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AN ASSESSMENT OF THE THERMAL STORAGE CAPACITY OF HEMP-LIME USING THE TRANSIENT PERFORMANCE RATIO METHOD

A. Reilly¹, O. Kinnane^{2*}

¹ Queen's University Belfast, Northern Ireland

² University College Dublin, Ireland

*Corresponding author; e-mail: oliver.kinnane@ucd.ie

Abstract

Many claims are made regarding the superior thermal performance of high heat capacity materials under the general heading of thermal mass. However, the benefits of thermal mass are poorly quantified in existing literature. These issues often become more important in the case of biobased materials, where thick, monolithic wall construction leads to a stronger connection between a building's structure and the indoor environment. New materials include hemp-lime concrete, which offers a combination of structural, thermal and hygroscopic properties that make it suitable for incorporation into the building envelope. Hemp-lime has long been proposed to offer excellent thermal mass performance, yet this impact is poorly quantified in existing literature. This paper uses the Transient Energy Ratio (TER) method, developed by these authors, to compare the performance of hemp-lime concrete walls with traditional solid wall and cavity wall constructions.

Keywords:

Transient energy ratio; TER; thermal mass; diffusivity; hemp-lime

1 INTRODUCTION

High thermal mass is often cited as a beneficial aspect of bio-based construction materials. However, many of the concepts surrounding these benefits are poorly quantified in the literature. This applies equally to the increased thermal mass in typical bio-based buildings, and secondly to the actual benefits this can offer. Both national construction guidelines, and academic literature, often offer little beyond platitudes and statements that are simply inaccurate (such as "A massive building uses less energy than a similar low mass building due to the reduced heat transfer through the massive elements"[Portland Cement Association 2017]).

These problems are particularly acute as regards hemp-lime concrete; as a comparatively new bio-based construction material, many claims are made, despite the fact that it remains somewhat poorly characterised. For example, its thermal conductivity is often stated to be lower than measured values actually show (such as a claim by the Building Research Establishment in the UK of a thermal conductivity: "0.07–0.09 Wm⁻¹K⁻¹ giving a typical U-value at 300 mm of 0.21 Wm⁻²K⁻¹", when conductivity values reported in the literature more commonly exceed 0.1 Wm⁻¹K⁻¹).

The benefits of thermal mass intuitively seem most applicable to regions with high diurnal temperature variation, and sites with high solar flux and cool nights would seem to have the most to gain. Indeed, most case studies in the literature have been in exactly

these sorts of climates, such as the Mediterranean region and hot arid or semi-arid climate zones. There is a widespread assumption that these results will be applicable in a qualitative sense to other climates, even if the exact results are not; but this is not the case. Indeed, recent work has shown that in heating dominated climates such as northern Europe, high thermal mass can lead to an increase in energy use rather than a decrease. Work conducted in parallel with the work presented here, using the same techniques, has shown that these conditions are not uncommon, and actually likely dominate in many regions. Consequently, in colder areas, the assumption that high thermal mass leads to energy savings is very often incorrect. Use of the transient energy ratio and transient performance ratio allows for rapid assessment of a given site, use case and construction typology: the method is more generalised than detailed building simulation and can be used by architects and engineers much earlier in the design process, before decisions on building layout and construction method have been taken; and therefore, decisions regarding appropriate construction methods can make use of this information at an earlier stage of the design process.

The generalisable nature of the technique also allows researchers to analyse wall typologies without the limitation of studying only specific case study buildings. This is the approach taken in this paper: the transient energy ratio technique is first summarised, and then used to assess a range of bio-based materials in terms of their dynamic thermal performance.

2 THE TRANSIENT ENERGY RATIO METHOD

2.1 Method Summary

The transient energy ratio was demonstrated by Reilly and Kinnane [Reilly and Kinnane 2017]. In summary, the method involves the following:

- Calculate the U-value for the wall section in question (termed U)
- Simulate the thermal behaviour of the wall, using boundary conditions representative of the climate and indoor occupancy pattern of interest
- Use the actual energy flow through the wall in the dynamic simulation to calculate an effective U-value (termed U_e)
- Divide U_e by U to find the transient energy ratio (TER)

The most time-consuming part of the method, is the dynamic simulation, and the calculation of the effective U-values; this is necessary to capture the true behaviour of the walls. As walls have heat capacity, their thermal response during fluctuating conditions is not described by the U-value alone. In conditions of changing surface temperatures, heat may be stored and returned to the indoor and outdoor environment: this is the basis of thermal mass. A dynamic simulation attempts to capture these effects by modelling the response of a wall to varying temperatures. The effective U-value is the quantity which, when used with the mean temperatures, gives the actual energy flow through the wall.

