Thermal performance and fitness of glacial till for
Rammed Earth construction

J. Tinsley, S. Pavía

PII: S2352-7102(18)31176-8
DOI: <https://doi.org/10.1016/j.jobee.2019.02.019>
Reference: JOBE727

To appear in: *Journal of Building Engineering*

Received date: 2 October 2018
Revised date: 16 January 2019
Accepted date: 25 February 2019

Cite this article as: J. Tinsley and S. Pavía, Thermal performance and fitness of glacial till for Rammed Earth construction, *Journal of Building Engineering*, <https://doi.org/10.1016/j.jobee.2019.02.019>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting galley proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Thermal performance and fitness of glacial till for Rammed Earth construction.

J. Tinsley^a and S. Pavia^b

^{a, b} Department of Civil Engineering, University of Dublin, Trinity College, Dublin 2, IRELAND. tinsleyj@tcd.ie;
pavias@tcd.ie
Corresponding author: pavias@tcd.ie

Abstract—The search for sustainability caused a revival of earth construction. Rammed earth (RE) construction is often preferred as compaction and stabilisation leads to stronger, more consistent materials. Tills are glacial sediments. Historically, they were used for construction and brick making. However, their heterogeneous nature has prevented standardisation into mainstream construction. This work contributes to make earth a reliable building material. It evaluates the suitability of till for RE construction by measuring its geotechnical parameters and comparing them against recommended RE values. The results are consistent with other tills and indicate fitness for RE construction. The tills were successfully stabilized with 5% lime, reaching compressive strengths c.1.09 MPa.

Thermal performance is vital in construction. High thermal mass materials such as RE can lower today's unsustainable energy demand for heating and cooling. This work experimentally measures the thermal properties of the till and compares them to other constructions. The experimental values are feed into models to compare thermal performance against other REs and concretes. The rammed till has high conductivity (1.65 W/m.K) and specific heat capacity (1218.66 J/kg.K) indicating a substantial scope to store heat and poor insulation ability. The thermal diffusivity ($7.42 \times 10^{-7} \text{ m}^2/\text{s}$) suggests that the till will impede heat flow to a greater extent than concrete.

In the simulations, the RE assemblies showed the thermal lag typical of high thermal mass materials reducing the fluctuations of external temperature and increasing the internal thermal stability when compared with concrete. All insulated assemblies maintained thermal comfort indexes however, the RE assemblies performed slightly better than concrete; in particular the internally insulated RE, with longer times in superior comfort indices and the smallest temperature drops. The annual heat load of insulated RE is 2-4.2% lower than the concrete construction.

Keywords—earth construction, rammed till, thermal properties, thermal lag, heating load, comfort index.

1. INTRODUCTION

The search for sustainable construction has caused a revival of earth construction in Europe. In rammed earth (RE) construction, soil is compacted inside formwork in successive layers. It is often preferred to other methods of earth construction because the resultant material has more consistent properties, a higher density and a greater mechanical strength than other forms of earth construction which are triggered by compaction and stabilisation during construction. It is generally accepted that low clay content soils are better suited for RE construction and a stabilising material such as lime or cement is often mixed into the earth [1, 2].

Till (also known as boulder clay) are poorly-sorted, glacial deposits of boulders and stones in a matrix of sand, silt and clay. Till deposits are widely distributed throughout Ireland, Scandinavia and other Northern European countries as a result of past glaciations. Till deposits have been used for earth construction and brick making throughout history. However, its non-homogeneous nature has prevented classification and standardisation of the material for modern construction [3, 4].

Due to rapidly escalating environmental problems such as global warming, pollution and natural resource depletion, there is an increasing demand for sustainable construction materials that can reduce both the operational energy and the embodied energy of buildings. Traditional construction materials such as steel, fired-clay brick and Portland cement blocks and concretes have high embodied energy and are responsible for significant greenhouse gas emissions. In contrast, earth materials have low embodied energy and do not involve

gas emissions. Earth is readily available in most parts of the world and requires little energy to excavate when compared to the mining required for concrete or steel [5]. In particular, the embodied energy RE can be much lower than that of traditional concrete, depending on the transport distances and the content and nature of stabiliser.

RE materials can also lower a building's operational energy. Almost 10% of the world's annual energy consumption is used for heating and cooling residential buildings [5, 6]. In Europe, the residential sector consumes c. 27% of the total energy use accounting for 630 million tons of CO₂ emissions per annum; and the average household emits 5.5 tonnes of CO₂ annually with 61% of those emissions due to heating [6]. Reducing this energy demand, even by a small amount, would yield significant environmental and economic savings [7].

Adopting passive thermal designs is one way to achieve this. A key component of this approach is the intelligent use of thermal mass: the passive ability to absorb and retain heat energy [8].

RE is a dense material (typically c.1834-2000 kg/m³ but can vary widely from 1700 to 2200 kg/m³ [1, 7, 9, 10] with high thermal mass. Therefore, it can absorb and store heat which can subdue large temperature variations and reduce peak heating/ cooling loads becoming a solar passive design. As a dense material, RE often presents a high thermal conductivity which is comparable to concrete and other dense building materials. However, this property can vary subject to the degree of compaction and constituents of the RE. The characteristic high thermal conductivity of RE walls results in a high thermal transmittance (U-Value) thus a poor insulation ability.

