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Can Paper Waste Be Utilised as an Insulation Material in Response to the Current Crisis

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Abstract: Recently, the climate and landfill crises have raised concerns in the UK as the country is struggling to meet the sustainability goal it set to achieve. One of the major reasons is due to the inadequate recycling rate of waste paper. Therefore, as an alternative solution to the issue, the aim of our research was to exploit the potential of waste paper as an insulating material to see whether it can be feasible to improve the recycling rate of waste paper in the country. Waste paper has already been in the construction industry for a while, and the use of cellulose insulation is a standard in the Passivhaus construction approach. The study examines cellulose's performance as an insulation material and its potential to combat the climate crisis by creating four separate comparisons and calculations using Life-Cycle Assessment and Standard Assessment Procedures. The study will investigate the benefits and limitations of the material as well as a case study to justify the use of it. A pioneer project in the field is a retrofit and new-built building project—54–58 Akerman Road in London. It utilises cellulose fibre insulation as the main material for the new-built part. The study will use this project as a context to compare whether cellulose fibre insulation is the best solution for the project. Also, the study will compare cellulose insulation with other conventional insulation materials in a more general setting as well as with the traditional paper recycling approach, by providing an indication of the carbon footprint of the insulation, the energy resources involved and the amount of raw material. By conducting the study, we can know whether recycling waste paper into cellulose insulation is the best solution to the crisis we face. This research can guide the UK's recycling and use of waste paper, reduce paper waste and energy consumption and improve the sustainability of building insulation materials.

Keywords: waste paper; insulating material; climate crisis

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1. Context

1.1. Climate Crisis

Research shows that human activities are changing the climate in unprecedented and sometimes irreversible ways. Since 1970, the global surface temperature has risen faster than any other 50-year period in the past 2000 years [1].

Whether it is the recent extreme heat experienced by Greece and the western part of North America or the floods in Germany and China, it proves that the climate has become more and more extreme [1]. The climate crisis is not only caused by natural disasters but also by sea level rise, putting millions of people at risk of flooding.

The COP26 climate change summit held in Glasgow this year aims to reduce global emissions by half by 2030 and achieve net zero emissions by the middle of this century [2]. Scotland is committed to reducing emissions to net zero by 2045 in a "just and fair" manner.

This goal is undoubtedly difficult, so the Scottish government needs to work hard in all aspects. The report also pointed out that the plan to reduce emissions from heating buildings was "very far-fetched", and recent studies point out that energy efficiency measures are the most cost-effective ones, whereas measures like e.g., solar photovoltaics and wind energy, are far less cost-effective than insulation retrofitting for buildings [3]. That is why we focus on building insulation.

1.2. Landfill Crisis

The Scottish Government has imposed a landfill ban to help move Scotland towards a "circular economy", which minimises wastage and maximises resource use. It could also help cut climate pollution from rubbish rotting in landfill sites.

However, the reality is not like what is predicted. The Scottish Environmental Services Association (Sesa), which represents waste companies, predicts that local authorities will not be able to meet the 2021 deadline set by the Scottish Government for ending the disposal of biodegradable waste in landfill sites [4].

As a result, an estimated one million tonnes of "homeless" Scottish waste per year will "follow the line of least resistance" and be transported south to England where companies will have to pay a landfill tax approaching £100 per tonne [5].

The incident indicates that Scotland has not yet achieved a sustainable way to deal with recyclable waste, which gives us an opportunity to suggest an alternative to recycling waste. The largest proportion of recyclable waste is paper waste, and that is why we are conducting a study on the possibility of paper waste as a construction material. In response to the landfill crisis, recycled paper has become the best choice, and it also reduces carbon emissions when disposing of waste paper that should be landfilled. In response to the landfill crisis, recycled paper has become the best choice, and it also reduces carbon emissions when disposing of waste paper at the landfill.

2. Waste Paper as Insulation

2.1. Justification

Although paper has long been used in construction as a material, it can be used as a structural material. For example, it can be processed into paper tubes for use as building beams and columns, or it can be processed into cardboard as a building maintenance structure; it can also be used as a maintenance structure.

However, these uses rarely use recycled paper because of the strength requirements of these materials in construction. The actual use of recycled paper that can be commercialized is to use it as cellulose insulation.

In addition, compared to traditional recycling methods, it is more environmentally friendly to make recycled paper into cellulose. This is because the process of recycling paper and making new paper still consumes a lot of energy and chemicals and produces emissions. However, if recycled into cellulose insulation material, the paper will be quickly shredded and only a little chemical treatment is required [6].

2.2. Benefit

From the insulation material comparison in Table 1, we can compare the performance differences between different materials.

Compared with glass wool, cellulose has a better specific heat capacity and embodied energy while the thermal conductivity and thermal resistance of cellulose are not much different from that of glass wool (Table 1).

High Specific Heat Capacity is a feature of materials providing Thermal Mass or Thermal Buffering. A good insulator has a higher Specific Heat Capacity because it takes time to absorb more heat before it actually heats up to transfer the heat [10].

Embodied Energy is a key concept in balancing the global warming gases in producing the material that is conserved throughout the lifetime of the insulation. Embodied Carbon is usually considered as the overall amount of gas released from, usually, fossil fuels and used to produce energy expended between the extraction of raw material via the manufacturing process to the factory gates [10].

Table 1. Insulation Materials Comparison [7–9].

	Cellulose	Wood Fibre	Wool	Glass Wool	Hemp
Thermal Conductivity K Value W/mK	0.035 in lofts; 0.038–0.040 in walls	0.038	0.038	0.035	0.039–0.040
Thermal Resistance at 100 mm $K \cdot m^2/W$	2.632	2.5	2.63	2.85	2.5
Specific Heat Capacity $J/(kg \cdot K)$	2020	2100	1800	1030	1800–2300
Density kg/m^3	27–65	160	23	Circa 20	25–38
Thermal Diffusivity cm^2/h	17	3 to 4	33	52	31
Embodied Energy MJ/kg	0.45	n/a	6	26	10
Vapour Permeable	Yes	Yes	Yes	Yes	Yes

Compared with hemp, cellulose has a lower thermal conductivity and Thermal diffusivity (Table 1). Thermal conductivity measures the ease with which heat can travel through a material by conduction. The lower the figure, the better the performance. Thermal Diffusivity measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. Good insulators should have lower values [10]. Compared with wood fibre, cellulose density is lower, and the mass is smaller under the same volume.

In summary, the thermal insulation performance of cellulose is similar to that of other sustainable insulation materials, but its embodied energy is much lower than other types of insulation. This proves the importance of using cellulose insulation to reduce carbon emissions.

2.3. Limitations

Although cellulose insulation has many advantages, it still has limitations.

Cellulose insulation is likely to settle during the blow moulding process, resulting in the actual density not reaching the designed density. Settlement is mainly affected by two factors. One is vibration. Vibration is often present in the blow moulding process and may have some effect on the adhesion of cellulose insulation materials. Another influencing factor is the change in relative humidity, which may lead to a change in the moisture content of the cellulose insulation material, which in turn affects the density of the material [11].

But this shortcoming can be compensated for during the installation process. Due to the compressibility of cellulose materials, we can adopt some strategies to increase its density during the installation process, so as to effectively prevent the phenomenon of falling off. These strategies include the use of appropriate compaction tools and techniques to ensure that the cellulosic material is uniformly and tightly installed, thereby increasing its density and enhancing its adhesion. In addition, wet spraying can also be used as an effective installation method. It has been shown that the dry density of cellulose materials increases linearly with the moisture content at the time of installation. Therefore, the correct installation with wet spraying can ensure that the density of the cellulose material meets the design requirements without the problem of falling off. Wet spraying can not only increase the density of cellulose materials but also improve the adhesion of materials and further increase their adiabatic properties.

Cellulose fibres are naturally hydroscopic, and an increase in the humidity of insulating materials will inevitably lead to an increase in thermal conductivity. Research has found that for a 10% increase in moisture, the thermal conductivity increases by 15% (Figure 1) [11].

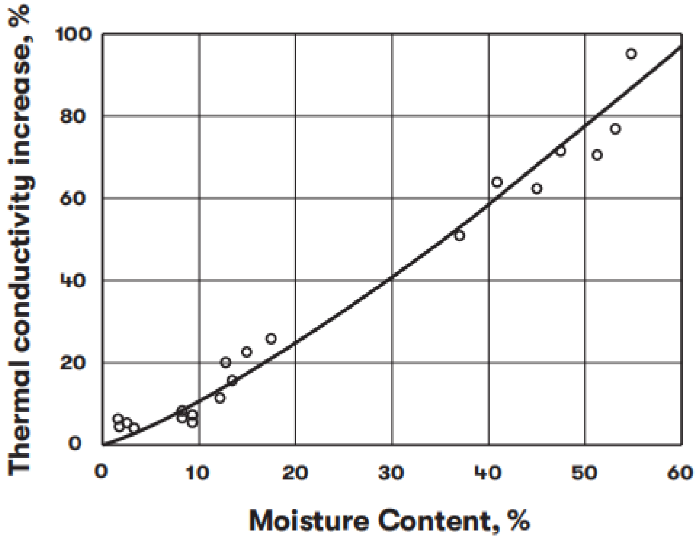

Figure 1. Calculated minimal density for settling the prevention of loose-fill cellulose in a wall under static humidity conditions [11].

In the process of installation, cellulose will have small fibres floating in the air. These fibres contain chemical substances, which can cause damage to the lungs when people inhale them. Studies have shown that inhalation of cellulose fibres can cause lung inflammation and sarcoma; however, compared to similar insulating materials such as asbestos, the level of damage is less (Figure 2) [1].

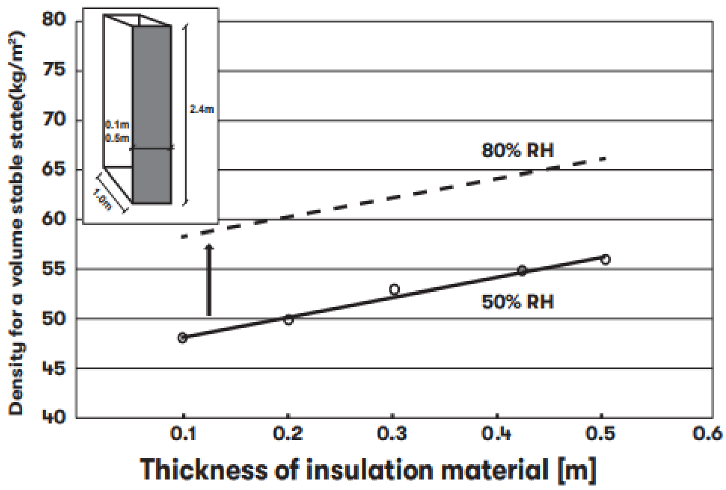

Figure 2. Increase in thermal conductivity with moisture content of cellulose fibre insulation [1].

Cellulose itself can easily become a container for fungi; therefore, even though normally installed cellulose insulation will not have fungus growth, once a pipe leaks and the cellulose becomes too humid, it will cause fungi to appear [12]. Also, the spores of these fungi usually carry toxicity and can cause harm to people who breathe them in.

3. Methodology

The research will focus on two aspects. One is the performance of cellulose insulation, and the other one is the sustainability and environmental impact of it. To conduct the research, we will do the following (Figure 3).

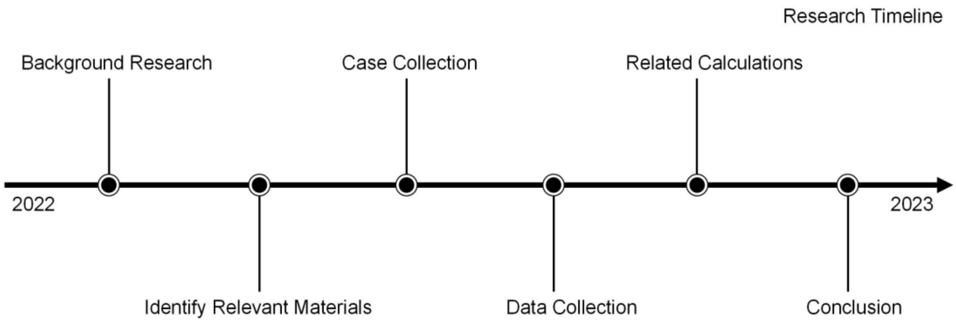

Figure 3. Research timeline.

3.1. Data Collection

We will collect data on our chosen thermal insulation materials, including the U-values and the LCA for each product. These data come from secondary studies conducted by the EPD [13]. Three of the materials used in the study were from the following:

Thermofoc—Cellulose Insulation,

SUPAFIL—Glass Mineral Wool Insulation,

STEICOfex—Wood Fibre Insulation.

In addition, we also collected Data on the production and disposal stages from the EPD.

3.2. Whole Life-Cycle Carbon Assessment

A Whole Life-Cycle Carbon Assessment (LCA) can predict the carbon footprint of a material or building from the extraction or construction to the disposal or demolition stage, covering the entire lifetime (Figure 4) [14]. It offers an accurate representation of a building's carbon footprint.