This actual energy flow may be greater or less than that predicted based on the static U-value, and this ratio is termed the TER. If the TER is less than one, the thermal mass of the wall offers energy savings, over and above any savings purely due to a low conductivity. In this case, higher thermal mass walls could offer greater benefits, and increasing the thermal mass should be considered. On the other hand, if the TER is greater than one, the wall is leading to greater energy use than predicted by a static analysis: in this case, the thermal mass is a drawback, and design changes should seek to minimise the thermal mass of the wall instead of maximising it. For a TER in the region of one, thermal mass has little influence, and in such a case other considerations (such as a low conductivity) will likely dominate. Greater detail of this method can be found in Reilly and Kinnane, 2017.

2.2 Static Analysis

The static analysis was simply an evaluation of each wall's U value, calculated in the standard manner as in Eqn. 1 below (where L is the thickness of each material, k is the conductivity, and the subscript indicates the material).

$$\frac{1}{U} = \frac{L_1}{k_1} + \frac{L_2}{k_2} + \dots + \frac{L_n}{k_n} \quad (1)$$

2.3 Dynamic Analysis

The principle of the TER method is to use a dynamic simulation of a wall section. To comply with the method, any simulation method that accurately predicts internal wall temperatures may be used, with a 1D numerical simulation generally the easiest. For this work, a finite element (FE) model was created using commercial FE software (Abaqus 6.12). The walls were modelled using heat transfer elements with a typical mesh dimension of around 1 mm, and the increment time in the model was set such that in no

step did the temperature change exceed 0.1 K. Heat transfer at the wall surfaces was modelled according to ISO 6946, as in Eqn. 2 below. (Where \bar{v} is the mean wind speed, ϵ the emissivity, σ_0 the Stefan-Boltzman constant and T_0 the relevant environmental temperature.)

$$h = 4 + 4\bar{v} + 4\epsilon\sigma_0T_0^3 \quad (2)$$

The external temperature was applied as a heat source/sink, connected to the outer surface of the wall via Eqn. 2. The internal temperature was either specified in the same manner (during periods of active heating/cooling), or allowed to float freely in response to heat exchange with the wall's internal surface. Solar flux was applied to the relevant surface as a power input per unit area. The details of the active heating/cooling system were not considered; while a more efficient system would obviously reduce the primary energy use, this study was concerned only with the heating/cooling energy demand.

The output from the model, was an energy transfer per unit area (J/m^2). This was measured on the interior surface of the wall, and gave an average heat flux for the time period in question (W/m^2). This average heat flux per unit area was divided by the mean temperature difference to give the effective U-value. In this way, the effective U-value accurately reflects the heat loss/gain through the wall, but has units of $W/m^2/K$, making it directly comparable with the standard U-value calculated through a static analysis.

3 WALL TYPOLOGIES AND CLIMATES CONSIDERED

3.1 Wall Typologies

Four bio-based wall materials are considered in this paper: hemp-lime concrete, straw bales, cob, and rammed earth. These were compared with a masonry cavity wall construction. The material properties and wall descriptions are given in Table 1. Providing general values is complicated by the wide range of thermal properties for many of the materials considered; it is not possible to give a definite value for the thermal conductivity of stone, for example, as there is so much natural variation. However, the values chosen are indicative mid-range values, and the general approach taken here could easily be adapted to model the specific differences between, for example, sandstone and granite walls. This study looks at broader classes of wall type, and more detailed analysis is left for further work.

3.2 Climate

For this study, outdoor weather data was used from Belfast, Northern Ireland. Belfast, in common with most of the UK and Ireland, has a wet maritime climate, with comparatively mild winters and summers and is characterised by high precipitation. A representative week of weather data was chosen for the dynamic analysis: a week in January 2016, with weather data obtained from UK Met Office. Temperatures ranged from 275 to 288 K. Temperatures, wind speeds and solar flux were all typical for the time of year.

