 1°C.

Figure 9 - 24h temperature averages over January and June 2010

Figure 9 shows the daily fluctuations in temperature over a summer month, January, and winter month June. The daily January temperature average helps to explain the annual summer trend of the timber frame house having a greater temperature than that of the Uku house. The indoor temperature is only greater during the day and at night the temperatures are very similar. Both houses reach a minimum at approximately 8:00am (DLST). However the peaks are slightly staggered. The timber frame house indoor temperature peaks at approximately 6:00pm (DLST) while the Uku house peaks at about 7:30pm (DLST). This reflects the property of a rammed earth's thermal mass. The material absorbs or stores heat energy during the day and releases it slowly overnight. This is supported by the outdoor temperature trend which both peak earlier at 3:00pm. The daily temperature of the Uku house in January averages between 20°C and 25°C which is desirable.

During June the entire 24h period shows the Uku house outperforming the timber frame house. The time for minimum indoor temperature is approximately the same at about 9:00am. This is probably due to the Sun's position during winter, which affects both houses similarly. The maximum indoor temperature is found at a similar time around 4:30pm. This is probably due to the heat energy absorbed being lower during winter such that the thermal gain for the Uku walls is not significant. The average daily temperature range during June indicates the Uku house achieveds a minimum of 13.5°C and a maximum of 16.0°C. As seen in the annual temperature graph Figure 9 and in Table 1 the achieved average is below the desired 16°C minimum indoor temperature. The timber frame house is actually colder than the Uku house with a temperature range from 11.5°C to 15.5°C.

Thermal comfort

Thermal comfort questionnaires were used to understand the thermal performance experienced by the end-user. The thermal comfort surveys were only completed by one occupant for the majority of the survey period. The results are provided in the form of averages over each season.

Table 2 - Thermal Comfort Summary 2009

Season	Comfort	Num of Clothes	% Heater Use
Summer	1.92	1.65	0.00
Autumn	-0.19	2.68	46.88
Winter	0	2.33	67.81

Table 3 - Thermal comfort summary 2010

Season	Comfort	Num of Clothes	% Heater Use
Summer	0.46	1.91	0.00
Autumn	0.00	3.16	0.00
Winter	-0.70	3.83	0.00

Table 2 2009 data was collected from the same individual who completed the surveys in 2010 shown in table 3. This could give a relative yearly comparison plus an analysis of perceived thermal comfort to compare with temperatures experienced within the dwelling. The comfort column represents an average daily recorded comfort level ranging from very cold (-3) to very hot (3). The number of clothes is an average value taken from 1 to 4. Heater use is given as a percentage of days used per month.

The occupant perception of each year would indicate that the summer temperature was hotter in 2009 with an average thermal comfort of 1.92 against 0.46 in 2010. The actual average room temperatures indicate little change with recorded temperatures 22.78°C (2009) and 22.80°C (2010) almost identical. The difference in the perceived temperature may be associated with the moisture content of the walls being higher immediately following completion. This would be consistent with the impact of humidity on perceived temperature. The change may also indicate the acclimatisation of the occupants and their behavior to the thermal characteristics of the Uku house.

A more relevant indication of the occupants' thermal comfort from the data is the measured variation from the favorable result of 0. In 2009 the total range is 2.11 with the Uku house perceived as warmer than required and with reasonable heater use in the colder months. In 2010 the range reduces by 45% to 1.16, and is more evenly spread around 0, indicating that the thermal comfort is acceptable to the occupants and that the heater is not considered necessary.

The 2010 data indicates that the performance of the Uku house is improving. Summer was only slightly warm 0.46, autumn was completely neutral at 0.00, and winter was slightly cold -0.70. The actual temperature recorded inside the house in winter is colder in 2010 (13.75°C) than 2009 (14.8°C). It is possible that the reducing humidity within the Uku house means that the house is more comfortable at lower temperatures and tolerable without heater use if mitigated by wearing, on average 1.5 more additional layers of clothing.

Conclusions

By comparing the temperature data of the Uku and timber frame houses, the Uku house delivers satisfactory performance. The Uku house is 0.73°C cooler on average during the summer and 0.39°C warmer on average during winter than the timber frame house. It must be noted that the timber frame house was not always occupied on a permanent basis and this may have influenced the indoor temperature. Note that as the occupants of the Uku house did not use any additional heating in 2010, then this difference is related to the heat generated by the occupants themselves and cooking activities.

The data recorded indicates that the average minimum temperatures are below the desired 16°C adopted from the NZ Building Code and WHO. It is noted that the timber frame house which complies with current building standards does not reach this benchmark either suggesting that people experiencing non-urban lifestyles may prefer temperatures more consistent with natural seasonal fluctuations.

Thermal comfort perceived by the occupants has improved from 2009 to 2010. The 2010 data indicates that there was on average a neutral climate indoors. In addition to this the heater was not used, likely attributed to the occupants wearing additional layers of clothing in the colder months, but also an acclimatization to the natural rhythms of the Uku house.

Overall the Uku house thermal performance results are a positive outcome. Out-performing the timber frame house and meeting the needs of the actual occupants has been demonstrated, albeit at average winter temperatures that fail to meet NZ Building Code and WHO recommendations. Increasing the thermal mass by adopting an increased wall thickness of 200mm is likely to further enhance thermal performance.

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