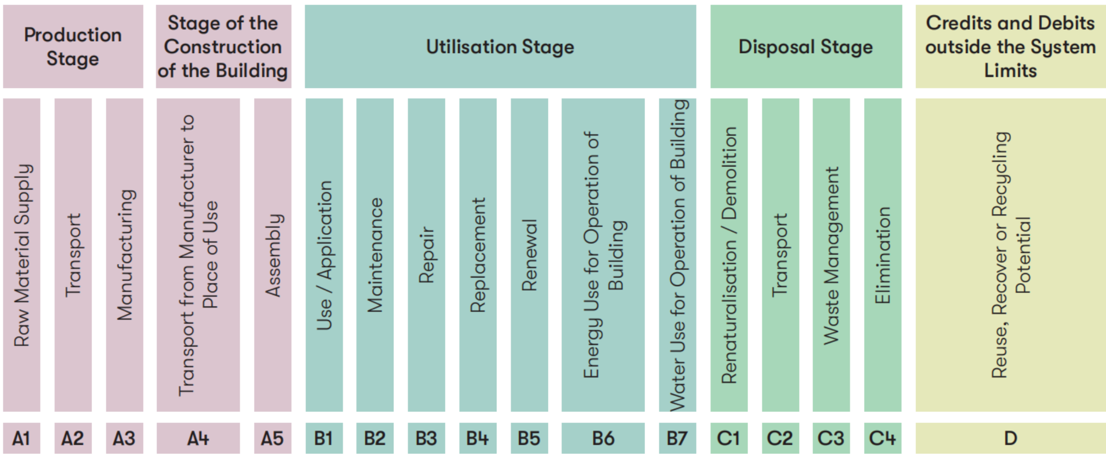

Figure 4. Whole Life-Cycle Carbon Assessments guidance.

As we can see from the diagram below, an LCA covers the production, construction, utilization and disposal stages of a material and the potential stages of recycling and reuse. A Life-Cycle Assessment of these options will be studied in the context of the case study house (54–58 Akerman Road). The research will make use of the LCA to compare the sustainability of different insulation materials with cellulose insulation, which mainly uses paper waste, to see whether the use of paper waste as insulation is a feasible way to reduce the carbon footprint. A Life-Cycle Assessment of these options in the context of the case study house (54–58 Akerman Road) will be conducted as follows:

Data of production and disposal stages from the EPD.

Utilisation stage considering the performance drop.

Circularity considering reusability and recyclability.

Comparison of an LCA of cellulose insulation with the environmental performance of paper recycling.

3.3. Standard Assessment Procedure

From Figure 5, the Standard Assessment Procedure (SAP) [2] is the methodology used by the government to assess and compare the energy and environmental performance of dwellings. Its goal is to offer accurate and trustworthy assessments of residential energy performance in order to support energy and environmental policy efforts.

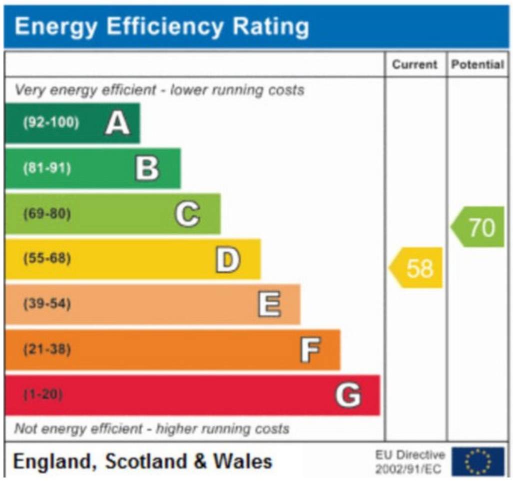

Figure 5. Standard Assessment Procedure.

A score in the SAP represents how well a dwelling performs in saving energy and reducing its carbon footprint. In general, a score above 50 is an acceptable score for a retrofit building and above 70 is acceptable for a new building.

The calculation of an SAP score comprises the combined U-value of the building wall and roof, the dimension of the dwelling, fabric and ventilation heat loss through openings, internal and passive solar gains, the heating demand and other factors.

A key factor in the calculation is the U-value, which we mainly use to compare the efficiency of different insulation materials. The calculation of the combined U-value of the wall and roof is listed for reference. An SAP rating of these options is considered in the context of the case study house (54–59 Akerman Road). The same amount of insulation is used for all options. Moreover, a U-value comparison of these options is completed in a general construction setting and with a general wall structure.

3.4. Calculation Formula

The Calculation of the U-value.

The U-value is the heat transmittance per unit area of fabric (W/m^{2}K).

U-value = 1/(Rsi + Rso + Ra + R1 + R2 + . . .) and Rsi= surface resistance on internal face.

Rso = surface resistance on external face and Ra = surface resistance on cavity.

Combined U-value of a wall/roof =

(U-frame × W-frame/W-total) + (U-cavity × W-cavity/W-total).

Among them,

l = material thickness in metres (m).

The resistance of a material is the R value (m^{2}K/W).

R = l*r.

The resistivity of a material is the R value (mK/W).

r = 1/k.

The conductivity of a material is the K value (W/mK). The lower the K value, the better it insulates.

The Calculation of Heat Loss.

Fabric Heat loss = Σ (A $\times$ U) $\times$ ΔT.

A = area of the element U = U-value of the element.

ΔT = the temperature difference.

The Calculation of Fabric Heat Loss Ventilation is as follows: Heat Loss = 0.33 $\times$ n $\times$ V $\times$ ΔT 0.33 = applied constant.

n = number of air changes per hour V = volume of the building.

ΔT = the temperature difference.

Heat Loss = Fabric Heat Loss + Ventilation Heat Loss.

3.5. Assumptions and Limitations

In this study, the utilisation stage of the insulation material rarely emits any carbon, so the calculation of the LCA will not include the data from this stage. Due to the lack of data for some materials in the potential recycling stage, the calculation will not include the data from this stage as well.

Furthermore, in the process of calculating heat loss, we assume the difference in temperature is 21 degrees.

4. Case Study

4.1. Basic Situation

The architecture in Figure 6 designed by 15:40 Collective, 54–58 Akerman Road, in the London Borough of Lambeth, SW9, is a housing project representative of the UK.

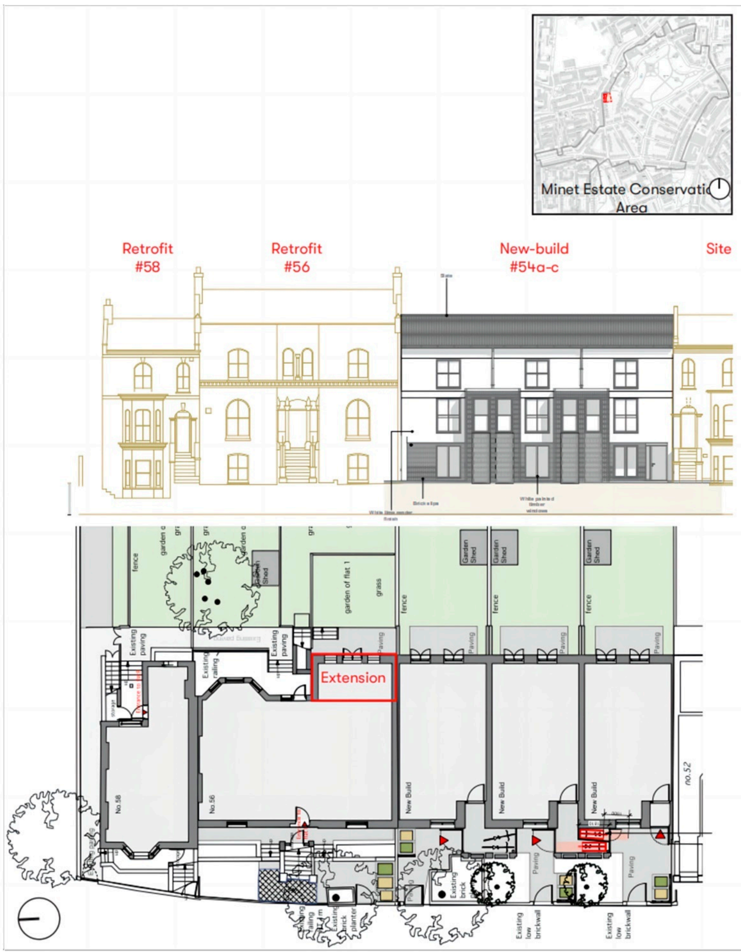

Figure 6. West Elevation and Ground Floor Plan.

The project is a combination of retrofits of historical housing and newly built terrace houses, both of which are common in British cities. Also representative of the future development of housing in the UK is the Council's drive to adopt the Passive House and Lifetime Homes standards [15].

Since the project is located within a conservation area (Minet Estate Conservation Area), also common in the UK, visual criteria on the façades were imposed, limiting the choice of insulation materials [15].

Hence, a range of insulation materials have been applied in different parts of the houses and apartments, including the cellulose insulation discussed in this report as well as wood fibre, mineral wool and PIR insulation [15].

This case study will be the basis for our further analysis of the performance of various insulation materials.

4.2. Insulation Strategies

According to Figure 7, the newly built terrace houses adopted a timber frame construction system with a 360 mm cellulose insulation infill and another external layer of 40 mm wood fibre insulation board. The same system is applied to both external walls and the roof, achieving an overall U-value of 0.112 W/m^{2}K and 0.108 W/m^{2}K, respectively [15].

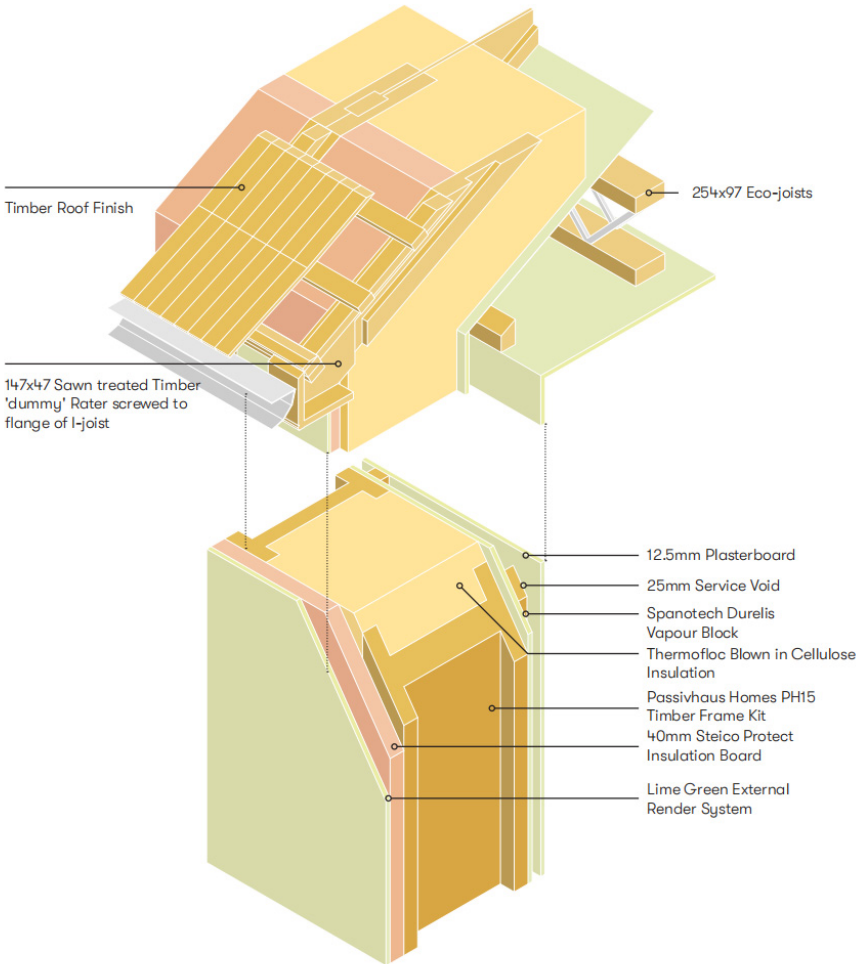

Figure 7. Roof and Wall Insulation Structure.

Existing buildings are constructed of solid masonry, which usually does not provide good insulation. Therefore, a new wood fibre insulation material with a thickness of 92.5 mm was added to the interior of the wall to improve the insulation effect. This treatment reduces the rate at which heat is transferred through the walls, thereby reducing energy consumption and improving indoor thermal comfort. The overall U-value of the wall is 0.36 W/m^{2}K, and a lower U-value indicates better insulation performance. Similarly, between the new wood rafters, 150 mm of wood fibre insulation has been added to the roof. This layer of insulation material can reduce heat loss and improve the insulation capacity of the roof. A total of 60 mm of wood fibre insulation was added below the wood fibre insulation to further reduce heat loss. This combination resulted in an overall roof U-value of 0.13 W/m^{2}K, showing high thermal insulation performance. In addition, insulating materials such as mineral wool, cellulose and polyurethane may have been used in the extension and cold roof sections. These insulation materials have a low heat transfer coefficient, enabling effective insulation and improving the energy efficiency of buildings. All in all, the use of these insulation materials is designed to improve the thermal insulation performance of the existing building, reduce energy consumption and increase indoor comfort [15].

5. Comparison

5.1. LCA of Cellulose vs. Other Insulation Materials

As the first step of the Life-Cycle Assessment of the insulation materials within the context of 54–58 Akerman Road, the total area of places where thermal insulation will be applied is calculated. According to Figures 8 and 9, we obtain the following calculations.

