EXPERIMENTAL ANALYSIS OF THE THERMAL PERFORMANCE OF PLASTIC BAG-BASED INSULATION

By

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ABSTRACT

As the environment continues to change, global warming is impacting the way that we design buildings. There is a push for more efficient insulation materials and higher performance HVAC systems in order to reduce energy consumption. As this push continues, the consideration of the materials to create these high efficiency insulation materials, nor what they are made from, are being considered. This impact on the environment will also be significant.

However, it may be possible to reduce waste by reusing one of the most wasteful materials as an alternative insulation material. Single use plastic bags are one of the least recycled materials that humans have ever manufactured (Geyer et al, 2017). Moreover, the systems in place today for recycling film plastic have proven to be inefficient and costly, making it even less likely that the bags are being truly recycled in the end. However, due the thermally insulating properties that plastics are known for, the bags may hold a place in the building industry where they can live out a second life. Moreover, plastics with the longest lifetime distribution are those used in the building sector (Geyer et al., 2017), and re-using them inside buildings would prevent them from ending up in the environment where they can wreak havoc on ecosystems.

This report presents the findings of the thermal resistance (R-value) of the standard grocery store bag and how they compare with current insulation materials. It was determined through experimental process that the plastic bags can achieve a minimum of R-13. This project presents the different ways of utilizing recycled grocery bags to fill a wall cavity as an insulation material and how those different configurations compare to other popularly used insulation materials. This report will also outline findings for the best way to fill a wall cavity with plastic bags in order to achieve the highest R-value for the material. Finally, an analytical comparison considering material optimization is discussed regarding the different parameters of building insulation materials.

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ACKNOWLEGEMENTS

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Lastly, I would like to thank the major retailers, Meijer, Kroger, Target, and Walmart, whose plastic grocery bags I collected the most of. Without the lack of adequate plastic bag recycling programs and the overuse of single use plastic grocery bags, this project would not have been possible.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Climate Crisis and Building Envelopes

As global warming increases in severity, one must realize the impacts on not just the planet, but the building industry as well. As outdoor temperatures become more extreme it becomes more difficult to maintain comfortable indoor temperatures without using an excess of energy. In order to combat the loss of energy, building envelopes need to be developed to withstand future outdoor temperatures, not just current ones.

Further, by providing sufficient building envelopes (in the form of wall, roof, and floor constructions that are effectively insulating), thermal comfort can be achieved easier and require less thermal correction from the Heating, Ventilation, and Air Conditioning (HVAC) system. According to Alves et al., the energy demand required to meet thermal comfort levels in commercial buildings makes up almost 50% of the energy consumption of the whole building. Less thermal correction means that the HVAC system will not need to be oversized and can run more efficiently, reducing the energy demand and therefore the energy costs for the building. More importantly, reduction in the energy load of HVAC systems will result in less greenhouse gas emissions, resulting in less environmental impact (Alves et al.).

1.3 Background Information: The Bag Problem

Film plastics such as plastic bags are some of the most wasted plastic products. “In 2015 about 730,000 tons of plastic bags, sacks and wraps were generated (including PS, PP, HDPE, PVC & LDPE) in the United States, but more than 87% of those items are never recycled, winding up in landfills and the ocean” (Center for Biological Diversity, 2018). There are several different reasons for this statistic, but mainly this is due to the fact that film plastic is hard to recycle.

More often than not, film plastic can get mixed in with other commingled recyclables and can damage machinery meaning film plastic must be recycled on its own with a different process than other plastics. When it comes to recycling film plastic in general, the most viable option is chemical recycling. Chemical recycling releases fumes that are toxic to the environment and to the workers in the recycling plants (Greenpeace). Furthermore, chemical recycling still generates plastic waste and some plastics can only be “down recycled” due to the nature of plastics ability to absorb contaminants (Greenpeace).

Furthermore, the main reason for grocery store bags being banned in the states of New York and California boils down to the lack of evidence that grocery store chains are actually recycling the bags they collect to “recycle” for the public, with retailers admitting that they have collected plastics just to dispose of them (Greenpeace) due to the lack of resale market. A major part of the reason that there is very little market for recycled plastics is due to how “picky” corporations can be with producing products, with some requiring only certain colors of plastic, meaning that mixed color film simply would not be accepted. Moreover, if the collected plastics are dirty or contaminated with any kind of garbage (or unrecyclable plastics) the whole batch will usually just be tossed to landfill. Out of all the film plastic ever produced (4.83 million tons), only an estimated 9.1% has been recycled. (Tineo, 2020). In fact, only 1% of Americans even have access to film plastic recycling (Greenpeace).

Between 2015 and 2018 film plastic generation increased from 750,000 tons to 4,200,000 tons (Greenpeace). In 2018 72.4% of the film plastic produced went to landfill. When film plastic is left to degrade in landfill, the way it ends up breaking down is by photodegrading. This means that direct sunlight is required for the plastic to even begin to break down. However, photodegradation of film plastic is extremely harmful to the environment because it creates microplastics (Center for Biological Diversity). Microplastics continue to pollute the environment and with our current technology are impossible to clean up, easily contaminating food, water, and people due to how microscopic they are (UNEP.org 2023).

The circular process of recycling plastics, in particular film plastics, is overall, failing. On top of being “economically and operationally challenging” (Meert et al.) to recycle film plastics, it is also just cheaper to produce virgin plastic than to use recycled plastics. Most companies will just continue to purchase newly made plastics (Tineo, 2020), especially due to the fact that the cost of virgin plastics keeps getting lower because it is a cheap byproduct produced by the petrochemical industry. There will not be much of a market for recycled film plastic unless consumers demand it by only purchasing products made with recycled plastics or unless laws are made to regulate the usage of virgin film vs recycled plastic.

In conclusion, the theoretical “circular” system of plastic bag recycling is not a feasible solution to the current growing world of plastics, especially film plastics. The ultimate solution would be to stop producing the material due to how it threatens the very life on this planet. However, it is very unlikely that that will happen any time soon. A practical resolution for the mean time would be to find a way to “recycle” film plastics in a way that removes them from the current doomed cycle where they are likely to end up in a landfill or incinerated.

1.4 The Bag Solution

Another solution to prevent film plastics from breaking down in a landfill or the ocean may involve taking advantage of the thermal properties of plastic itself. Plastic is a material known to be a poor thermal conductor (used to make rigid foam insulation), and re-using it as an insulation material in buildings would remove it from the plastic cycle and prevent it from breaking down into microplastics in landfills or the oceans. Using the bags as insulation could provide a way to reuse them in a way that does not generate more plastic and helps deal with the bags that already exist.

According to Geyer et al. (2017) in the article “Production, Use, and Fate of all Plastics Ever Made,” plastics that are used in the building and construction industry are the category of plastic with the longest lifetime distribution (see Figure 1.3). If film plastics (which make up some portion of the “Packaging” category in Figure 1.3) were to be utilized in the building and construction industry, their product lifetime distribution would significantly increase. Ultimately, film plastics would be utilized in a much more efficient way and could afterwards be properly recycled in mass when the life of the building is over. Using film plastics as a building insulation would be taking a single use grocery store bag and getting a lifetime of use out of it.

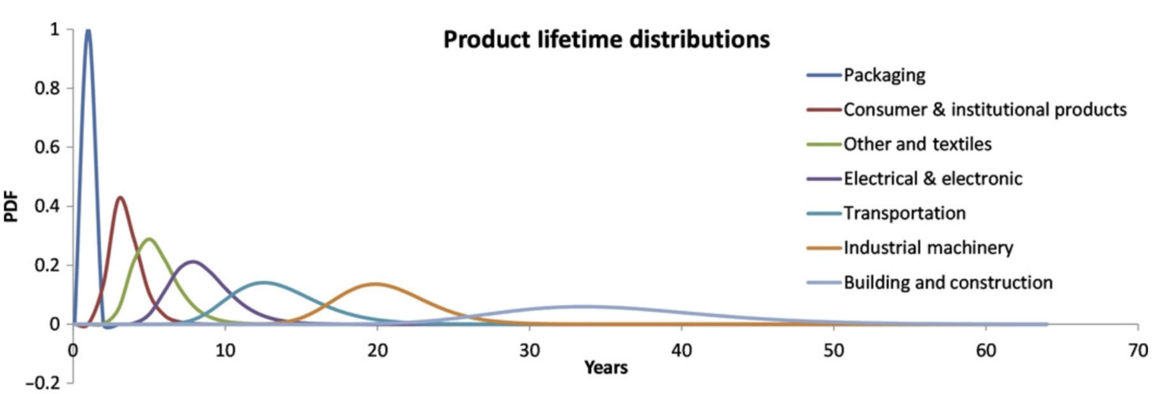


Fig. 1 **Product lifetime distributions for the eight industrial use sectors plotted as log-normal probability distribution functions (PDF).**

Figure 1.3: Product Lifetime Distributions (Geyer et al., 2017)

In conclusion, using film plastic within a wall cavity as an insulating material would prevent the bags from breaking down and generating microplastics in the environment. This solution would also give more time to figure out a better way to handle the material at the end of the building's life. In fact, if the bags do not break down or degrade at all within the wall cavity they may be able to be reused again and again in the same application, providing perhaps even more than a lifetime of use.

1.5 The Research Gap

One of the most important pieces of information that must be known about an insulation material before it can be used in construction is the R-value. Very little experimental study has been done to determine a working, standalone, R-value for recycled plastic bags. This piece of information is imperative to know before it can be determined if recycled plastic bags could make a suitable insulation that abides by International Energy Conservation Code. Further, it is important to consider where plastic bags compare to current insulation materials in terms of costs, performance, lifespan, and environmental impact.

CHAPTER 2: LITERATURE REVIEW

2.1 Insulation in Building Envelopes

One of the main properties of a good insulation material is a low thermal conductivity value. In other words, an efficient insulation does not allow heat to be transferred easily. As it gets more challenging to effectively maintain comfort due to global warming, the demand for higher R-value materials continues to grow. There are certain minimums depending on climate zone for different building component R-value and insulation requirements, as seen in can be seen in Figure 2.1. Per the International Energy Conservation Code (IECC) 2018, Table R402.12 (Figure 2.1), climate zones 1 and 2 can utilize a minimum R-value (in a wood frame wall or floor) of R-13 alone without any other insulation required. Further, R-13 can be used in conjunction with continuous insulation in all climate zones for a wood frame or mass frame wall. Michigan is in climate zone 5, so based on Figure 2.1, R-13 can be used in coincidence with continuous R-10 insulation.

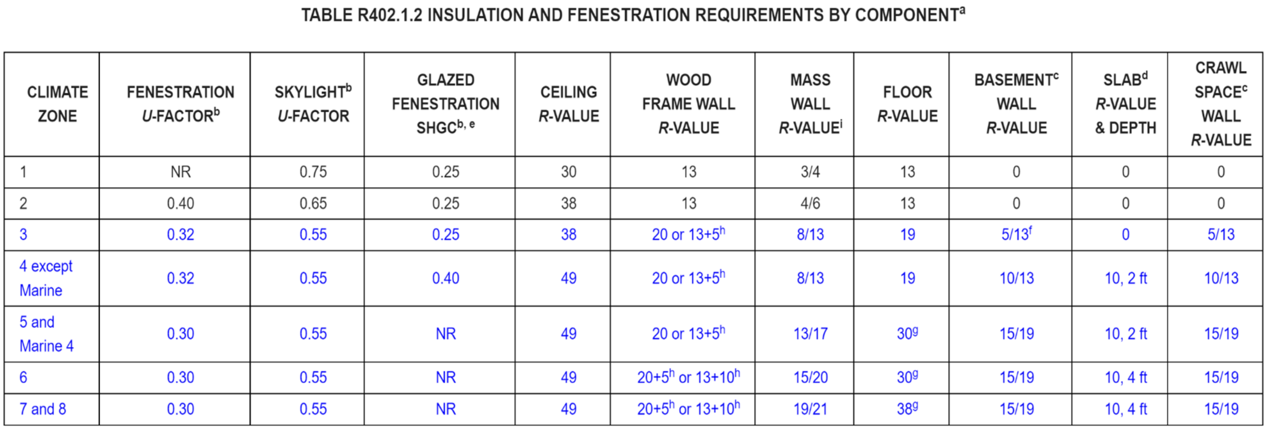


TABLE R402.1.2 INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT[a]

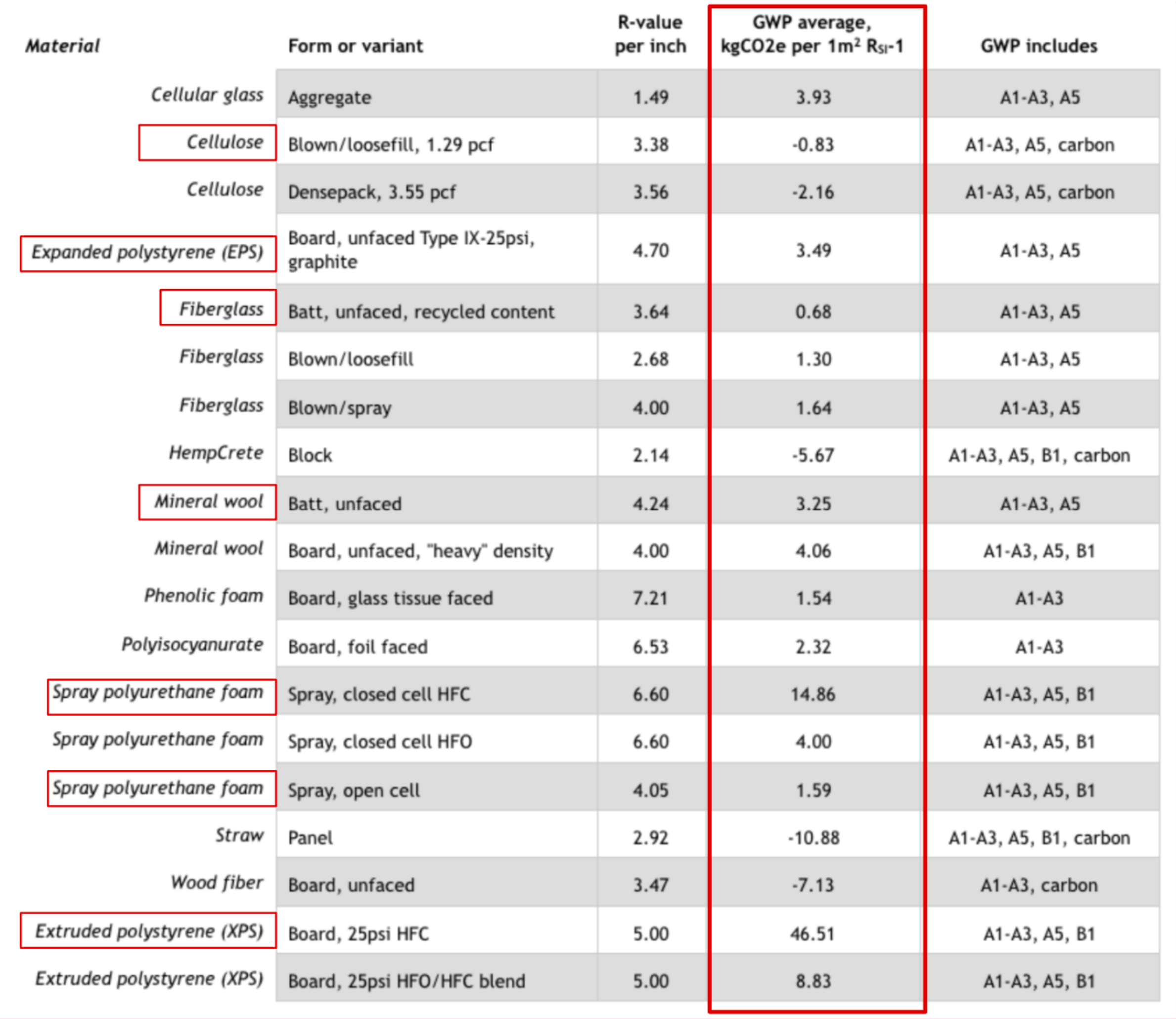
CLIMATE ZONE	FENESTRATION *U*-FACTOR[b]	SKYLIGHT[b] *U*-FACTOR	GLAZED FENESTRATION SHGC[b, e]	CEILING *R*-VALUE	WOOD FRAME WALL *R*-VALUE	MASS WALL *R*-VALUE[i]	FLOOR *R*-VALUE	BASEMENT[c] WALL *R*-VALUE	SLAB[d] *R*-VALUE & DEPTH	CRAWL SPACE[c] WALL *R*-VALUE
1	NR	0.75	0.25	30	13	3/4	13	0	0	0
2	0.40	0.65	0.25	38	13	4/6	13	0	0	0
3	0.32	0.55	0.25	38	20 or 13+5[h]	8/13	19	5/13[f]	0	5/13
4 except Marine	0.32	0.55	0.40	49	20 or 13+5[h]	8/13	19	10/13	10, 2 ft	10/13
5 and Marine 4	0.30	0.55	NR	49	20 or 13+5[h]	13/17	30[g]	15/19	10, 2 ft	15/19
6	0.30	0.55	NR	49	20+5[h] or 13+10[h]	15/20	30[g]	15/19	10, 4 ft	15/19
7 and 8	0.30	0.55	NR	49	20+5[h] or 13+10[h]	19/21	38[g]	15/19	10, 4 ft	15/19

Figure 2.1: Table R402.1.2 Insulation and Fenestration Requirements by Component (IECC, 2018)

Further, as long as the insulation meets code requirements it is generally permissible. When it comes to building materials, insulations can be made from a multitude of different materials, depending on the desired R-value of the wall construction, costs, desired environmental impact, and project specific needs. The insulation materials researched to assess these properties and compare to the properties of recycled plastic bags include: fiberglass, cellulose, mineral wool, natural fiber (sheep's wool), spray foam (open cell), spray foam (closed cell), expanded polystyrene (EPS), and extruded polystyrene (XPS).

