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A MULTI-OBJECTIVE FIRE SAFETY AND SUSTAINABILITY SCREENING TOOL FOR SPECIFYING INSULATION MATERIALS

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ABSTRACT

Fire safety and sustainability goals in building design are frequently interdependent. Design elements chosen for their fire safety can have energy efficiency implications and vice versa. Furthermore, the environmental damage and carbon emissions from a single fire event can negate the utility of green features invested in the building. Therefore, while not obvious, fire safety and its impact on sustainability are inextricably linked. One of the decisions related to both sustainability and fire safety is the selection of thermal insulation materials. Insulating materials have always been an integral part of building design, serving as a key component in thermally controlling indoor environments. Modern designs and construction techniques often incorporate sustainability goals by seeking to minimize life cycle energy consumption and environmental impact. A well-insulated building reduces thermal load on the HVAC system, thus reducing energy consumption of the building. Therefore, a sustainably designed building is typically a heavily insulated building. In addition to thermal resistance characteristics, the choice of insulating material is often based on acoustic damping and cost. However, fire safety is generally overlooked as a factor for insulation material selection. Few treatments have considered how the competing objectives for sustainability and fire safety should be assessed when choosing insulation. This paper discusses a methodology for balancing these requirements by evaluating the aforementioned attributes of various insulating materials through implementation of a weighted mean. Each variable is normalized and then weighted according to the emphasis placed on each attribute, using experimental data for the relevant material property. Four weighting scenarios are presented, each emphasizing a different area of consideration: installed cost, fire safety, life-cycle assessment, and thermal. Materials considered are cellulose (newspaper), denim (cotton), fiberglass, stone wool, polyurethane, and polystyrene. Results of this analysis rank the materials in order of desirability and provide a method to reorder this ranking based on the priority assigned to each attribute. For the weighting scenarios presented herein, stone wool was consistently ranked as the best performer, while extruded polystyrene was typically the weakest. The intent is that this methodology would be informative for designers selecting materials and for planners contemplating revised building codes.

Keywords: sustainability, energy efficiency, green, insulation, fire safety

INTRODUCTION

Modern building design considerations frequently include reduced energy consumption and environmental impact. New types of materials and features have been developed to address these priorities, because these new elements help to attain lower life cycle energy and environmental costs for the site. Several of these elements have garnered attention from the fire safety community, due to the uncertainty of their performance in a fire event [1].

Ubiquitous to built structures is insulating material. These materials reduce the thermal load of the building, thus minimiz-

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ing the energy consumption needed to climate control the indoor environment. The task of choosing the proper insulation is not as straightforward as one might imagine, and several attributes must be weighed to optimize the selection. This paper aims to offer such an optimization tool, by selecting a sample of commercially available insulation and rating each on a relative scale.

Sustainability and Fire

Although the choice of materials and design elements for sustainable design does not focus on performance during a fire, it is possible that a single fire event can negate several, if not all, elements of green design. Environmental consequences of a fire include: toxic smoke, greenhouse gas emissions, water consumption to control the fire, wastewater runoff, solid waste disposal in landfills, and carbon costs in damaged material replacement. Standard life cycle assessments (LCA), which quantify either the cradle-to-gate or cradle-to-grave environmental impact of a product or system, do not incorporate risk assessment (e.g. environmental harm of a building fire). It has been shown that a building's life cycle CO_2 emissions can increase between 2% to 14% if a fire and subsequent rebuild occurs. Further, without risk consideration during sustainability improvements, the contribution of fire risk to the total lifecycle carbon emissions of a building can increase as much as threefold [2]. In contrast, addition of fire risk assessment in LCA of a product with flame retardant (FR) chemicals can illustrate the increased environmental impact when weighed against statistical risk [3]. In this way, LCA, incorporated with statistical risk, can help reduce overall environmental impact while keeping safety in mind.

