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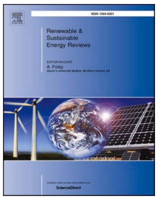

Energy performance, environmental impact and cost of a range of insulation materials

T. Dickson, S. Pavía *

Department of Civil Engineering, University of Dublin, Trinity College, Ireland

A R T I C L E I N F O

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A B S T R A C T

The need for the selection of an appropriate insulation is becoming more important as environmental problems continue to grow. This paper investigates insulation performance in terms of heating energy requirement, environmental impact and cost. The thermal performance of insulations (natural, petrochemical, rock/slag based) is modelled, on brick, rammed earth (RE) and cavity walls, in different locations (external, internal and inside the wall), using software. The environmental performance of the insulation is determined using the Life Cycle Assessment-LCA-technique. A new scoring tool is created which allows inputted data, across the three areas of performance (energy, environmental, economic), to be standardized and compared, providing a final score that represents the overall performance. The input data and weightings can be modified easily to investigate new materials and to meet user requirements.

Out of all the insulations, cellulose fibre showed the best overall performance. The model results highlight the importance of the hygrothermal properties of the insulation, and their compatibility with the substrate, for best energy performance. The insulated earth buildings require less energy for heating and are responsible for lower carbon emissions than the insulated brick buildings. This is attributed to the lower diffusivity of the earth walls attenuating external temperature fluctuation and economizing energy. The permeable insulations (cork and hemp) tend to perform better with earth than with brick, which is attributed to a more compatible hydric performance. The model results indicate that the best thermal performance is obtained when insulation is placed outside the wall.

1. Introduction

The building sector contributes to environmental damage through resource depletion, CO_2 and other gas emissions and waste disposal. According to the 2018 Global Report [1] released by the International Energy Agency and the United Nations, the building sector accounts for the highest energy use (36%) and emissions (39%) of all industries. With the increasing importance of climate change, the building sector is under pressure to reduce its environmental impact. The rising global population will bring about an increase in the number of buildings. Therefore, it is essential that solutions are found to combat the environmental damage of the building sector.

Abundant policy has appeared in the last decades to combat environmental damage. Energy Performance Certificates are mandatory for new buildings, and all buildings need to be decarbonised by 2050 [2]. The 2018 amendment to this directive enhances the renovation of existing buildings, which often includes the installation of insulation to improve the operational energy. Within this framework, the choice of insulation is yet to become even more important. The need to heat buildings during the winter, and cool them during the summer, means that selecting an appropriate insulation material is a key factor in building design.

One of the most common solutions to lower the environmental damage of construction is to apply thermal insulation, and many insulating materials have appeared in the market in the last decades. The abundant choice, coupled to the lack of performance data, makes it difficult to make an informed decision on the type of insulation that is best for a given construction. This paper provides a holistic evaluation of insulations. It intends to help users choose an appropriate insulation for a given construction. A scoring tool is created to determine the overall insulation performance. The main novelty is that this is the first tool of its kind. It allows inputted data, across three areas of performance (energy, environmental, economic), to be standardized and compared (to other insulations), providing a final score. The tool also allows for customisation based on user preferences. For example, the weightings

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* Corresponding author. University of Dublin Trinity College, Dept. of Civil Engineering, University of Dublin Trinity College, Ireland.
E-mail addresses: dicksont@tcd.ie (T. Dickson), pavias@tcd.ie (S. Pavía).

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List of abbreviations including units and nomenclature

EPD	Environmental Product Declaration
ICB	Expanded cork board
ICFs	insulated concrete forms
LCA	Life Cycle Assessment
MMVF	Man-Made Vitreous Fibres
NHL	Natural hydraulic lime
OSB	oriented strand board
PUR	polyurethane
PIR	board-polyisocyanurate
RE	rammed earth
T	temperature
t	time
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
C	specific heat capacity (J/kgK)

for each performance area can be changed (e.g. reduce the importance of price on the final score if money is not an issue).

1.1. Insulation types and performance

Much research has focussed on insulation in the last decades including reviews of types and properties, analyses of specific materials or insulation systems and evaluations of payback periods [3–5] and thermal comfort [6]. Al-Homoud [7] reviews the principles of thermal insulation, and the performance and application of common insulation drawing a series of general recommendations. Aditya et al. [8] Completed a comprehensive review of thermal and acoustic insulating materials, highlighting the importance of establishing the optimum insulation thickness as it impacts performance and life cycle cost. Other authors have attempted to enhance the insulation's performance by optimizing its thickness and position, and relate the insulation's thickness to its environmental impact [9–14]. Sanea and Zedan [9] showed that the optimum thickness of a single insulation layer is independent of its location in the wall; and that, when more than one insulation layer is used, their total optimum thickness equals the optimum thickness of a single layer. Ozel [10] concludes that, by applying an optimum insulation thickness, annual fuel consumption and emissions decrease by 68–89% depending on the type of insulation. Dombaycı [11], using coal as fuel, proved that, when the optimum polystyrene thickness is used, energy consumption decreased by 46% and CO_2 and SO_2 emissions by 41%. Özkan and Onan [12] studied the effect of insulation thickness on fuel consumption, payback period and pollutant emissions for different insulations and fuels, reporting a 50–54% drop in CO_2 emissions for extruded polystyrene foam, agreeing with [13] who also reported a 50% decrease in CO_2 emissions by means of optimizing the insulation thickness.

These studies are comprehensive, and some revealed interesting results. However, it is out of the scope of this paper to investigate the properties and behaviour of insulation materials. The aim of this work is to provide a framework whereby any insulation can be easily included and evaluated against set environmental, cost and thermal values. Furthermore, the paper intends to provide a direct simple rating to help make informed choices based on performance, cost and environmental impact.

1.2. Modelling to assess the energy performance of insulations and constructions

Modelling has become the basis for the analysis of building operations, especially to forecast energy demand. There is abundant literature on the modelling of energy performance of different buildings and occupancies [15–19]. Modelling with a focus on insulation performance is also found in the literature however more scarcely [17,18,20]. Ibrahim et al. [17], investigated aerogel insulation with the WUFI Pro 5.1 software. Their simulation and experimental results showed that adding aerogel externally reduces or removes moisture risks and significantly lowers heat loss through the wall. Cho et al. [18] used Autodesk Ecotect to compare insulated concrete forms (ICFs), closed cell soy-based spray foam and traditional batt insulation in a model, and concluded that the soy-based spray foam, on all external walls, was the most energy efficient solution. Anastaselos et al. [20] evaluated expanded and extruded polystyrene, mineral wool and rigid polyurethane foam insulation using energy, environmental and economic data. The evaluation looked at various wall configurations including insulated and non-insulated walls, and external thermal insulation systems but does not offer a simple, combined energy, environmental and economic rating. As it can be seen from the above, much published literature evaluates the performance of either specific or a small range of insulations. However, Kumar et al. [21] issued a comprehensive study based on insulation properties, comparison of cost and total embodied energy, proposing four criteria to select the optimum insulation for a given climate (operational energy and carbon; embodied energy and carbon; cost and comfort). The authors consider thermal conductivity, specific heat, embodied energy, cost, water vapour diffusion resistance factor, noise reduction coefficient and fire resistance. However, they do not consider LCA data for the estimation of the environmental performance. As a result, core environmental impact indicators such as global warming potential, ozone depletion, acidification potential of soil and water, eutrophication potential, photochemical ozone creation potential and the depletion of abiotic resources are overlooked.