Total Ground Floor Area
= 334.8 m^2
Total Retrofit Slanted Roof Area
= 12.14 + 22.14 + 28.62 + 48.23 + 40.04 + 13.75
= 164.9 m^2
Total Retrofit Flat Roof Area
= 2.96 + 3.12
= 6.1 m^2
Total New-build Slanted Roof Area
= 60.97 + 110.96 + 42.33
= 214.3 m^2
LG/F Retrofit External Wall Total Area
= 46.3 m × 2.95 m = 136.6 m^2
LG/F Retrofit New Wall Total Area
= 7.2 m × 2.95 m = 21.2 m^2
G/F New-build External Wall Total Area
= 38.5 m × 2.7 m = 104.0 m^2
G/F New-build Party Wall Total Area
= 34.0 m × 2.7 m = 91.8 m^2
G/F Retrofit External Wall Total Area
= 47.5 m × 3.8 m = 180.5 m^2
G/F Retrofit New Wall Total Area
= 7.2 m × 3.8 m = 27.4 m^2
1/F New-build External Wall Total Area
= 33.6 m × 2.7 m = 90.7 m^2
1/F New-build Party Wall Total Area
= 40.4 m × 2.7 m = 109.1 m^2
1/F Retrofit External Wall Total Area
= 52.6 m × 3.9 m = 205.1 m^2
2/F New-build External Wall Total Area
= 35.6 m × 2.5 m = 89.0 m^2
2/F New-build Party Wall Total Area
= 29.4 m × 2.5 m = 73.5 m^2

Total New-build Party Wall Area
= 91.8 + 109.1 + 73.5
= 274.4 m^2
Total Retrofit External Wall Area
= 136.6 + 180.5 + 205.1
= 522.2 m^2
Total Retrofit Extension New Wall Area
= 21.2 + 27.4
= 48.6 m^2
Total New-build External Wall Area
= 104.0 + 90.7 + 89.0
= 283.7 m^2

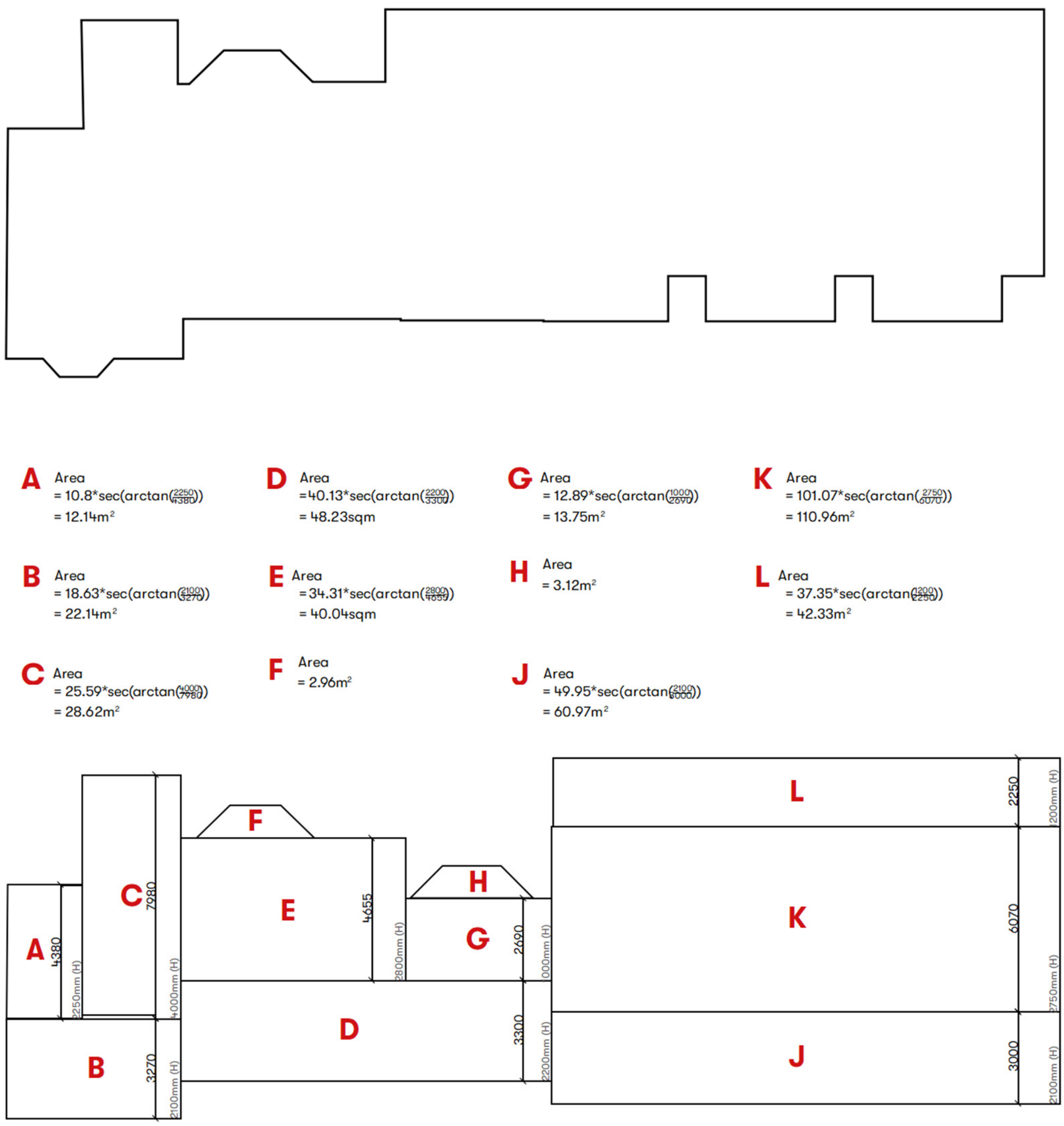

Figure 8. Ground Floor Area Diagram.

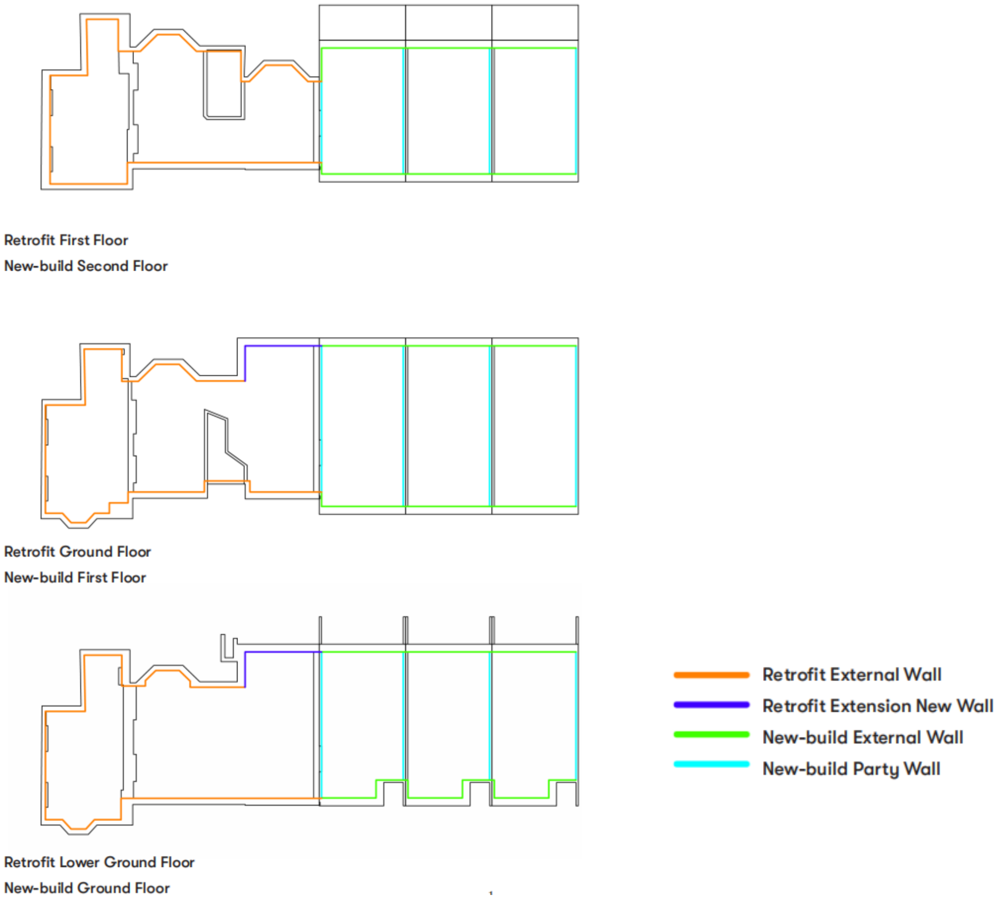

Figure 9. Wall Area Diagram.

5.2. Overall U-Values and Insulation Volume

Based on the calculated areas, the volume of thermal insulation is calculated with the assumption of an overall U-value identical to the existing construction. Please refer to Appendix A for the details of the calculations deriving the wall thicknesses for the U-values.

Tables 2–9 [16–19] show the differences in wall thickness is also depicted. Due to the thermal conductivity values, traditional mineral wool insulation generally leads to a thinner wall, while straw insulation always implies a thicker wall.

Table 2. New-build External Wall/283.7 m^2.

Insulation Material	Thermal Conductivity/W/mK	Wall Thickness/mm	% Difference in Wall Thickness	Insulation Thickness/mm	Difference in Insulation Thickness/mm	Overall U-Value/W/m^{2}K	Insulation Volume/m^3
Existing (Cellulose)	N/A	465	0	360	0	0.110	102.132
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.033	480	+3.23%	375	+15		106.388
Thermofloc Blown-in Cellulose Insulation	0.038	465	0	360	0		102.132
STEICOzell Air-injected Wood Fibre Insulation	0.038	465	0	360	0		102.132
Straw Insulation	0.052	567	+21.9%	462	+102		131.069

Table 3. New-build Party Wall/274.4 m^2.

Insulation Material	Thermal Conductivity/W/mK	Wall Thickness/mm	% Difference in Wall Thickness	Insulation Thickness/mm	Difference in Insulation Thickness/mm	Overall U-Value/W/m^2K	Insulation Volume/m^3
Existing (Mineral wool)	N/A	390	0	254	0	0.137	69.698
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.033	410	+5.13%	274	+20		75.186
Thermofloc Blown-in Cellulose Insulation	0.038	402	+3.08%	266	+12		72.990
STEICOzell Air-injected Wood Fibre Insulation	0.038	402	+3.08%	266	+12		72.990
Straw Insulation	0.052	461	+18.21%	325	+71		89.180

Table 4. Retrofit External Wall/522.2 m^2.

Insulation Material	Thermal Conductivity/W/mK	Wall Thickness/mm	% Difference in Wall Thickness	Insulation Thickness/mm	Difference in Insulation Thickness/mm	Overall U-Value/W/m^2K	Insulation Volume/m^3
Existing (Wood fibre board)	N/A	350	0	93	0	0.331	48.565
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.033	433	+23.71%	150	+57		78.330
Thermofloc Blown-in Cellulose Insulation	0.038	429	+22.57%	146	+53		76.241
STEICOzell Air-injected Wood Fibre Insulation	0.038	429	+22.57%	146	+53		76.241
Straw Insulation	0.052	458	+30.86%	175	+82		91.385

Table 5. Retrofit Extension New Wall/48.6 m^2.

Insulation Material	Thermal Conductivity/W/mK	Wall Thickness/mm	% Difference in Wall Thickness	Insulation Thickness/mm	Difference in Insulation Thickness/mm	Overall U-Value/W/m^2K	Insulation Volume/m^3
Existing (Mineral wool)	N/A	404	0	204	0	0.160	9.914
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.033	416	+2.97%	216	+12		10.498
Thermofloc Blown-in Cellulose Insulation	0.038	411	+1.73%	211	+7		10.255
STEICOzell Air-injected Wood Fibre Insulation	0.038	411	+1.73%	211	+7		10.255
Straw Insulation	0.052	450	+11.39%	250	+46		12.150

Table 6. New-build Roof/214.3 m^2.

Insulation Material	Thermal Conductivity/W/mK	Wall Thickness/mm	% Difference in Wall Thickness	Insulation Thickness/mm	Difference in Insulation Thickness/mm	Overall U-Value/W/m^2K	Insulation Volume/m^3
Existing (Cellulose)	N/A	534	0	360	0	0.084	77.148
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.033	551	+3.18%	377	+17		80.791
Thermofloc Blown-in Cellulose Insulation	0.038	534	0	360	0		77.148
STEICOzell Air-injected Wood Fibre Insulation	0.038	534	0	360	0		77.148
Straw Insulation	0.052	649	+21.54%	475	+115		101.793

Table 7. Retrofit Slanted Roof/164.9 m^2.

Insulation Material	Thermal Conductivity/W/mK	Wall Thickness/mm	% Difference in Wall Thickness	Insulation Thickness/mm	Difference in Insulation Thickness/mm	Overall U-Value/W/m^{2}K	Insulation Volume/m^3
Existing (Wood fibre board)	N/A	308	0	150	0	0.128	24.735
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.033	290	−5.84%	132	−18		21.767
Thermofloc Blown-in Cellulose Insulation	0.038	308	0	150	0		24.735
STEICOzell Air-injected Wood Fibre Insulation	0.038	308	0	150	0		24.735
Straw Insulation	0.052	356	+15.58%	198	+48		32.650

Table 8. Retrofit New Cold Roof/6.1 m^2.