Concealed Space Fires

Insulation may be installed in attics or roofs or in concealed spaces, such as wall or floor cavities. Combustible material is allowed in such spaces, provided sufficient protection from a thermal barrier (such as gypsum board) is present. Evidence suggests that insulation, regardless of material, will not contribute significantly to flame spread if the concealed space is sealed, fire blocks are properly installed and the air gap is less than 25 mm within the cavity [4]. As air availability within the cavity is the key component in allowing significant flame propagation, contact between the insulation and the thermal barrier is recommended. Fire blocks, spaced effectively to disallow large continuous areas of insulation, additionally act as a mechanism to prevent flame spread, if oxygen is sufficient. Variations and ambiguity in local code requirements can ultimately result in the neglect of either or both of these two installation techniques [5]. If these fire mitigation methods are employed, but proper installation is not performed, or later alterations to the building or aging of the building create such a situation as to allow increased ventilation, material flammability becomes more important. Although, in theory, these installation techniques make the combustibility of insulation moot, in practice it is unlikely that these methods can be completely effective, due either to irregularities during installation or alterations to the building later on. For example. the appropriate fire block technique was employed in the construction of a vegetable processing building in Yuma, Arizona, which was insulated with plastic foam. In 1992, despite the blocks, fire spread uninhibited throughout the concealed spaces, causing irreparable harm [5]. Annually, about 16,600 (5%) of reported home structure fires in the U.S. originate within attic/ceiling/roof assemblies or walls and other concealed spaces. These types of fires result in 50 (2%) civilian deaths, 260 (2%) civilian injuries, and account for 10% of direct property damage to home structures, topping $740 million in loss. Contribution of concealed spaces to fire spread is not as easily quantified, as it is difficult to classify when the fire does not start in a room [6]. The extent to which attics and concealed spaces affect other types of structures (such as high rises or commercial buildings) in fire is unknown. Anecdotally, contents of concealed spaces can have a major impact in fire. In 2013, a fire occurred at the Organic Valley dairy cooperative headquarters in Wisconsin. The fire was believed to have originated within the wall cavity, and progressed throughout the building via the concealed space. Again, the installed fire blocks had little, if any effect, on impeding the fire spread. Additionally, the building was equipped with sprinklers, but sprinkler extinction was impossible because of the fire's location in the concealed spaces inside the walls. Ultimately, the fire was able to spread for 18 hours, despite firefighting efforts, causing $13 million in property damage and other losses (the building cost $5.9 million to build in 2004). The extent of damage was in no small part due to the combustion of the insulation within the attic and wall cavities. This fire incident is an example of sustainable design resulting in increased fire risk. The insulation material was recycled denim (cotton) fiber. Other sustainable features (such as photovoltaic roof panels and lightweight engineered wood framing) also contributed to the extensive fire damage [7].

Compartment Fires

Insulation can prevent heat from escaping during a compartment (room) fire, which intensifies the fire and reduces the time to flash-over. But, if the insulation can maintain its thermal performance at elevated temperatures (without melting or burning away), it can also protect structural elements from the heat of the fire. In other words, a thermal insulator can both hurt and help during a compartment fire. Full-scale burn tests, as well as wall assembly experiments have been performed to assess the impact of various insulation types in a fire event [8–11]. Due to the nuance involved with insulation's impact in these scenarios, and the current debate on the subject, this paper will not incorporate such data into the assessment of the selected materials. However, in future work it should be considered.

MATERIALS CONSIDERED

The following is a list of the specific products considered in this paper. Composition of the materials considered are percentages by weight, and are those disclosed on the material safety data sheets (MSDS) for the product. The flame retardant chemical, if present, has been indicated by (FR).

Mineral

Glass. The fiberglass insulation is a flexible, fibrous batting sheet. Several fiberglass products were sampled.

Conventional, unfaced, fiberglass (FG-C), containing fibrous glass (78-97%), phenol, polymer with formaldehyde and urea (3-9%) [12, 13].