Nevertheless, a high thermal mass or inertia can significantly improve the thermal performance of a wall despite having high U-values [8, 9, 11, 12, 13]. Experimental research by Serrano et al 2016 [14] demonstrated that, even though insulated RE had higher thermal transmittance than insulated cavity wall, it had the best dynamic parameters with the longest thermal lag and the best thermal stability.

Thermal conductivity is moisture dependent, as it is well known that heat travels faster through water and moisture than through the air (empty pores and voids). It is also known that, due to its clay mineral content, earth is a hygroscopic material, capable of absorbing water vapour from the air when the relative humidity increases and release this moisture when humidity falls. This regulates indoor humidity, eliminating condensation and decay due to moisture accumulation such as fungal growth. Hall and Allison [11] experimentally measured the improvement of the indoor environment due to the hygric properties of RE. The authors concluded that the total hygroscopic storage capacity of earth materials vary little with varying mix parameters, and that the vapour storage capacity of an earth wall would normally be more than sufficient in relation to the volume of air inside a room. However, the authors claim that the response to varying humidity differs significantly in different RE walls, and that it is essential to optimise their response to fluctuations in vapour pressure gradients in order to make their humidity buffering functional. Gomes et al [10] showed that adding mineral binders as stabilizers negatively affects the hygric behaviour of earth materials increasing their water absorption and slowing down drying.

This research intends to contribute to the designation of suitable earth for construction; and establish control over properties and quality to enable the use of earth as a reliable building material. It assesses the suitability of glacial till for RE construction by experimentally measuring geotechnical parameters and comparing them against other tills and recommended RE construction values. The thermal conductivity, specific heat capacity and diffusivity of the rammed till are measured experimentally and feed into mathematical models to compare the thermal performance of the rammed till against other REs and traditional, concrete cavity wall construction.

2. MATERIALS AND METHODS

Black Boulder Clay was taken from excavations in Ballymun, Dublin, conducted as part of the works on the M50 route. The mineral composition by X-ray diffraction evidenced the presence of clay minerals, quartz, calcite and traces of amorphous iron. The clay minerals comprise a small fraction of kaolinite (4-14% of the clay minerals), with the balance being split between illite (28-43% of the clay minerals) and interstratified illite / smectite (48-57% of the clay) [15].

To use earth as a building material, a range of parameters and ideal constituents must be identified to ensure good performance and safety. Significant disparity exists between different countries' regulations on earth construction. In Europe, earth construction is not considered under Eurocode 6, and European CEN Standards specific to earth construction do not exist. However, there are valuable standards and reference documents in different countries. Among these, Spanish standard UNE 41410 [16] includes specifications and test methods for compressed earth blocs. Design and construction guidelines have also been published in the UK [17], and standards for earth construction exist in Germany (DIN 18945, 18946 and 18947). New Zealand's Standards are probably the most comprehensive. Maniatis and Walker [7] review the contents of these standards. According to these authors, there are three standards that set out structural design methods for earth walls and include performance criteria and guidance on durability, strength, flexure limit, shrinkage, fire resistance, reinforcement and anchorage details and the design of foundations and maximum floor live loads. Jimenez Delgado and Guerrero [18] include a detailed comparative study of the contents and specifications in standards and normative documents for earth construction in New Zealand, Mexico, Spain, Australia and Zimbabwe, some including requirements for width and slenderness (depending on restraint conditions) and stabilisation with reference to seismic areas. In Europe, Spain is probably the most advanced country in this matter. In Spain, earth standards are not included in the mandatory building norms however, normative documents were published in 1970 and 1992. According to Jimenez Delgado and Guerrero [18], IETcc-1970 sets the specifications for masonry units, including the use of adobe and rammed earth; and MOPT-1992 is particularly focused on rammed earth. These documents deal with unreinforced load bearing earth walls and do not include earthquake resistant design which can be found under Peruvian adobe norm or the New Zealand standards for earth construction [18].

Despite the significant disparity on regulations for earth construction, a common thread is the use of standard geotechnical tests to identify soil suitability including Particle Size Distribution (PSD), Plastic Limit (PL), Liquid Limit (LL) Plasticity Index (PI) and Linear Shrinkage (LS) [19, 20]. These and the density were determined according to European standard BS EN 1377-2 [21] and compared against recommended values to determine the material's suitability for RE construction.

As the percentage of material passing the 63 μm sieve was reasonably high, the soil was analysed to determine the percentage of silt and clay in accordance with [21]. Each soil has a moisture content that allows for maximum compaction. When constructing RE elements, it is important to ensure that high density is achieved to increase strength and durability. Therefore, the optimum moisture content (OMC) or moisture at which a material reaches maximum dry density (MDD) was determined with the Proctor test [21].