1.3. Evaluation of environmental impact with the Life Cycle Assessment-LCA

This paper evaluates the environmental performance of 21 insulations using the LCA method. This is a widely accepted technique to quantitatively evaluate the impact of a material on the environment and on human's health and well-being [22,23]. It considers the entire life of a product, from extraction, through manufacturing, use, end of life treatment and disposal. Standards ISO 14040 and ISO 4044 [24,25] outline the procedure for conducting a LCA. A review of the literature found that there are many ways of conducting a LCA due to the lack of rigidity within the framework [25–28], and that LCA can be assisted by Building Information Modelling (BIM) to reduce the time-consuming process of inventory analysis [29]. Comprehensive environmental assessments (of either specific or a relatively small range of insulations) using the LCA technique have been reported in the literature [26–31]. A comparative LCA of external insulation was carried out by Tingley et al. [30] including expanded polystyrene, phenolic foam and mineral wool. Sixteen environmental indicators were used. The results showed that expanded polystyrene had the lowest environmental impact. Audenaert et al. [31] carried out an LCA of a 19-flat building using the Eco-indicator'99 method. Insulations on the roof (polyurethane-PUR), exterior walls (oriented strand board-OSB), interior walls (rock wool) and floors (PUR) were investigated. An eco-score was calculated for each material, and an optimal building configuration was proposed, with alternative materials, to reduce the eco-score by 99%.

This paper not only estimates the environmental impact of specific insulations but it also provides a flexible framework to study any insulation, and simultaneously compare it with some of the most common in the market. The assessment is based on essential data including core environmental impact indicators (global warming potential, ozone depletion, acidification potential of soil and water, eutrophication potential, photochemical ozone creation potential and the depletion of abiotic resources) whose weighing as inputs can be altered.

1.4. Insulation assessment tools

Anastaselos et al. [20] developed an assessment tool based on the results of the LCA of insulations. They studied cavity walls and the most common thermal insulation systems in Greece - extruded polystyrene, expanded polystyrene, mineral wool and rigid polyurethane foam. Emissions from production, transportation and installation ($CO_2/SO_2/PO_4/C_2H_4$ equivalent) and environmental impact (climate change potential, acidification, eutrophication and photochemical oxidation) are modelled with a LCA software (SimaPro). Similarly to Ref. [20], a tool is developed in this paper to help decision making which also contemplates energy, economic and environmental efficiency. However, the purpose, application and end results of the tool, as well as the structure and the nature and weighing of the variables, are totally different. In Anastaselos et al. [20], there is a database of building materials where thermal and physical properties, environmental and energy parameters and costs are included. The user designs thermal insulation system by selecting materials from the database. It seems that the tool calculates automatically the cost (for supply and installation), thermal conductivity, embodied energy and emissions related to production, transport and installation and an overall rating is awarded.

2. Methodology

2.1. Evaluation of thermal performance: modelling software and settings

IES-VE software, was used as a platform for comparing the performance of insulation materials in a functioning building. IES is used in the design and testing of buildings, and can offer insights into energy use, carbon emissions and occupant comfort. A three-bedroom bungalow (Fig. 1) was designed and configured to undergo standard meteorological conditions in Dublin, Ireland. The heating system was an oil boiler with radiators. Natural ventilation by opening windows was chosen as the cooling system. Each room was assigned a heating and cooling setpoint so that, if temperatures went below or above, heating or cooling of the room would occur. The occupants are assumed to have full time jobs which would see them leave for work at 8 a.m. and return at 5 p.m. Internal heat gains for each room were defined to include lighting, cooking and people. However, these inputs were not given high importance as they would be constant throughout the simulation. With respect to air exchanges, the default IES-VE values for infiltration and natural ventilation were assigned, and auxiliary ventilation was not included.

The thermo hygric properties of the insulations were inputted into the model (Table 2), and the IES-VE software calculated the U-value for each insulation based on the inputted values and thickness. The models investigated in this paper simulate heat transfer through conduction, convection and radiation. The IES-VE software uses a central simulation processor (ApacheSim) which enables to assess every aspect of thermal performance. Therefore, in the models, for each element of the building fabric, conduction, convection and radiation heat transfer processes are individually modelled, and integrated with models of room heat gains and air exchanges. The simulation also encompasses real weather data and lapses through any time period which can vary from a day to a year. The evolution of the building's thermal conditions over time is tracked at time intervals of 1 min.

2.2. Configuration of the external walls in the models and position of the insulation

The external wall was the only component which varied (Fig. 2). The rest of the building components (roof, floor, ceiling, windows, doors, internal partitions) were set according to the National Calculation Method, to create a model as close as possible to a notational house in the Building Energy Rating Certification. The energy loads were simulated, for each insulation, with both brick and rammed earth configurations (Fig. 2). The simulation runs from January 1st to December 31st, with a time step of 10 min. The insulation materials were chosen, based on available data, to represent the three main types (rock/slag, petrochemical and plant-based) [20–23]. They were modelled on brick and rammed earth external walls and applied internally, in the cavity and externally. Six different wall configurations were tested (Fig. 2).

2.3. Insulations modelled and their properties

Existing products and experimentally tested insulations [32,33] were modelled. They are included in Table 1. The experimentally tested materials were only included in the energy performance analysis. An experimentally tested lime plaster [32] was used as the internal finish for all the wall configurations. As it can be seen from Table 1, a range of insulation spanning over the three main types (rock/slag, petrochemical and plant-based) are studied [34]. As shown in Fig. 2, they are modelled in different locations (cavity, external and internal), on the external walls of rammed earth (RE), solid brick and cavity walls, of a standard construction.

As aforementioned, the thermo hygric properties of the insulations (Table 2) were inputted in the model which calculated the U-value for each insulation based on the inputted values and thickness. The simulation processor models conduction, convection and radiation heat transfer for each element of the building fabric, and integrates these with room heat gains, air exchanges and real weather data, tracking the evolution of the building's thermal conditions at 1-min intervals.

The model considers heat conduction and storage fundamentals, hence it takes into account the density, thermal conductivity and specific heat capacity of the materials. It also considers the heat diffusion in the calculations, and that λ, ρ, and c may vary with position according to equation (1):

T is the temperature; t is the time (1).

λ is the thermal conductivity of the solid (W/m K).

ρ is the density of the solid (kg/m^3).

C is the specific heat capacity of the solid (J/kgK).

Furthermore, the model considers heat storage in air masses contained within the building, and the thermo-physical properties (λ, ρ, and c) of each wall layer are assumed to be uniform within the layer. Vapour resistivity is used for condensation analysis, so it does influence the simulation. The properties entered in the model are included in Table 2.