Insulation Material	Thermal Conductivity/W/mK	Wall Thickness/mm	% Difference in Wall Thickness	Insulation Thickness/mm	Difference in Insulation Thickness/mm	Overall U-Value/W/m^{2}K	Insulation Volume/m^3
Existing (Cellulose)	N/A	281	0	250	0	0.181	1.525
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.033	290	+3.20%	259	+9		1.580
Thermofloc Blown-in Cellulose Insulation	0.038	281	0	250	0		1.525
STEICOzell Air-injected Wood Fibre Insulation	0.038	281	0	250	0		1.525
Straw Insulation	0.052	347	+23.49%	316	+66		1.928

Table 9. All wall types.

Insulation Material	Density/kg/m^3	Total Insulation Volume/m^3	Total Mass/kg
Existing (Cellulose)	N/A	333.72	N/A
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	30	378.66	
Thermofloc Blown-in Cellulose Insulation		365.03	
STEICOzell Air-injected Wood Fibre Insulation		365.03	
Straw Insulation		460.16	

Due to the necessity of an enclosed cavity for the studied loose-fill insulation materials, all four materials lead to a significant increase (>20%) in wall thickness in the retrofit external solid masonry wall.

5.3. Comparison of Environmental Performance

The global warming potential, primary energy consumption and waste production of the four loose-fill insulation materials are obtained from their corresponding Environmental Product Declarations and weighted by their respective masses required in Akerman Road as calculated in the previous section.

Since the U-value is controlled, it can be assumed that the performances are equal across all four materials, assuming that the effect of settlement is negligible.

In terms of waste generation, it is mainly the insulation material itself during the disposal stage, while in other stages it is more about other waste involved in production and installation. Hence, the number is comparable to the total mass of insulation material, and a "percentage of mass" is calculated. Finally, we will obtain the data integration from

Figure 10 to Figure 11 and from Table 10 to Table 11. (For the Detailed Relevant Data, see Appendix B).

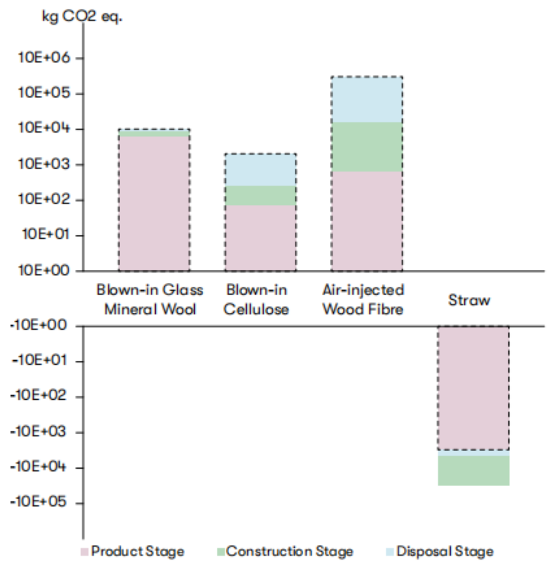

Figure 10. Global Warming Potential.

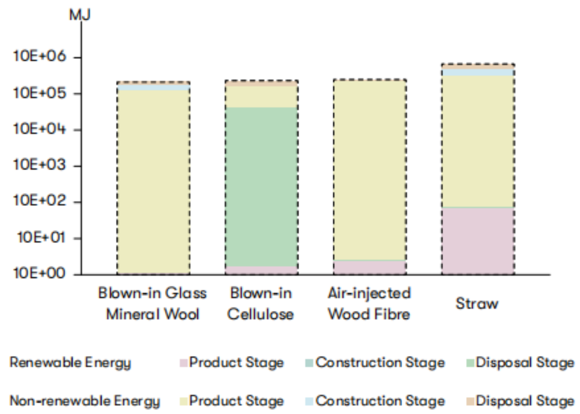

Figure 11. Primary Energy Consumption.

Table 10. Global Warming Potential.

Insulation Material	Product Stage/kg CO_2 eq.	Construction Stage/kg CO_2 eq.	Utilisation Stage/kg CO_2 eq.	Disposal Stage/kg CO_2 eq.	Total/kg CO_2 eq.
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	9.67×10^3	3.64×10^2	EQ	1.58×10^2	1.02×10^4
Thermofloc Blown-in Cellulose Insulation	1.17×10^3	3.21×10^2	EQ	5.68×10^2	2.06×10^3
STEICOzell Air-injected Wood Fibre Insulation	1.58×10^5	7.59×10^4	EQ	7.16×10^4	3.06×10^5
Straw Insulation	-3.76×10^4	6.86×10^3	EQ	1.44×10^3	-2.93×10^4

Table 11. Renewable Primary Energy Consumption.

Insulation Material	Renewable Energy				Non-Renewable Energy				Total/MJ
	Product Stage/MJ	Construction Stage/MJ	Utilisation Stage/MJ	Disposal Stage/MJ	Product Stage/MJ	Construction Stage/MJ	Utilisation Stage/MJ	Disposal Stage/MJ	
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	2.59×10^3	7.75×10^1	EQ	6.27×10^1	2.01×10^5	4.80×10^3	EQ	3.13×10^3	2.11×10^5
Thermofloc Blown-in Cellulose Insulation	9.48×10^3	5.84	EQ	1.90×10^5	2.37×10^4	4.38×10^1	EQ	7.69×10^3	2.31×10^5
STEICOzell Air-injected Wood Fibre Insulation	1.86×10^4	5.83×10^1	EQ	3.70×10^1	2.26×10^5	2.87×10^2	EQ	6.60×10^2	2.46×10^5
Straw Insulation	2.40×10^5	-2.61×10^4	EQ	3.84×10^2	4.17×10^5	1.42×10^4	EQ	1.98×10^4	6.66×10^5

From Figures 12–14 and Tables 12–14, the amounts of non-hazardous waste (and thus the total amount of waste) differ considerably. Due to low recyclability, traditional glass mineral wool insulation has a 100% rate of waste generation in the disposal stage. The remaining three choices, including cellulose insulation, perform considerably better in terms of waste creation.

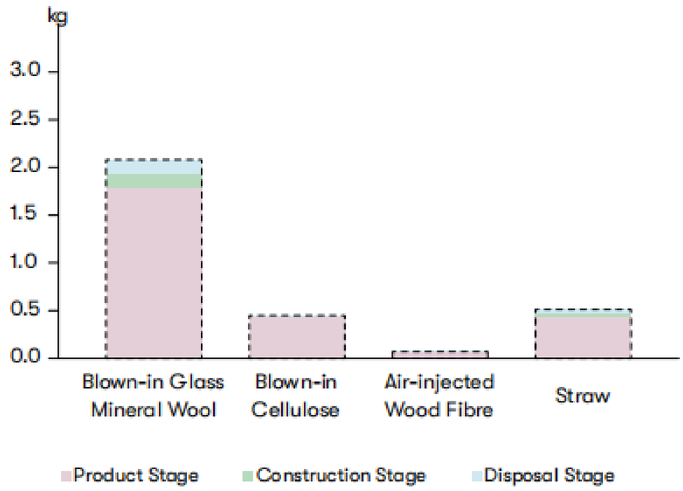

Figure 12. Hazardous Waste.

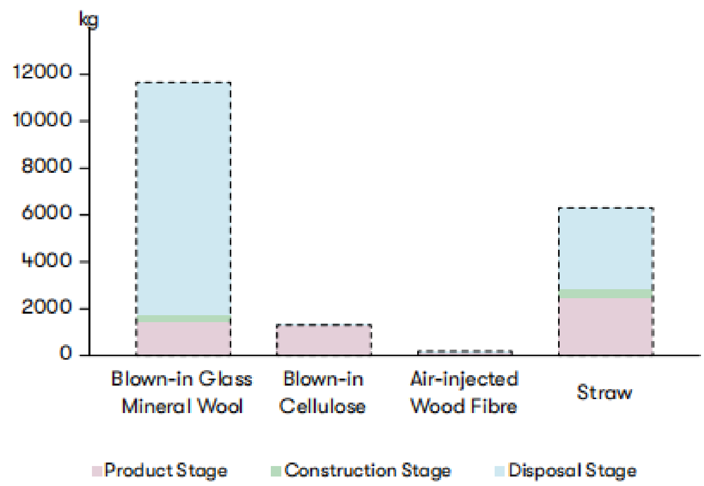

Figure 13. Non-hazardous Waste.

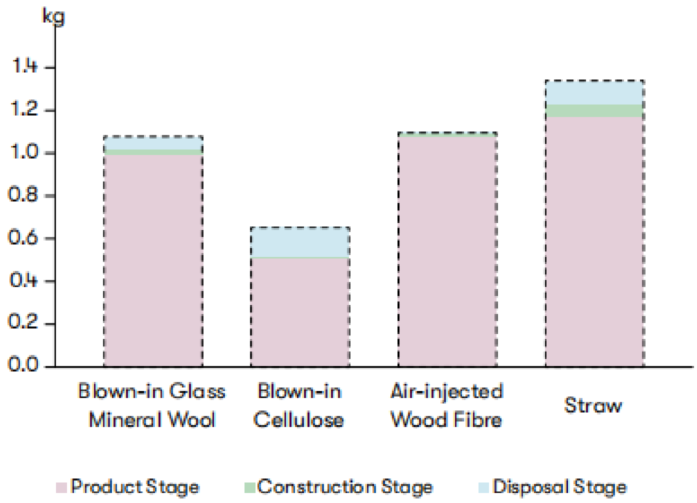

Figure 14. Radioactive Waste.

Table 12. Hazardous Waste.

Insulation Material	Product Stage/kg	Construction Stage/kg	Utilisation Stage/kg	Disposal Stage/kg	Total/kg	Percentage of Mass
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	1.79	1.61×10^{-1}	EQ	1.33×10^{-1}	2.08	0.02%
Thermofloc Blown-in Cellulose Insulation	4.47×10^{-1}	1.85×10^{-6}	EQ	1.23×10^{-3}	4.48×10^{-1}	0.00%
STEICOzell Air-injected Wood Fibre Insulation	6.95×10^{-2}	1.10×10^{-6}	EQ	3.07×10^{-5}	6.95×10^{-2}	0.00%
Straw Insulation	4.39×10^{-1}	2.46×10^{-2}	EQ	4.88×10^{-2}	5.13×10^{-1}	0.00%

Table 13. Non-hazardous Waste.

Insulation Material	Product Stage/kg	Construction Stage/kg	Utilisation Stage/kg	Disposal Stage/kg	Total/kg	Percentage of Mass
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	1.42×10^{3}	2.78×10^{2}	EQ	9.99×10^{3}	1.17×10^{4}	117.72%
Thermofloc Blown-in Cellulose Insulation	1.30×10^{3}	3.04×10^{-1}	EQ	1.58×10^{1}	1.31×10^{3}	8.98%
STEICOzell Air-injected Wood Fibre Insulation	1.26×10^{2}	5.39×10^{1}	EQ	1.01×10^{-1}	1.80×10^{2}	1.10%
Straw Insulation	2.50×10^{3}	3.42×10^{2}	EQ	3.47×10^{3}	6.32×10^{3}	13.73%

Table 14. Radioactive Waste.

Insulation Material	Product Stage/kg	Construction Stage/kg	Utilisation Stage/kg	Disposal Stage/kg	Total/kg	Percentage of Mass
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	9.93×10^{-1}	2.58×10^{-2}	EQ	5.79×10^{-2}	1.08	0.01%
Thermofloc Blown-in Cellulose Insulation	5.10×10^{-1}	3.48×10^{-3}	EQ	1.38×10^{-1}	6.52×10^{-1}	0.00%
STEICOzell Air-injected Wood Fibre Insulation	1.08	1.08×10^{-2}	EQ	8.16×10^{-4}	1.09	0.01%
Straw Insulation	1.17	6.63×10^{-2}	EQ	1.07×10^{-1}	1.34	0.00%

5.4. SAP of Celluloses

The previous study used the U-value of wall/roof assemblies as the controlled variable. The SAP controls instead the wall thickness (Figure 15).

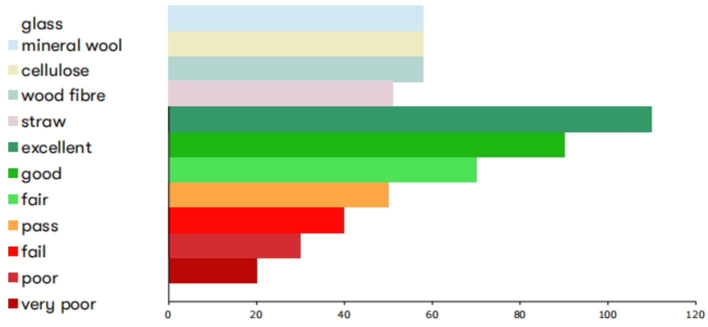

Figure 15. Thermal Properties of Different Materials.