2.2. Current Building Insulations Environmental Impact

Insulation properties should not just be judged on their performance, lifetime, and costs. The process in which the materials are produced can also have huge impacts on the environment. The GWP for the materials discussed in this section can be seen in Figure 2.2.



Material	Form or variant	R-value per inch	GWP average, kgCO2e per 1m^2 R_{SI}-1	GWP includes
Cellular glass	Aggregate	1.49	3.93	A1-A3, A5
Cellulose	Blown/loosefill, 1.29 pcf	3.38	-0.83	A1-A3, A5, carbon
Cellulose	Densepack, 3.55 pcf	3.56	-2.16	A1-A3, A5, carbon
Expanded polystyrene (EPS)	Board, unfaced Type IX-25psi, graphite	4.70	3.49	A1-A3, A5
Fiberglass	Batt, unfaced, recycled content	3.64	0.68	A1-A3, A5
Fiberglass	Blown/loosefill	2.68	1.30	A1-A3, A5
Fiberglass	Blown/spray	4.00	1.64	A1-A3, A5
HempCrete	Block	2.14	-5.67	A1-A3, A5, B1, carbon
Mineral wool	Batt, unfaced	4.24	3.25	A1-A3, A5
Mineral wool	Board, unfaced, "heavy" density	4.00	4.06	A1-A3, A5, B1
Phenolic foam	Board, glass tissue faced	7.21	1.54	A1-A3
Polyisocyanurate	Board, foil faced	6.53	2.32	A1-A3
Spray polyurethane foam	Spray, closed cell HFC	6.60	14.86	A1-A3, A5, B1
Spray polyurethane foam	Spray, closed cell HFO	6.60	4.00	A1-A3, A5, B1
Spray polyurethane foam	Spray, open cell	4.05	1.59	A1-A3, A5, B1
Straw	Panel	2.92	-10.88	A1-A3, A5, B1, carbon
Wood fiber	Board, unfaced	3.47	-7.13	A1-A3, carbon
Extruded polystyrene (XPS)	Board, 25psi HFC	5.00	46.51	A1-A3, A5, B1
Extruded polystyrene (XPS)	Board, 25psi HFO/HFC blend	5.00	8.83	A1-A3, A5, B1

Figure 2.2: Summary of Global Warming Potential and R-values for Frequently Used Construction Materials (Just, 2021).

2.2.1 XPS and EPS

Performance does not necessarily correlate with R-value. In fact, the only correlation between R-value and embodied carbon can be seen in Figure 2.3. Figure 2.3 provides a visual for how the embodied carbon in the selected insulations actually appears to increase with the higher value of thermal resistance. This pattern can be seen in excess for the older versions of XPS.

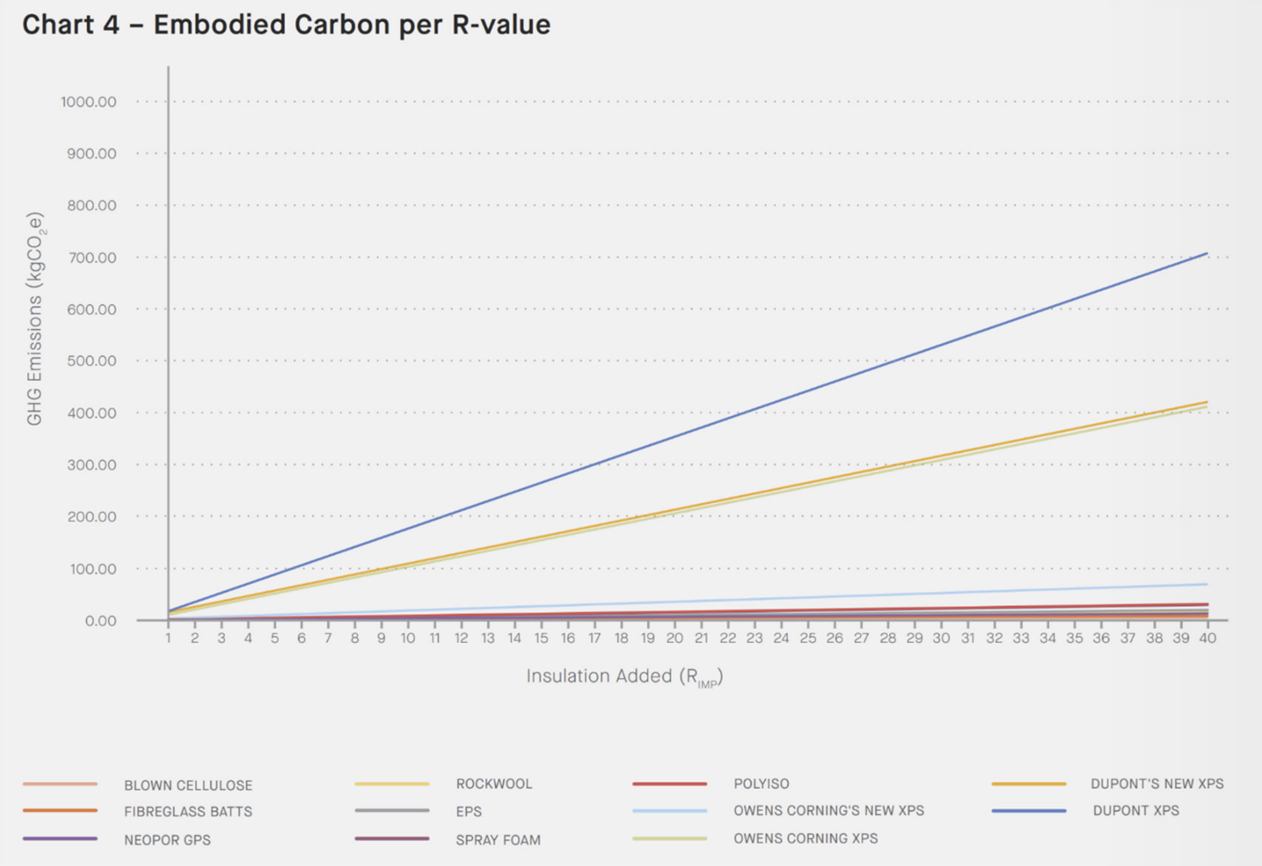


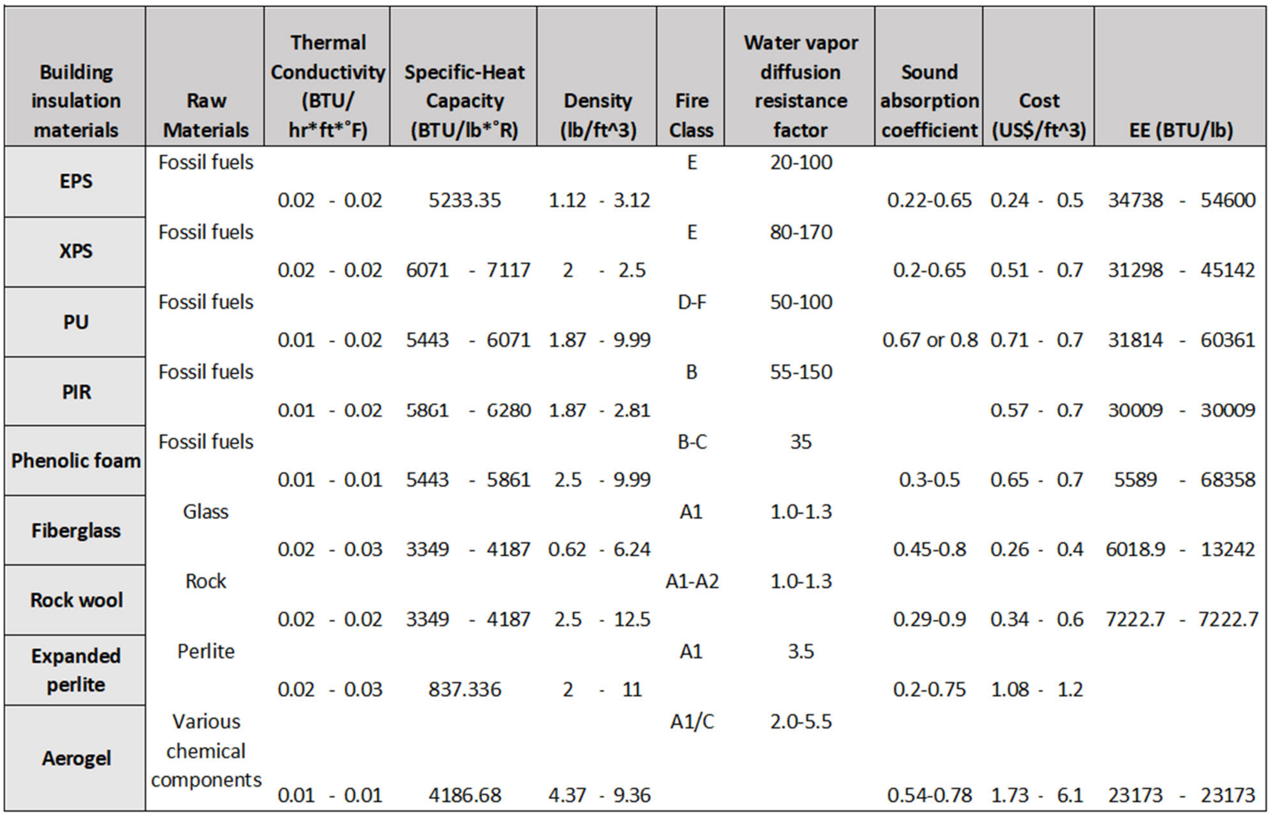
Figure 2.3: Chart 4 – Embodied Carbon Per R-Value (Turnbull et al.)

In fact, one of the insulators that is considered to be the best is actually one of the worst options for the environment. XPS is a type of styrofoam wall insulation manufactured from plastic and resin using a blowing agent called hydrochlorofluorocarbons (HCFCs), which are known to have a high factor of Global Warming Potential due to the dangerous gasses released upon burning. When subjected to a lifecycle analysis, XPS "behaved worse than EPS, PU, expanded cork agglomerate, expanded clay lightweight aggregates or mineral wools" when it came to both Global Warming Potential factors and Ozone Depletion Potential factors. (Zhao et al.).

XPS is made from plastic because plastic itself is known to be a poor conductor (ie, has a low coefficient of thermal conductivity). However, with the rise of environmentally friendly insulation alternatives becoming more available, some have chosen to stray away from the usage of plastics in preference for wool, cellulose, or other natural materials. These materials have been substituted in place of "better" products (such as XPS), regardless of having relatively poorer performance. Natural or alternative insulations are not necessarily “bad” insulators, they just do not provide the same thermal resistance of styrofoams derived from plastics. Still, this is a disadvantage that many are willing to take if it means the insulation is better for the environment.

Furthermore, XPS insulation cannot be recycled and is the largest contributor of the plastic waste generated by the building industry. Additionally, plastic insulations are made using fossil fuels, an unsustainable source (Zhao et al.). Table 2.4 details the most common insulation material originations, and as one can see over half of the insulations listed are derived directly from fossil fuels.

Table 2.1 – Performance Characteristics of Common Building Insulation Materials Used in Exterior Walls (Converted into IP units with values sourced from Zhao et al.)



Building insulation materials	Raw Materials	Thermal Conductivity (BTU/ hr*ft*°F)	Specific-Heat Capacity (BTU/lb*°R)	Density (lb/ft^3)	Fire Class	Water vapor diffusion resistance factor	Sound absorption coefficient	Cost (US$/ft^3)	EE (BTU/lb)
EPS	Fossil fuels	0.02 - 0.02	5233.35	1.12 - 3.12	E	20-100	0.22-0.65	0.24 - 0.5	34738 - 54600
XPS	Fossil fuels	0.02 - 0.02	6071 - 7117	2 - 2.5	E	80-170	0.2-0.65	0.51 - 0.7	31298 - 45142
PU	Fossil fuels	0.01 - 0.02	5443 - 6071	1.87 - 9.99	D-F	50-100	0.67 or 0.8	0.71 - 0.7	31814 - 60361
PIR	Fossil fuels	0.01 - 0.02	5861 - 6280	1.87 - 2.81	B	55-150		0.57 - 0.7	30009 - 30009
Phenolic foam	Fossil fuels	0.01 - 0.01	5443 - 5861	2.5 - 9.99	B-C	35	0.3-0.5	0.65 - 0.7	5589 - 68358
Fiberglass	Glass	0.02 - 0.03	3349 - 4187	0.62 - 6.24	A1	1.0-1.3	0.45-0.8	0.26 - 0.4	6018.9 - 13242
Rock wool	Rock	0.02 - 0.02	3349 - 4187	2.5 - 12.5	A1-A2	1.0-1.3	0.29-0.9	0.34 - 0.6	7222.7 - 7222.7
Expanded perlite	Perlite	0.02 - 0.03	837.336	2 - 11	A1	3.5	0.2-0.75	1.08 - 1.2	
Aerogel	Various chemical components	0.01 - 0.01	4186.68	4.37 - 9.36	A1/C	2.0-5.5	0.54-0.78	1.73 - 6.1	23173 - 23173

Moreover, “it was estimated that 25% of global polymer products were manufactured for application in buildings in the past 30 years,” and on top of that, the usage of XPS and polyurethane spray foam insulations is expected to grow in 2023 (Zhao et al.). That is a large amount of product being derived from virgin plastics, i.e. made directly from fossil fuels. To make matters worse, XPS is prone to thermal drift, wherein over time the R-value actually drops over time due to the gasses in the foam leaking out (Energy.gov, 2023) – meaning that the usage of virgin plastics to produce the material do not even maintain their peak performance, ultimately resulting in replacement. The GWP for XPS per Figure 2.2 is the highest out of all the materials shown, at 46.61. The emissions for XPS insulation can be seen in Figure 2.4, wherein the legacy formulation can be observed to have extraordinarily high emissions compared to other foam board insulations (as well as non-foam board insulations in Figure 2.6).

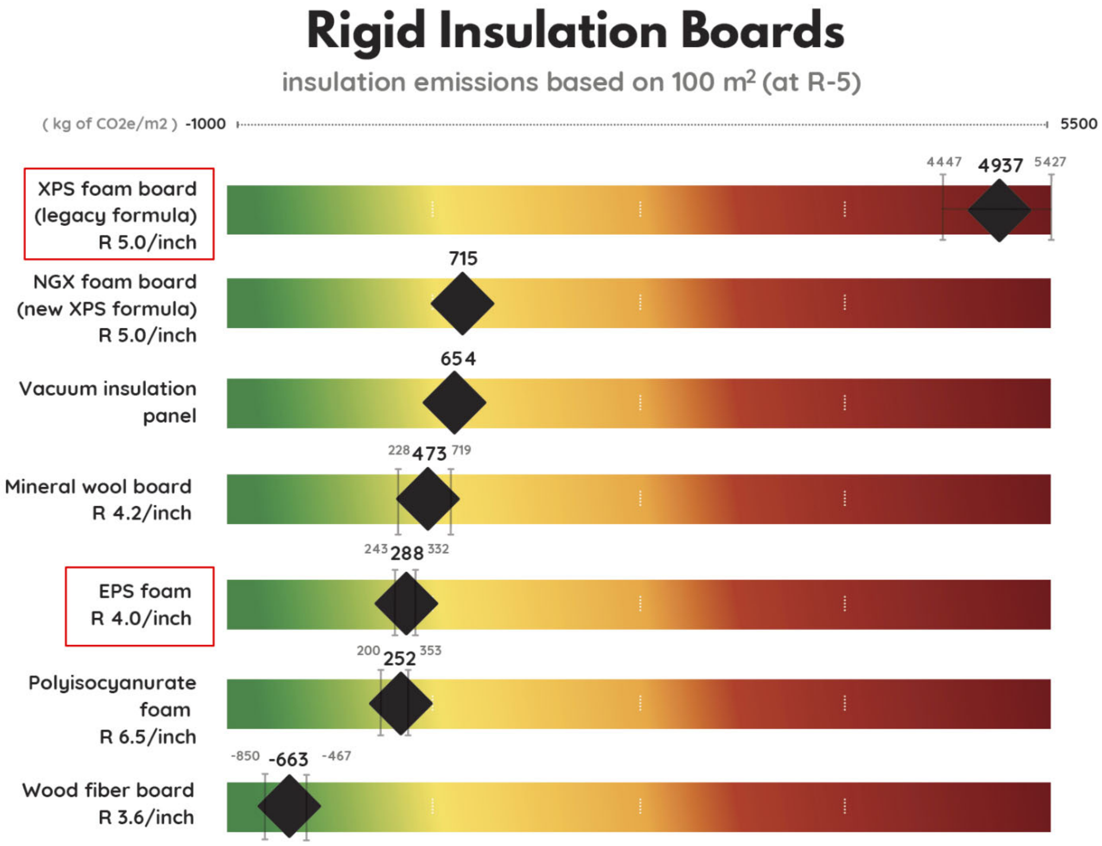


Figure 2.4: Rigid Insulation Boards (Magwood et al, 2022)

Figure 2.4 also shows the emissions for the other major rigid insulation board, EPS foam. Expanded polystyrene (EPS) is a rigid foam board insulation that is made by fusing together small plastic beads. The insulation is manufactured in blocks that are then cut to the appropriate sizes for the desired thickness (Energy Saver, 2023). EPS generally has an R-value of R-4 per inch, and due to its moisture resistance, it can be used to prevent thermal bridging. EPS foam is notably lower in emissions than XPS because it does not require the use of HFCs and molten plastic to produce. However, it is still derived from virgin plastics (Table 2.1) and due to the "bead" structure of the material it is prone to producing microplastics upon breaking down (Sanjoserecycles.org, 2023). Moreover, EPS is not a recyclable material, so at the end of a building's life (upon deconstruction), the EPS insulation will likely just be disposed of.