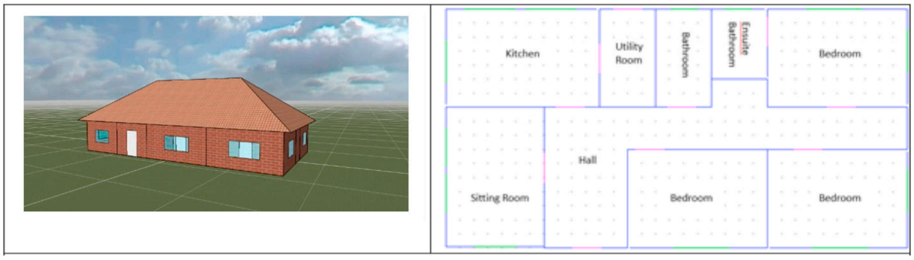


Fig. 1. Plan and isometric view of the three-bedroom bungalow, designed with IES-VE, on which the insulations were modelled.

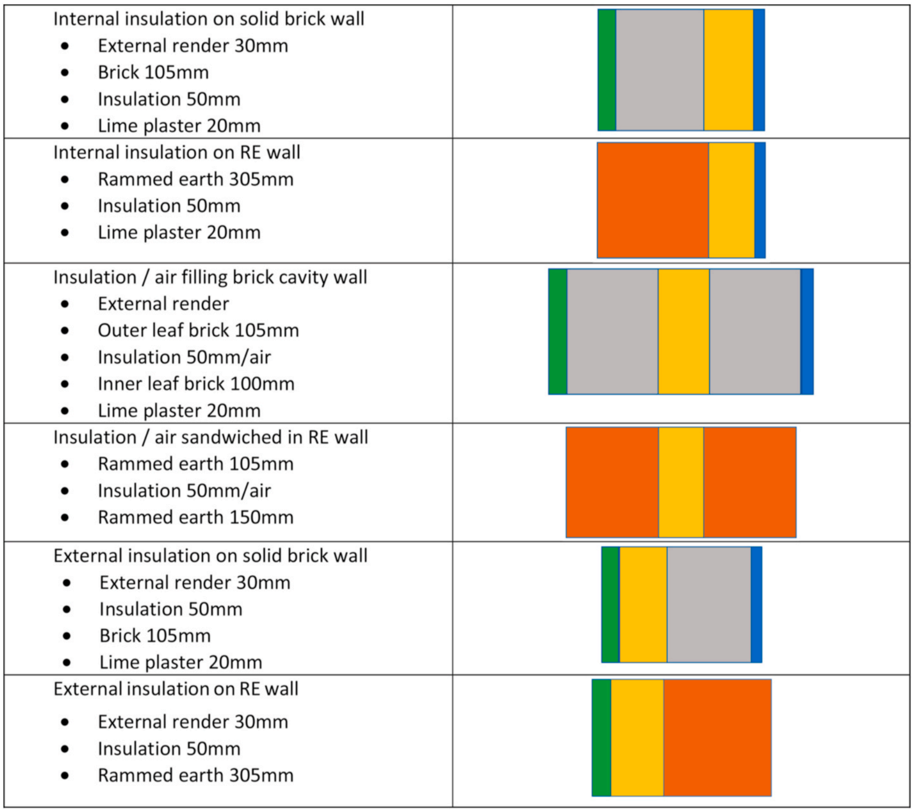


Fig. 2. Configuration of the external (brick and RE) walls in the models. The insulation is yellow coded and given a constant depth (50 mm) for consistency.

2.4. *Assessment of the environmental impact*

As aforementioned, the environmental impact of the insulation was evaluated using the Life Cycle Assessment (LCA). The LCA was completed following the steps in ISO 14040 and 14044 [24,25] (goal/scope, inventory analysis, impact assessment, interpretation) and the core indicators outlined in them. The declared functional unit of the LCA is 1 m^2, hence data is related to 1 m^2 of insulation. The system boundary is defined as 'cradle to gate' (or embodied energy) and includes all production life cycle stages. The core environmental impact indicators in EN 15804 [47] were chosen for the LCA including: global warming potential, ozone depletion, acidification potential of soil and water, eutrophication potential, photochemical ozone creation potential and the depletion of abiotic resources. The data for the environmental impact indicators was collected from each material's EPD (Environmental Product Declaration). The EPDs are official, widely accepted documents that are completed according to the relevant regulatory standards.

2.5. *Analysis of cost*

The economic performance of the insulation materials was determined using the price to purchase 1 m^2 of the material at a thickness of 50 mm, and the cost of space heating for 1 year calculated from the IES-VE modelling results. As each insulation is manufactured at different thicknesses, these prices are for comparison purposes only. The price of heating was calculated using the current market value where 1 kWh of energy costs 7.32 cents (oil fuel).

2.6. *Development of a tool to assess the overall performance*

A tool comprising a standardised scoring system was designed and used to evaluate the combined performance of the insulation with respect to energy, environmental impact and cost. The three performance areas were used as inputs in the scoring system (Fig. 3).

As aforementioned, ISO 40440 [25] does not provide guidance on the weighting of the different parameters within a LCA, hence there are many ways of conducting a single LCA whereby weightings are decided by whoever is carrying out the assessment which is subjective. Therefore, the weighting of the inputs in the scoring system was considered important, and an interactive tool was created where weightings could be easily changed by the user using Excel as the platform. An Excel tool was designed for data input. The results from the three performance areas were transferred into separate tabs as follows:

1. Energy tab containing U-Value and other properties and space heating energy results.
2. Environmental tab including the CO_2 produced to meet space heating requirements and results from each of the 7 LCA impact categories.
3. Economy tab comprising the cost of each insulation and the annual cost of heating.

In this paper, it was decided to give an equal weighting to each of the three performance areas (33.33 each for a total of 100). The results within each of these areas were also assigned equal weights. Therefore, the weighting in the scoring tool are as follows:

- Energy inputs = 33.33 (Σ U-value of wall (16.665) + annual energy consumption for space heating (16.665)).
- Environmental inputs = 33.33 (Σ 7 LCA parameters (16.665–2.38 each) + CO_2 emitted for annual space heating (16.665)). Fig. 4 shows the weightings of environmental inputs.
- Economic inputs – 33.33 (Σ annual space heating cost (16.665) + price per m^2 of insulation (16.665)).

Scores were obtained for each insulation with Excel formulas and a reference score (best performing insulation in the dataset). For example,

Table 1
Insulations modelled. NHL-Natural hydraulic lime. (*) experimental in Walker and Pavia [32,33].