Very coarse gravel was removed. Screening to remove the fraction sized between 10 and 20 mm is generally recommended [22]. This is probably to avoid strength loss (due to discontinuities and interfaces) and the damage due the differential thermal and hygric expansion coefficients of the earth matrix and the gravel during environmental exposure. However, other authors do not consider the coarse fraction as a limiting factor [23].

The thermal properties of the material were measured with 300x302x290 mm RE specimens constructed with 5% lime stabilisation by weight. The low lime percentage was chosen in an effort to maintain the sustainability and natural hygroscopic properties of the raw material. Natural hydraulic lime (NHL) 3.5 complying with EN 459-1 [24] was used and the soil's moisture kept within the OMC. It can be argued that the OMC might be too low to ensure hydraulic reaction of hydraulic binders such as PC, but the NHL 3.5 used in this study contains free CaO c.30 % and, as a result, the moisture content combined with the curing time has probably allowed hydration of the clinker fraction in the NHL3.5.

To evaluate the thermal conductivity (k), a guarded hot plate (GHP) rig was built [25, 26]. A steady heat flow was applied (via a heat mat) to one face of the specimen under the assumption that 1D heat flow runs across the sample. K-type thermocouples were embedded at equidistance points along the direction of heat flow with additional thermocouples on the heated and opposite faces. The rig was sealed using polystyrene and polyurethane insulation (Fig 1). The power input to the mat was recorded and the temperature at each thermocouple logged per minute. The conductivity was then calculated using Fourier's law of heat conduction:

Eq. 1

$$k = \frac{QL}{A_c \Delta T}$$

Where k is the thermal conductivity (W/m.K), Q is the power input (W), L is the distance between subsequent thermocouples (m), A_c is the cross sectional area (m²), and ΔT is the change in temperature between subsequent internal thermocouples. The position of the thermocouples is shown in figure 1.

Figure 1. Exploded diagram of the GHP rig.

The specific heat of the RE was determined with a copper calorimeter based on [27]. Ten specimens of c. 2cm³ were tested by placing them inside a highly insulated copper calorimeter filled with water at high temperature (~900°C). The equilibrium temperature was determined with a digital probe thermometer. The specific heat was then calculated using Equations 2 and 3:

$$m_{R.E} c_{R.E} (T_{R.E} - T_e) = m_w c_w (T_w - T_e) + m_c c_c (T_c - T_e) \quad \text{Eq. 2}$$

$$c_{R.E.} = \frac{m_w c_w (T_w - T_e) + m_c c_c (T_w - T_e)}{m_{R.E.} (T_e - T_{R.E})} \quad \text{Eq. 3}$$

Where:

$m_{R.E}$, m_w , m_c are the masses of the sample, water, and calorimeter respectively (kg),

$c_{R.E}$ is the unknown specific heat of R.E (J/kg.K),

c_w and c_c are the specific heats of water and copper (4186 J/kg.K and 377 J/kg.k respectively)

The thermal mass and diffusivity were calculated using the density, k and $C_{R.E}$ experimentally measured.

A simulation software (IES Virtual Environment software VE 2016) was used. The VE is a 3D, performance analysis software with graphic and numerical reporting features that can be used for design and construction but also at building operation stages. Here, it was used to test different options using experimental and standard data. A 5x5 m room of wall height 2.5 m was modelled. RE and common traditional floor and roof constructions were used in all simulations which were performed in both heated (1hr in the morning and 3hr in the evening to a maximum temperature of 19°C) and unheated scenarios, for a period of one year, in typical Irish weather conditions.

Four construction types were modelled including standard cavity wall, externally insulated RE, RE with sandwiched insulation and RE with no insulation. To evaluate their thermal performance, the internal air temperature was plotted vs the external air temperature. Also, the percentage of time that the internal air temperature spent in different indices of thermal comfort in accordance with ISO 7730 [28] were evaluated as well as the annual heating loads for the different fabrics (kWh).

3. RESULTS

3.1 Geotechnical parameters

Table 1 compares the geotechnical parameters of the till studied against other boulder clays and recommended values for RE construction. The geotechnical properties of the material are consistent with tills previously studied. However, it has more fines and therefore slightly superior PI and LL than others (often indicative of higher clay content and/or active clay minerals) which agrees with its higher linear shrinkage. The low PI indicates that the soil will soften significantly with increasing moisture content. The PI indicates an earth with medium plasticity, slightly higher than other tills (table 1). The water content at which the soil begins to flow (LL) is 22% and the lowest moisture content at which the soil remains plastic (PL) is 8%. The LL is slightly higher than other tills, but within the limits considered suitable for RE construction (Table 1).

Burroughs [20], based on univariate analysis of 219 specimens, found that PI and LS are the best discriminators of soil predisposition for successful lime-stabilized RE. The PI is within the limit put forward by other authors [17, 22, 29] but slightly exceeds Burroughs' ideal soil value for soils with sand content under 64% (table 2). The LS marginally exceeds limits and this is likely caused by the high content in fines.