Virtually all domestic construction in the UK and Ireland employs some form of mechanical heating system for several months of the year, and in this respect Belfast is entirely typical.

Tab. 1: Wall typologies and material properties

Wall type	Material	Thickness (mm)	Conductivity	Diffusivity (mm ² /s)
Cavity wall	Plaster	12.5	0.52	1.71
	Insulation	40	0.055	1.74
	Blockwork	100	0.44	0.451
	Cavity insulation	150	0.047	0.582
	Brick	102	0.721	0.472
Hemp-lime	Plaster	12.5	0.52	1.71
	Hemp-lime concrete	450	0.12	0.5
	Lime render	40	0.7	0.52
Cob	Plaster	12.5	0.52	1.71
	Cob	600	0.4	0.5
Straw bale	Plaster	12.5	0.52	1.71
	Straw bale	450	0.07	1.6
	Lime render	40	0.7	0.52
Rammed earth	Plaster	12.5	0.52	1.71
	Earth	600	1.2	0.97
	Facing stone	100	2	1.1

Many of these values are subject to considerable variation; the specific heat capacity of straw bales, in particular, seems poorly characterised in existing literature, and those for earth and stone vary substantially (a factor of two or more) depending on the exact source. These values are based on a review work by Clarke (1990), with the exception of the values for Cob (Goodhew 2011).

4 RESULTS

4.1 Heat capacity

The heat capacity of traditional wall types is often assumed to be dramatically higher than modern construction. However, there are very many exceptions to this rule, particularly when the 'modern construction' used is a masonry cavity wall meeting contemporize standards. Table 2 gives values of the heat capacity per unit wall area for the walls considered here, and it can be seen that a masonry cavity wall construction falls about midway between the natural materials, with straw and hemp substantially lower and cob and rammed earth much higher. Of course, these values depend on the wall thickness, which will vary from case to case; but it would be very difficult to build a wall of rammed earth with equivalent heat capacity to the masonry wall presented here – it would be less than 300 mm thick in total – while a straw bale wall of equivalent heat capacity would be impractically thick (around 5 m).

While the heat capacity of a wall gives an indication of its dynamic performance, in an inhomogeneous wall the ordering of the layers is also important, and different walls with the same heat capacity can perform differently – hence the importance of the TER.

4.2 Static performance

The static performance of the walls is determined by the thickness and thermal conductivity of each layer, measured by the standard U-value. These are presented in Table 2. In this regard, the hemp-lime wall is the closest match to the cavity wall, with straw being rather better and cob being worse. For a permanently

occupied building in static outdoor conditions, the heat loss (or gain) would be determined entirely by U.

Rammed earth stands out as being particularly poorly performing, with a static U-value more than ten times that for the straw bale wall. Conductivity values for rammed earth vary dramatically, with quoted values in the literature ranging (at least) from 0.4 to 2.1, primarily depending on moisture content. However, even at the lower end of this range, the U-value will be much higher than that for a straw bale wall; and many claims are made for rammed earth structures on the basis of its high thermal mass enhancing their performance. Consequently, a comparison between the straw bale and rammed earth walls provides a very good study of the influence of thermal mass.

4.3 Dynamic Performance and Transient Energy Ratio

The dynamic performance of these walls was assessed by carrying out a one-week finite element simulation, as described in Sections 2 and 3. For the analysis in Belfast, it was assumed that the occupants would heat the building between 6 and 8 am, and 6 and 10 pm. The building was unheated outside these hours.