Internal insulation materials	
Polyisocyanurate-PIR board: 1. Xtratherm'sCavityTherm [35] 2. Experimental values (*)	Thermoset plastic produced as a foam. Typically a cavity insulation, it was modelled as an internal insulation to compare the results with the experimental values.
Lime plaster (*)	•Floating coat c.12 mm: 3: 1 : 0.60 (sand:NHL3.5: water) •Skim coat 3 mm: 1: 1: 0.5 (sand:NHL2:water) •Gypsum skim coat 3 mm
Aerogel: 1. Spaceloft by Aspen [36] 2. Experimental values (*)	Dried silica gel of very high porosity.
Wood wool board - internal	Wood fibres bonded and compressed to give rigid boards. Heraklith woodwool board by Knauf was used as the reference material [37]
Timber fibre board (*)	Natural wood fibre insulation panels typically made from defibrated softwood.
Expanded cork board (ICB)	100% Cork, a natural material of high porosity. Data based on Amorim's ICB [38]
Hemp block	Hemp Block from Isohemp [39] made with lime and hemp.
Cork-lime render (*)	A render made with cork aggregate, hydraulic lime and cement mortar. 2*20 mm layers Cork/lime: water 2.15: 1 (by weight)
Hemp-lime render (*)	Lime-based binder, hemp shiv and water. 2*20 mm layers Hemp:NHL2:water 1: 2.9: 3.5 (by weight)
Cavity insulations	
Glass mineral wool	Felt material made from melted sand and recycled glass ISOVER CWS 32 is used [40]
Stone wool- cavity	Made from natural rock which is melted into a liquid and then spun into fibres. Data used is from Rockwool's Cavity Insulation [41]
Sheep wool	Treated and sold in flexible batts. Natuwool by Black Mountain is used [42]
Cellulose fibre	Recycled newspaper with flame retardants. Available in loose form or as batts. Data by the EU Cellulose Insulation Association [43]
Expanded cork board (ICB)	Amorim's ICB [38]- Same as the internal insulation
Hemp	Isohemp cavity insulation (same as the internal insulation)
Recycled cotton fabric	Epotex 60 manufactured by Isoltex [44]
External insulation	
Phenolic foam	Heating, hardening and curing of a wet foam mix between two outer facing layers. Kooltherm K5 is used as a product reference [45]
Stone wool-external	Knauf Insulation's rock mineral wool, similar to the stone wool for cavity but for external application
Wood wool board- external	Heraklith by Knauf was used as the reference material [37]
Expanded cork board (ICB)	[38]- Same as the internal and cavity insulation
Hemp	[39]-Same as the internal and cavity insulation

the insulation which achieves the lowest heating energy consumption is assigned a score of 16.665, and all the other materials are then compared to this reference score. With this scoring system, the lower the value the better the performance. Therefore, the results were inverted, in order to assign the highest scores to the best performers. All scores were calculated in this manner except for the U-value scores which use the U-value requirement for new buildings in Part L of the building regulations [48]. The scores in the three areas are summed and outputted in a total, as shown in Fig. 5 for PIR board insulation.

Table 2
Thermohygric properties of the insulations inputted in the software and used to calculate the final U-values. λ-Thermal Conductivity; (*) experimental values from Walker and Pavia [32,33] (**) Allison and Hall [46].

Name	λ (W/m K)	ρ (kg/ m^3)	C (J/ Kg.K)	Vapour resistivity (MNs/gm)
PIR Board	0.021	30	1400	100
PIR Board (*)	0.034	233	1421	379
Aerogel	0.015	150	1000	25
Aerogel (*)	0.016	509	1233	140
Wood wool board	0.080	500	2100	25
Timber Fibre Board (*)	0.050	231	1218	45
Glass mineral wool	0.032	48	1030	5
Rock/stone wool (cavity)	0.037	22	840	5
Rock mineral wool (external)	0.036	60	1000	5
Sheep wool	0.039	19	1700	10
Cellulose fibre	0.039	50	2150	10
Expanded Insulation Corkboard ICB	0.040	110	1530	100
Cork lime render (*)	0.065	806	866	43
Hemp - Isohemp	0.071	340	2300	14
Hemp lime render (*)	0.090	602	1068	46
Recycled cotton-Epotex	0.032	60	1340	5
Phenolic foam	0.020	35	1400	300
Lime Plaster (*)	0.800	1820	863	58
Brick	0.840	1700	800	0
Rammed Earth (**)	0.643	1900	868	71

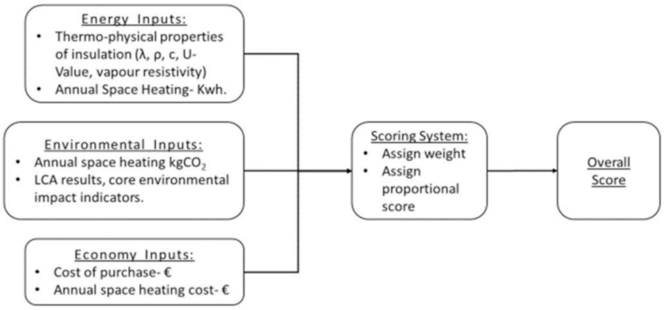
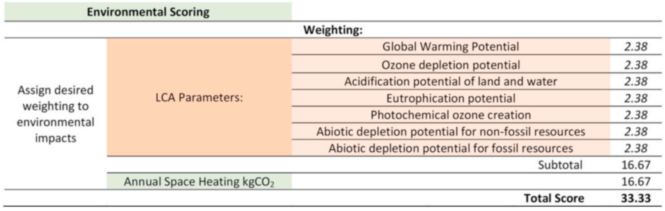
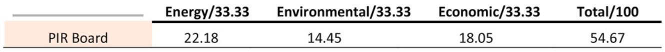


Fig. 3. Flow chart of inputs and outputs for the scoring system in the tool.



Environmental Scoring			
		Weighting:	
Assign desired weighting to environmental impacts	LCA Parameters:	Global Warming Potential	*2.38*
		Ozone depletion potential	*2.38*
		Acidification potential of land and water	*2.38*
		Eutrophication potential	*2.38*
		Photochemical ozone creation	*2.38*
		Abiotic depletion potential for non-fossil resources	*2.38*
		Abiotic depletion potential for fossil resources	*2.38*
		Subtotal	16.67
	Annual Space Heating $kgCO_2$		16.67
		Total Score	**33.33**

Fig. 4. Weighting inputs for the environmental scoring.



	Energy/33.33	Environmental/33.33	Economic/33.33	Total/100
PIR Board	22.18	14.45	18.05	54.67

Fig. 5. Overall score display for PIR board insulation on solid brick wall.

3. Results and discussion

3.1. Energy performance

The energy performance of the different buildings, insulations and wall configurations is presented below. It is ranked based on the U-values and the annual heating energy requirement of the constructions. Figs. 6 and 7 show the energy needed for heating the building versus the

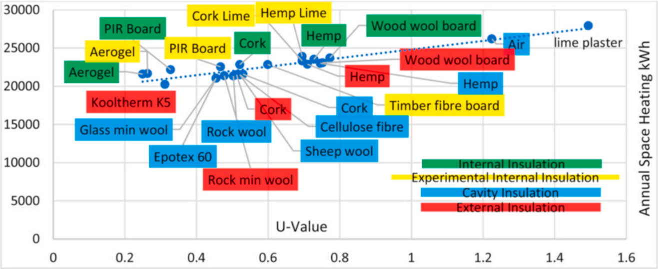


Fig. 6. U-value vs the annual heating demand (kWh) on the brick wall building.