The PSD (figure 2) corresponds with predicted values for boulder clay [30, 31, 32]. The amount of silt and clay is slightly higher than the values ideally recommended for RE construction (table 2). According to Walker et al. [17], the minimum percentage of combined clay and silt should be between 20 and 25% and the maximum between 30 and 35%. In the boulder clays, the clay and silt content is slightly superior to the maximum limit stated by these authors.

Figure 2: PSD of the till.

According to the proctor test, the optimum moisture content was 14.1% (figure 3), with a maximum dry density of 1.84 Mg/m^3 agreeing with previous authors [30]. This material reached a mean unconfined compressive strength (UCS) of 1.09 MPa. As aforementioned, RE was stabilised with 5% NHL3.5. The density of the material (1840 kg/m^3) and its UCS agree with Ciancio et al. [33] on the optimum lime content for RE. Tests by Burroughs' [34] with similar lime content but slightly different geotechnical parameters achieved 2.0 MPa strength. Therefore, despite the higher silt/clay content of the till studied, it produced a dense material on ramming with low (5) % lime stabilization, achieving strengths comparable to other earths with more sand and similar % lime.

Properties of boulder clay			Recommended values for RE construction			
	Present study	McPadden & Pavía [30]	Long & Menkiti [15] Farrell et al. [31] Farrell & Wall [32]	Jimenez Delgado & Guerrero [29]	Houben & Guillaud [22]	Walker et al [17] Burroughs [20]
PL (%)	19	8	15.1-17.8			
LL (%)	35	22	28.3-29.5	24 - 45	25-46; 25-50	<45
PI (%)	17	14	11.8-13.2 (~10-15)	2-28	2-30; 10-25	<2-30 <15; 15-30(*)
LS (%)	7.76	3.08		<2		<5 <6; 6-11(*)
PSD (%)	20.3 gravel 29.0 sand 28.5 silt 22.5 clay	31.8 gravel 26.9 sand 41.3 silt/clay	20-30 gravel 20-70 sand 10-30 silt <20 clay(~fines 35)	50-70 sand/gravel 15-30 silt 5-26 clay	8-16 clay	<30-35 clay/silt 5-25 clay 45-80 sand 10-30 silt 5-20 clay

Table 1. Geotechnical properties of glacial till in this and other studies compared with recommended soil characteristics for RE construction.(*) for sand >64%.

Figure 3: Maximum dry density vs water content for the rammed till.

Burroughs [20, 34] found that materials with moderate clay/silt contents (21–35%) were more likely to be successfully stabilized (i.e. to reach 2 MPa UCS) than those with higher or lower clay/silt content. He also found that sand contents c.48% were successfully stabilized whereas above this value, the rate of failure increased with higher sand contents; and high proportions of sand (>70%) are poor in terms of stabilization success. The tills studied in this paper are lower in sand and higher in clay/silt than the thresholds proposed by Burroughs. This can be responsible for the USC value under 2 MPa. In a further study, using 4–8% cement and/or lime stabilization, Burroughs [34] identifies “favorable” soils, with stabilization success over 80%, as those with linear shrinkage under 6.0% and PI under 15%; or linear shrinkage 6.0 -11.0%, PI 15-30% and sand content under 64%. According to these, the soil in this paper would be suitable for stabilization.

3.2 Thermal properties

The GHP equipment consistently provided steady state temperatures (Figure 4) and the average value of thermal conductivity (k) vary by less than 0.1 W/mk in three different tests. The k values produced by the internal thermocouples are consistent while the first pair (CH 3-5) showed a slightly higher conductivity in all tests. This is

possibly due to variations in positioning as, although the distance between thermocouples was measured with callipers, a slight variation in the angle of drilling can cause deviations in the measurements.

Figure 4. Thermal conductivity of the rammed till over time. CH- thermocouple.

The arithmetic mean of the thermal conductivity measured for the RE (4 tests) is compared with values from other REs and concretes- Table 2. The thermal conductivity of the RE (1.65 W/m.K) is slightly superior to other REs with comparable densities previously reported [35-37, 7, 1]. This variation was expected as thermal conductivity can vary by 0.8 W/m.K due to soil constituents and 0.13 W/m.K due to moisture [36]. As expected, the RE values are similar to PC concretes [38, 39] much greater than low density concretes such as lime-hemp [40, 41]. For high thermal mass materials, thermal conductivity usually needs to be moderate so that the absorption and release of heat harmonizes with the building's heating and cooling cycle.

Source	Material	Thermal conductivity k (W/m.K)	Specific heat capacity C (J/kg K)
Present study	RE / 5% NHL 3.5	1.65	1218
Soudani et al [35]	RE / 2.5% CL90	0.60	648
Hall & Allison [36]	RE/ 6% CEM IIa	0.83 - 1.01	-
AI RAH [37]	RE Standard Value	1.25	1260
Minke [1]	RE Standard Value	0.90-1.51	1000
Standards Australia [7]	RE Standard Value	0.42 - 0.85	-
Carman & Nelson [38]	PC Concrete	1.03 – 1.79	750-1000
Chan [39]	PC Concrete	1.34 – 2.94	268-973
Walker and Pavía [40, 41]	hemp–lime concretes	0.12 - 0.14	1240 - 1350

Table 2. Comparison of thermal properties of the rammed till with other REs and concretes by previous authors.