Furthermore, it can also be observed for both XPS and EPS that the Fire Class Rating of the Material is Class E (Table 2.1), which is defined as "combustible" with a high contribution to fire (Knauf Insulation, 2023). See Figure 2.5 for definitions of each respective Fire Class. While fire testing is not within the scope of this project, it is important to keep this in mind when considering insulations made from plastic. The information on plastic bag insulations reaction and resistance to fire it not yet tested, however even if it is "combustible" that property would not be outside of the norm of popular insulations used in buildings. Moreover, the fact that one of the most popular and best performing insulation materials is not only made from virgin materials but is Fire Class E seems excessively dangerous.

Degree of flammability

A1 = non-combustible, No contribution to fire

A2 = limited combustibility,
Very limited contribution to fire

B = Combustable, Limited contribution to fire

C = Combustable, Minor contribution to fire

D = Combustable, Medium contribution to fire

E = Combustable, High contribution to fire

F = Combustable, Easily flammable

Figure 2.5: Reaction to Fire (Knauf Insulation, 2023)

The other insulation materials considered are not considered to be "rigid" styrofoam boards, however the environmental factors are present in other facets that contribute to the embodied emissions of the materials. In Figure 2.6, the emissions data can be seen for the other common insulation materials discussed in this work: spray foam (open and closed cell), mineral wool, fiberglass, and cellulose.

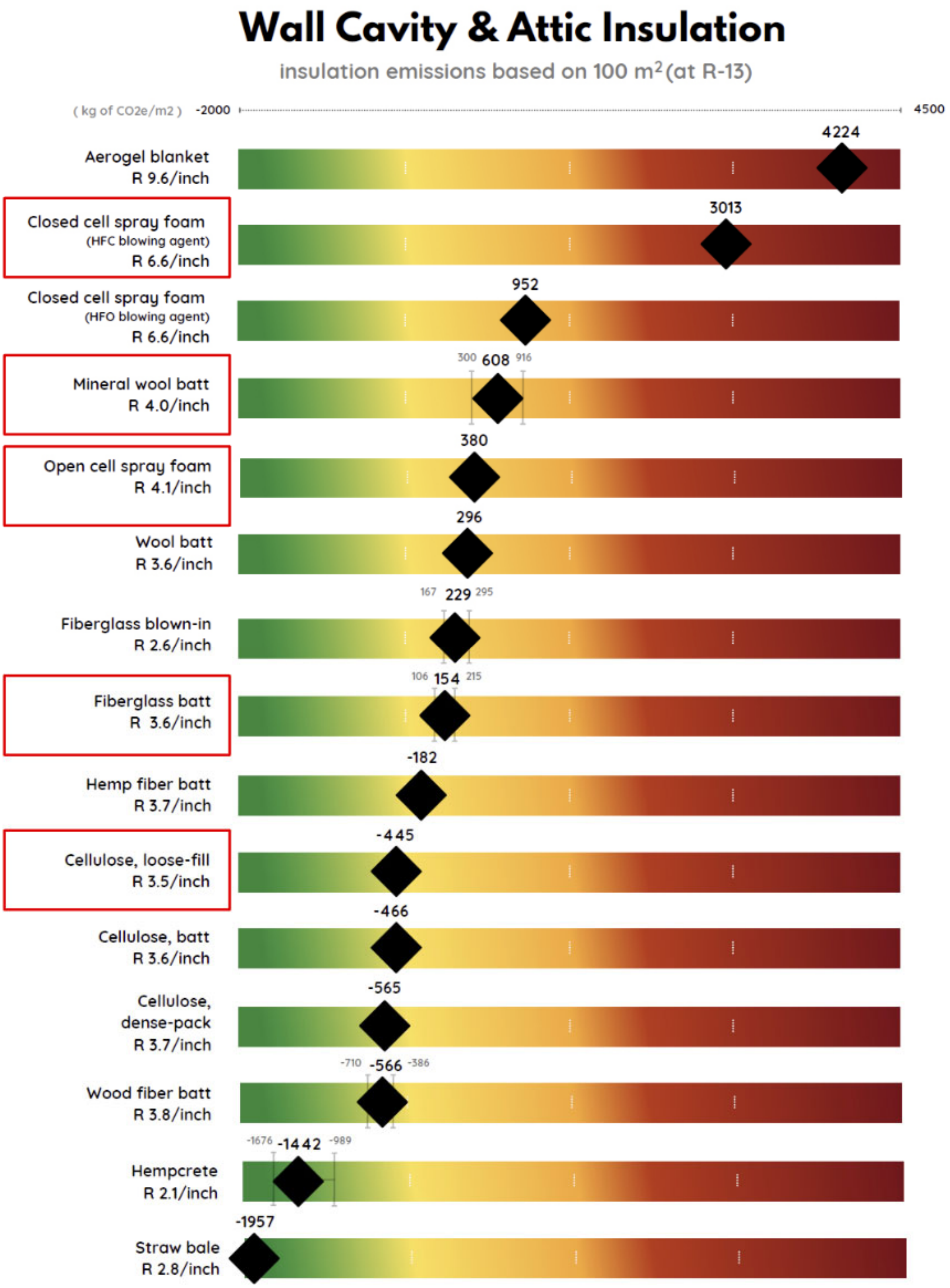


Figure 2.6: Wall Cavity & Attic Insulation (Magwood et al, 2022)

2.2.2 Closed Cell Spray Foam

Spray foam made from polyurethane is better for existing constructions as it can be sprayed directly into any cracks and around existing framework and piping. Closed cell spray foam insulation is generally composed of zero recycled content and cannot be recycled at the end of its working life. Closed cell spray foam is also derived from fossil fuels and is manufactured using chlorine. Further, the foam requires HFCs to create the gas pockets in the material and must use certain flame retardants that are "probable human carcinogens" according to the U.S. Consumer Product Safety Commission and "moderate hazards" to human reproductive and development effects (Wilson, 2021). Per Figure 2.6, the emissions for closed cell spray foam is the second only to the legacy formula of XPS, in the well above average range. The GWP is also unsurprisingly at 14.86 (Figure 2.2).

2.2.3 Open Cell Spray Foam

Open cell spray foam insulation is significantly better for the environment than closed cell. However, it also usually has a recycled material content of zero, and it still unrecyclable at the end of its working life (Wilson, 2021). Moreover, it is also produced using fossil fuels and the uses same chlorine and flame retardant in manufacturing as closed cell. The main difference between the two (closed and open cell) insulations is that the open cell option uses water as its blowing agent instead of HFCs (Wilson, 2021). As can be seen in Figure 2.5, the emissions for open cell spray foam is solidly in the average range and the GWP is 1.59 (Figure 2.2).

2.2.4 Fiberglass

Fiberglass, or batt insulation, is made from glass fibers and resin. Fiberglass is known for being relatively quick and easy to install, and is a common go-to choice for residential applications (Habas, 2021). Fiberglass has an R-value of R-3.7 per inch, and also requires the installation of a vapor barrier because the material is highly susceptible to performance degradation due to moisture permeance. According to the EPA, most of the emissions generated from using fiberglass as an insulation material are from processing the raw materials into the final product, which historically has had formaldehyde emissions. However, all of the fiberglass production in North America is now converted to use non-formaldehyde binders for loose-fill and batts. Depending on the manufacturer, fiberglass can actually be up to 40 to 60% recycled material that has been repurposed from glass production plants (Wilson, 2021). As seen in Figure 2.6, the emissions for fiberglass are slightly below the average range, and the GWP is listed as 0.68 in Figure 2.2.

2.2.5 Mineral Wool

Mineral wool insulation is made from either iron ore slag or molten rock that has been spun into fibers. Those fibers are then coated with a binder and then can be formed into batts or even rigid boards (Wilson, 2021). For this project, only the batts are considered for comparison. While mineral wool insulation can contain up to 90% recycled material, the energy consumption required to melt the materials down is considerably high, resulting in higher embodied energy and carbon. Furthermore, formaldehyde is also used as a binder and can be released during the process of the material curing (Wilson, 2021). Figure 2.6 shows that the emissions for mineral wool are higher than fiberglass due to these factors, much more solidly in the average range. Figure 2.2 lists the GWP for mineral wool at 3.25.

2.2.6 Sheep Wool

Sheep's wool insulation is the only insulation material that is completely sustainable and renewable, requiring no finite resources to produce. However, there are still environmental concerns. Sheep farms require lots of water and pesticides to run, and can produce methane emissions. Still, the methane emissions produced are much smaller than that of manufactured insulation products (Wilson, 2021). Since sheep's wool is not a large-scale insulation product, the emissions are not exactly a known and calculated parameter. Moreover, since the production of sheep's wool insulation is comparatively so small, sustainable, and requires minimal processing, the emissions and GWP are assumed to be a benchmark zero for this project.

2.2.7 Cellulose

Cellulose insulation is generally made from recycled paper and cardboard, and has a better R-value than both fiberglass and mineral wool (R-3.65 per inch). However, it can be impractical and expensive to install; cellulose insulation requires special installation procedures and the process can be impractical and time consuming. Cellulose insulation is made up of 80% recycled content with low energy required to manufacture (Wilson, 2021), granting it a much lower GWP and much lower emissions. In fact, both values seen in Figure 2.2 and Figure 2.6, respectively, are in the negatives. Moreover, most cellulose can usually be found regionally so little to no emissions are required for transportation (Wilson 2021).

2.3 How R-Value is Determined Experimentally

According to The American Society for Testing and Materials (ASTM), R-value testing should be in line with the standard ASTM C518-21: "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus." This standard defines that the approved method for determination of the R-value of an insulation is by using a heat flow meter. A heat flow meter is a device that determines the thermal conductivity coefficient of a material. The device consists of two plates, one hot and one cold, that create a temperature gradient within the material using a Peltier System. A Peltier System is also known as "thermoelectric modules" precisely control the temperature of the heating and cooling plates (Rose, B. 2023). An example of the Peltier System can be seen in Figure 2.7.

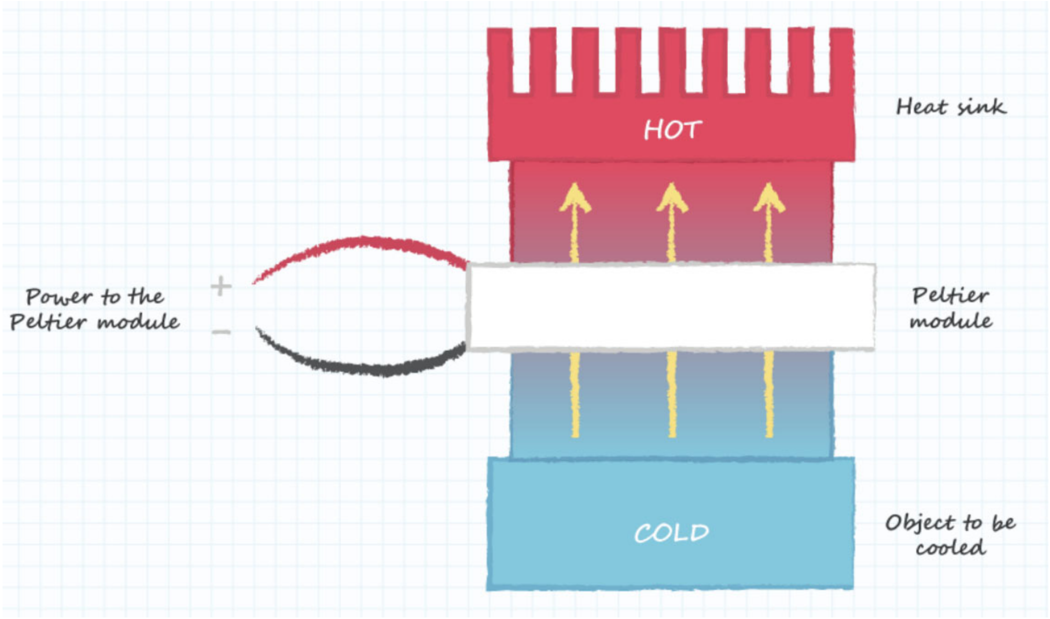


Figure 2.7: Typical Heat Flow Through a Peltier Module (Rose, 2023).

In other words, the Peltier system controls the exact temperature of the two plates by controlling the cooling and heating loads on either side of the device. Heat flux transducers placed center to center between the plate and the materials capture the temperature gradient. A typical heat flow meter system can be seen illustrated in Figure 2.8, from Netzsch's ASTM C518-21 compliant heat flow meter system.

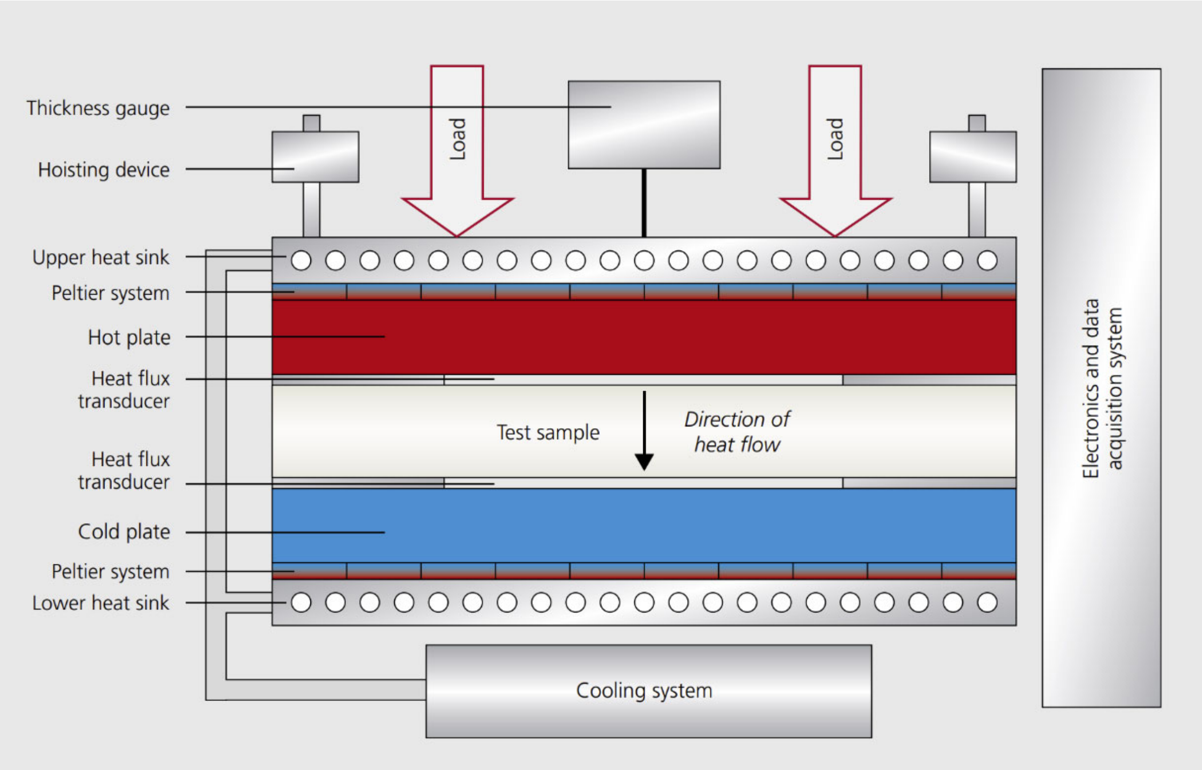


Figure 2.8: Schematic Design of the NETZCH HFM 436/3/1 *Lambda,* (Netzsch).

When testing, every insulation material will respond differently and therefore will have a different gradient respective to said materials' coefficient of thermal conductivity. That being said, even when using a heat flow meter, it is still important to calibrate it using a known material in order to get accurate results. The heat flow meter device still needs a comparative "known" material to reference in order to calculate a new materials R-value.

2.4 General Overview of Recycled Materials in The Engineering Field

Recycled materials can be used in the engineering field fairly effectively, particularly in buildings. In fact, LEED encourages the use of recycled materials in new construction and offers up to two credits for utilization of recycled materials. One credit may be earned by using a minimum of 25% of building material that is made up of aggregate containing "a minimum weighted average" of 20% recycled post-consumer material (USGBC.org 2023). Recycled post-consumer material is generally made up of material that the general consumer (person) recycles. Another way to achieve this credit is by utilizing 25% of building material made of "a minimum weighted average" of 40% of post-industrial recycled materials (USBGC.org 2023). Post-industrial recycled material is recycled material resulting from industrial processes. An additional credit is available if the building also uses *an additional* 25% of building materials containing “a minimum weighted average” 20% recycled aggregate. The other option to achieve the additional credit is by having an additional 25% of building material made up of “a minimum weighted average” of 40% of post-industrial recycled material (USGBC.org 2023).

Steel and concrete are some of the most recyclable building materials. In fact, steel itself is 93% recycled and can be recycled over and over again, making is an entirely sustainable material (AISC.org 2023). However, there is still the cost of energy that it takes to reprocess to consider, and what source that energy is produced from. Concrete on the other hand can be directly crushed and reused as aggregate in more concrete with no heating required (Concrete.org 2023). There is still energy required for the recycling of concrete but it is not nearly as much as steel.

Demolition waste recycling is one way that a building can integrate recycled content. When a building is demolished, building materials that are still in good condition can be reused again in a new building, resulting in an increase in grey energy savings for most applications (Gruhler and Schiller 2023). However, there may be issues with this due to the degradation of materials over time resulting in increased energy usage to maintain the building. In this case, the materials the “maintain their characteristics” throughout their working life should not be treated the same as materials that are prone to degradation (Vefago and Avellaneda 2013). Another barrier to demolition waste reuse and recycling is that are not currently standard process chains for the demolition of buildings in ways that allow for harvesting of the materials (Gruhler and Schiller 2023).

Edun and Hachem-Vermette (2022) assess recycling tires, PET, and paper and cardboard as building materials in terms of their respective performance of interior paneling, thermal massing, and insulation in a cold environment. Based on the findings about the performance of the materials it was concluded that when recycling post-consumer materials, low energy processing options should be prioritized, with their preference to use whole tires and bottles. Further, the thermal massing properties of the recycled materials can actually be more beneficial than the insulating properties (Edun and Hachem-Vermette 2022).