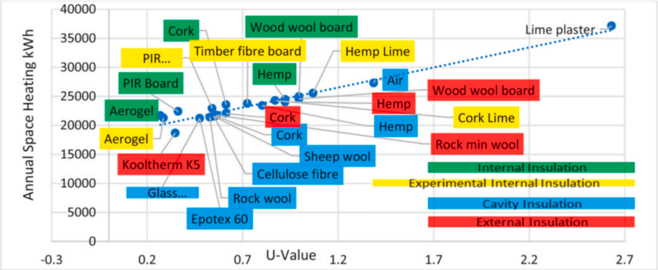


Fig. 7. U-value vs annual heating demand (kWh) for the rammed earth building.

U-value of the different insulations in the brick and earth walls. The annual energy consumption ranges from 18,000 to 27,000 kWh (excluding the lime plaster which features alone, with no insulation). This is slightly superior to typical values due to the set-up of the model, as heating takes place whenever the temperature falls below a set-point, even in the summer, whereas, in reality, heating would not be used. Also, the simplified occupancy profiles result in a higher occupancy rate and hence higher energy demand. However, these values are useful to compare the performance of the insulation.

The earth walls obtain lower U-values than the brick walls (Fig. 7). This result needs to be treated with caution because the thermal conductivity for RE inputted in the model (0.643 W/m.K) is in the low range, and values ranging from 0.83 to 1.65 W/m.K are common [49].

The earth walls tend to rank better on energy performance than the brick ones (Table 3). This is attributed to their lower diffusivity. The diffusivity of rammed earth walls is lower than that of other high mass materials such as brick and concrete [48], the material changes temperature slower, impeding heat flow, hence attenuating external temperature fluctuation and economizing energy. The U-values of the walls (Fig. 8) are above the maximum of 0.18 required for new buildings [48]. This is due to the constant insulation thickness used for consistency (50 mm) which sometimes doesn't meet the manufacturer's specifications.

The aerogel's high score (Table 3) is not realistic, the overall performance of the aerogel is overestimated by the model due to the input thickness (50 mm), much greater than in real applications (5 and 10 mm). The phenolic foam, used externally, ranks as the top insulation, with a lower energy demand than expected for its U -value (greater or comparable to PIR and aerogel). This is attributed to its high impermeability which is beneficial in its external position. The internal PIR board also ranks well. However, as highlighted by previous authors, it needs to be used with caution due to its high impermeability [32,33]. The energy performance of the recycled cotton fabric -Epotex 60 [44]- is consistently superior to other cavity insulation materials (glass mineral wool, stone/rock wool, sheep wool and cellulose fibre). Finally, it can also be seen from the results that, when experimental results are used in

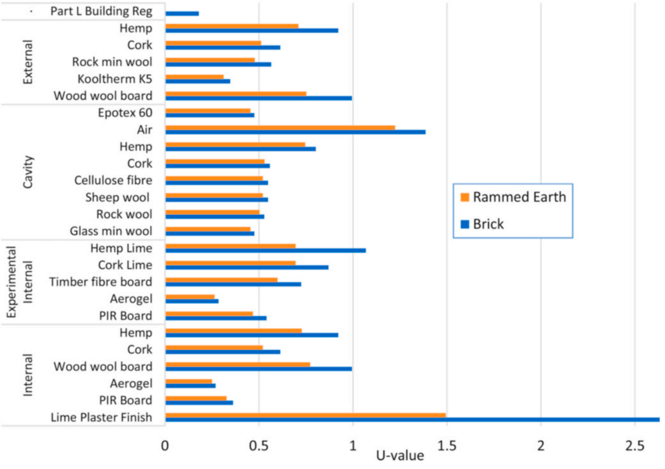


Fig. 8. Comparison of U-values for brick and rammed earth configurations.

Table 3
Ranking of insulation materials based on energy performance only. (*) experimental values.

Rank	Wall Configuration	Insulation	Score	Rank	Wall Configuration	Insulation	Score
1	Internal/RE	Aerogel	79.29	**25**	Internal/RE	Cork- ICB	58.16
2	(*) Internal/RE	Aerogel	77.23	**26**	(*)Internal/brick	PIR Board	57.38
3	Internal/brick	Aerogel	76.47	**27**	External/brick	Cork- ICB	56.99
4	External/brick	Phenolic foam	75.92	**28**	(*)Internal/RE	Timber fibre board	55.91
5	(*) Internal/brick	Aerogel	75.44	**29**	Internal/brick	Cork- ICB	54.32
6	External/RE	Phenolic foam	74.98	**30**	External/RE	Hemp	53.50
7	Internal/RE	PIR Board	69.57	**31**	(*)Internal/RE	Cork lime render	53.00
8	Internal/brick	PIR Board	66.53	**32**	Cavity/RE	Hemp	52.66
9	Cavity/RE	Recycled cotton	64.15	**33**	External/RE	Wood wool board	52.43
10	Cavity/RE	Glass min. wool	64.15	**34**	Internal/RE	Hemp	52.05
11	Cavity/brick	Recycled cotton	62.97	**35**	(*)Internal/RE	Hemp lime render	52.01
12	Cavity/brick	Glass min. wool	62.97	**36**	(*)Internal/brick	Timber fibre board	51.72
13	External/RE	Stone wool	62.54	**37**	Cavity/brick	Hemp	51.10
14	Cavity/RE	Stone/Rock wool	61.62	**38**	Internal/RE	Wood wool board	51.03
15	External/RE	Cork- ICB	60.98	**39**	(*)Internal/brick	Cork lime render	48.79
16	Cavity/RE	Sheep wool	60.70	**40**	External/brick	Hemp	48.60
17	Cavity/RE	Cellulose fibre	60.70	**41**	Internal/brick	Hemp	47.92
18	(*) Internal/RE	PIR Board	60.67	**42**	External/brick	Wood wool board	47.08
19	Cavity/brick	Rock wool	60.65	**43**	Internal/brick	Wood wool board	46.46
20	Cavity/RE	Cork-ICB	60.26	**44**	(*)Internal/brick	Hemp lime render	44.97
21	Cavity/brick	Cellulose fibre	59.71	**45**	Cavity/RE	Air	42.99
22	Cavity/brick	Sheep wool	59.71	**46**	Cavity/brick	Air	40.69
23	Cavity/brick	Cork-ICB	59.32	**47**	Internal/RE	Lime Plaster	39.46
24	External/brick	Rock mineral wool	58.89	**48**	Internal/brick	Lime Plaster	28.56

the model, the energy performance of the insulation is worse than when using existing product data in the market.