The SAP studies show that with similar thermal conductivity values (0.033–0.038 W/mK), a similar thermal performance could be achieved even without adjusting the wall thickness. This suggests that sustainability factors other than thermal conductivity could play a larger role in the choice of thermal insulation materials (Table 15).

Table 15. Overall Dwelling Dimensions.

Overall Dwelling Dimensions	**Area/m^2**	**Volume/m^3**	
ground floor	336.27	950.27	
first floor	354.56	1140	
second floor	299.06	954.91	
total floor area/m^2	989.89		
dwelling volume/m^3		3045.18	
Fabric Heat Loss			
element	**area/m^2**	**U-value/W/m^2 K**	**A × U/W/K**
doors	15.53	1.50	23.30
windows	148.94	1.50	223.41
ground floor	334.79	0.15	50.22
walls framed constructions only	1128.90	0.1011	114.13
roof framed construction only	385.30	0.099	38.14
total area of elements/m^2	2013.46		
total fabric heat loss W/K			449.20
external air temperature			−1
internal air temperature			20
total fabric heat loss/W			9433.20

5.5. LCA of Cellulose vs. Other Insulation Materials in a General Setting

Apart from the comparison we have completed in the context of 54–58 Akerman Road, we need to know more about whether cellulose insulation can perform better in a more general setting. Therefore, we chose a typical wall structure in a newly built construction context (Figure 16) and calculated the minimum amount of each insulation material needed to achieve the recommended standard for the U-value of a wall, which is 0.17 W/m^{2}k in Scotland.

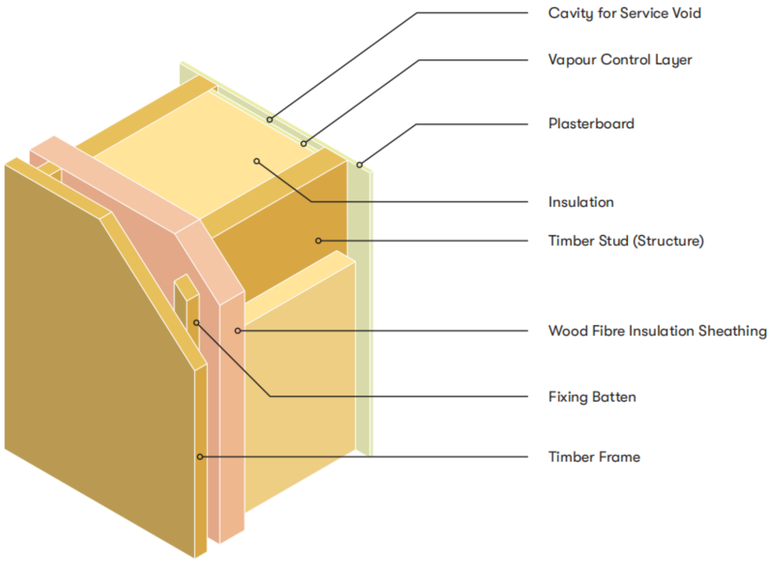

Figure 16. Common Wall Structure in Timber Frame Construction.

From the result, we can conclude that cellulose insulation performs similarly to wood fibre insulation, better than straw insulation but worse than glass mineral wool insulation. In considering the non-recyclability of glass mineral wool insulation, the use of cellulose is a feasible alternative to achieve a better sustainability value (For the Detailed Calculation Process, see Appendix C).

Traditionally, paper can be divided into virgin and reprocessed. Virgin means new paper while reprocessed means paper produced from recycled materials. From previous research, we can see that the production of reprocessed paper emits less CO_2 than virgin paper. There is another paper recycling method, which is to incinerate paper to produce electricity. The approach contributes to the environment, rather than emitting more CO_2. A combination of recycling virgin paper and recycling them into reprocessed paper may also contribute to the environment in some situations, as stated in Table 16. Therefore, it is hard to tell whether the recycling of paper waste is beneficial or harmful to the environment.

Table 16. Material Performance of Different Insulations.

Insulation Material	Thermal Conductivity/W/mK	Insulation Thickness/mm	Difference in Insulation Thickness/mm	Overall U-Value/W/m^{2}K
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.033	160	−25	**0.17**
Thermofloc Blown-in Cellulose Insulation	0.038	185	0	
STEICOzell Air-injected Wood Fibre Insulation	0.038	185	0	
Straw Insulation	0.052	240	+55	

From the data of the LCA of cellulose insulation (Figure 17 and Table 17), we can see that it performs average in comparison to traditional paper recycling methods. The. incineration of waste paper with low or medium-low technology, the production of reprocessed solid cardboard from virgin cardboard with Sulphate, CTMP and other purchased pulp can achieve a similar rating to cellulose insulation. Therefore, we can conclude that the production of cellulose insulation can act as an alternative to the traditional paper recycling method, but in some cases, the traditional methods can reduce CO_2 emissions more.

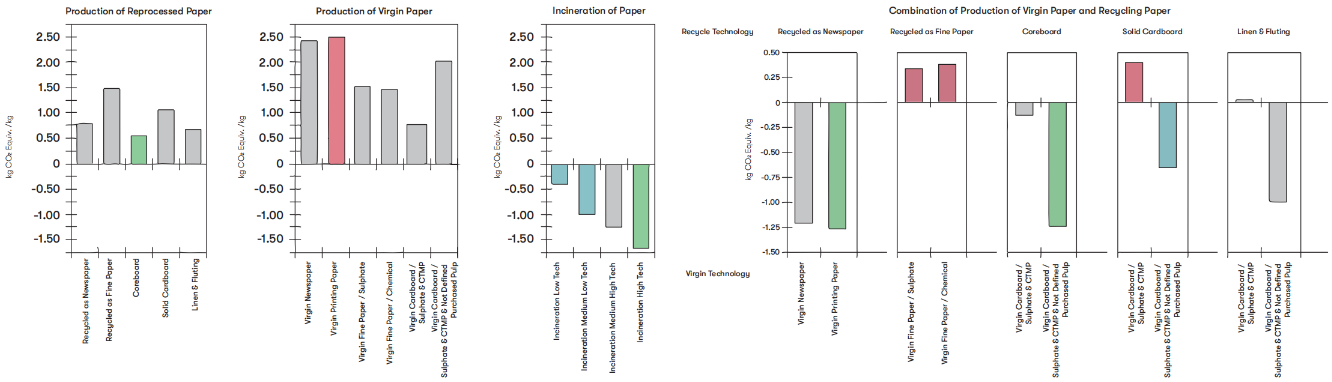

Figure 17. Global Warming Potential of Paper Production and Recycling.

Table 17. Comparison of Global Warming Potential of Paper Recycling and Cellulose Insulation.

	Cellulose Insulation	**Traditional Paper Recycling**	**Paper for Incineration**
Units	kg CO_2 equiv.	kg CO_2 equiv.	kg CO_2 equiv.
A1	0.043	n/a	n/a
A2	0.019	n/a	n/a
A3	0.018	n/a	n/a
A4	0.033	n/a	n/a
A5	0.022	n/a	n/a
C1	0	n/a	n/a
C2	0.00787	n/a	n/a
C3	0	n/a	n/a
C4	0.031	n/a	n/a
D	−0.826	n/a	n/a
Total	−0.65213	−1.30~0.3	−1.65~−0.3

6. Finding and Evaluation

An LCA of the insulation materials provides an indicator of the carbon footprint, energy resources involved and amount of raw materials going into and out of the system. The material that performs the best in one category often performs extremely poorly in another. Traditional glass mineral wool insulation has the lowest thermal conductivity, but its low recyclability leads to a huge amount of waste, albeit non-hazardous. Wood fibre insulation wastes the least raw materials, but its carbon footprint is very large. Straw bale insulation has a negative global warming potential, but it generates quite a large amount of waste too. Cellulose insulation is not the best in any category, but it provides a balanced performance. Overall, straw bale insulation was found to perform the best in terms of sustainability.

With reference to the study of the Akerman Road project, different insulation materials should be applied for the best overall performance in different scenarios and different parts of the building. Considering the relatively high thermal conductivity and density of straw bale insulation, a combination of straw bale insulation as wall insulation and cellulose insulation as roof insulation appears to be a reasonable choice for new houses. For retrofit housing, if the existing building was built in solid masonry, an insulation board might be a more reasonable choice than the studied loose-fill insulation types, in order to avoid the need to build a new framework for the loose insulation. If loose-fill insulation were to be chosen nonetheless, cellulose insulation would be a good choice to control the wall depth while maintaining sustainability.

Although cellulose insulation has certain advantages over other loose-fill insulations, its comparison with traditional paper processing methods does not establish an advantage over incineration and recycling. Hence, it should not be suggested as a replacement for paper reprocessing, but rather as a further step in the life cycle of paper before it becomes incinerated.

7. Application

When considering building types and climate and construction methods, cellulose insulation can be applied in a variety of practical scenarios. Let us take residential buildings as an example: if located in a hot area, architects and designers can choose to use cellulose insulation to reduce the heat absorption inside the building. This can be achieved by installing cellulose insulation in the walls, roofs and floors, thereby reducing the amount of air conditioning systems used and reducing energy consumption. For buildings in cold areas, cellulose insulation can provide better insulation. It creates a layer of insulation between the walls, roof and floor, preventing heat loss, reducing energy waste and improving the energy efficiency of the building. This can help keep the interior warm during the particularly cold winter months and reduce the use of heating systems.

Cellulose insulation is not only suitable for residential buildings but also can be applied in commercial buildings and industrial buildings. Whether it is an office building, shopping mall or factory, cellulose insulation can help improve the energy efficiency performance of a building. In commercial buildings, it can reduce the load on air conditioning and heating systems and reduce energy costs. In industrial buildings, cellulose insulation can provide good fire and sound insulation, while reducing energy waste.

In terms of construction methods, cellulose insulation can be applied in different ways. It can be sprayed on walls and roofs, filled in gaps in walls, or overlaid on existing building structures. These construction methods can be selected according to the specific situation, making the installation of cellulose insulation more flexible and convenient.

In summary, cellulose insulation materials can provide practical application scenarios under different building types, climatic conditions and construction methods. Its ability to provide a comfortable indoor environment and reduce energy consumption is essential for sustainable building development.

8. Conclusions

The purpose of our research was to find solutions to the climate and landfill crises; thus, we focused on recycled paper. We decided to investigate whether waste paper can be used as an insulating material in response to the current crisis after considering the practical application of recycled paper in the construction field.

To obtain the solution, we selected 54–58 Akerman Road as a case study and used the Life-Cycle Assessment and Standard Assessment Procedures to create four separate comparisons and calculations.

The findings show that, while cellulose insulation does not have the best thermal insulation U-value, the performance is average and sufficient to meet the needs of the majority of customers. When it comes to sustainability, cellulose insulation has a lot to offer. It emits the least carbon dioxide in the life cycle compared to other different insulating materials, according to our calculations. This shows that cellulose has a lot of potential for reducing global warming.

When it comes to thermal insulation performance and sustainability, cellulose insulation is an insulating material that delivers both. Furthermore, we weighed the environmental impact of cellulose insulation made from recycled paper versus traditional recycling methods. According to our studies, the carbon emissions produced by cellulose and traditional recycling methods are similar, but traditional recycling methods produce less carbon emissions in some cases. As a result, it is difficult to say that the cellulose-making method is superior to the traditional method; however, it has been demonstrated that it can replace or be comparable to the traditional method of recycling.

To sum up, through research and learning, we believe that making waste paper into cellulose insulation is a feasible way to deal with the current crisis. It can replace some paper recycling approaches that are not that sustainable, and it can deliver acceptable thermal performance.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Combined U-values and Required Thickness:
(A) As-built Condition (New-build Walls)
New-build External Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.14
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.045	Thermofloc Cellulose Insulation	0.038	9.47	STEICO Timber i-joist Flange	0.130	0.35
	0.270				STEICO Timber i-joist Web	0.180	1.50
	0.045				STEICO Timber i-joist Flange	0.130	0.35
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.013	Lime Render	0.120	0.11	Lime Render	0.120	0.13
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.09**	**U-value/W/m^2K**		**0.28**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.465**	**Combined U-value/W/m^2K**		**0.110**

New-build Party Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.56
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.097				Timber Studs	0.180	0.54
	0.060	Mineral Wool Insulation	0.035	7.26	Mineral Wool Insulation	0.035	1.71
	0.097				Timber Studs	0.180	0.54
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.025	Service Void	0.026	0.96	Service Void	0.026	0.96
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.11**	**U-value/W/m^2K**		**0.20**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.390**	**Combined U-value/W/m^2K**		**0.137**

Combined U-values and Required Thickness:
(A) As-built Condition (Retrofit Walls)
Retrofit External Wall

	Thickness of Material/m	Name of Building Material	Conductivity K Value of Material W/mK		Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face			0.12
	0.013	Gypsum Plasterboard	0.160		0.08
	0.015	Services Void	0.045		0.33
	0.093	Pavadry Wood Fibre Insulation	0.043		2.15
	0.010	Baumit RK38 lime plaster	0.830		0.01
	0.005	Baumit Speedfill	0.100		0.05
	0.215	Solid Masonry	0.900		0.24
OUTSIDE		Surface resistance on external face			0.04
		U-value/W/m^2K			**0.33**
Width/m		N/A			
Total Wall Thickness/m			**0.350**	**Combined U-value/W/m^2K**	**0.331**

Retrofit Extension New Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.097	Mineral Wool Insulation	0.035	5.83	Timber Stud	0.180	0.54
	0.010				Mineral Wool Insulation	0.035	0.29
	0.097				Timber Stud	0.180	0.54
	0.060	Pavatherm Plus Wood Fibre Board	0.043	1.40	Pavatherm Plus Wood Fibre Board	0.043	1.40
	0.025	Ventilation Void	0.045	0.56	Ventilation Void	0.026	0.96
	0.103	Brick	0.600	0.17	Brick	0.600	0.17
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.12**	**U-value/W/m²K**		**0.24**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.404**	**Combined U-value/W/m²K**		**0.160**

Combined U-values and Required Thickness:
(A) As-built Condition (New-build Roofs)
New-build Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.045	Thermofloc Cellulose Insulation	0.038	9.47	STEICO I-joist Flange	0.130	0.35
	0.270				STEICO I-joist Web	0.180	1.50
	0.045				STEICO I-joist Flange	0.130	0.35
	0.000	Vapour Control Membrane	2.300	0.00	Vapour Control Membrane	2.300	0.00
	0.150	STEICO Special Dry Wood Fibre Insulation	0.040	3.75	STEICO Special Dry Wood Fibre Insulation	0.040	3.75
	0.001	Solitex Plus Roofing Membrane	2.300	0.00	Solitex Plus Roofing Membrane	2.300	0.00
	0.010	Reconstituted Slate	1.900	0.01	Reconstituted Slate	1.900	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.07**	**U-value/W/m²K**		**0.16**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.534**	**Combined U-value/W/m²K**		**0.084**

N.B. The calculated combined U-value is lower than the overall U-value of 0.108 W/m²K declared by the architect. This might be due to a simplification of the ro of construction in our c calculation methods, but for the purpose of comparing the performance of insulation materials, it suffices to simply ensure the same error exists across the calculations for all four materials.