Generally, recycled materials are acceptable in building construction when they are capable of maintaining their performance, and the parameters of that performance depend on the exact application. For instance, materials recycled for structural purposes need to be capable of maintaining their physical properties of strength and durability. Materials recycled for their insulating properties need to be capable of maintaining the performance of their thermal resistance and sometimes even their moisture resistance. Edun and Hachem-Vermette (2022) found that the energy it took to turn the recycled tires into a chipped product resulted in it being less sustainable. Therefore, it is also important to consider the processing requirements of the recycled material as well because heavy energy requirements may negate any benefits.

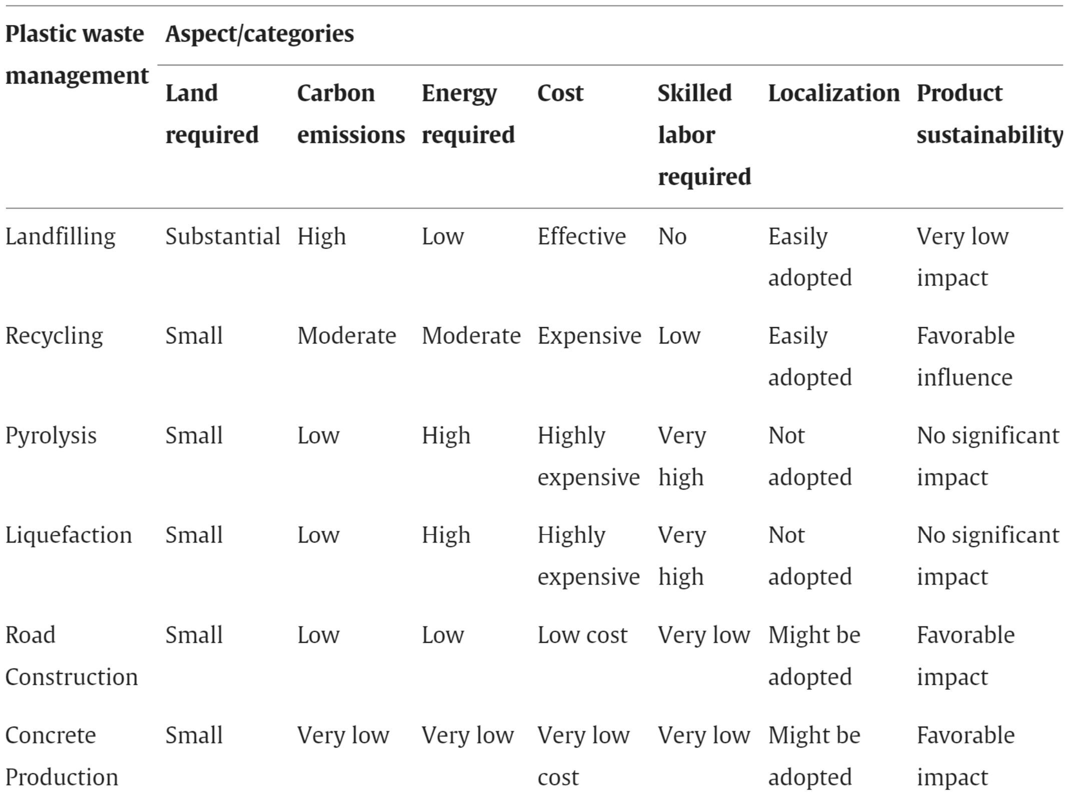
2.5 Previous Research on Recycled Plastic in Building Construction

The recycling of plastics in building construction not only prolongs the lifecycle of the waste, but is also increases its value (Nyika and Dinka 2022). Another aspect of utilizing recycled plastics in building construction is the lack of a need for transportation. In other words, waste plastic can likely be found locally. According to Nyika and Dinka (2022), innovative approaches (such as reusing plastic as building materials) "to channel plastic wastes away from landfills are imperative" to reducing both plastic waste in landfills and atmospheric pollution due to transportation. This is especially true since (as mentioned previously) plastics used within the building sector have the longest lifetime distribution.

2.5.1 Recycled Plastics as an Aggregate

When it comes to recycled plastics as a material in new building construction, there have been a multitude of implementation strategies. According to Nyika and Dinka (2022), recycled plastics can be used in building construction in conjunction with other material compositions, or even by themselves. Recycled plastics can be used to make asphalt, tiles, blocks, bricks, door panels, geosynthetics, insulation materials, bitumen, and cementitious composites. However, mainly hard plastics are used because softer plastics such as PET are much more difficult to sort and process. Generally, hard plastics (resins, LDPE, PVC, PS, PP, HDPE, and PLA) are recycled and can be used as aggregates in composites (Nyika and Dinka 2022). When used as composites, recycled plastic aggregates can decrease the thermal conductivity of the concrete as well as reduce the weight, usually at the cost of the concrete's strength (Nyika and Dinka 2022).

Furthermore, the impacts of reusing plastic in the form of concrete can be seen in Figure 2.9 from Jawaid et al, 2023. It can be observed from Figure 2.9 that the carbon emissions for reusing waste plastic in concrete construction is very low, with very low energy required and very low cost.



Plastic waste management	Aspect/categories						
	Land required	Carbon emissions	Energy required	Cost	Skilled labor required	Localization	Product sustainability
Landfilling	Substantial	High	Low	Effective	No	Easily adopted	Very low impact
Recycling	Small	Moderate	Moderate	Expensive	Low	Easily adopted	Favorable influence
Pyrolysis	Small	Low	High	Highly expensive	Very high	Not adopted	No significant impact
Liquefaction	Small	Low	High	Highly expensive	Very high	Not adopted	No significant impact
Road Construction	Small	Low	Low	Low cost	Very low	Might be adopted	Favorable impact
Concrete Production	Small	Very low	Very low	Very low cost	Very low	Might be adopted	Favorable impact

Figure 2.9 - Qualitative Impact of Different Plastic Waste Management Processes on Various Categories (Jawaid et al. 2023)

When comparing the properties of recycled plastic in concrete production to regular recycling, it is much cheaper and requires less energy (Jawaid et al 2023). This is due to the way that plastic waste is usually recycled, which can be complex and require chemical breakdown depending on the type of plastic. The production of hard plastic into aggregates only requires mechanical breakdown of the plastic rather than any heat or chemical requirements. However, both recycling and concrete production have favorable impact in terms of product sustainability (Jawaid et al 2023).

Almhesal et al. did further studies on recycled plastic as a fine aggregate within a concrete mixture. The fine plastic aggregates were used in place of a portion of the sand within the mixture. It was found that as the amount of plastic aggregate increases within the mixture, thermal conductivity decreased by up to 86%. However, due to the presence of the plastic particles within the concrete, the mixture did increase in flammability. The presence of the plastic aggregates also decreased the structural properties of the concrete, such as the compressive strength, etc.

Another study on the integration of waste plastic as an insulating component in composites was conducted by Corinaldesi et al. In this research, recycled plastic in the form of small recycled beads of various sizes was integrated into a lightweight plaster in order to fully replace any virgin materials. This research concluded that the thermal resistance and moisture permeability of the new composite extremely decreased due to the presence of the recycled plastic. The conclusions of Almhesal and Corinaldesi suggest that while recycled plastic may not be the best structural substitution, the thermal and moisture resistance properties can absolutely be taken advantage of as an insulation. However, film plastic is much more difficult to recycle and therefore would not make a suitable aggregate or powder to mix into a plaster.

2.5.2 Recycled Plastic in Eco-Bricks

Eco-bricks are another way to integrate waste plastic into building construction. The term "eco-brick" is used to cover a large range of recycled materials formed into bricks. Vigneshwar et al (2023) presents a study on eco-bricks made from plastic bottles filled with fly-ash as a structural component, finding that in comparison to regular bricks, the compressive strength is better and the cost is significantly lower. However, according to Barman et al, eco-bricks can also be defined as plastic bottles filled with other plastic, soil, foams, cellophanes, and other inorganic waste materials. These types of eco-bricks are especially good low-cost building materials for regions where waste dumping is a huge problem. (Barman et al 2022). Barman et al (2022) also generates a type of sand-based brick that utilizes film plastics specifically at different ratios to assess the properties that the bags effect. In order to make this type of eco-brick, the film plastic was melted down and mixed with sand while still molten. An image of the new eco-bricks can be seen in Figure 2.9.

Figure 2.9: Plastic Sand Brick (Barman et al. 2022)

Barman et al (2022) also found that the integration of sand likely added a fire resistance factor to the bricks as they did not burn at all, but rather "deteriorated" at extremely high temperature. However, the heating requirement of the plastics in order to recycle them would result in more energy requirements and potential release of hazardous fumes. While this construction method may be beneficial to regions where plastic waste is unfortunately dumped, the process is not advisable.

Barman et al (2022) also tested another type of eco-brick that compromises of plastic bottles packed with compacted film plastics of all types, ranging from food wrappers to cling wrap. The cleaned bottles, after being packed with the plastic film, are then capped and used in structural applications. The resulting eco-brick was found to have comparable compression strength to that of concrete blocks.

2.5.3 Recycled Styrofoam

Styrofoam is a packaging plastic foam very similar to EPS. Orlik-Kożdoń (2017) looked at the specifics of recycled stryofoam as a thermal insulation. Styrofoam waste granulate was formed into a flexible plate with an aluminum cover for testing. The new insulation material was tested in a lab and the results of which were then used in WUFI for a comparative analysis. Based on the analysis it was found that the flexible plates would make an insulation comparable to rockwool, concluding that the reuse of recycled wastes in building construction provides a way to keep a large amount of plastic from landfill (Orlik-Kożdoń (2017).

Solid waste plastic packaging was also researched as a basement slab on grade insulation by Megri et al., finding that "the quantitative values of the heat loss through the ground from the building floor demonstrate the effective performance of the rigid polyethylene packing waste insulation and substantiate the pertinence of its use." However, no documentation specified what type of plastic waste packaging was used, so it is assumed that likely styrofoam packaging would have yielded such results.

2.5.4 Recycled Film Plastics

Students at the University of Oregon conducted a study to determine the R-value of plastic bags to be used as wall insulation. These students constructed a guarded hot box, i.e. a box that heats on one side and cools on the other, and thermocouples to determine the amount of heat that went through the wall containing the bags based on temperature changes. The bags were crammed into the wall cavity to a density of about 151 bags per cubic foot. This study achieved an R-value of R-9.43 (Meier et al 2007).

While this study did find an R-value for the bags, they were only tested with one kind of arrangement: crammed into a wall haphazardly. Further, the amount of air that could have been in the cavity was not considered. It is very likely that if the bags were compressed within the wall to remove air content, more bags could have achieved a higher density and therefore a higher R-value. Furthermore, different arrangements within the wall cavity should be tested. Rather than simply stuffing them into the wall they could be laid flat and stacked in order to utilize as many barriers as possible between the indoors and out, therefore preventing heat flow through the wall. This study also concluded that future research should consider shredding the bags in order to compact them further and achieve a higher R-value, which will also be considered with this project.

Plastic bags have also been considered as a composite to improve the properties of expanded polystyrene (EPS). Fard et al. conducted a study to see how plastic bags utilized within a wall cavity influence water absorption and fire resistance when layered with expanded polystyrene to create a new composite. This experiment recycled the bags into plastic sheets by heat treating them at 50 degrees Celsius before layering them between the EPS. Two composites were created, one with 3 layers of EPS and one with 2 layers of EPS. Figure 2.10 shows the two composites compared side by side. Figure 2.11 shows the process of creating the panels and the composition of each panel.

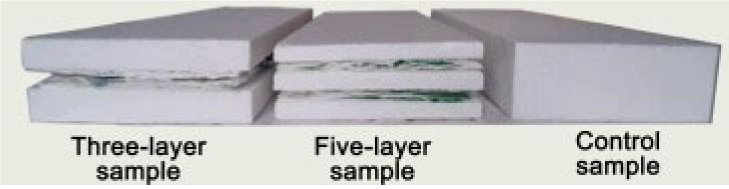


Figure 2.10: The three types of samples with different content of plastic wastes and EPS (Fard et al., 2021).

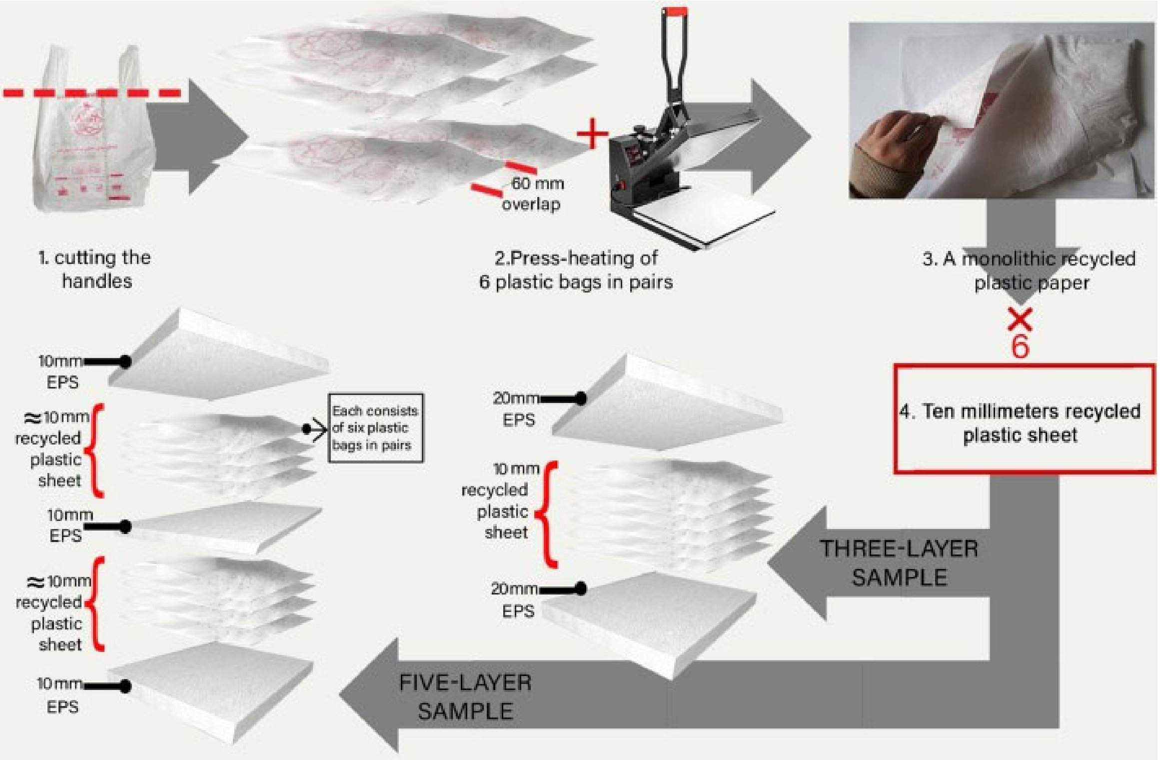


Figure 2.11: Schematic representation diagram for the production of both three- and five-layer samples (Fard et al., 2021).

Using these new composites, Fard et al. conducted three tests including: fire spread, water absorption, and compressive strength. The results for each of these tests can be seen summarized in Figure 2.12. The bag panels were found to decrease the water absorption of the whole panel due to the hydrophobic nature of the plastic bags themselves. Interestingly, during the fire test, the flame spread rate actually went down for the composites containing the bags than for the control sample. Further, the two composites also produced significantly less smoke than the control. The reason that the bags did not contribute to fire spread the same way that the EPS did is because the EPS is so porous, containing air that intensifies the fire. In fact, the plastic bag boards acted as a fire barrier between the EPS sections. Lastly, as expected, the compressive strength of the composite panels did decrease compared to the control.

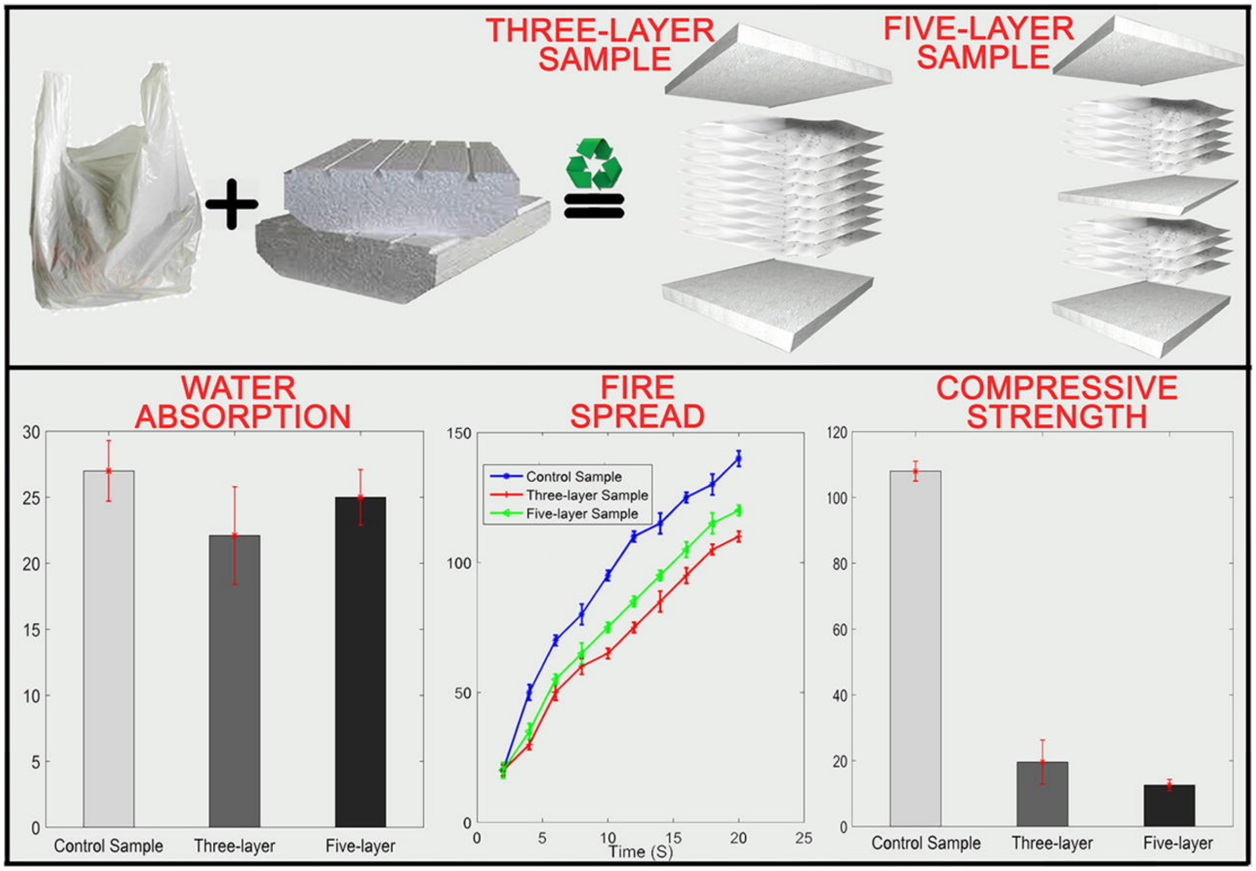


Figure 2.12: Graphical Abstract (Fard et al., 2021).