The dynamic response is very different from the steady-state analysis, as Figure 1 shows. Due to the heat capacity of the wall, the indoor temperature only falls to around 288 K during the unoccupied times (when the heating is off), despite an outdoor temperature that falls below 280 K. The heat capacity of the wall leads to both an energy saving and an energy penalty, and these two effects counteract each other: a wall with a high heat capacity, takes more energy to heat up, but then stores its heat for longer,

Tab. 2: U-value, Heat Capacity, Effective U-value and Transient Energy Ratio

Wall	U-value	Heat capacity (kJ/m ² /K)	Effective U-value	Transient Energy Ratio
Cavity	0.23	271	0.60	2.57
Hemp-lime	0.26	166	0.68	2.59
Cob	0.66	484	1.83	2.79
Straw bale	0.15	77	0.34	2.19
Rammed earth	1.67	928	4.49	2.58

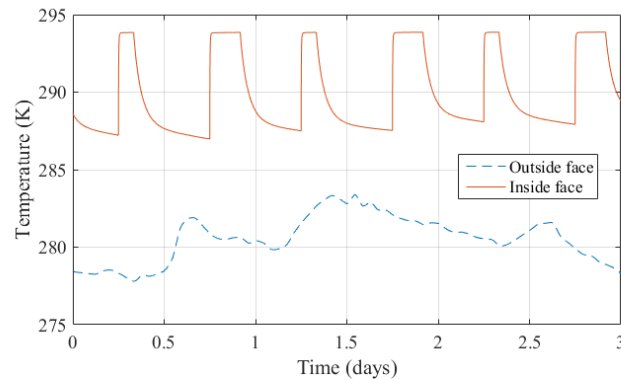


Fig. 1: Temperatures of the cavity wall indoor and outdoor surface for three days in Belfast

meaning the temperature at the start of the next heating period is higher. Which of these two effects dominates determines whether thermal mass is beneficial or detrimental in a particular scenario.

Figure 2 shows the indoor temperatures for the cavity, straw and cob walls (with medium, low and high heat capacities, respectively). It is clear that the cob wall takes longer both to heat up and to cool down; by contrast, the straw wall heats and cools much more rapidly. Its low heat capacity means that the wall responds more quickly both to undesired (externally-induced) and desired (mechanically-induced) changes.

In addition to predicting temperatures, the model also predicts heat fluxes through the walls. Dividing the total heat flux over the course of the week by the mean temperature difference, gives the effective U-value U_e . U_e for each wall is given in Table 2, along with the transient energy ratio, which is found as in Equation 3 below.

$$\text{TER} = \frac{U_e}{U} \quad (3)$$

The TER for all these scenarios lies between 2 and 3. This indicates that the drawback of greater heat input at the start of each heating period, more than outweighs the benefits of heat retention from one heating period to the next. In these cases, thermal mass is detrimental, and substantially so: a theoretical wall with no heat capacity (but the same conductivity) would use less than half the energy for heating than these walls do.

As the TERs for all the walls lie in the range 2 to 3, they can be discussed as a group in terms of their dynamic performance. For a cold climate requiring constant indoor heating, such as that of Belfast, thermal mass is a significant drawback. The effect of heating up the structure at the start of each heating

period takes a substantial amount of energy, and only a small fraction of this energy is returned to the occupied space at a later time, with most being lost to the outside environment. For a typical domestic use case, between half and two thirds of the heating energy used will be lost in heating up the building structure – this is what is indicated by the TER values, where a TER of 1 would indicate energy consumption exactly equal to a prediction based on the U-value alone.

Results showing a TER greater than 1, suggest that reducing the heat capacity of the wall (for an equivalent insulating capacity) will lead to better thermal performance. To test this, a new, thinner straw bale wall was modelled, with the thickness of the straw layer reduced to 100 mm. The U-value for this wall matched that for the original cob wall (0.66), thereby allowing a direct comparison between a low and high thermal mass wall with the same mean conductivity. U_e for the thin straw wall was 0.74: this wall used less than half the energy that the cob wall did, despite the two walls having the same U-value.

5 DISCUSSION

Cob and rammed earth are examples of vernacular construction techniques that have recently received more attention due to their perceived environmental benefits, not least benefits associated with high thermal mass structures. Straw bale and hemp-lime construction are newer developments, which also appear to offer reduced environmental impact as compared to conventional contemporary construction using concrete and masonry. While all these materials do indeed offer many benefits, the claims associated with reduced heating and cooling loads in high thermal