The permeable insulations (cork and hemp) tend to perform better with earth than with brick. In particular hemp, which performs best with RE in all configurations (external, internal, cavity). This can be attributed to their compatible hydric performance (both permeable to water vapour). Hemp and cork were tested in all three configurations (external, internal and cavity). With respect to the best location for the insulation, the ranking (Table 3) suggests that the best thermal performance is obtained when insulation is placed outside the wall, agreeing with Ozel [50]. The author states that the location of the insulation does not affect annual heat loads but affects the yearly averaged time lag and decrement factor, so that maximum temperature swings and peak loads occur when insulation is placed inside the wall while external insulation gives the smallest fluctuation.

The regression analysis of the data indicates that there is a strong relationship between the U-value and the annual energy consumption for space heating (coefficient of determination- $R^2 = 0.78$ for brick and 0.70 for rammed earth)- Figs. 9–10. Hence, the models allow for the prediction of space heating energy values from inputted U-values.

3.2. Environmental performance

The environmental performance score combines the impacts associated to the production of the insulation and the CO_2 emitted for heating the insulated building. Therefore, the insulation materials are judged on the basis of their embodied energy and the operational energy they require. The CO_2 produced as a result of the heating requirement for each type of wall/insulation configuration, determined with the IES-VE appears in Fig. 11. As aforementioned, the results are slightly high compared to real life values due to the simplifications of the IES-VE model regarding occupancy and constant temperature. However, the outcomes of the study are useful to establish comparisons. The insulated RE walls require less heating that the brick walls to maintain the internal temperature within comfort levels, hence resulting in less emissions. This agrees with the energy modelling results, where it was evidenced that the earth buildings rank better than the brick ones likely due to their lower diffusivity which attenuates external temperature fluctuation economizing heating energy.

The results for four of the LCA parameters appear in Fig. 12. As expected, all the plant-based insulations (hemp, cork, cellulose) are carbon negative, as plants absorb CO_2 in order to grow; and the carbon print of the recycled cotton insulation (Epotex) is very small. In contrast, the carbon prints of the petrochemical and the rock/slag insulations are considerably greater, above all the PIR board and the aerogel. As anticipated, the natural insulations perform the best in all the LCA parameters. An exception is sheep's wool, which has the highest ozone depletion potential. This is possibly due to the sheep's impact throughout its life. However, in practice, some of this adverse impact can be offset by their many other applications.

The environmental performance of the insulations appears in Table 4 (scores for energy and economic weightings changed to zero). Cellulose is the best performers for overall environmental impact. This score is not surprising, as it is made from recycled newspaper. Mineral/rock wool (also known as man-made mineral fibre or mineral cotton) is manufactured using furnaces to melt stone particles, so its good environmental performance is unexpected, and the reason unknown. Furthermore, it belongs to the so-called Man-Made Vitreous Fibres (MMVF) which were once classified as carcinogen and later declassified (on view of further test results), and associated to toxic emissions [51]. Air also performs well as it has no environmental impact and it is a poor thermal conductor. There is a data gap in the literature for the recycled cotton (ozone and acidification data) and for the sheep's wool (abiotic depletion potential for non-fossil resources). Therefore, weightings for these parameters were set to zero to obtain the environmental score.

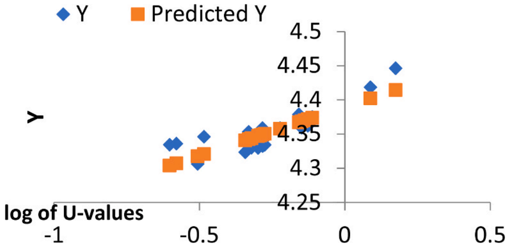


Fig. 9. Regression line for brick walls (R2 = 0.78, p-value = 1.02E-8¬).

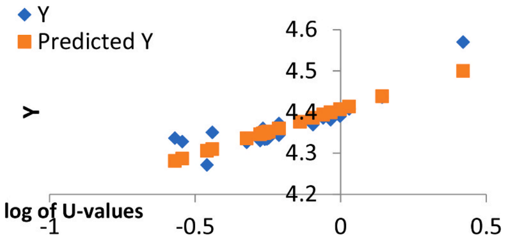


Fig. 10. Regression line fit for RE walls (R2 = 0.71, p-value = 2.85E07).

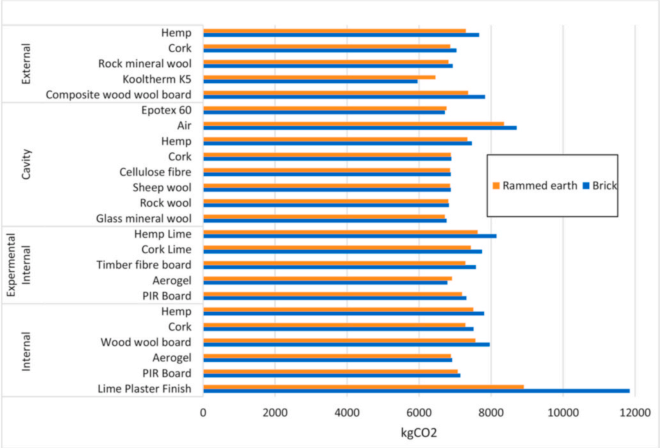


Fig. 11. CO2 produced as a result of the heating requirement of each type of wall/insulation configuration in the brick building compared with the RE building.

3.3. Economy performance

The economic performance of the insulation was assessed as the combined effect of the material cost (Fig. 13) and the annual cost of heating the insulated building (Fig. 14). The cost of space heating ranges from €1500 - €2000, which is slightly higher than real-life costs due to the IES-VE model simplifications as explained earlier. The combined results (Table 5), show that the best materials are cellulose, rock wool and recycled cotton (Epotex), which have lower manufacturing cost while also keeping operating costs for space heating lower than other insulations. Air also rates well as it provides insulation at no cost. It is unlikely that any construction project would choose materials based solely on economic performance, however, these scores give an insight into which materials cost less while also keeping competitive operating costs for space heating.

3.4. Overall performance based on the tool developed

The final scores give an insight into the overall performance of the insulations in the different walls and the different configurations (Table 6). Cellulose fibre obtained the highest score and performed