Combined U-values and Required Thickness:
(A) As-built Condition (Retrofit Roofs)
Retrofit Slanted Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Service Void	0.025	0.60	Service Void	0.025	0.60
	0.060	Pavatherm Combi Wood Fibre Insulation	0.041	1.46	Pavatherm Combi Wood Fibre Insulation	0.041	1.46
	0.150	Pavaflex Wood Fibre Insulation	0.038	3.95	Softwood Rafter	0.140	1.07
	0.030	Air Gap	0.025	1.20	Timber Battens	0.140	0.21
	0.030	Air Gap	0.025	1.20	Timber Counter Battens	0.140	0.21
	0.010	Reclaimed and New Slates	1.490	0.01	Reclaimed and New Slates	1.490	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.12**	**U-value/W/m^2K**		**0.26**
Width/m		**0.55**			**0.05**		
Total Wall Thickness/m				**0.308**	**Combined U-value/W/m^2K**		**0.128**

Retrofit Flat Cold Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.018	Oriented Strand Board	0.130	0.14	Oriented Strand Board	0.130	0.14
	0.250	Cellulose Insulation	0.038	6.58	Timber Batten	0.130	1.92
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.14**	**U-value/W/m^2K**		**0.44**
Width/m		**0.35**			**0.05**		
Total Wall Thickness/m				**0.281**	**Combined U-value/W/m^2K**		**0.181**

Combined U-values and Required Thickness:
(B) Blown-in Glass Mineral Wool Insulation (New-build Walls)
New-build External Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.14
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.045	Knauf Supafil Frame Blowing Wool Insulation	0.033	9.76	STEICO Timber i-joist Flange	0.130	0.35
	0.232				STEICO Timber i-joist Web	0.180	1.29
	0.045				STEICO Timber i-joist Flange	0.130	0.35
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.015	Lime Render	0.120	0.11	Lime Render	0.120	0.13
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.09**	**U-value/W/m²K**		**0.30**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.427**	**Combined U-value/W/m²K**		**0.110**

New-build Party Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.56
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.097	Knauf Supafil Frame Blowing Wool Insulation	0.033	7.48	Timber Studs	0.180	0.54
	0.053				Knauf Supafil Frame Blowing Wool Insulation	0.033	1.61
	0.097				Timber Studs	0.180	0.54
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.025	Service Void	0.026	0.96	Service Void	0.026	0.96
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.10**	**U-value/W/m^2K**		**0.21**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.383**	**Combined U-value/W/m^2K**		**0.137**

Combined U-values and Required Thickness:
(B) Blown-in Glass Mineral Wool Insulation (Retrofit Walls)
Retrofit External Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Services Void	0.045	0.33	Services Void	0.045	0.33
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.135	Knauf Supafil Frame Blowing Wool Insulation	0.033	4.09	Timber Stud	0.180	0.75
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.010	Baumit RK38 lime plaster	0.830	0.01	Baumit RK38 lime plaster	0.830	0.01
	0.005	Baumit Speedfill	0.100	0.05	Baumit Speedfill	0.100	0.05
	0.215	Solid Masonry	0.900	0.24	Solid Masonry	0.900	0.24
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.20**	**U-value/W/m^2K**		**0.61**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.418**	**Combined U-value/W/m^2K**		**0.331**

Retrofit Extension New Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m²K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m²K/W
	0.097				Timber Stud	0.180	0.54
	0.005	Knauf Supafil Frame Blowing Wool Insulation	0.033	6.03	Knauf Supafil Frame Blowing Wool Insulation	0.040	0.15
	0.097				Timber Stud	0.180	0.54
	0.060	Pavatherm Plus Wood Fibre Board	0.043	1.40	Pavatherm Plus Wood Fibre Board	0.043	1.40
	0.025	Ventilation Void	0.045	0.56	Ventilation Void	0.026	0.96
	0.103	Brick	0.600	0.17	Brick	0.600	0.17
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.12**	**U-value/W/m²K**		**0.25**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.399**	**Combined U-value/W/m²K**		**0.160**

Combined U-values and Required Thickness:
(B) Blown-in Glass Mineral Wool Insulation (New-build Roofs)
New-build Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m²K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m²K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.045				STEICO I-joist Flange	0.130	0.35
	0.230	Knauf Supafil Frame Blowing Wool Insulation	0.033	9.70	STEICO I-joist Web	0.180	1.28
	0.045				STEICO I-joist Flange	0.130	0.35
	0.000	Vapour Control Membrane	2.300	0.00	Vapour Control Membrane	2.300	0.00
	0.150	STEICO Special Dry Wood Fibre Insulation	0.040	3.75	STEICO Special Dry Wood Fibre Insulation	0.040	3.75
	0.001	Solitex Plus Roofing Membrane	2.300	0.00	Solitex Plus Roofing Membrane	2.300	0.00
	0.010	Reconstituted Slate	1.900	0.01	Reconstituted Slate	1.900	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.07**	**U-value/W/m²K**		**0.17**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.494**	**Combined U-value/W/m²K**		**0.084**

Combined U-values and Required Thickness:
(B) Blown-in Glass Mineral Wool Insulation (Retrofit Roofs)
Retrofit Slanted Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Service Void	0.025	0.60	Service Void	0.025	0.60
	0.060	Pavatherm Combi Wood Fibre Insulation	0.041	1.46	Pavatherm Combi Wood Fibre Insulation	0.041	1.46
	0.132	Knauf Supafil Frame Blowing Wool Insulation	0.033	4.00	Softwood Rafter	0.140	0.94
	0.030	Air Gap	0.025	1.20	Timber Battens	0.140	0.21
	0.030	Air Gap	0.025	1.20	Timber Counter Battens	0.140	0.21
	0.010	Reclaimed and New Slates	1.490	0.01	Reclaimed and New Slates	1.490	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.12**	**U-value/W/m^2K**		**0.27**
Width/m		**0.55**			**0.05**		
Total Wall Thickness/m				**0.290**	**Combined U-value/W/m^2K**		**0.128**

Retrofit Flat Cold Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.018	Oriented Strand Board	0.130	0.14	Oriented Strand Board	0.130	0.14
	0.226	Knauf Supafil Frame Blowing Wool Insulation	0.033	6.85	Timber Batten	0.130	1.74
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.14**	**U-value/W/m^2K**		**0.48**
Width/m		**0.35**			**0.05**		
Total Wall Thickness/m				**0.257**	**Combined U-value/W/m^2K**		**0.181**

Combined U-values and Required Thickness:
(C) Blown-in Cellulose Insulation (New-build Walls)
New-build External Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.14
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.045	Thermofloc Blown-in Cellulose Insulation	0.038	9.47	STEICO Timber i-joist Flange	0.130	0.35
	0.270				STEICO Timber i-joist Web	0.180	1.50
	0.045				STEICO Timber i-joist Flange	0.130	0.35
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.013	Lime Render	0.120	0.11	Lime Render	0.120	0.13
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.09**	**U-value/W/m^2K**		**0.28**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.465**	**Combined U-value/W/m^2K**		**0.110**

New-build Party Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.56
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.097	Thermofloc Blown-in Cellulose Insulation	0.038	7.00	Timber Studs	0.180	0.54
	0.072				Thermofloc Blown-in Cellulose Insulation	0.038	1.89
	0.097				Timber Studs	0.180	0.54

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.025	Service Void	0.026	0.96	Service Void	0.026	0.96
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.11**	**U-value/W/m^2K**		**0.20**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.402**	**Combined U-value/W/m^2K**		**0.137**

Combined U-values and Required Thickness:
(C) Blown-in Cellulose Insulation (Retrofit Walls)
Retrofit External Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Services Void	0.045	0.33	Services Void	0.045	0.33
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.146	Thermofloc Blown-in Cellulose Insulation	0.038	3.84	Timber Stud	0.180	0.81
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.010	Baumit RK38 lime plaster	0.830	0.01	Baumit RK38 lime plaster	0.830	0.01
	0.005	Baumit Speedfill	0.100	0.05	Baumit Speedfill	0.100	0.05
	0.215	Solid Masonry	0.900	0.24	Solid Masonry	0.900	0.24
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.21**	**U-value/W/m^2K**		**0.59**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.429**	**Combined U-value/W/m^2K**		**0.331**

Retrofit Extension New Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.097	Thermofloc Blown-in Cellulose Insulation	0.038	5.55	Timber Stud	0.180	0.54
	0.017				Thermofloc Blown-in Cellulose Insulation	0.038	0.45
	0.097				Timber Stud	0.180	0.54
	0.060	Pavatherm Plus Wood Fibre Board	0.043	1.40	Pavatherm Plus Wood Fibre Board	0.043	1.40
	0.025	Ventilation Void	0.045	0.56	Ventilation Void	0.026	0.96
	0.103	Brick	0.600	0.17	Brick	0.600	0.17
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.13**	**U-value/W/m²K**		**0.23**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.411**	**Combined U-value/W/m²K**		**0.160**

Combined U-values and Required Thickness:
(C) Blown-in Cellulose Insulation (New-build Roofs)
New-build Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.045	Thermofloc Blown-in Cellulose Insulation	0.038	9.47	STEICO I-joist Flange	0.130	0.35
	0.270				STEICO I-joist Web	0.180	1.50
	0.045				STEICO I-joist Flange	0.130	0.35
	0.000	Vapour Control Membrane	2.300	0.00	Vapour Control Membrane	2.300	0.00
	0.150	STEICO Special Dry Wood Fibre Insulation	0.040	3.75	STEICO Special Dry Wood Fibre Insulation	0.040	3.75

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
	0.001	Solitex Plus Roofing Membrane	2.300	0.00	Solitex Plus Roofing Membrane	2.300	0.00
	0.010	Reconstituted Slate	1.900	0.01	Reconstituted Slate	1.900	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^{2}K		**0.07**	**U-value/W/m^{2}K**		**0.16**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.534**	**Combined U-value/W/m^{2}K**		**0.084**

Combined U-values and Required Thickness:
(C) Blown-in Cellulose Insulation (Retrofit Roofs)
Retrofit Slanted Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Service Void	0.025	0.60	Service Void	0.025	0.60
	0.060	Pavatherm Combi Wood Fibre Insulation	0.041	1.46	Pavatherm Combi Wood Fibre Insulation	0.041	1.46
	0.150	Thermofloc Blown-in Cellulose Insulation	0.038	3.95	Softwood Rafter	0.140	1.07
	0.030	Air Gap	0.025	1.20	Timber Battens	0.140	0.21
	0.030	Air Gap	0.025	1.20	Timber Counter Battens	0.140	0.21
	0.010	Reclaimed and New Slates	1.490	0.01	Reclaimed and New Slates	1.490	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^{2}K		**0.12**	**U-value/W/m^{2}K**		**0.26**
Width/m		**0.55**			**0.05**		
Total Wall Thickness/m				**0.308**	**Combined U-value/W/m^{2}K**		**0.128**

Retrofit Flat Cold Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.018	Oriented Strand Board	0.130	0.14	Oriented Strand Board	0.130	0.14

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
	0.250	Thermofloc Blown-in Cellulose Insulation	0.038	6.58	Timber Batten	0.130	1.92
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.14**	**U-value/W/m²K**		**0.44**
Width/m		**0.35**			**0.05**		
Total Wall Thickness/m				**0.281**	**Combined U-value/W/m²K**		**0.181**