The thermal conductivity does not take into account the effects of thermal mass, and by itself, is insufficient to describe the heat transfer properties of construction materials and assemblies with significant thermal mass such as RE. Therefore, further thermal properties are discussed below.

The specific heat measurements (table 2) were consistent and produced an average of 1218 J/kg.K. (1645 for the PC concrete control specimens) agreeing with previous authors [1, 38-39]. The lime used in this experiment was

fully slaked therefore, no additional heat coming from slaking contributed to the specific heat measured. The high specific heat capacity of the RE, consistent with materials of high thermal mass, means that considerable heat energy is required to raise the temperature of the material and that the material has a substantial capacity to store heat for every kilogram of mass. As aforementioned, these thermal characteristics are desirable to suppress or lower indoor air temperature variation and reduce peak heating or cooling loads.

The thermal diffusivity (α in m^2/s), was measured (using Equation 4) to inform on the rate at which temperature change would pass through the RE. It was calculated using the experimentally determined values of k and C . It represents the rate at which temperature changes within the material's mass.

Eq. 4

$$\alpha = \frac{1.657 \frac{W}{m \cdot K}}{1833.65 \frac{kg}{m^3} * \frac{1218.66 J}{kg \cdot K}}$$

$$\alpha = 7.415 * 10^{-7} m^2/s$$

As steady state conditions are extremely unlikely to occur in practice, the thermal diffusivity allows the quantification of the rate of heat flow in RE considering moisture change. A higher diffusivity means that the material changes temperature faster. The RE diffusivity lies at the lower end of reported concrete values which range from 55 – 197x10⁻⁸m²/s (table 3). This suggests that RE will impede heat flow to a greater extent than typical concrete, reaching values considerably closer to those of low density materials with good insulating properties such as cork lime and hemp lime concrete (table 3) with low diffusivities and outstanding thermal inertias, valuable attributes for attenuating external temperature fluctuation.

		Density kg/m ³	Thermal conductivity W/m K	Specific heat capacity J/kg K	thermal diffusivity m ² /s x10 ⁻⁸
present study	RE 5%	1833	1.65	1218	74
	NHL 3.5				
	PC concrete	2200	2.17	1645	60
PC concrete [42]		2200	1.70	840	92
		2400	2.20	840	109
		2300	1.90	840	98
		2500	2.30	840	109
PC concrete [43]		2300	1.75	840-1170	55 - 166
PC concrete [44]		2000	1.13	1000	102 - 122
Hemp-lime concrete;		602	0.09	1068	14
Cork lime [40, 41]		806	0.06	866	9

Table 3. Comparison of thermal properties of the rammed till in this study with other materials.

3.3 Software simulation

As aforementioned, a 5x5 m room of wall height 2.5 m was simulated with insulated and non-insulated RE and compared with standard concrete block cavity wall. Common traditional floor and roof construction were used in all simulations which were performed in both heated (1hr in the morning and 3hr in the evening to a maximum temperature of 19°C) and unheated scenarios, for a period of one year. The construction types studied are summarised in Table 4. The thermal properties were also calculated using the values and methods in ISO 6946 [45].

Construction type	1-Standard concrete block cavity wall	2- RE with external insulation	3- RE, no insulation	4- RE with sandwiched insulation
Elements	19mm render 100mm concrete block 40mm air cavity 80 mm polyurethane 100mm concrete block 13mm plaster	19mm render 100mm polyurethane 300mm RE 13 mm plaster	300mm RE	150mm RE 100mm polyurethane 150mm RE
U-Value - W/m².K	0.26	0.22	2.84	0.23
Thermal mass -kJ/m².K	207.9	202.2	223.5	223.5

Table 4: Summary of simulated construction types.

Figures 5 and 6 show the response of internal air temperatures to the external temperature variation in unheated and heated situations respectively. The behaviour of all insulated RE sections follows a similar pattern with temperatures being maintained during the day and dropping later in response to the external temperature changes. The heat retention reduces the magnitude of the temperature falls. This thermal lag is typical of high thermal mass materials and has been evidenced by former authors [11, 13]. Experimental results by Serrano et al. [14] showed that the use of insulation in RE systems provides a significant increase in the thermal lag, while no effect was observed in conventional cavity wall construction. The uninsulated RE also reduces the extent of the external temperature fluctuations. However, temperature fluctuations are greater than in any other fabric probably due to its greater thermal transmittance (U-value, table 4).

Figure 5. Unheated internal air temperature vs external air temperature (June).

The applied heating profile allows for the internal temperature of the insulated fabrics to remain in the range of 17.5 - 19°C. For the majority of the time, the internally insulated RE caused the smallest daily temperature drops followed by externally insulated RE and the concrete-block cavity wall. At high external temperatures (>19°C) the slower response of the RE allows for concrete to heat up faster than the RE elements and maintain a higher temperature.