Similar to Fard et al., Wu et al. analyzed a way to recycle film waste by heating it up. This research stacked and welded together film plastic at a low temperature before infusing it with air to transform it into a foam. The material was then analyzed structurally and in terms of its thermal conductivity. The thermal conductivity was found to be excellent. While Wu et al. essentially created a new foam insulating material from recycled film plastic, this process took a very long time and would be hard to implement on a large scale. However, this research is promising because it shows that film plastic can be used to create a material with very low thermal conductivity due to the nature of the plastic itself.

Multiple types of plastics including film plastics were considered in a new particle board material presented by Chanhoun et al., wherein the bags are shredded and combined with waste wood fibers using glue to form door core, floor coverings, and other building components. This research documents a way to keep plastics out of the environment by containing them in the construction of a building. Chanhoun et al. explains that this new composite was locally necessary to create due to the plastic pollution killing local livestock and ruining water supplies. No thermal study was done on these composites; however, the material does exemplify that building materials can be made in a way that benefits the local (and therefore overall) environment.

2.5.5 Conclusion of Literature Review

Based on the works discussed in this chapter, it is prevalent that while much research has been done regarding recycled plastic as a building and construction material, there is a significant gap in information regarding the thermal properties of recycled plastic bags themselves as an insulation material independently. In particular, there is an overall lack of information on the implementation of recycled film plastics in buildings and construction. The most similar research that has been done was by Meier et al (2007), however, even their research left more to be done. There is no analytical data regarding the R-value of recycled plastic bags, and no further experiments have been done to see if different application methods would produce a higher R-value. The following chapters will fill the gap regarding the thermal performance of the recycled plastic bags, outlining the experimental process, followed by a comparative optimization analysis with other common insulation materials.

CHAPTER 3: EXPERIMENTAL METHODOLOGY

3.1 Research Scope

The scope of this research included testing different applications of recycled plastic bags within a wall cavity in order to achieve a minimum of R-13. Then, based on the R-value achieved through a series of experiments, the recycled plastic bags were analytically compared to existing common insulation materials considering the following parameters: performance, cost, lifespan, and environmental impact.

3.2 Research Objectives

- Determine if recycled plastic bags can achieve a minimum of R-13 by experimental process.
- Determine the best way plastic bags can be utilized in a wall cavity to result in the highest R-value.
- Compare the parameters of performance, cost, lifespan, and environmental impact of the recycled plastic bag insulation to current common insulation materials.

3.3 Testing Configurations

Different testing configurations of recycled plastic bags as insulation includes:

- Bags laid flat into modular “panels” within a wall cavity (with air pressed out)
- Bags laid flat into modular “panels” within a wall cavity (air not pressed out)
- Bags shredded to fill a wall cavity (air not pressed out)
- Bags shredded to fill a wall cavity (with air pressed out)

3.4 Bag Collection

Since a rather large amount of plastic grocery bags would be required for this project, plastic bag recycling boxes were placed in each of the dorm buildings on Lawrence Tech’s campus, for a total of 4 collection boxes that were checked and emptied bi-weekly from September through November 2022. All of the bags utilized in this experiment were collected and recycled. All forms of standard film plastic grocery / retail bags were collected and utilized equally in order to realistically consider what actual collection for such a material would result in without the need for intensive sortation. Moreover, considering large scale bag collection it would be very difficult and costly to sort collected bags by their physical properties (size, color, thickness, etc). Not requiring this extra step helps provide a result that can be used for similar collection processes where sortation is not required to achieve the same results. It was important, however, to sort out any garbage that was inevitably placed in the collection boxes. Fortunately, there was not a lot of garbage, but this type of sortation would be necessary for collection on a large scale.

3.4 R-Value Calculation

The R-value for collected recycled bags was determined using a cooling unit and thermocouples to monitor the temperature change through the bags over a set period of time. The bags were placed over the cooling unit and then sealed with tape to ensure no air leaks occur that could skew the data. The logged data was then compared to a control test that analyzes the same temperatures but with an insulation with a known R-value (XPS). This project follows the same calculation process that the students at The University of Oregon utilized. Based on the collected data, heat flow indexes can be determined and compared to calculate the unknown value.

The heat flow index (HFI) is a ratio of the average outside temperature to the average inside temperature (Equation 2-1). The HFI of the known material and the HFI of the unknown material (plastic bags) should both be calculated. From there, a performance ratio can be calculated (Equation 2-2). Based on the performance ratio, the R-value of the unknown material (plastic bags) can be calculated by multiplying the performance ratio by the R-value of the known material (Equation 2-3):

$$HFI = \frac{T_{avg,out}}{T_{avg,in}} \tag{2-1}$$

$$PR = \frac{HFI_{known} - HFI_{bags}}{HFI_{known}} \tag{2-2}$$

$$R\ value_{pg} = PR * R\ value_{known} \tag{2-3}$$

Where:

HFI represents the heat flow index

PR represents the performance ratio

R value_p represents the new R-value found for the plastic bags

R value_known represents the R-value for the known material (in this case, XPS)

3.5 Set-Up and Instrumentation

Three main tools were used to run the experiments. The first tool required was the cooling unit. A small refrigeration unit was used in order to create a difference in temperature on one side of the sample. The cooling unit would be turned on at the beginning of each experiment once the sample was placed and the temperature on either side of the sample had reached a state of near equilibrium. The cooling unit would attempt to maintain a constant temperature and depending on the insulating properties would in turn perform better or worse, resulting in a lower or higher internal temperature.

The next tool utilized was the thermocouples. Thermocouples are sensors used to measure temperature. Thermocouples work by utilizing the conductive properties of two dissimilar metals in order to generate an instantaneous temperature reading. Four thermocouples were used for temperature readings. The first was placed on the inside of the cooling unit. The second was placed on the inner surface of the sample, and the third was placed on the outer surface of the sample. The second and third thermocouples were strategically placed so that they were center to center with the sample for the best reading across the material. The last thermocouple was placed on the outside of the cooling unit so that the temperature flux between the cooling unit and testing room could be calculated. A standard thermocouple can be seen in Figure 3.1.

Figure 3.1: WTC-GG-24-SL Type K Glass Insulated 24 AWG Beaded Wire Thermocouple with Stripped Leads (IOThrifty, 2023).

The next instrument used was the data logger. The data logger is the device that the thermocouples plug into for the translation of the signals collected into temperatures. The data logger has eight channels that it uses to collect signals. Each thermocouple splits into two different sides and each side is plugged into its own channel in order to measure the resistance and convert the signals received. The setup of the data logger to the thermocouples can be seen below in Figure 3.2.

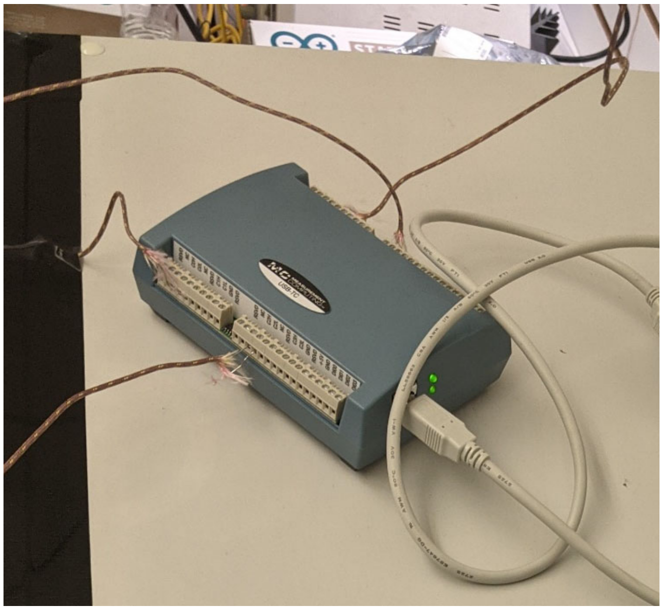


Figure 3.2: Thermocouple and Data Logger

The last essential instrument was Raspberry Pi. Raspberry Pi is a very small computer and one of its many uses is that can be used to constantly collect data; in this project the device was used to collect and log the data of all four thermocouples. The device was programmed to take a reading once a minute for each thermocouple over the course of 24 hours. Raspberry Pi can be seen connected to the data logger as well as a small screen in Figure 3.3.

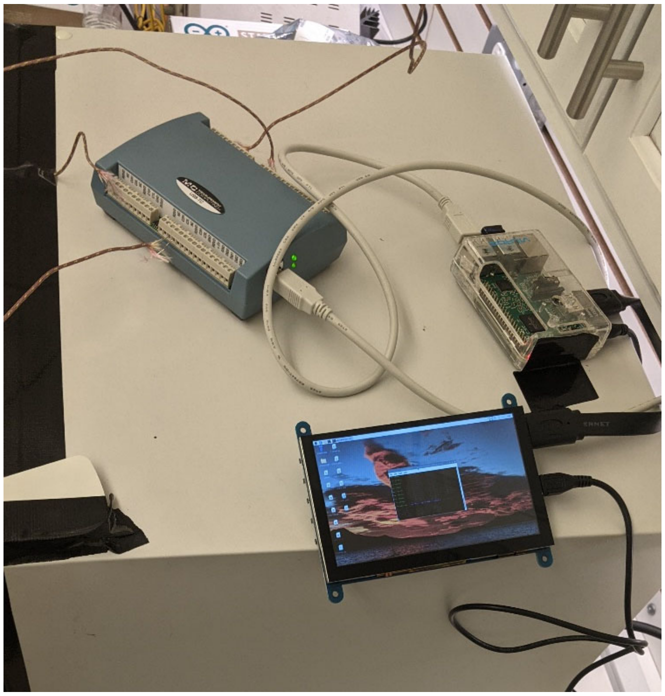
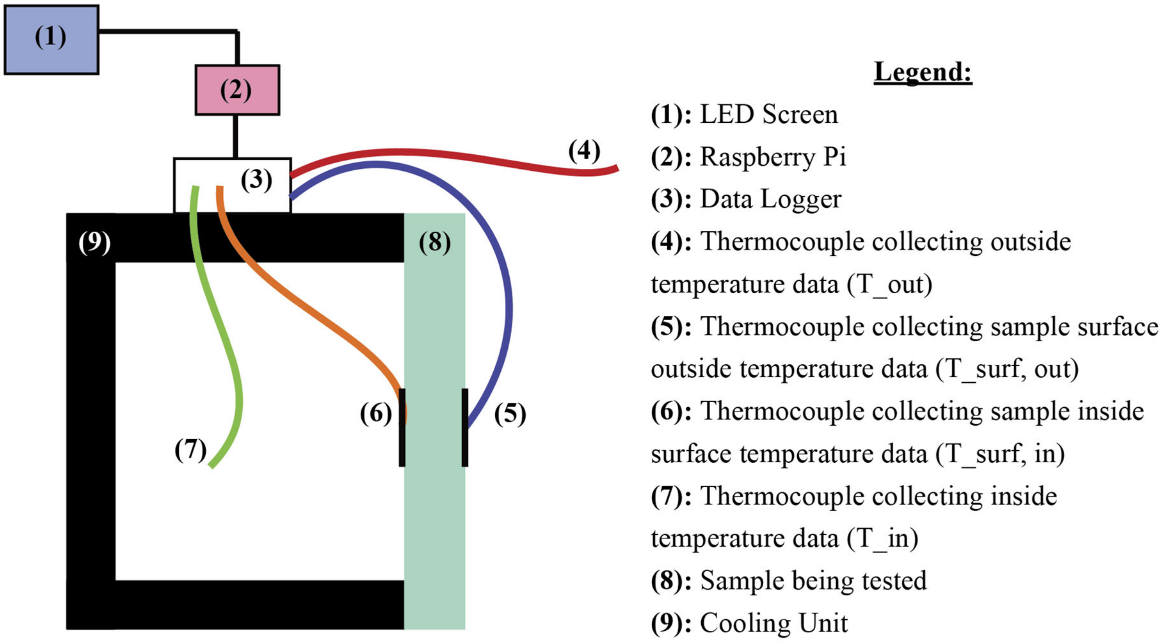


Figure 3.3: Raspberry Pi and Data Logger with Thermocouples Set-up

An overall section of the setup can be seen in a section diagram in Figure 3.4, for clarity. The “Sample being tested” represents each type of configuration experimentally tested.



Legend:

(1): LED Screen
(2): Raspberry Pi
(3): Data Logger
(4): Thermocouple collecting outside temperature data (T_out)
(5): Thermocouple collecting sample surface outside temperature data (T_surf, out)
(6): Thermocouple collecting sample inside surface temperature data (T_surf, in)
(7): Thermocouple collecting inside temperature data (T_in)
(8): Sample being tested
(9): Cooling Unit

Figure 3.4: Section Diagram of experimental setup (general)

3.6 Preliminary Testing & Calibration

Beginning in November 2022, preliminary testing of experimental setup was begun in order to establish the heat flow index of the known material. The material tested was green XPS insulation with an R-value of 5 per inch. The setup involved 4 thermocouples, one placed on the inside of the cooling unit, one placed on the inside of the cooling unit on the insulation surface, one placed outside the cooling unit, and one placed on the exterior surface of the insulation (See Figure 3.5). This setup can also be seen diagrammatically in Figure 3.4, where the “Sample being tested” represents the XPS.

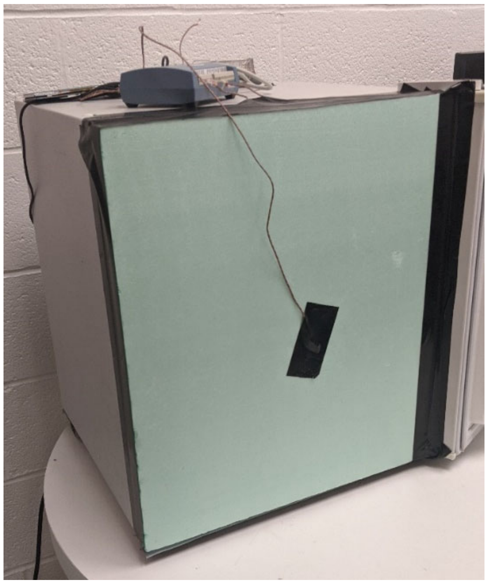


Figure 3.5: Experimental setup with XPS

Based on the average temperature difference between the two thermocouples on the interior and exterior of the insulations surface over the course of a day, the HFI came out to be approximately .542 using Equation 2-1. This test was ran twice and the second calculated HFI was approximately .552, with an overall average of .556. This HFI is based on the heat transfer (temperature change) between the inside and outside temperatures to the point of convergence of the data. In other words, the temperature difference up until the model reached steady state conditions was considered. Further, the HFI of .556 will be used as a reference for 1 inch of R-5 insulation to calculate the R-value for the unknown recycled plastic bag insulation. The averaged data for this initial calibration can be seen below in Figure 3.6.

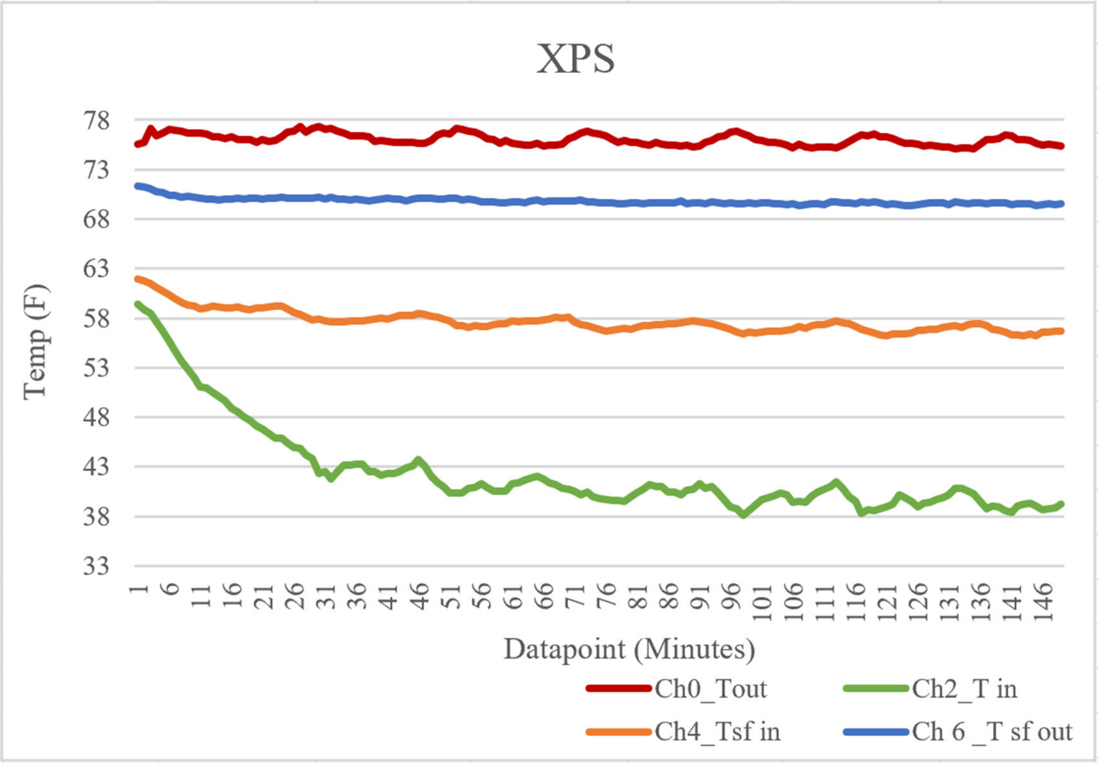


Figure 3.6: XPS Average Data

CHAPTER 4: EXPERIMENT

4.1 Layered Plastic Bags (Uncompressed)

The first configuration of recycled plastic bags tested was uncompressed, layered bags, as seen in Figure 4.1(a). This test consisted of 160 plastic bags all facing one direction. The idea was to create many individual layers or boundaries that the heat would have to transfer through, including the layer of air between each bag.