Combined U-values and Required Thickness:
(D) Air-injected Wood Fibre Insulation (New-build Walls)
New-build External Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.14
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.045	STEICOzell Air-injected Wood Fibre Insulation	0.038	9.47	STEICO Timber i-joist Flange	0.130	0.35
	0.270				STEICO Timber i-joist Web	0.180	1.50
	0.045				STEICO Timber i-joist Flange	0.130	0.35
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.013	Lime Render	0.120	0.11	Lime Render	0.120	0.13
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.09**	**U-value/W/m²K**		**0.28**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.465**	**Combined U-value/W/m²K**		**0.110**

New-build Party Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08

	Thickness of Material/m	**Name of Building Material (Cavity)**	**Conductivity K Value of Material W/mK**	**Resistance R Value of Element m²K/W**	**Name of Building Material (Frame)**	**Conductivity K Value of Material W/mK**	**Resistance R Value of Element m²K/W**
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.56
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.097				Timber Studs	0.180	0.54
	0.072	STEICOzell Air-injected Wood Fibre Insulation	0.038	7.00	STEICOzell Air-injected Wood Fibre Insulation	0.038	1.89
	0.097				Timber Studs	0.180	0.54
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.025	Service Void	0.026	0.96	Service Void	0.026	0.96
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.11**	**U-value/W/m²K**		**0.20**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.402**	**Combined U-value/W/m²K**		**0.137**

Combined U-values and Required Thickness:
(D) Air-injected Wood Fibre Insulation (Retrofit Walls)
Retrofit External Wall

	Thickness of Material/m	**Name of Building Material (Cavity)**	**Conductivity K Value of Material W/mK**	**Resistance R Value of Element m²K/W**	**Name of Building Material (Frame)**	**Conductivity K Value of Material W/mK**	**Resistance R Value of Element m²K/W**
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Services Void	0.045	0.33	Services Void	0.045	0.33
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.146	STEICOzell Air-injected Wood Fibre Insulation	0.038	3.84	Timber Stud	0.180	0.81
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.010	Baumit RK38 lime plaster	0.830	0.01	Baumit RK38 lime plaster	0.830	0.01
	0.005	Baumit Speedfill	0.100	0.05	Baumit Speedfill	0.100	0.05
	0.215	Solid Masonry	0.900	0.24	Solid Masonry	0.900	0.24
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.21**	**U-value/W/m²K**		**0.59**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.429**	**Combined U-value/W/m²K**		**0.331**

Retrofit Extension New Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^{2}K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^{2}K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.097	STEICOzell Air-injected Wood Fibre Insulation	0.038	5.55	Timber Stud	0.180	0.54
	0.017				STEICOzell Air-injected Wood Fibre Insulation	0.038	0.45
	0.097				Timber Stud	0.180	0.54
	0.060	Pavatherm Plus Wood Fibre Board	0.043	1.40	Pavatherm Plus Wood Fibre Board	0.043	1.40
	0.025	Ventilation Void	0.045	0.56	Ventilation Void	0.026	0.96
	0.103	Brick	0.600	0.17	Brick	0.600	0.17
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^{2}K		**0.13**	**U-value/W/m^{2}K**		**0.23**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.411**	**Combined U-value/W/m^{2}K**		**0.160**

Combined U-values and Required Thickness:
(D) Air-injected Wood Fibre Insulation (New-build Roofs)
New-build Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^{2}K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^{2}K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.045	STEICOzell Air-injected Wood Fibre Insulation	0.038	9.47	STEICO I-joist Flange	0.130	0.35
	0.270				STEICO I-joist Web	0.180	1.50
	0.045				STEICO I-joist Flange	0.130	0.35
	0.000	Vapour Control Membrane	2.300	0.00	Vapour Control Membrane	2.300	0.00
	0.150	STEICO Special Dry Wood Fibre Insulation	0.040	3.75	STEICO Special Dry Wood Fibre Insulation	0.040	3.75
	0.001	Solitex Plus Roofing Membrane	2.300	0.00	Solitex Plus Roofing Membrane	2.300	0.00
	0.010	Reconstituted Slate	1.900	0.01	Reconstituted Slate	1.900	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^{2}K		**0.07**	**U-value/W/m^{2}K**		**0.16**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.534**	**Combined U-value/W/m^{2}K**		**0.084**

Combined U-values and Required Thickness:
(D) Air-injected Wood Fibre Insulation (Retrofit Roofs)
Retrofit Slanted Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Service Void	0.025	0.60	Service Void	0.025	0.60
	0.060	Pavatherm Combi Wood Fibre Insulation	0.041	1.46	Pavatherm Combi Wood Fibre Insulation	0.041	1.46
	0.150	STEICOzell Air-injected Wood Fibre Insulation	0.038	3.95	Softwood Rafter	0.140	1.07
	0.030	Air Gap	0.025	1.20	Timber Battens	0.140	0.21
	0.030	Air Gap	0.025	1.20	Timber Counter Battens	0.140	0.21
	0.010	Reclaimed and New Slates	1.490	0.01	Reclaimed and New Slates	1.490	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.12**	**U-value/W/m^2K**		**0.26**
Width/m		**0.55**			**0.05**		
Total Wall Thickness/m				**0.308**	**Combined U-value/W/m^2K**		**0.128**

Retrofit Flat Cold Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.018	Oriented Strand Board	0.130	0.14	Oriented Strand Board	0.130	0.14
	0.250	STEICOzell Air-injected Wood Fibre Insulation	0.038	6.58	Timber Batten	0.130	1.92
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.14**	**U-value/W/m^2K**		**0.44**
Width/m		**0.35**			**0.05**		
Total Wall Thickness/m				**0.281**	**Combined U-value/W/m^2K**		**0.181**

Combined U-values and Required Thickness:
(E) Straw Insulation (New-build Walls)
New-build External Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.14
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.045	Straw Insulation	0.052	8.88	STEICO Timber i-joist Flange	0.130	0.35
	0.372				STEICO Timber i-joist Web	0.180	2.07
	0.045				STEICO Timber i-joist Flange	0.130	0.35
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.015	Lime Render	0.120	0.11	Lime Render	0.120	0.13
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^2K		**0.09**	**U-value/W/m^2K**		**0.24**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.567**	**Combined U-value/W/m^2K**		**0.110**

New-build Party Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.025	Service Void	0.045	0.56	Service Void	0.045	0.56
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.097	Straw Insulation	0.052	6.25	Timber Studs	0.180	0.54
	0.131				Straw Insulation	0.052	2.52
	0.097				Timber Studs	0.180	0.54
	0.018	Fermacell Gypsum Board	0.320	0.06	Fermacell Gypsum Board	0.320	0.06
	0.012	Durelis Vapour Block	0.144	0.08	Durelis Vapour Block	0.144	0.08
	0.025	Service Void	0.026	0.96	Service Void	0.026	0.96
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^{2}K		**0.12**	**U-value/W/m^{2}K**		**0.18**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.461**	**Combined U-value/W/m^{2}K**		**0.137**

Combined U-values and Required Thickness:

(E) Straw Insulation (Retrofit Walls)

Retrofit External Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Services Void	0.045	0.33	Services Void	0.045	0.33
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.175	Straw Insulation	0.052	3.37	Timber Stud	0.180	0.97
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.010	Baumit RK38 lime plaster	0.830	0.01	Baumit RK38 lime plaster	0.830	0.01
	0.005	Baumit Speedfill	0.100	0.05	Baumit Speedfill	0.100	0.05
	0.215	Solid Masonry	0.900	0.24	Solid Masonry	0.900	0.24
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m^{2}K		**0.24**	**U-value/W/m^{2}K**		**0.54**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.458**	**Combined U-value/W/m^{2}K**		**0.331**

Retrofit Extension New Wall

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.097	Straw Insulation	0.052	4.81	Timber Stud	0.180	0.54
	0.056				Straw Insulation	0.052	1.08
	0.097				Timber Stud	0.180	0.54
	0.060	Pavatherm Plus Wood Fibre Board	0.043	1.40	Pavatherm Plus Wood Fibre Board	0.043	1.40
	0.025	Ventilation Void	0.045	0.56	Ventilation Void	0.026	0.96
	0.103	Brick	0.600	0.17	Brick	0.600	0.17

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.14**	**U-value/W/m²K**		**0.20**
Width/m		**0.10**			**0.05**		
Total Wall Thickness/m				**0.450**	**Combined U-value/W/m²K**		**0.160**

Combined U-values and Required Thickness:
(E) Straw Insulation (New-build Roofs)
New-build Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.045	Straw Insulation	0.052	9.13	STEICO I-joist Flange	0.130	0.35
	0.385				STEICO I-joist Web	0.180	2.14
	0.045				STEICO I-joist Flange	0.130	0.35
	0.000	Vapour Control Membrane	2.300	0.00	Vapour Control Membrane	2.300	0.00
	0.150	STEICO Special Dry Wood Fibre Insulation	0.040	3.75	STEICO Special Dry Wood Fibre Insulation	0.040	3.75
	0.001	Solitex Plus Roofing Membrane	2.300	0.00	Solitex Plus Roofing Membrane	2.300	0.00
	0.010	Reconstituted Slate	1.900	0.01	Reconstituted Slate	1.900	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.08**	**U-value/W/m²K**		**0.15**
Width/m		**0.355**			**0.045**		
Total Wall Thickness/m				**0.649**	**Combined U-value/W/m²K**		**0.084**

Combined U-values and Required Thickness:
(D) Straw Insulation (Retrofit Roofs)
Retrofit Slanted Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
	0.015	Service Void	0.025	0.60	Service Void	0.025	0.60

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
	0.060	Pavatherm Combi Wood Fibre Insulation	0.041	1.46	Pavatherm Combi Wood Fibre Insulation	0.041	1.46
	0.198	Straw Insulation	0.052	3.81	Softwood Rafter	0.140	1.41
	0.030	Air Gap	0.025	1.20	Timber Battens	0.140	0.21
	0.030	Air Gap	0.025	1.20	Timber Counter Battens	0.140	0.21
	0.010	Reclaimed and New Slates	1.490	0.01	Reclaimed and New Slates	1.490	0.01
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.12**	**U-value/W/m²K**		**0.24**
Width/m		**0.55**			**0.05**		
Total Wall Thickness/m				**0.356**	**Combined U-value/W/m²K**		**0.128**

Retrofit Flat Cold Roof

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.018	Oriented Strand Board	0.130	0.14	Oriented Strand Board	0.130	0.14
	0.316	Straw Insulation	0.052	6.08	Timber Batten	0.130	2.43
	0.013	Gypsum Plasterboard	0.160	0.08	Gypsum Plasterboard	0.160	0.08
OUTSIDE		Surface resistance on external face					0.04
		U-value/W/m²K		**0.16**	**U-value/W/m²K**		**0.36**
Width/m		**0.35**			**0.05**		
Total Wall Thickness/m				**0.347**	**Combined U-value/W/m²K**		**0.181**

Appendix B

Life-Cycle Assessment by Mass

(A) Global Warming Potential

Global Warming Potential

Insulation Material	Mass/ kg	A1 per kg/kg CO_2 eq.	A2 per kg/kg CO_2 eq.	A3 per kg/kg CO_2 eq.	Production Stage per kg/kg CO_2 eq.	Production Stage Total/kg CO_2 eq.	A5 per kg/kg CO_2 eq.	Construction Stage Total/ kg CO_2 eq.	C2 per kg/kg CO_2 eq.	C3 per kg/kg CO_2 eq.	C4 per kg/kg CO_2 eq.	Disposal Stage per kg/kg CO_2 eq.	Disposal Stage Total/ kg CO_2 eq.	Total/ kg CO_2 eq.
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	9930.5			9.73×10^{-1}	9.73×10^{-1}	$\mathbf{9.67 \times 10^{2}}$	3.67×10^{-2}	$\mathbf{3.64 \times 10^{2}}$	1.05×10^{-2}		5.37×10^{-3}	1.59×10^{-2}	$\mathbf{1.58 \times 10^{2}}$	$\mathbf{1.02 \times 10^{4}}$
Thermofloc Blown-in Cellulose Insulation	14,601.0	4.30×10^{-2}	1.90×10^{-2}	1.80×10^{-2}	8.00×10^{-2}	$\mathbf{1.17 \times 10^{3}}$	2.20×10^{-2}	$\mathbf{3.21 \times 10^{2}}$	7.87×10^{-3}	0.00	3.10×10^{-2}	3.89×10^{-2}	$\mathbf{5.68 \times 10^{2}}$	$\mathbf{2.06 \times 10^{2}}$
STEICOzell Air-injected Wood Fibre Insulation	16,426.2	−1.36	1.54	9.45	9.63	$\mathbf{1.58 \times 10^{5}}$	4.62	$\mathbf{7.59 \times 10^{4}}$	2.90	1.46		4.36	$\mathbf{7.16 \times 10^{4}}$	$\mathbf{3.06 \times 10^{5}}$
Straw Insulation	46,015.5	−1.17	1.13×10^{-2}	3.42×10^{-1}	-8.17×10^{-1}	$\mathbf{-3.76 \times 10^{4}}$	1.49×10^{-1}	$\mathbf{6.86 \times 10^{2}}$	1.99×10^{-2}	8.35×10^{-3}	3.00×10^{-3}	3.13×10^{-2}	$\mathbf{1.44 \times 10^{2}}$	$\mathbf{-2.93 \times 10^{4}}$