Similarly to the unheated scenario, the uninsulated RE has a much greater magnitude of temperature drop suggesting that an uninsulated RE wall of 300 mm thickness cannot achieve a sufficient U-value to resist the flow of heat gained through the walls. This agrees with Dong et al. [46] who state that uninsulated RE is not viable for locations with a temperate climate (mild summers and cold winters).

None of the unheated fabrics were capable of maintaining comfortable internal temperatures. All insulated sections performed similarly in maintaining a suitable thermal comfort index with both RE assemblies performing slightly better than concrete construction (Table 5).

Figure 6. Heated internal air temperature vs external air temperature (June).

Comfort indices	% R.E no Insulation	% R.E external insulation	% R.E internal insulation	% Concrete
1- very cold	0.90	0.00	0.00	0.00
2- cold, shivering	4.91	0.00	0.00	0.00
3- cool, unpleasant	31.69	0.00	0.00	0.00
4- cool, acceptable	14.57	3.07	1.24	6.79
5- slightly cool/acceptable	34.34	53.64	54.09	52.41
6 - comfortable, pleasant/cool	12.45	43.21	44.59	40.61
7- comfortable, pleasant	0.99	0.08	0.08	0.19
8- comfortable, pleasant/warm	0.15	0.00	0.00	0.00

Table 5. Percentage of year spent in the different comfort indices (heated scenario) conforming with ISO 7730 [28].

All the insulated RE constructions required similar heating loads. Their annual heat load is between 2 and 4.2% lower than the standard concrete block construction. The uninsulated RE used twice the load of any other construction type and hardly maintained comfortable temperatures (table 5).

Despite having similar thermal conductivity and U-values than the concrete construction, the RE reduced the fluctuations of the external temperature to a greater extent, increasing the thermal stability of the internal air and slightly reducing the annual heat load when compared with the concrete cavity walls. This agrees with the lower diffusivity experimentally measured and the thermal lag in the figures.

It was noted that, in the calculation of κ - the factor governing thermal mass, the simulations assume that the wall construction is symmetrical and the value is calculated from the outside face inward. This means that simulations of externally insulated RE do not account for the thermal mass' capability of storing heat generated on the inside of the building. Therefore, the thermal performance of the externally insulated RE is underestimated in the simulation, as it assumes that the wall construction is symmetrical, not accounting for varying thermal mass characteristics for non-symmetrical construction. Other authors have evidenced a poor match between simulated and measured performance of RE constructions, with measured performance being superior. Becket et al. [13] measured the thermal stability and thermal lag of RE houses in Australia and demonstrated that the match between simulated and measured performance was poor and that the measured performance was superior.

4. CONCLUSION

This research assessed the suitability of glacial till for RE construction. Also, the thermal properties of the rammed till were measured and numerically modelled to compare the performance to other REs and traditional construction.

The values of PI and LS indicated that the material is fit for RE construction. This was confirmed experimentally as the tills were successfully stabilized with 5% NHL3.5, reaching a UCS of 1.09 MPa. The sand content (sand + gravel=50%) is partially accountable for the successful stabilization, and the slightly high clay/silt content is likely responsible for the UCS value under 2 MPa. The till contains slightly more fines and therefore superior PI and LL than other tills. The till's OMC is 14.1%, with a maximum dry density of 1.84 Mg/m³. Similarly to other tills, the amount of silt/clay is comparable or slightly superior to the values ideally recommended for RE construction while the LS marginally exceeds limits probably due to the higher fine content.

The thermal conductivity and specific heat capacity were experimentally measured at 1.657 W/m.K and 1218.66 J/kg.K respectively; and the thermal diffusivity reached 7.42x10⁻⁷ m²/s. The specific heat indicates a substantial capacity to store heat while the thermal conductivity, as expected, is significant evidencing a poor insulation ability. The RE diffusivity lies at the lower end of reported concrete values suggesting that the rammed till will impede heat flow to a greater extent than typical concrete.

The simulation behaviour confirmed the experimental values. Despite having similar thermal conductivity and U-values than concrete construction, the RE reduced the fluctuations of external temperature to a greater extent, increasing the thermal stability of the internal air and slightly reducing the annual heat load when compared with the concrete cavity walls. The RE assemblies showed the thermal lag typical of high thermal mass materials reducing and delaying external temperature fluctuations. It was also evidenced that the use of insulation in the RE walls significantly increased the thermal lag, agreeing with their lower diffusivity.

All insulated assemblies maintained suitable thermal comfort indexes. The insulated RE assemblies performed slightly better than concrete. In particular, the RE with sandwiched insulation provided the greatest amount of time in comfortable comfort indices and caused the smallest temperature drops. The insulated RE constructions required similar heating loads. Their annual heat load is 2-4.2% lower than the concrete construction. It is concluded that insulated RE constructions perform similarly to standard concrete construction but require lower annual heating loads and provide enhanced comfort.