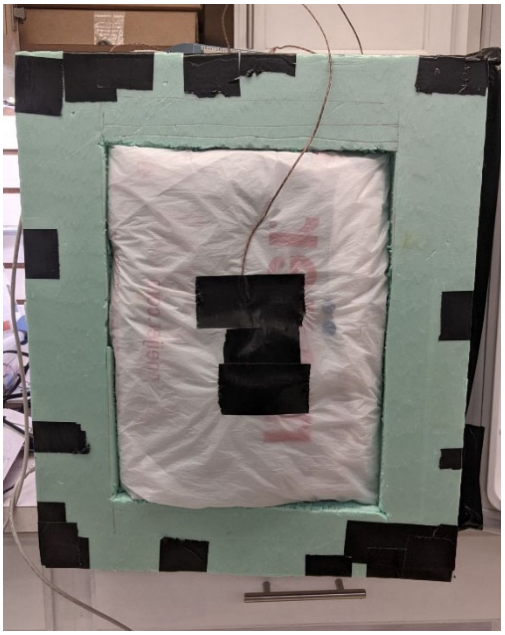


Figure 4.1(a): Layered Plastic Bags, Uncompressed

Figure 3.4 can be referenced where the "Sample being tested" represents this option. There is one inch of R-5 sandwiching the bags in this scenario in order to keep the air content as a variable and the surrounding R-5 XPS insulation is tightly sealed to the cooling unit. This was done because the bags were not quite large enough to cover the entire cooling unit face and therefore required a frame to test within. The total thickness of the bags was about 3 inches and the thermocouples were placed center to center on the test material for the most accurate results.

The temperature data below in Figure 4.1(b) shows how the temperature reading on each thermocouple changed over time with each datapoint being one minute. Convergence was observed at around 180 minutes, therefore the HFI was using the inside and outside temperature averages up to that point using Equation 2-1. The calculated average HFI was .566, meaning that the expanded plastic bags had a performance ratio of about .9753 using Equation 2-2. This means that the expanded bags performed about 2.05% worse than the XPS. Based on Equation 2-3, this would result in an R-value of 4.88. However, the thickness must also be considered to calculate an accurate the R-value. The uncompressed layered bag sample was about 3” thick, meaning that the R-value per inch is actually 1.625. Further, in order to achieve R-13, approximately 8 inches would be required. The data conclusions for the uncompressed, layered bags can be seen summarized in Table 4.1:

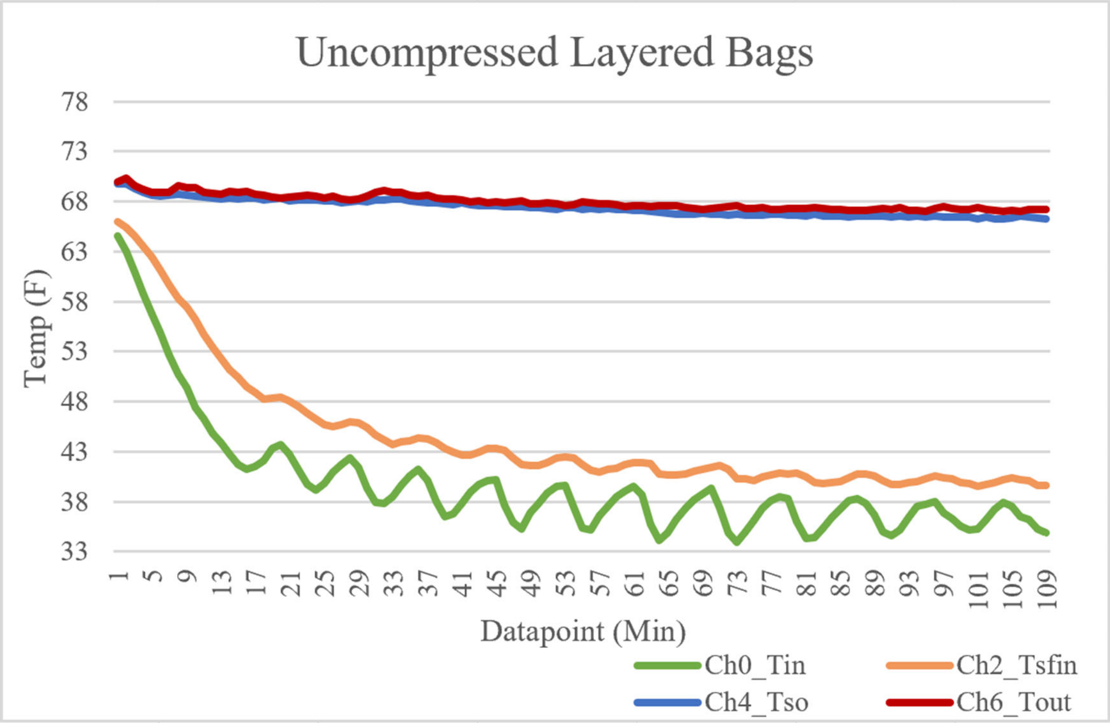


Figure 4.1(b): Averaged Data Uncompressed, Layered Setup

Table 4.1 – Uncompressed, Layered Bags Data Summary

Average Inside Temp (F)	Average Outside Temp (F)	HFI (Avg T_in / Avg T_out)	XPS HFI	Thickness (in)	Improvement	Improvement From R-5 (%)	R-value	R-value / in	Thickness Needed for R-13
38.27354	67.61912	0.56601658	0.55235	3	-0.024742603	-2.47426031	4.876287	1.625429	7.997889

4.2 Layered Plastic Bags (Compressed)

The next configuration of bags see in Figure 4.2(a) also considered the layered option, however this setup did not inlcude the air between the bags as a variable. This setup consisted of 160 bags as well, however these bags were folded in half in order to create twice as many layers, creating a total of 320 layers with the majority of air squeezed out prior to testing.

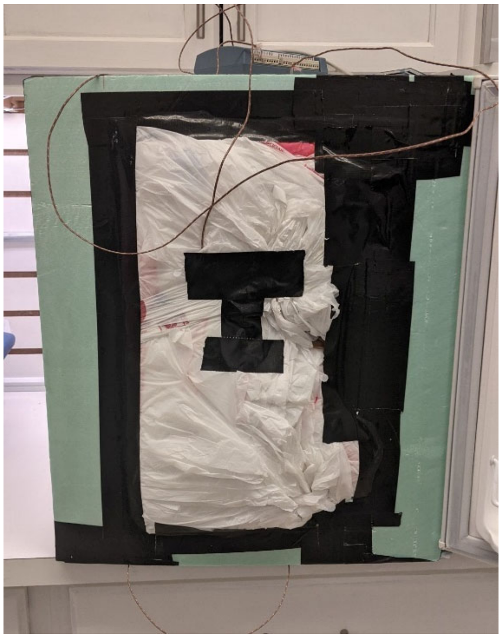


Figure 4.2(a): Layered Plastic Bags, Compressed

There is one inch of R-5 sandwiching the bags in this scenario with the bags sealed at the boundary in order to keep the bags from expanding with air and maintaining a compressed element that would in reality exist due to the surrounding walls. The surrounding R-5 XPS insulation is tightly sealed to the cooling unit as well to prevent any fenestration. As with the previous experiment, the surrounding frame was also needed because the bags were not quite large enough to cover the entire cooling unit face and therefore required a frame to test within. The total thickness of the bags is about 2.5 inches and the thermocouples were placed center to center on the test material for the most accurate results.

The temperature data below in Figure 4.2(b) shows how the temperature reading on each thermocouple changed over time with each datapoint being one minute. This data represents the average of the trials for this experiment, where convergence of the data was observed at approximately 180 minutes. The average HFI using Equation 2-1 was calculated to be approximately .531. Using Equation 2-2 this means that the performance ratio of the compressed, layered bags is about 1.0388, meaning that the bags are performing about 3.88% better than the XPS. Considering the thickness at about 2.5 inches, the R-value for this bag configuration is about 2.08 per inch. Therefore, in order to achieve R-13, about 6.26 inches would be required. The data summary for the compressed, layered bags can be seen in Table 4.2

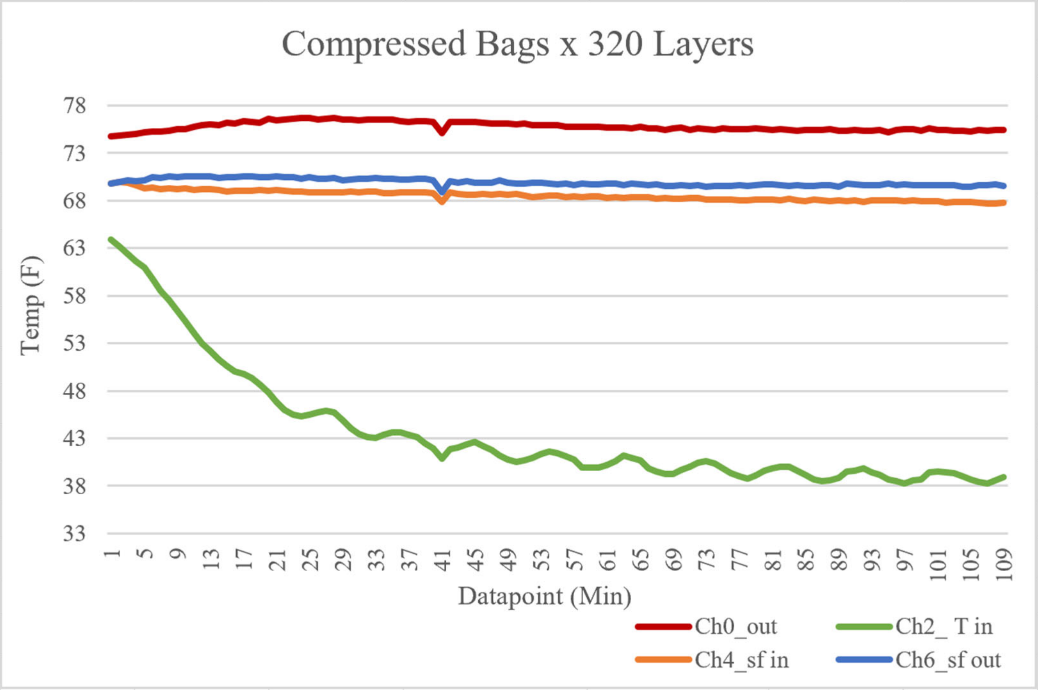


Figure 4.2(b): Averaged Data of Compressed, Layered Setup

Table 4.2 – Compressed, Layered Bags Data Summary

Average Inside Temp (F)	Average Outside Temp (F)	HFI (Avg T_in / Avg T_out)	XPS HFI	Thickness (in)	Improvement	Improvement From R-5 (%)	R-value	R-value / in	Thickness Needed for R-13
39.92819	75.20845	0.5309	0.55235	2.5	0.038833445	3.883344547	5.194167	2.077667	6.257018

4.3 Shredded Plastic Bags (Uncompressed)

Shredded bags were also tested to see if they could achieve R-13. First, uncompressed, shredded bags were experimentally tested to see if the air content within the shredded bags played a role in improving the R-value. Figure 4.3(a) shows the shredded bag insulation before being sealed as can be seen in Figure 4.3(b). Both of these figures represent what both the compressed and uncompressed shredded configurations consist of. In order to test the shredded bags, the frame was also required to hold the insulation in place similar to how a wall would in reality. The bags were placed between two layers of plastic that were securely taped to the frame on both the inner and outer sides. The overall setup of the testing configuration can be seen in Figure 3.4, where the "Sample being tested" is the shredded bags with the inner and outer thermocouples secured center to center to the inner and outer plastic bags.

Figure 4.3(a): Shredded Plastic Bags, Compressed & Uncompressed (Open)

Figure 4.3(b): Shredded Plastic Bags, Compressed & Uncompressed (Sealed)

The temperature data for the shredded, compressed bags can be seen in Figure 4.3(c). This configuration resulted in an observed convergence to steady state at 180 minutes. The average HFI using Equation 2-1 is calculated to be approximately .526, meaning that the performance ratio of the shredded, uncompressed bags performed 4.72% better than the R-5 XPS. The thickness of the sample was about 3 inches, so the calculated R-value using Equation 2-3 is approximately 1.745 per inch. Based on this R-value, about 7.45 inches would be required of the shredded, uncompressed bags in order to achieve R-13. The data summary for this configuration can be seen in Table 4.3.

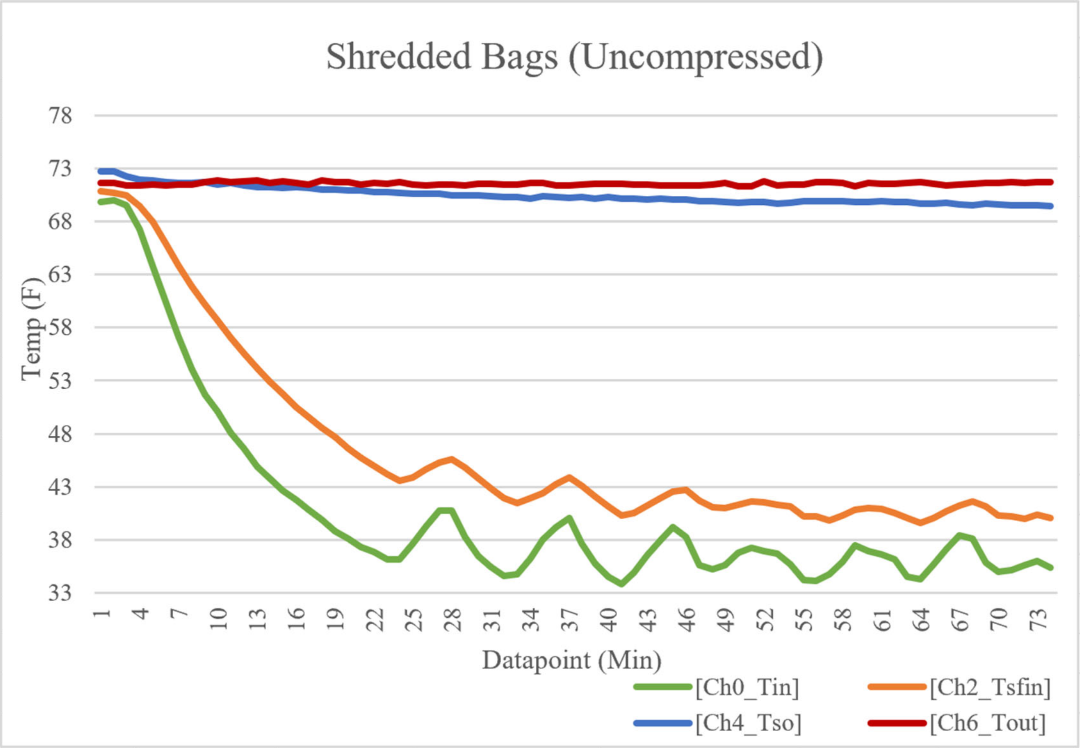


Figure 4.3(c): Average Data of Uncompressed, Shredded Plastic Bag Setup

Table 4.3 – Shredded, Uncompressed Bags Data Summary

Average Inside Temp (F)	Average Outside Temp (F)	HFI (Avg T_in / Avg T_out)	XPS HFI	Thickness (in)	Improvement	Improvement From R-5 (%)	R-value	R-value / in	Thickness Needed for R-13
37.6313	71.50742	0.5262573	0.55235	3	0.04723941	4.723940995	5.236197	1.745399	7.448154

4.4 Shredded Plastic Bags (Compressed)

Next, the shredded bags were compressed within the cavity. Twice as many bags were put into the same space between the two outer and inner layers of plastic attached to the frame. As the bags were stuffed into the space, the air was squeezed out. Figures 4.3(a) and 4.3(b) can be referenced as the setup was the same using the same frame, the only difference was the amount of shredded bags used. The "Sample being tested" in Figure 3.4 in this case again represents the shredded bags between the two layers.

The temperature data for the compressed, shredded bags can be seen in Figure 4.4. The average calculated HFI using Equation 2-1 and is approximately .511. Therefore, the performance ratio is 1.0757, meaning that the compressed, shredded bags performed about 7.57% better than the XPS. Considering the thickness of 2.5 inches for the sample, the R-value for this configuration is approximately 2.15 per inch. Thus, in order to achieve R-13, about 6.04 inches of the compressed, shredded bags would be required. The data for this configuration can be seen summarized in Table 4.4.