Life-Cycle Assessment by Mass

(B) Primary Energy Consumption

Renewable Primary Energy Consumption

Insulation Material	Mass/ kg	A1 per kg/ML	A2 per kg/ML	A3 per kg/ML	Production Stage per kg/ML	Production Stage Total/ML	A5 per kg/ML	Construction Stage Total/ML	C2 per kg/ML	C3 per kg/ML	C4 per kg/ML	Disposal Stage per kg/ML	Disposal Stage Total/ML	Total/ ML
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	9930.5			2.61×10^{-1}	2.61×10^{-1}	$\mathbf{2.59 \times 10^{2}}$	7.80×10^{-3}	$\mathbf{7.75 \times 10^{1}}$	2.41×10^{-3}		3.90×10^{-3}	6.31×10^{-3}	$\mathbf{6.27 \times 10^{1}}$	$\mathbf{2.73 \times 10^{2}}$
Thermofloc Blown-in Cellulose Insulation	14,601.0	3.80×10^{-2}	1.50×10^{-2}	5.96×10^{-1}	6.49×10^{-1}	$\mathbf{9.48 \times 10^{2}}$	4.00×10^{-4}	**5.84**	8.00×10^{-3}	0.00	1.30×10^{1}	1.30×10^{1}	$\mathbf{1.90 \times 10^{5}}$	$\mathbf{1.99 \times 10^{5}}$
STEICOzell Air-injected Wood Fibre Insulation	16,426.2	7.33×10^{-2}	1.20×10^{-2}	1.05	1.14	$\mathbf{1.86 \times 10^{4}}$	3.55×10^{-3}	$\mathbf{5.83 \times 10^{1}}$	2.25×10^{-3}	0.00		2.25×10^{-3}	$\mathbf{3.70 \times 10^{1}}$	$\mathbf{1.87 \times 10^{4}}$
Straw Insulation	46,015.5	2.53	2.14×10^{-3}	2.69	5.22	$\mathbf{2.40 \times 10^{5}}$	-5.68×10^{-1}	$\mathbf{-2.61 \times 10^{4}}$	3.76×10^{-3}	3.84×10^{-3}	7.37×10^{-4}	8.34×10^{-3}	$\mathbf{3.84 \times 10^{2}}$	$\mathbf{2.15 \times 10^{5}}$

Non-renewable Primary Energy Consumption

Insulation Material	Mass/kg	A1 per kg/ML	A2 per kg/ML	A3 per kg/ML	Production Stage per kg/ML	Production Stage Total/ML	A5 per kg/ML	Construction Stage Total/ML	C2 per kg/ML	C3 per kg/ML	C4 per kg/ML	Disposal Stage per kg/ML	Disposal Stage Total/ML	Total/ML
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	9930.5			2.02×10^{1}	2.02×10^{1}	**2.01×10^{5}**	4.83×10^{-1}	**4.80×10^{2}**	1.62×10^{-1}		1.54×10^{-1}	3.15×10^{-1}	**3.13×10^{2}**	**2.09×10^{5}**
Thermofloc Blown-in Cellulose Insulation	14,601.0	7.52×10^{-1}	2.63×10^{-1}	6.07×10^{-1}	1.62	**2.37×10^{4}**	3.00×10^{-3}	**4.38×10^{1}**	1.05×10^{-1}	0.00	4.22×10^{-1}	5.27×10^{-1}	**7.69×10^{2}**	**3.14×10^{4}**
STEICOzell Air-injected Wood Fibre Insulation	16,426.2	2.14	2.13×10^{-1}	1.14×10^{1}	1.38×10^{1}	**2.26×10^{5}**	1.75×10^{-2}	**2.87×10^{2}**	4.02×10^{-2}	0.00		4.02×10^{-2}	**6.60×10^{2}**	**2.27×10^{5}**
Straw Insulation	46,015.5	7.56×10^{-1}	1.82×10^{-1}	8.12	9.06	**4.17×10^{5}**	3.09×10^{-1}	**1.42×10^{4}**	3.19×10^{-1}	9.28×10^{-2}	1.81×10^{-2}	4.30×10^{-1}	**1.98×10^{4}**	**4.51×10^{5}**

Life-Cycle Assessment by Mass

(C) Waste Categories

Hazardous Waste

Insulation Material	Mass/kg	A1 per kg/kg	A2 per kg/kg	A3 per kg/kg	Production Stage per kg/kg	Production Stage Total/kg	A5 per kg/kg	Construction Stage Total/kg	C2 per kg/kg	C3 per kg/kg	C4 per kg/kg	Disposal Stage per kg/kg	Disposal Stage Total/kg	Total/kg
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	9930.5			1.80×10^{-4}	1.80×10^{-4}	**1.79**	1.62×10^{-5}	**1.61×10^{-1}**	4.40×10^{-6}		9.03×10^{-6}	1.34×10^{-5}	**1.33×10^{-1}**	**2.08**
Thermofloc Blown-in Cellulose Insulation	14,601.0	7.56×10^{-7}	1.33×10^{-7}	2.97×10^{-5}	3.06×10^{-5}	**4.47×10^{-1}**	1.27×10^{-10}	**1.85×10^{-6}**	8.43×10^{-8}	0.00	0.00	8.43×10^{-8}	**1.23×10^{-3}**	**4.48×10^{-1}**
STEICOzell Air-injected Wood Fibre Insulation	16,426.2	4.21×10^{-6}	9.91×10^{-9}	8.45×10^{-9}	4.23×10^{-6}	**6.95×10^{-2}**	6.69×10^{-11}	**1.10×10^{-6}**	1.87×10^{-9}	0.00		1.87×10^{-9}	**3.07×10^{-5}**	**6.95×10^{-2}**
Straw Insulation	46,015.5	1.34×10^{-6}	4.33×10^{-7}	7.77×10^{-6}	9.55×10^{-6}	**4.39×10^{-1}**	5.35×10^{-7}	**2.46×10^{-2}**	7.61×10^{-7}	2.43×10^{-7}	5.64×10^{-8}	1.06×10^{-6}	**4.88×10^{-2}**	**5.13×10^{-1}**

Non-hazardous Waste

Insulation Material	Mass/kg	A1 per kg/kg	A2 per kg/kg	A3 per kg/kg	Production Stage per kg/kg	Production Stage Total/kg	A5 per kg/kg	Construction Stage Total/kg	C2 per kg/kg	C3 per kg/kg	C4 per kg/kg	Disposal Stage per kg/kg	Disposal Stage Total/kg	Total/kg
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	9930.5			1.43×10^{-1}	1.43×10^{-1}	**1.42×10^{2}**	2.80×10^{-2}	**2.78×10^{2}**	6.17×10^{-3}		1.00	1.01	**9.99×10^{2}**	**1.17×10^{4}**
Thermofloc Blown-in Cellulose Insulation	14,601.0	6.17×10^{-2}	2.50×10^{-3}	2.45×10^{-2}	8.87×10^{-2}	**1.30×10^{2}**	2.08×10^{-5}	**3.04×10^{-1}**	1.06×10^{-3}	0.00	2.11×10^{-5}	1.08×10^{-3}	**1.58×10^{1}**	**1.31×10^{2}**
STEICOzell Air-injected Wood Fibre Insulation	16,426.2	1.40×10^{-3}	3.26×10^{-5}	6.25×10^{-3}	7.68×10^{-3}	**1.26×10^{2}**	3.28×10^{-3}	**5.39×10^{1}**	6.15×10^{-6}	0.00		6.15×10^{-6}	**1.01×10^{-1}**	**1.80×10^{2}**
Straw Insulation	46,015.5	1.09×10^{-2}	1.08×10^{-2}	3.27×10^{-2}	5.44×10^{-2}	**2.50×10^{2}**	7.44×10^{-3}	**3.42×10^{2}**	1.90×10^{-2}	6.21×10^{-3}	5.02×10^{-2}	7.54×10^{-2}	**3.47×10^{2}**	**6.32×10^{2}**

Life-Cycle Assessment by Mass

(C) Waste Categories

Radioactive Waste

Insulation Material	Mass/kg	A1 per kg/kg	A2 per kg/kg	A3 per kg/kg	Production Stage per kg/kg	Production Stage Total/kg	A5 per kg/kg	Construction Stage Total/kg	C2 per kg/kg	C3 per kg/kg	C4 per kg/kg	Disposal Stage per kg/kg	Disposal Stage Total/kg	Total/kg
Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	9930.5			1.00×10^{-4}	1.00×10^{-4}	**9.93×10^{-1}**	2.60×10^{-6}	**2.58×10^{-2}**	3.73×10^{-6}	1.09×10^{-6}	1.01×10^{-6}	5.83×10^{-6}	**5.79×10^{-2}**	**1.08**
Thermofloc Blown-in Cellulose Insulation	14,601.0	3.34×10^{-5}	5.41×10^{-7}	1.02×10^{-6}	3.50×10^{-5}	**5.10×10^{-1}**	2.38×10^{-7}	**3.48×10^{-3}**	1.85×10^{-7}	0.00	9.25×10^{-6}	9.44×10^{-6}	**1.38×10^{-1}**	**6.52×10^{-1}**
STEICOzell Air-injected Wood Fibre Insulation	16,426.2	8.73×10^{-6}	2.63×10^{-7}	5.69×10^{-5}	6.59×10^{-5}	**1.08**	6.58×10^{-7}	**1.08×10^{-2}**	4.97×10^{-8}	0.00		4.97×10^{-8}	**8.16×10^{-4}**	**1.09**
Straw Insulation	46,015.5	2.79×10^{-6}	1.12×10^{-6}	2.14×10^{-5}	2.53×10^{-5}	**1.17**	1.44×10^{-6}	**6.63×10^{-2}**	1.97×10^{-6}	2.61×10^{-7}	8.81×10^{-8}	2.32×10^{-6}	**1.07×10^{-1}**	**1.34**

Appendix C

Combined U-values and Required Thickness:
General Construction Structure Achieving the Same Combined U-Value

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.012	Plasterboard	0.160	0.08	Plasterboard	0.160	0.08
	0.025	Service Void		0.18	Timber Batten	0.140	0.18
	0.012	Vapour Control Layer	0.380	0.03	Vapour Control Layer	0.38	0.03
	0.185	Thermofloc Blown-in Cellulose Insulation	0.038	4.87	Timber Structure	0.140	1.25
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.040	Fixing Batten	0.140	0.29	Fixing Batten	0.140	0.29
	0.040	Timber Cladding	0.140	0.29	Timber Cladding	0.140	0.29
OUTSIDE		Surface resistance on external face					0.04
		U-value		**0.15**	**U-value**		0.32
Width/m		**0.05**			**0.035**		
Combined U-value							0.17

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.012	Plasterboard	0.160	0.08	Plasterboard	0.160	0.08
	0.025	Service Void		0.18	Timber Batten	0.140	0.18
	0.012	Vapour Control Layer	0.380	0.03	Vapour Control Layer	0.38	0.03
	0.185	STEICOzell Air-injected Wood Fibre Insulation	0.038	4.87	Timber Structure	0.140	1.25
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.040	Fixing Batten	0.140	0.29	Fixing Batten	0.140	0.29
	0.040	Timber Cladding	0.140	0.29	Timber Cladding	0.140	0.29
OUTSIDE		Surface resistance on external face					0.04
		U-value		**0.15**	**U-value**		0.32
Width/m		**0.05**			**0.035**		
Combined U-value							0.17

Combined U-values and Required Thickness:
General Construction Structure Achieving the Same Combined U-Value

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.012	Plasterboard	0.160	0.08	Plasterboard	0.160	0.08
	0.025	Service Void		0.18	Timber Batten	0.140	0.18
	0.012	Vapour Control Layer	0.380	0.03	Vapour Control Layer	0.38	0.03
	0.160	Knauf Supafil Frame Blown-in Glass Mineral Wool Insulation	0.042	4.85	Timber Structure	0.140	1.14

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.040	Fixing Batten	0.140	0.29	Fixing Batten	0.140	0.29
	0.040	Timber Cladding	0.140	0.29	Timber Cladding	0.140	0.29
OUTSIDE		Surface resistance on external face					0.04
		U-value		**0.15**	**U-value**		0.31
Width/m		**0.05**			**0.035**		
Combined U-value							0.17

	Thickness of Material/m	Name of Building Material (Cavity)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W	Name of Building Material (Frame)	Conductivity K Value of Material W/mK	Resistance R Value of Element m^2K/W
INSIDE		Surface resistance on internal face					0.12
	0.012	Plasterboard	0.160	0.08	Plasterboard	0.160	0.08
	0.025	Service Void		0.18	Timber Batten	0.140	0.18
	0.012	Vapour Control Layer	0.380	0.03	Vapour Control Layer	0.38	0.03
	0.240	Straw Insulation	0.052	4.62	Timber Structure	0.140	1.71
	0.040	Wood Fibre Insulation Board	0.049	0.82	Wood Fibre Insulation Board	0.049	0.82
	0.040	Fixing Batten	0.140	0.29	Fixing Batten	0.140	0.29
	0.040	Timber Cladding	0.140	0.29	Timber Cladding	0.140	0.29
OUTSIDE		Surface resistance on external face					0.04
		U-value		**0.16**	**U-value**		0.28
Width/m		**0.05**			**0.035**		
Combined U-value							0.17

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