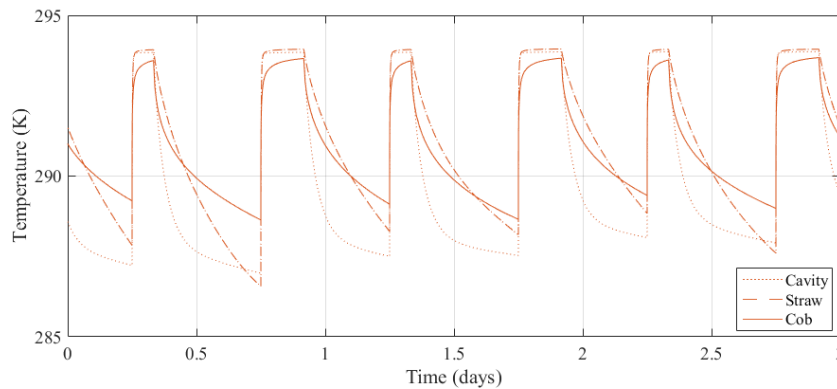


Fig. 2: Comparison of indoor surface temperatures in three wall types with light, heavy and intermediate heat capacity (straw, cob and cavity respectively)

mass buildings need to be examined much more carefully.

In a heating-dominated climate such as that of northern Europe, high thermal mass is likely to be associated with increased energy consumption rather than decreased consumption. While it is often claimed that poor insulation values associated with some construction types can be offset by virtue of high thermal mass, this is demonstrably not the case, and indeed the reverse is often true: high thermal mass construction leads to worse performance than predicted based solely on insulation values.

This is shown by the result given here for the thin straw wall compared to the cob wall: for the same U -value, the thin straw bale wall takes less than half as much energy for heating as the cob wall. indeed, of the representative walls in this study, only the (thick) straw wall (with $U_e = 0.34$) comes close to achieving the performance assumed in most national codes, which typically specify U -values in the region of 0.2.

Given that high thermal mass will often not lead to the purported energy savings in cold climates, are the wall types considered here appropriate? It remains true that the embodied energy of the cavity wall is likely to be much higher than the others considered here; but the embodied energy for most buildings is very much smaller than the use energy. This is particularly the case for long-lasting buildings such as houses. In order to minimise the lifetime energy use, the embodied energy should be equal to the use energy. In most cases, this would result in an impractically thick wall; consequently, in order to minimise overall energy use the objective will often become one of using the lowest conductivity materials available, almost regardless of embodied energy.

Of course, there are many other factors involved in choosing construction materials besides energy consumption, which may tilt the balance in favour of one or another material. But bearing in mind the high conductivity of earth and stone, monolithic walls made from these materials do not seem to be appropriate choices in cold climates where building energy use is dominated by heating. Hemp-lime walls, on the other hand, have a thermal performance similar to that of good masonry cavity wall construction; and in this case, other factors such as the lack of thermal bridges, lower embodied energy, hygroscopic nature, etc., may make it a better choice. The addition of an extra

insulating layer, while using hemp for the structural component, may improve the performance further.

However, straw bale construction seems to outperform both masonry and other biobased materials without the need for extra insulation. Its poor loadbearing capabilities likely render it unusable for highrise buildings, but where it can be used it seems to offer superior thermal performance. Its low heat capacity is a distinct advantage in cold climates, where high heat capacity materials result in wasted energy use in many cases.

The TER analysis of these scenarios captures the dynamic behaviour of a range of wall types. The analysis *method* is applicable to any wall typology, building use case and climate; but the specific results given here must be used cautiously if applied outside the cases considered. There will be cases where the assumptions are incorrect; for example, in the case of a cold climate where substantial solar energy is available outside occupied hours, the capacity to store heat may be beneficial. But in general, it is unlikely that any advantages of thermal mass can be sufficient to offset poor insulation values, and except in very specific cases, thermal mass is a drawback rather than an advantage in cold regions.

6 CONCLUSIONS

In cold climates, high thermal mass cannot be relied on to counteract poor thermal insulating performance. In heating dominated climates high thermal mass is much more likely to be a hindrance than a boon, and other things being equal minimising heat capacity would be a better objective than maximising it. Certain biobased materials, in particular straw, have a combination of low thermal mass and low conductivity; simulations show that these will perform well. Hemp-lime also seems to offer comparable thermal performance to masonry cavity walls, and may offer other advantages. Solid earth and stone structures, without insulation, tend to have higher U -values than masonry cavity walls, and the downsides attached to this cannot be remedied by the high thermal mass associated with these materials.

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