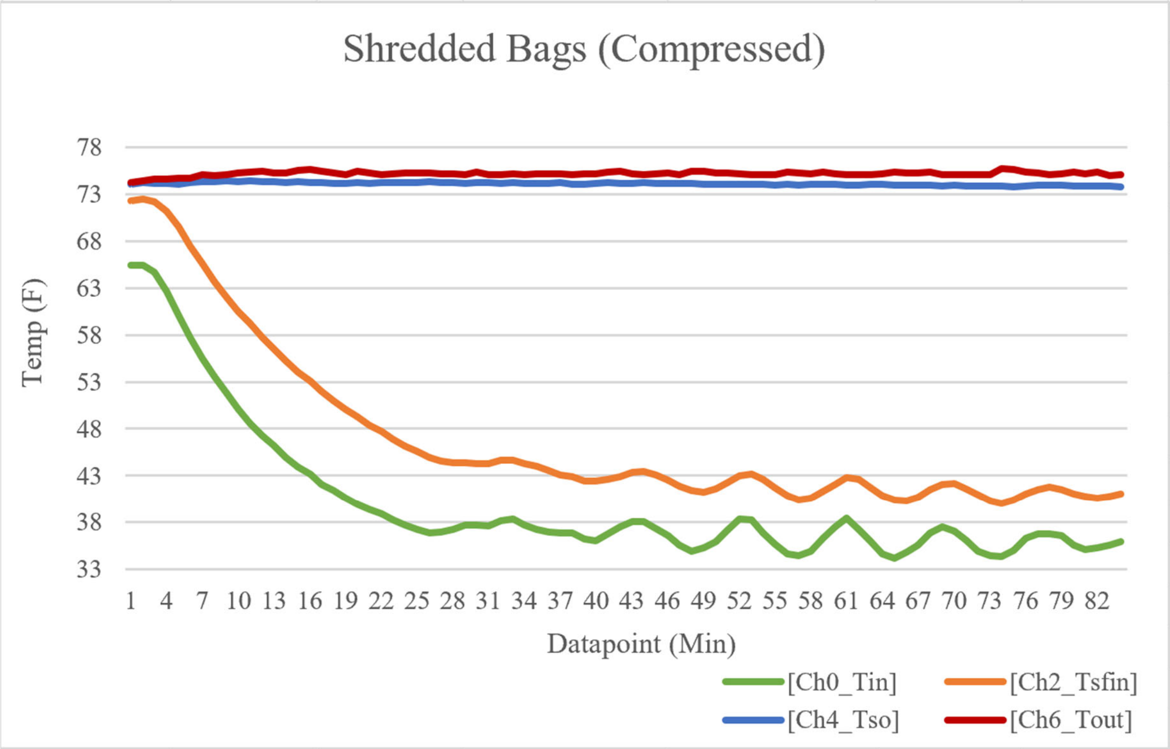
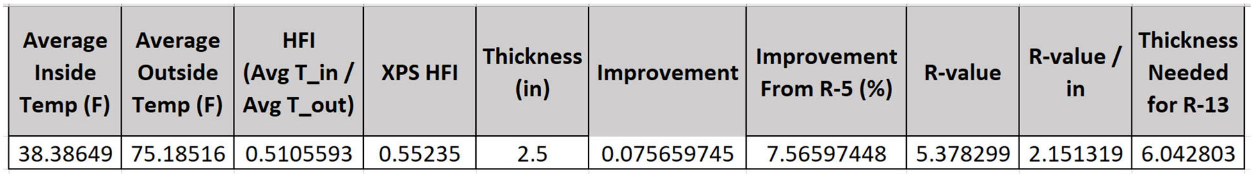


Figure 4.4: Averaged Data of Shredded, Compressed Setup

Table 4.4 – Shredded, Compressed Bags Data Summary



Average Inside Temp (F)	Average Outside Temp (F)	HFI (Avg T_in / Avg T_out)	XPS HFI	Thickness (in)	Improvement	Improvement From R-5 (%)	R-value	R-value / in	Thickness Needed for R-13
38.38649	75.18516	0.5105593	0.55235	2.5	0.075659745	7.56597448	5.378299	2.151319	6.042803

CHAPTER 5: DATA ANALYSIS & OPTIMIZATION

5.1 Recycled Plastic Bag Insulation Cost Analysis

Cost is a factor that does not always correlate to a material's respective performance, but can instead vary on other factors involved in the materials manufacturing, demand, and ease of installation. Recycled plastic grocery bags used in this project are assumed to be Grade B Recycled Film. According to Recyclingmarkets.net, Grade B Recycled Film is defined as: "any mix of polyethylene film," which includes low-density polyethylene (LDPE) or linear low-density polyethylene (LLDPE), where at least 80% of the film is clear or natural and up to 20% of the final product is allowed be colored or printed. Further, low levels of contaminants are allowed of the following materials: "HDPE (#2) film (10% allowable), labels, plastic strapping and rubber bands, rigid or foam PE (HDPE #2 or LDPE #4), loose paper, cardboard (OCC) - including cardboard endcaps, and moisture residues" (recyclingmarkets.net). Many retail plastic bags actually are made from HDPE (#2), so this assumption is conservative to the calculation of costs for recycled plastic bag insulation because is it more expensive per pound than Grade C.

As of September 2022, the cost per pound of Grade B Recycled Film was about 7 cents (recyclingmarkets.net). One plastic bag weighs about 7 grams, or approximately .0022 pounds. For the Layered – Compressed and Uncompressed configurations, 160 bags were used. This means that the sample was about 0.359 pounds, so by weight 160 plastic bags would come out to be about 3 cents. The dimensions of the bags were taken to be 15 by 15 inches (approximately), coming out to a surface area of about 1.563 square feet. That means that the cost per square foot for the raw material usage of the layered configuration is 1.61 cents, or $.061 per square foot.

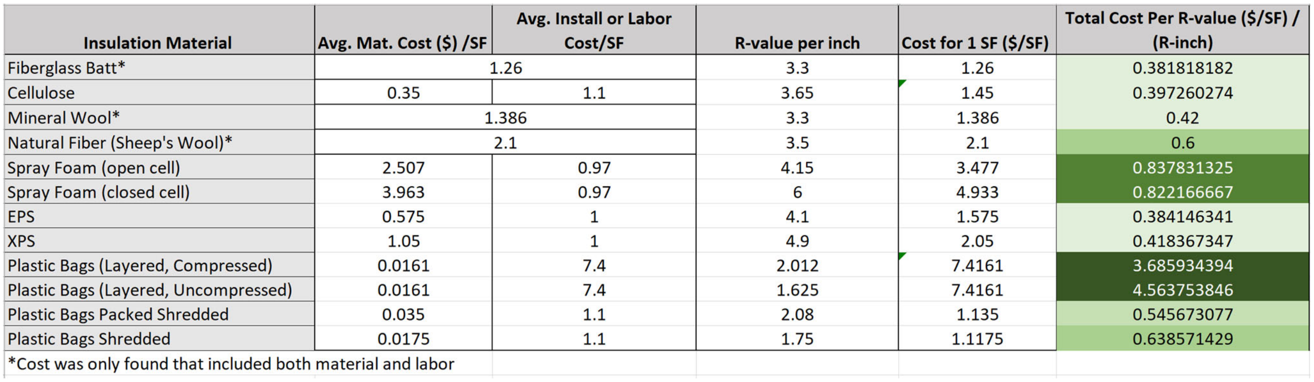
For the shredded bag configuration, the bags were compressed to 2 different densities and weighed as a total. The uncompressed shredded bags were used at a density of about .25 pounds per square foot. Based on the cost per pound of 7 cents, this comes to a total of about 3.5 cents per square foot, or $.035 per square foot. The compressed shredded bags were used at a density of about 0.5 pounds per square foot. Based on 7 cents per pound, the compressed shredded bags cost about 1.75 cents or $.075 per square foot as a raw material.

Labor costs for the recycled plastic bag insulation configurations also needs to be considered. Since this experiment is the first to generate layered plastic bag insulation panels, the time it took to make the panels personally is what will be used to determine the labor costs for the layered option. There is currently no manufacturing process to speed up the creation of the recycled panels, so the labor cost calculation will be higher than expected but it is the only current reference available. The time that it takes to make the layered panel configuration is about 40 minutes, or 2/3 of an hour. At a national minimum wage of $10.10 per hour, that means that the labor cost would be about $7.4 per square foot.

On the other hand, shredding the bags is much easier. It takes about 10 minutes to shred enough bags for one module by hand, which comes out to be $1.683 per hour. However, there are already high efficiency machines made to shred film plastic that can shred at rates of 400 – 1200 kg per hour. Further, the installation process for shredded plastic would be comparable to that of cellulose insulation because it will likely use the same type of process due to the shredded aspect of the material. This means that the installation labor cost for the shredded bags will be assumed to be the same as cellulose insulation, at $1.1 per square foot.

In order to assess how the recycled plastic bag insulation would compare to common insulation materials it is important to consider total combined cost per R-value ($ per square foot / R-value per inch). Table 5.1 below illustrates how some of the most common wall insulations perform in this respect and how the different configurations for recycled bag insulation compares.

Table 5.1 – Total Cost Per R-Value Analysis



Insulation Material	Avg. Mat. Cost ($) /SF	Avg. Install or Labor Cost/SF	R-value per inch	Cost for 1 SF ($/SF)	Total Cost Per R-value ($/SF) / (R-inch)
Fiberglass Batt*	1.26		3.3	1.26	0.381818182
Cellulose	0.35	1.1	3.65	1.45	0.397260274
Mineral Wool*	1.386		3.3	1.386	0.42
Natural Fiber (Sheep's Wool)*	2.1		3.5	2.1	0.6
Spray Foam (open cell)	2.507	0.97	4.15	3.477	0.837831325
Spray Foam (closed cell)	3.963	0.97	6	4.933	0.822166667
EPS	0.575	1	4.1	1.575	0.384146341
XPS	1.05	1	4.9	2.05	0.418367347
Plastic Bags (Layered, Compressed)	0.0161	7.4	2.012	7.4161	3.685934394
Plastic Bags (Layered, Uncompressed)	0.0161	7.4	1.625	7.4161	4.563753846
Plastic Bags Packed Shredded	0.035	1.1	2.08	1.135	0.545673077
Plastic Bags Shredded	0.0175	1.1	1.75	1.1175	0.638571429

*Cost was only found that included both material and labor

The darker green gradient in Table 5.1 represents a higher cost per R-value ratio. It can be observed that the insulation material that performs best in this parameter is just barely Fiberglass batt, followed by cellulose and EPS. The recycled plastic bags (layered), due to having a lower R-value per inch, do not perform as well in this category. The shredded recycled plastic bags perform better than the spray foam however, due to having lower costs for materials and installation. This outweighs the lower R-value of the Shredded bags. Reference Tables A.1 – R-Value Data

References and A.2 – Cost Data References in the Appendix to see references for all R-value and cost values used in Table 5.1

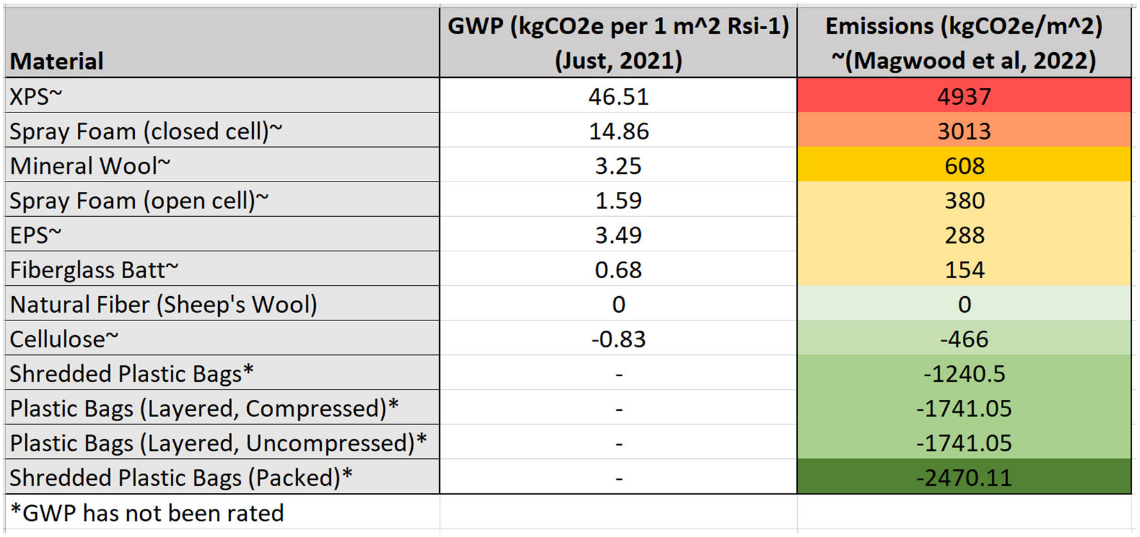
5.2 Environmental Impact of Plastic Bag Insulation

In order to estimate what kind of environmental impact the recycled bags may have the total emissions embodied in one plastic bag was considered. One single use plastic bag is equivalent to 1.58 kg CO2e per square meter of carbon emissions (Edwards et al). In the layered composition, for 160 bags, that is 252.8 kg CO2e. At an area of 1.562 square feet, the total emissions negated is 1741.05 kg CO2e per square meter.

The shredded bag insulation emissions on the other hand are calculated using weight. For an estimated .25 pounds of shredded bags per square foot in application, about 114 bags are used in the uncompressed shredded configuration. That comes out to a total negated emissions of 1240.5 kg CO2e per square meter.

The packed, shredded bags use an estimated .5 pounds per square foot of bags in application, so by weight that comes out to approximately 227 bags. Based on the emissions data for one bag, the shredded packed bags negate about 2470.11 kg CO2e per square meter. Table 5.2 illustrates some of the most common insulation materials ranked by emissions data.

Table 5.2 – Insulation Materials Ranked by Emissions



Material	GWP (kgCO2e per 1 m^2 Rsi-1) (Just, 2021)	Emissions (kgCO2e/m^2) ~(Magwood et al, 2022)
XPS~	46.51	4937
Spray Foam (closed cell)~	14.86	3013
Mineral Wool~	3.25	608
Spray Foam (open cell)~	1.59	380
EPS~	3.49	288
Fiberglass Batt~	0.68	154
Natural Fiber (Sheep's Wool)	0	0
Cellulose~	-0.83	-466
Shredded Plastic Bags*	-	-1240.5
Plastic Bags (Layered, Compressed)*	-	-1741.05
Plastic Bags (Layered, Uncompressed)*	-	-1741.05
Shredded Plastic Bags (Packed)*	-	-2470.11

*GWP has not been rated

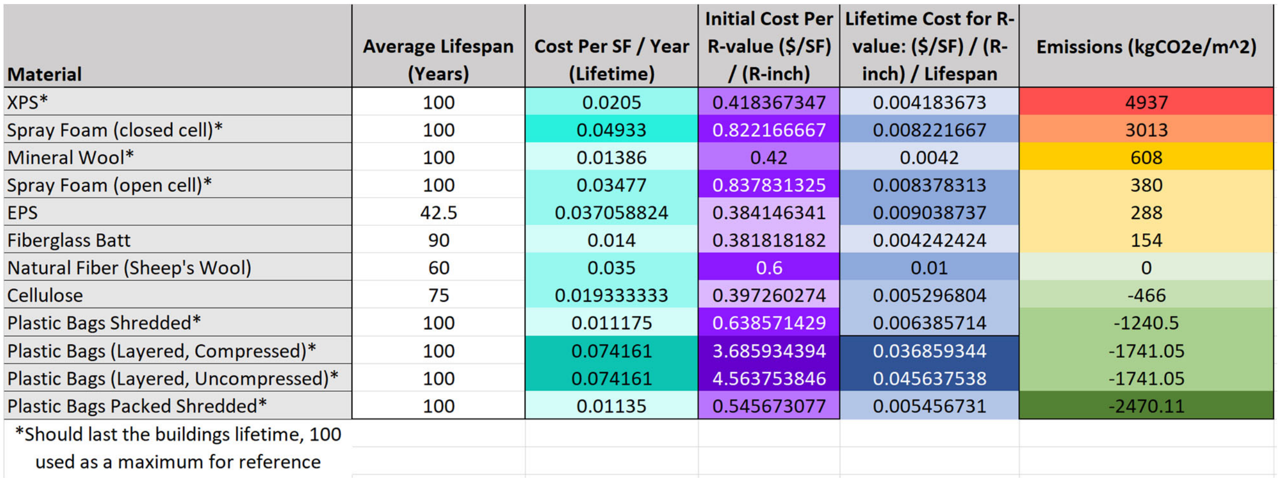
Further, the factor of Global Warming Potential for the shredded bags of all configurations has not yet been rated based on manufacturing and production data. Based on the data in Table 5.2, it can be observed that the recycled plastic bag insulations all have the smallest amount emissions. This is due to the insulation being comprised of 100% recycled material, and the value of the material's specific emissions per bag factor. The second and third best performing insulation options in terms of emissions are cellulose (which is also a recycled option and therefore is negating carbon), and sheep's wool.

5.3 Lifespan

The next important factor to consider in a building insulation is the service lifespan. Having a limited lifespan means potentially replacing that insulation within the building's lifetime, which can be extremely costly and generate lots of waste. When considering how much an insulation material initially costs vs the functional lifetime of that material, initially cheap insulations might end up being a costly replacement down the road.

When it comes to the consideration of recycled plastic bags as an insulation material, the lifespan is a powerful argument. Since there is nothing to degrade the plastic within the wall, the material will likely outlive the building, meaning that there will be no need to replace it. One must consider how much the initial investment is for the material and how long it is expected to last. On top of that, the value of the cost for the performance of the insulation over the lifetime should also be considered. The data found for the lifespan of the considered insulations, with initial and lifetime performance considerations can be seen in Table 5.3. The materials are represented with a rank by the value of the Emissions data for reference. See Table A.3 – Lifespan Data References in the Appendix for references for all lifetime values used.