ACKNOWLEDGMENT

A special thanks to Gerard Joseph McGranaghan, Kevin Ryan, Michael Grimes, Dave McAuley and Eoin Dunne for their support and guidance in the laboratories. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

REFERENCES

1. Minke G., *Building with Earth: Design and Technology of a Sustainable Architecture*. 2006, Berlin: Birkhauser.
2. Downton, P., *Rammed Earth*. 2013.
3. Pavia S., Determination of brick provenance and technology using analytical techniques from the physical sciences, *Archaeometry* 48 (2) (2006) 201 – 218 <https://doi.org/10.1111/j.1475-4754.2006.00251.x>
4. Pavia, S. and Roundtree, S., An Investigation into Irish historical ceramics: the brick of Arch Hall, Wilkinstown, Co. Meath, *Proceedings of the Royal Irish Academy* 105C (6) (2005) 221 – 242 DOI: 10.3318/PRIC.2005.105.1.221
5. Morel, J.C., Mesbah A., Oggero M., Walker P., Building houses with local materials: means to drastically reduce the environmental impact of construction. *Building and Environment* 36(10) (2001) 1119-1126. [https://doi.org/10.1016/S0360-1323\(00\)00054-8](https://doi.org/10.1016/S0360-1323(00)00054-8)
6. Howley, M. and M. Holland, *Energy in Ireland 1990 -2015*, SEAI, Ed. (2016).
7. Maniatidis V. and Walker P., A Review of Rammed Earth Construction DTi Partners in Innovation Project 'Developing Rammed Earth for UK Housing' (2003).
8. Taylor, P. and M.B. Luther, Evaluating rammed earth walls: a case study, *Solar Energy* 76 (1) (2004) 79-84.
9. Allinson D. and Hall M. (2010) Hygrothermal analysis of a stabilised rammed earth test building in the UK, *Energy Build.* 42 (2010) 845–852. doi:10.1016/j.enbuild.2009.12.005
10. Gomes, M.I., Gonçalves, T.D., Faria, P., Hydric behavior of earth materials and the effects of their stabilization with cement or lime: study on repair mortars for historical rammed earth structures, *J. Mater. Civ. Eng.* 28 (7) (2016) [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001536](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001536)
11. Hall M. and Allinson D., Analysis of the hygrothermal functional properties of stabilised rammed earth materials, *Building and Environment* 44 (9) (2009) 1935–1942 <https://doi.org/10.1016/j.buildenv.2009.01.007>
12. Ciancio D., Jaquin P., Walker, P., Advances on the assessment of soil suitability for rammed earth, *Constr. Build. Mater.* 42 (2013) 40–47. <https://doi.org/10.1016/j.conbuildmat.2012.12.049>
13. Beckett C.T.S., Cardell-Oliver R., Ciancio D., Huebner C., Measured and simulated thermal behaviour in rammed earth houses in a hot-arid climate. Part A: Structural behaviour. *Journal of Building Engineering* 15 (2018) 243–251 <https://doi.org/10.1016/j.jobbe.2017.11.013>
14. Serrano S., de Gracia A., Cabeza L F., Adaptation of rammed earth to modern construction systems: Comparative study of thermal behavior under summer conditions, *Applied Energy* 175 (2016) 180–188 <http://dx.doi.org/10.1016/j.apenergy.2016.05.010>
15. Long, M. and Menkiti C.O., Geotechnical properties of Dublin Boulder Clay, *Géotechnique*, 57 (7) (2007) 595-611. <http://dx.doi.org/10.1680/geot.2007.57.7.595>
16. UNE 41410 (2008) Bloques de tierra comprimida para muros y tabiques. Definiciones, especificaciones y metodos de ensayo. AENOR.
17. Walker, P., Keable, R. Martin, J., Maniatidis V. (2005) *Rammed Earth: Design and Construction Guidelines*. BRE, UK.
18. Jimenez Delgado M. C. and Guerrero I.C. Earth building in Spain. *Construction and Building Materials* 20 (2006) 679–690 <http://dx.doi.org/10.1016/j.conbuildmat.2005.02.006>
19. Ciancio, D., Jaquin P., Walker P., Advances on the assessment of soil suitability for rammed earth. *Construction and Building Materials* 42 (2013) 40-47 <https://doi.org/10.1016/j.conbuildmat.2012.12.049>
20. Burroughs, S., Soil Property Criteria for Rammed Earth Stabilization. *Journal of Materials in Civil Engineering* 20 (3) (2008) 264-273.