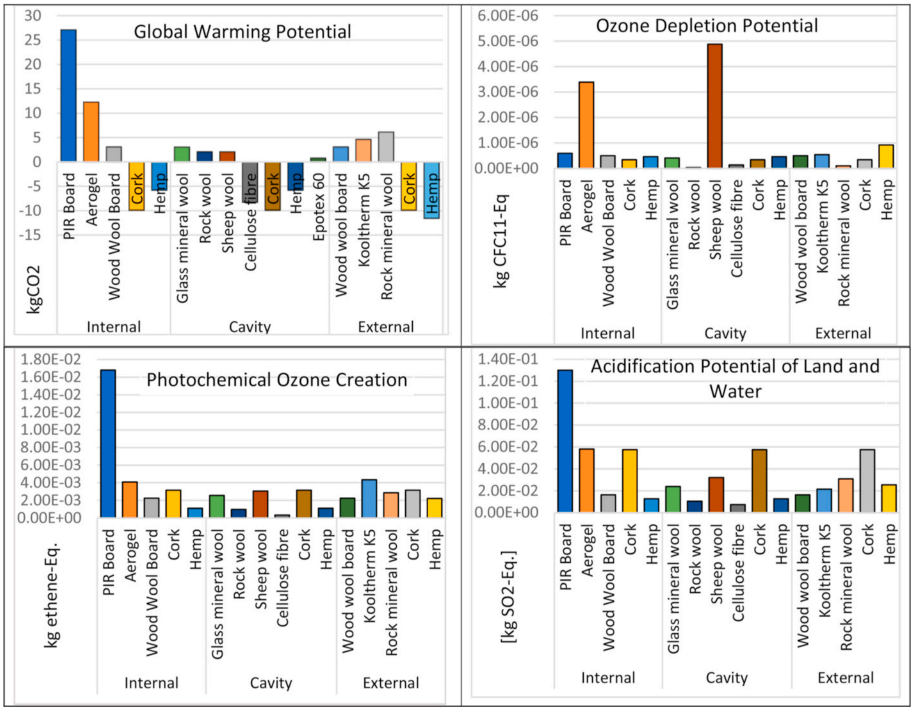


Fig. 12. Core environmental impact indicators EN 15804 [47] of the insulations used to evaluate their LCA and environmental impact.

Table 4
Ranking based on the environmental performance only.

Rank	Wall Configuration	Insulation	Score	Rank	Wall Configuration	Insulation	Score
1	Cavity/RE	Cellulose fibre	80.57	**19**	Cavity/brick	Cork	51.01
2	Cavity/brick	Cellulose fibre	80.43	**20**	External/brick	Hemp	50.90
3	Cavity/RE	Air	79.05	**21**	Cavity/brick	Hemp	50.78
4	Cavity/brick	Air	77.61	**22**	Internal/RE	Hemp	50.58
5	Cavity/RE	Rock wool	71.54	**23**	External/brick	Cork	50.13
6	Cavity/brick	Rock wool	71.43	**24**	Internal/brick	Hemp block	49.05
7	Cavity/brick	Recycled cotton	71.24	**25**	Internal/RE	Cork	48.70
8	Cavity/RE	Recycled cotton	70.92	**26**	External/RE	Wood wool board	48.11
9	External/brick	Phenolic foam	55.83	**27**	Cavity/RE	Sheep wool	47.98
10	Cavity/RE	Glass min. wool	55.33	**28**	Cavity/brick	Sheep wool	47.85
11	Cavity/brick	Glass min. wool	55.01	**29**	Internal/brick	Cork	47.47
12	External/RE	Rock min. wool	53.40	**30**	Internal/RE	Aerogel	47.22
13	External/RE	Hemp	52.89	**31**	Internal/RE	Wood wool board	47.02
14	External/brick	Rock min. wool	52.67	**32**	Internal/brick	Aerogel	47.01
15	External/RE	Phenolic foam	51.97	**33**	External/brick	Wood wool board	45.68
16	Cavity/RE	Hemp	51.48	**34**	Internal/brick	Wood wool board	45.05
17	External/RE	Cork	51.21	**35**	Internal/RE	PIR Board	43.71
18	Cavity/RE	Cork	51.10	**36**	Internal/brick	PIR Board	43.28

better with rammed earth than brick. Cellulose was the cheapest material and the best environmental performer. This can be attributed to its simple manufacturing process and the use of recycled newspaper. Cellulose fibre consists of approximately 75% recycled paper, with the remaining 25% made up of flame retardants and anti-fungal agents. The simple manufacturing process, involving the shredding of the paper and mixing with other constituents, results in cellulose fibre being inexpensive. Cellulose fibre insulation also has a high energy performance, which contributes to its overall high score. Air was the second highest performing insulation. Despite its lower energy performance, its overall score is increased since it has no environmental impact and no cost. As the space heating CO_2 was only measured over the course of 1 year, the long-term effects of using air as insulation for the lifetime of a building are overlooked. Over a longer period, air would result in higher CO_2 emissions and space heating cost, reducing its score significantly.

The phenolic foam was the fourth highest scoring material after mineral/rock wool. It was the only material to obtain a higher score using brick instead of rammed earth. All other insulations performed better on earth. This points to its compatibility alongside brick, which may be due to the its low permeability enhancing performance on external walls.

Cork and hemp were tested in all three configurations; internal, cavity and external. The overall scores show that they perform best when used externally with rammed earth which is likely due to their compatible, high, water vapour permeability. Aerogel achieved one of the highest energy scores, however its overall score is lowered by its high cost. Aerogel is the most expensive material but by choosing a thickness of 50 mm rather than the 5–10 mm thicknesses at which it is usually marketed its overall score is lowered.

4. Conclusion

This paper compares the energy performance, environmental impact and cost of 21 insulations.

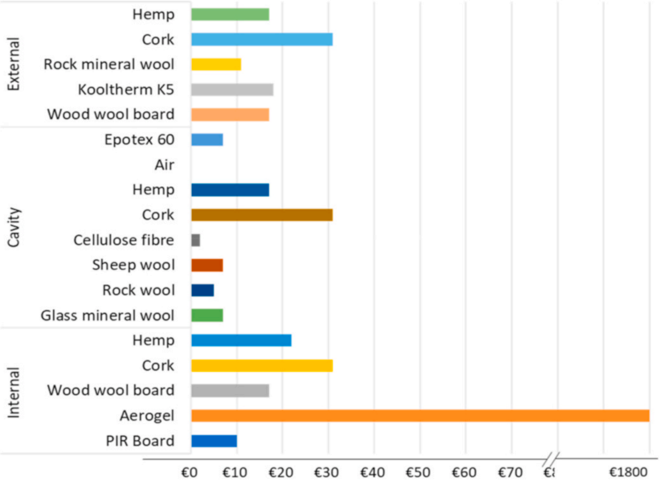


Fig. 13. Comparative cost of the insulations.

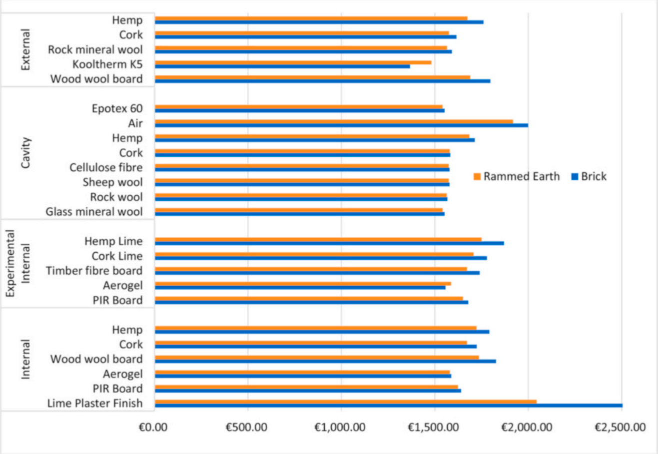


Fig. 14. Annual space heating costs: brick vs RE wall configurations.

The thermal performance was determined by modelling with software. The simulation considers the thermo-hygric properties of the insulations, heat transfer by conduction, convection and radiation, room heat gains, air exchanges and weather data. The insulations were modelled, on brick, rammed earth and cavity walls in different locations.