Table 5.3 – Lifetime Costs Ranked by Emissions



Material	Average Lifespan (Years)	Cost Per SF / Year (Lifetime)	Initial Cost Per R-value ($/SF) / (R-inch)	Lifetime Cost for R-value: ($/SF) / (R-inch) / Lifespan	Emissions (kgCO2e/m^2)
XPS*	100	0.0205	0.418367347	0.004183673	4937
Spray Foam (closed cell)*	100	0.04933	0.822166667	0.008221667	3013
Mineral Wool*	100	0.01386	0.42	0.0042	608
Spray Foam (open cell)*	100	0.03477	0.837831325	0.008378313	380
EPS	42.5	0.037058824	0.384146341	0.009038737	288
Fiberglass Batt	90	0.014	0.381818182	0.004242424	154
Natural Fiber (Sheep's Wool)	60	0.035	0.6	0.01	0
Cellulose	75	0.019333333	0.397260274	0.005296804	-466
Plastic Bags Shredded*	100	0.011175	0.638571429	0.006385714	-1240.5
Plastic Bags (Layered, Compressed)*	100	0.074161	3.685934394	0.036859344	-1741.05
Plastic Bags (Layered, Uncompressed)*	100	0.074161	4.563753846	0.045637538	-1741.05
Plastic Bags Packed Shredded*	100	0.01135	0.545673077	0.005456731	-2470.11

*Should last the buildings lifetime, 100 used as a maximum for reference

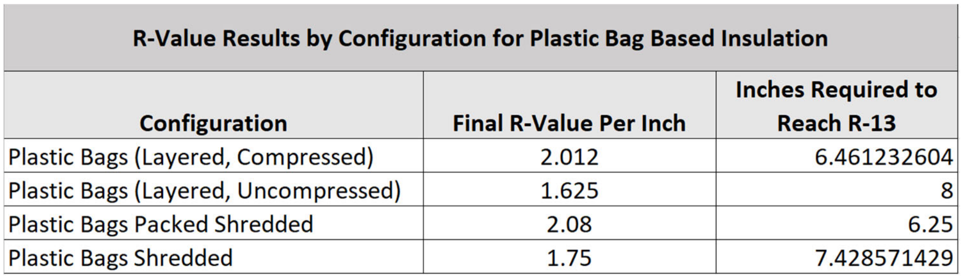
In Table 5.3, the lighter shaded cells are the more beneficial options under each parameter. When looking at the Lifetime Cost, the recycled bag options that perform the best are the shredded configurations, with the layered options performing the worst. When considering the initial cost that is being paid per R-value, the Shredded, Packed bags still perform the best for the recycled plastic insulation, with the best insulation material options in this category being EPS, Fiberglass Batt, and Cellulose. When considering the lifetime cost, however, both uncompressed and compressed options are fairly close, falling into the same range as Cellulose. However, the best overall for Lifetime Cost per R-value is XPS, Mineral Wool, and Fiberglass Batt. The last important element to consider is the emissions. While the XPS and Mineral Wool may be good financial payoffs for their performance and how long they last, they are in the top three for worst emissions. When considering emissions, the best performing insulation materials in terms of their Lifetime Costs Per R-value are actually Cellulose, Compressed, Shredded Plastic Bags, and Uncompressed, Shredded Plastic Bags.

CHAPTER 7: CONCLUSION

7.1 Conclusion

Recycled plastic bag-based insulation can achieve the minimum recommended value of R-13, with the best method to do so being the shredded, compressed configuration due to ease of manufacturability and overall R-value per inch. Table 7.1 below summarizes the results of the experimental R-Value testing for each configuration and how many inches would be required to achieve R-13, respectively.

Table 7.1 – R-Value Results by Configuration



R-Value Results by Configuration for Plastic Bag Based Insulation

Configuration	Final R-Value Per Inch	Inches Required to Reach R-13
Plastic Bags (Layered, Compressed)	2.012	6.461232604
Plastic Bags (Layered, Uncompressed)	1.625	8
Plastic Bags Packed Shredded	2.08	6.25
Plastic Bags Shredded	1.75	7.428571429

Shredded recycled plastic bag insulation (compressed) could potentially be used in climate zones 1 and 2 as the main insulation in a wood frame wall or floor at 6.26 inches thick. In all climate zones it could be used in addition to continuous insulation in a wood frame or mass frame wall. Furthermore, industrial compression techniques may be able to further advance the R-value of the shredded bags by removing more air content.

The shredded, compressed bags can achieve R-13 when at a density of about one-half pound per square foot. When considering the manufacturing processes available, the shredded insulation would also be fairly easy and cheap to produce. Also, the bags can be easily locally sourced so no large amount of transportation would be required.

Furthermore, the shredded, compressed recycled plastic bag insulation configuration performs the best out of all the recycled bag options compared (layered uncompressed, layered compressed, and shredded uncompressed) when considering all parameters lifetime, R-value, cost, and emissions negated. Based on the data discussed in Chapter 5, the shredded bags generally perform similarly to cellulose insulation when considering cost, R-Value, estimated service lifetime, and environmental impact, with cellulose insulation only performing slightly better overall.

7.2 Potential Applications

Since R-13 is considered a minimum and not the most efficient R-value, it will likely not be the first choice in many commercial construction projects where comfort and internal temperature control are major factors. However, it would be an excellent option if used alone for insulating semi – conditioned spaces, such as garages or warehouses that are not used for cold storage.

Moreover, the main benefit of using shredded (compressed) recycled plastic bag configuration would recycle a very large mass of film plastic, even in just one application of usage. For example, if the bags were used as the main insulation in just one, one million square foot, unrefrigerated warehouse (with 35-foot-tall walls) the amount of emissions negated could be calculated as follows:

1. Consider the unit weight per square foot required to meet R-13. Since approximately 6.26 inches thick of the shredded, compressed bags is needed, the weight will no longer be .5 pounds per square foot like it was for 2.5 inches thick, but rather 1.252 pounds per square foot.
2. Calculate the total amount (by weight) of bags needed. For a 1 million square foot warehouse, each wall will be 1000 feet long by 35 feet tall.
    - The calculation for the total weight needed for one wall can be seen as follows:
      $$(1000 * 35) ft^2 * ((1.252\ lb)/(1.563\ ft^2)) = 28{,}035.83\ lb$$
    - If one bag weighs approximately .0022 pounds:
      $$28{,}035.83\ lb * (1\ bag)/(.0022\ lb) \approx 12{,}628{,}752\ bags\ per\ wall$$
    - The total amount of bags required for all 4 walls:
      $$12{,}628{,}752\ bags\ x\ 4\ walls \approx 50{,}515{,}007\ bags\ total$$
3. Consider that 1 single use bag is equivalent to 1.58 kgCO2e per square meter:
   $$50{,}515{,}007\ bags * 1.58 \frac{kgCO2_e}{m^2 bag} \approx 79{,}813{,}710.06\ (kgCO2\_e)/(m^2 bag)$$

One singular 1 million square foot warehouse could keep about 50,515,007 plastic bags from degrading in landfill, the oceans, the ecosystem, and human bodies. That same warehouse would be negating approximately 79,813,710.06 kgCO2e per square meter of emissions.

7.3 Impact on the AE Industry and Mechanical Systems

Mechanical systems generally rely on a building to have a decent insulation in order to run efficiently, hence the minimum recommendation of R-13. Since recycled plastic bag insulation can achieve this minimum (and even surpass it depending on how thick it is applied), the material can contribute to more efficient buildings that also reduce the amount of plastic bags polluting the environment, and even human bodies. The AE industry is inherently impacted because recycled plastic bag-based insulation would provide a new green building material and improve the carbon footprint of new buildings. Furthermore, if the recycled plastic bag-based insulation becomes a LEED approved way to integrate recycled materials then there will be motivation for new buildings to implement it.

7.4 Drawbacks and Limitations

The main drawback that the current state of recycled bag insulation is the thickness required to reach R-13. It might be difficult to use in conjunction with another insulation material since it takes up so much space within the wall cavity (6.26 inches for the shredded, compressed option).

The next drawback would be the collection and sortation process. Since the recycled bags would need to be picked up, have the garbage sorted out, and cleaned, the price would likely go up for the raw material itself once a manufacturing process is established.

Another potential drawback is that the shredded bags may have a problem similar to cellulose insulation where over time the bags settle down within the wall cavity, leaving a gap without insulation, also known as “slump.” This could be a major problem, and more shredded bag insulation may be required to be added after the period of time that it takes to settle. However, it is not confirmed if this would be an issue or not since the idea behind the shredded bag insulation is that is should be densely packed into the wall cavity.

7.5 Disclaimer

The market of insulation prices and labor rates is ever changing. Values of labor and material pricing was found to have discrepancies that can depend on many factors. Location, quality of work, manufacturer, experience, transportation, and project specific obstacles can all play a role in how much an insulation material costs to install. The numbers presented in this report in regard to costs are not exact for this reason. There is no exact value for this parameter. In order to numerically analyze the costs for each insulation material the researched values for the labor and material costs were averaged for each material.

Furthermore, since the recycled plastic bags would be a new insulation material, the actual values for production costs and overall emissions will likely be different. The values provided in this report are only educated estimations.

7.6 Future Considerations and Parting Thoughts

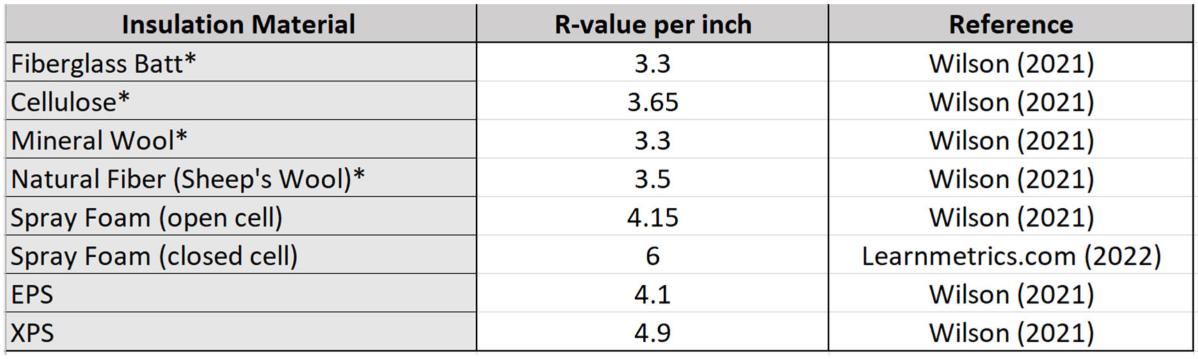
There is more experimental research that should be done before recycled plastic bag insulation can become a reality. All insulation materials are required to be fire tested, therefore the recycled plastic bag insulation should be fire tested using methods approved by ASTM E119: Standard Test Methods for Fire Tests of Building Construction and Materials. Moisture testing for the shredded bag configurations should also be done.

Furthermore, there are some recommendations for the improvement of the shredded, compressed recycled plastic bag insulation: (1) industrial compression techniques may be able to further advance the R-value of the shredded bags by removing more air content, and (2) potentially utilizing low-grade heat such as Wu et al. did may also help remove more air content while not generating toxic emissions.

Lastly, recycled plastic bag insulation cannot be the only solution to the film plastic waste problem, although it may help the current state of the issue. The long-term goal needs to be to ban film plastic outright. Recycling the film plastic as building insulation may help provide a temporary solution but the problem is much larger and begins with the use of fossil fuels and production processes of plastic.

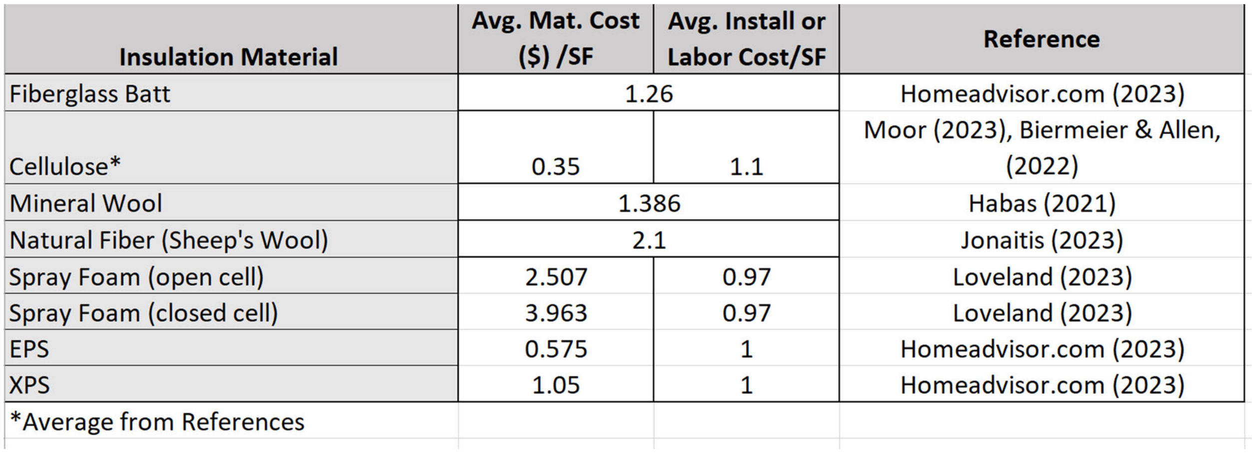
APPENDIX

Table A.1 – R-Value Data References



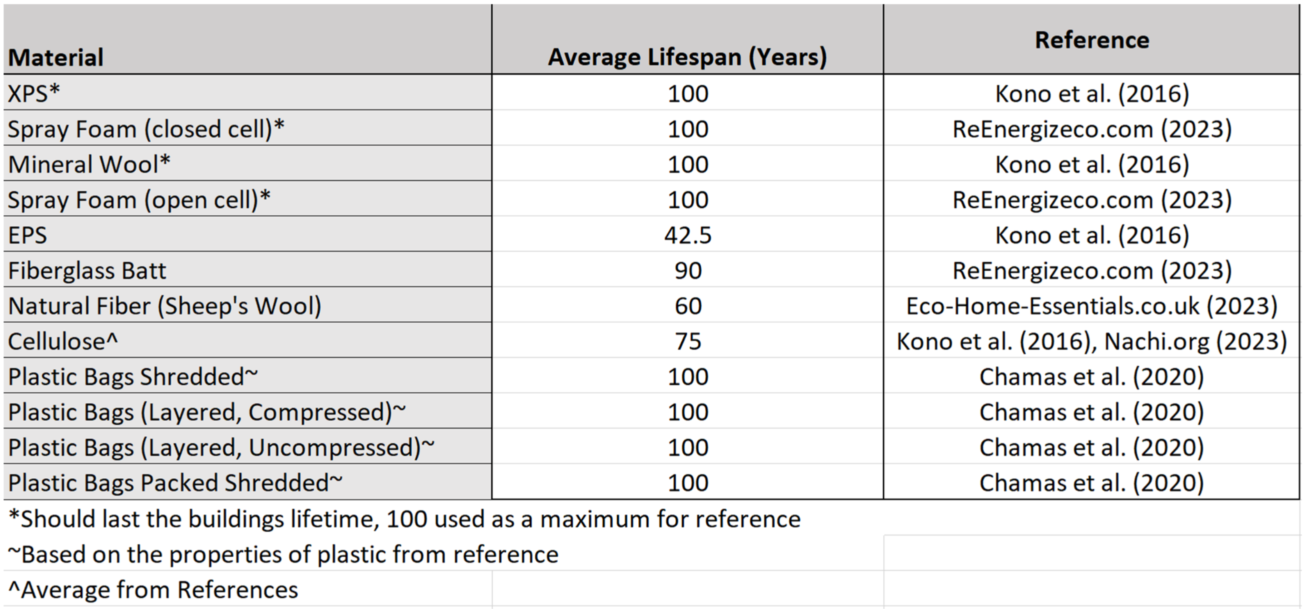
Insulation Material	R-value per inch	Reference
Fiberglass Batt*	3.3	Wilson (2021)
Cellulose*	3.65	Wilson (2021)
Mineral Wool*	3.3	Wilson (2021)
Natural Fiber (Sheep's Wool)*	3.5	Wilson (2021)
Spray Foam (open cell)	4.15	Wilson (2021)
Spray Foam (closed cell)	6	Learnmetrics.com (2022)
EPS	4.1	Wilson (2021)
XPS	4.9	Wilson (2021)

Table A.2 – Cost Data References



Insulation Material	Avg. Mat. Cost ($) /SF	Avg. Install or Labor Cost/SF	Reference
Fiberglass Batt	1.26		Homeadvisor.com (2023)
Cellulose*	0.35	1.1	Moor (2023), Biermeier & Allen, (2022)
Mineral Wool	1.386		Habas (2021)
Natural Fiber (Sheep's Wool)	2.1		Jonaitis (2023)
Spray Foam (open cell)	2.507	0.97	Loveland (2023)
Spray Foam (closed cell)	3.963	0.97	Loveland (2023)
EPS	0.575	1	Homeadvisor.com (2023)
XPS	1.05	1	Homeadvisor.com (2023)
*Average from References			

Table A.3 – Lifespan Data References



Material	Average Lifespan (Years)	Reference
XPS*	100	Kono et al. (2016)
Spray Foam (closed cell)*	100	ReEnergizeco.com (2023)
Mineral Wool*	100	Kono et al. (2016)
Spray Foam (open cell)*	100	ReEnergizeco.com (2023)
EPS	42.5	Kono et al. (2016)
Fiberglass Batt	90	ReEnergizeco.com (2023)
Natural Fiber (Sheep's Wool)	60	Eco-Home-Essentials.co.uk (2023)
Cellulose^	75	Kono et al. (2016), Nachi.org (2023)
Plastic Bags Shredded~	100	Chamas et al. (2020)
Plastic Bags (Layered, Compressed)~	100	Chamas et al. (2020)
Plastic Bags (Layered, Uncompressed)~	100	Chamas et al. (2020)
Plastic Bags Packed Shredded~	100	Chamas et al. (2020)

*Should last the buildings lifetime, 100 used as a maximum for reference

~Based on the properties of plastic from reference

^Average from References

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