21. EN BS 1377-2-1990: Methods of test for Soils for civil engineering purpose- Part 2: Classification tests.
22. Houben, H. and Guillaud H., *Earth Construction: A Comprehensive Guide*. 1994: Intermediate Technology Publication.
23. Gomes M. I., Faria P., Diaz Gonçalves T., Earth-based mortars for repair and protection of rammed earth walls. Stabilization with mineral binders and fibers. *Journal of Cleaner Production* 172 (2018) <https://doi.org/10.1016/j.jclepro.2017.11.170>
24. EN 459-1 (2015) Building lime. Definitions, specifications and conformity criteria.
25. Zhao, D., Qian X., Gu X., Jajja S A., Yang R. Measurement Techniques for Thermal Conductivity and Interfacial Thermal Conductance of Bulk and Thin Film Materials. *Journal of Electronic Packaging*, 138 (4) (2016) 040802-040802-19. doi: 10.1115/1.4034605
26. EN 12667:2001. Thermal Performance of Building Materials and Products - Determination of Thermal resistance by means of guarded hot plate and heat flow methods (Vol. 12667).
27. Abu-Hamdeh, N.H. and Alnefaie K.A., Specific heat and volumetric heat capacity of some Saudian soils as affected by moisture and density, *Applied Mechanics and Materials* 575 (2014) 103-107.
28. ISO 7730: 2005 Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. <https://doi.org/10.1016/j.jclepro.2017.11.170>
29. Jiménez Delgado, M. C. and Guerrero, I. C., The selection of soils for unstabilised earth building: A normative review, *Construction and Building Materials* 21 (2) (2007) 237-251 <http://dx.doi.org/10.1016/j.conbuildmat.2005.08.006>
30. McPadden, J and Pavia, S., An assessment of raw materials for earth construction in Co. Offaly, Ireland. Congreso Euro - Americano Rehabend: Patología de la Construcción, Tecnología de la Rehabilitación y Gestión del Patrimonio, Burgos (2016) E.T.S. Ingenieros de Caminos, Canales y Puertos de Santander Eds.
31. Farrell E., Coxon P., Doff D. and Pried'homme L., The genesis of the brown boulder clay of Dublin. *Quarterly Journal of Engineering Geology* 28 (1995) 143-152
32. Farrel E. and Wall D., Soils of Ireland. Institution of Engineers of Ireland. Meeting of the Geotechnical Society and the Institution of Structural Engineers (1990).
33. Ciancio, D., Beckett C.T.S., Carraro J.A.H., Optimum lime content identification for lime-stabilised rammed earth, *Construction and Building Materials* 53 (2014) 59-65 DOI: 10.1016/j.conbuildmat.2013.11.077
34. Burroughs, S., Strength of compacted earth: linking soil properties to stabilizers. *Building Research and Information* 34 (1) (2006) 55-65 <https://doi.org/10.1080/09613210500279612>
35. Soudani, L., Woloszyn M., Fabbri A., Morel J. C, Grillet A C., Energy evaluation of rammed earth walls using long term in-situ measurements, *Solar Energy* 141 (2017) 70-80 <https://doi.org/10.1016/j.solener.2016.11.002>
36. Hall, M. and Allinson D., Assessing the effects of soil grading on the moisture content-dependent thermal conductivity of stabilised rammed earth materials, *Applied Thermal Engineering*, 29(4) (2009) 740-747 DOI: 10.1016/j.applthermaleng.2008.03.051
37. AIRAH, Technical Handbook (Millenium Edition), The Australian Institute of Refrigeration, Air-Conditioning and Heating (2000).
38. Carman, A.P. and R.A. Nelson, Thermal Conductivity and Diffusivity of Concrete. *University of Illinois Bulletin*, 1921 (18) 122.
39. Chan, J., Thermal Properties of Concrete with Different Swedish Aggregate Materials, Unpublished Research, Faculty of Engineering (2013) LTH: Lund, Sweden.
40. Walker R. and Pavia S., Moisture transfer and thermal properties of hemp–lime concretes, *Construction and Building Materials* 64 (2014) 270 – 276 DOI: 10.1016/j.conbuildmat.2014.04.081
41. Walker R. and Pavia S., Thermal performance of a selection of insulation materials suitable for historic buildings, *Building and Environment* 94 (2015) 155-165 <http://dx.doi.org/10.1016/j.buildenv.2015.07.033>
42. Hammond, G.P. and Jones C.I., *Inventory of Carbon & Energy (ICE)*, CircularEcology, Ed. (2011)
43. The Concrete Centre Part L1A (2013): Conservation of fuel and power (new dwellings). The Concrete Centre Publ. London (2016)
44. ISO 13786:2017 Thermal performance of building components -- Dynamic thermal characteristics -- Calculation methods.

45. ISO 6946:2017 Building components and building elements — Thermal resistance and thermal transmittance — Calculation method.
46. Dong, X., Soebarto V., Griffith M., Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses, *Energy and Buildings* 77 (2014) 323-331 DOI: 10.1016/j.enbuild.2014.03.031

Highlights

Geotechnical parameters measured experimentally demonstrate the fitness of glacial till for RE. This work contributes to make of earth a reliable building material and promotes using high thermal mass materials to lower today's unsustainable energy demand for heating and cooling buildings.

The rammed till has high thermal conductivity (1.65 W/m.K) and specific heat capacity (1218.66 J/kg.K) indicating a substantial scope to store heat and poor insulation ability however, the thermal diffusivity ($7.42 \times 10^{-7} \text{ m}^2/\text{s}$) suggests that it will impede heat flow to a greater extent than concrete.

The experimental values are feed into models to compare the till's thermal performance against traditional building assemblies.

In the simulations, the insulated rammed till assemblies perform better than concrete, with annual heat load 2-4.2% lower than the concrete construction.

The insulated rammed till assemblies increased the internal thermal stability and maintained thermal comfort indexes slightly better than concrete; in particular the rammed till with sandwiched insulation.