The environmental performance was determined using the Life Cycle Assessment method according to the standards, using core environmental impact indicators such as global warming potential, ozone depletion and acidification potential. The data for the indicators was collected from each insulation's Environmental Product Declaration.

The economic performance was resolved using the price to purchase the insulation and the cost of heating the building calculated from the modelling results.

A new scoring tool is created which allows inputted data, across the three areas of performance to be standardized and compared, providing a final score that represents the overall performance of the insulation. The input data and weightings in the tool can be easily altered to incorporate new materials and meet user requirements e.g. to give more importance to specific parameters.

In this paper, the equal weighting assigned to the three performance areas meant that for a material to score well, they must perform well in all three areas. For example, aerogel insulation obtained a high score for its energy performance, but its overall score fell due to its environmental impact and high cost. The results from the scoring tool show that cellulose fibre was the best performing insulation over the three performance areas.

The scores are assigned based on a reference material: the best performer in the dataset to which the highest score is assigned. This improves the score of this material compared to others. Hence, to further the accuracy of the scoring tool, it is recommended that an external reference value is used for each parameter. This is already in place for the scoring of U-values, where a reference value is taken from Part L of the Building Regulations.

The results highlight the importance of the hygrothermal properties of the insulation:

- The insulated earth buildings require less energy for heating and are responsible for lower carbon emissions than the insulated brick buildings. This is attributed to the lower diffusivity of earth walls attenuating external temperature fluctuation and economizing energy.
- The permeable insulations (cork and hemp) tend to perform better with earth than with brick. In particular hemp which performs best with rammed earth in all configurations (external, internal, cavity). This can be attributed to their compatible hygric performance.
- The results indicate that the best thermal performance is obtained when insulation is placed outside the wall.

Table 5
Ranking of insulations based on their economic performance only.

Rank	Wall Configuration	Insulation	Score	Rank	Wall Configuration	Insulation	Score
1	Cavity/RE	Cellulose fibre	93.43	**21**	Cavity/RE	Hemp	47.67
2	Cavity/brick	Cellulose fibre	93.30	**22**	External/RE	Cork	47.47
3	Cavity/RE	Air	85.64	**23**	Cavity/RE	Cork	47.36
4	Cavity/brick	Air	84.20	**24**	Cavity/brick	Cork	47.28
5	Cavity/RE	Rock wool	67.87	**25**	Cavity/brick	Hemp	46.97
6	Cavity/brick	Rock wool	67.76	**26**	Internal/RE	Wood wool board	46.74
7	Cavity/RE	Recycled cotton	60.79	**27**	External/brick	Cork	46.40
8	Cavity/RE	Glass min. wool	60.58	**28**	External/brick	Hemp	45.92
9	Cavity/RE	Sheep wool	60.48	**29**	External/brick	Wood wool board	45.39
10	Cavity/brick	Recycled cotton	60.47	**30**	Internal/RE	Hemp	45.29
11	Cavity/brick	Sheep wool	60.35	**31**	Internal/RE	Cork	44.97
12	Cavity/brick	Glass mineral wool	60.25	**32**	Internal/brick	Wood wool board	44.77
13	External/brick	Phenolic foam	57.03	**33**	Internal/brick	Hemp	43.77
14	External/RE	Rock min.wool	54.74	**34**	Internal/brick	Cork	43.73
15	Internal/RE	PIR Board	54.58	**35**	Internal/RE	Aerogel	43.33
16	Internal/brick	PIR Board	54.15	**36**	Internal/brick	Aerogel	43.12
17	External/brick	Rock min. wool	54.01	**33**	Internal/brick	Hemp	43.77
18	External/RE	Phenolic foam	53.17	**34**	Internal/brick	Cork	43.73
19	External/RE	Hemp	47.91	**35**	Internal/RE	Aerogel	43.33
20	External/RE	Wood wool board	47.82	**36**	Internal/brick	Aerogel	43.12

Table 6
Overall ranking of insulation materials in the different wall types and configurations.

Rank	Wall type	Insulation type	Scores			Total
			Energy	Environmental	Economic	
1	Cavity/RE	Cellulose fibre	20.23	26.85	31.14	78.22
2	Cavity/brick	Cellulose fibre	19.90	26.81	31.10	77.81
3	Cavity/RE	Air	14.32	28.54	28.54	71.40
4	Cavity/brick	Air	13.56	28.06	28.06	69.68
5	Cavity/RE	Rock wool	20.54	23.85	22.62	67.00
6	Cavity/brick	Rock wool	20.22	23.81	22.59	66.61
7	External/brick	Phenolic foam	25.30	18.61	19.01	62.92
8	External/RE	Phenolic foam	24.99	17.32	17.72	60.03
9	Cavity/RE	Glass min. wool	21.38	18.44	20.19	60.02
10	Cavity/brick	Glass min. wool	20.99	18.33	20.08	59.41
11	Cavity/RE	Recycled cotton	21.38	17.23	20.26	58.87
12	Cavity/brick	Recycled cotton	20.99	17.33	20.15	58.47
13	External/RE	Rock min.wool	20.84	17.80	18.25	56.89
14	Internal/RE	Aerogel	26.43	15.74	14.44	56.61
15	Cavity/RE	Sheep wool	20.23	15.78	20.16	56.16
16	Internal/RE	PIR Board	23.19	14.57	18.19	55.95
17	Cavity/brick	Sheep wool	19.90	15.73	20.11	55.75
18	Internal/brick	Aerogel	25.49	15.67	14.37	55.53
19	External/brick	Rock min. wool	19.63	17.55	18.00	55.18
20	Internal/brick	PIR Board	22.18	14.43	18.05	54.65
21	External/RE	Cork board	20.32	17.07	15.82	53.21
22	Cavity/RE	Cork board	20.08	17.03	15.79	52.90
23	Cavity/brick	Cork board	19.77	17.00	15.76	52.53
24	External/RE	Hemp	17.83	17.63	15.97	51.43
25	External/brick	Cork board	18.99	16.71	15.46	51.17
26	Internal/RE	Cork board	19.39	16.23	14.99	50.61
27	Cavity/RE	Hemp	17.55	17.16	15.89	50.60
28	Cavity/brick	Hemp	17.03	16.93	15.66	49.61
29	External/RE	Wood wool board	17.48	16.04	15.94	49.45
30	Internal/RE	Hemp	17.35	16.86	15.10	49.30
31	Internal/brick	Cork board	18.10	15.82	14.58	48.50
32	External/brick	Hemp	16.20	16.97	15.31	48.47
33	Internal/RE	Wood wool board	17.01	15.67	15.58	48.26
34	Internal/brick	Hemp	15.97	16.35	14.59	46.91
35	External/brick	Wood wool board	15.69	15.22	15.13	46.04
36	Internal/brick	Wood wool board	15.48	15.02	14.92	45.42

Author statement

Tiarnan Dickson Methodology, Software Writing- Original draft preparation. **Sara Pavia** Supervision Investigation. Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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