Sustainable, unfaced, fiberglass (FG-UF), containing fiber glass (85-100%), cured binder (0-15%) [14, 15].

Sustainable, kraft (paper) faced, fiberglass (FG-KF), containing fiber glass (85-100%), cured binder (0-15%), and asphalt, oxidized (facing adhesive) (1-5%) [14, 16].

Rock. The rockwool insulation (RW) is a flexible, fibrous batting sheet, containing mineral fiber (94-99%) and cured urea extended phenolic formaldehyde binder (1-6%) [17, 18].

Cellulose

Paper. Although cellulose can legitimately refer to any plant-based insulation, the term has evolved to refer to newspaper insulation. Modern-day cellulose insulation in made from recycled newspaper. The product sampled is a spray-applied, soft fiber pulp (SC). Product composition is recycled shredded-paper (82%) with sodium polyborate (FR) (18%) [19, 20].

Cotton. Another form of cellulosic insulation is recycled denim (cotton) scrap. Although not nearly as common as the other types of insulation studied in this paper, it is gaining popularity due to the sustainability of the product. The cotton insulation is a flexible batting sheet (CB) and contains recycled fiber products, boric acid (FR), ammonium sulfate (FR), and binder fiber. No composition percentages are given [21, 22]. After an extensive and concerted effort to find data on CB, there was not enough information available to make a compelling assembly of attributes for this product. Therefore, it has been excluded from assessment in this paper.

Plastic

Polyurethane. The spray polyurethane foam insulation (SPF) is a rigid (once cured), expanding spray-on, foam.

The low density SPF is an open-cell (SPF-OC) foam with components of tris-(2-chloroisopropyl)-phosphate (25-35%), surfactant (10-20%), tertiary amine (5-10%), and tertiary amine (1-5%). Flame retardant is present, but unspecified [23, 24].

The medium density SPF is a closed-cell (SPF-CC) foam with components of hydrofluorocarbon (5-10%), tris-(2-chloroisopropyl)-phosphate (3-7%), triethanolamine (3-7%), trans-1,2-dichloroethylene (1-5%), tertiary amine (1-5%), 2-butoxyethanol (1-5%), Polyester Polyol ($\geq$ 1%), Non-halogenated flame retardant (FR) ($\geq$ 1%), Polyether Polyol ($\geq$ 1%), and tertiary amine (0.1-1%) [25, 26].

Polystyrene. The extruded polystyrene insulation is a rigid, closed-cell (XPS-CC) foam panel. The XPS panel is composed of polystyrene (80-90%), HCFC-142b (7-12%), hexabromocyclododecane (FR) (0.5-1.5%), Talc (0-2%) [27, 28].

ATTRIBUTES OF INSULATION

Several attributes of insulation must be weighed against each other to determine the most appropriate material for the specific application. Attributes considered for each insulation can be seen in Table 1. The values presented in Table 1 are for the stated density (ρ) of the sample material.

Thermal Resistance

The paramount attribute of thermal insulation is, of course, its response to a temperature gradient. Standard practice requires insulating materials to be rated based on the thermal conductivity (k) and thickness (δ) of the product. The thermal resistance (R_{SI}) is determined through Equation 1 and the standard test method, ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*, which measures the thermal conductivity of a material for a specified thickness and temperature difference [48]. The thermal resistance is listed in product specifications as the *R-Value* and has units of h-ft^2-^{o}F-Btu^{-1} in the USA. Insulating products are tested at a mean temperature (average between hot and cold sides), T_m, of 75^{o}F (24^{o}C) for the published R-Values. For convenience, all stated R-values have been converted to SI units, and will be referred to as R_{SI} (units of m^2-K-W^{-1}), for clarity.

$$R_{SI} = \frac{\delta}{k} \tag{1}$$

Due to changes in environmental conditions during operation, the thermal conductivity of the material will be affected. Studies show that the thermal conductivity of insulation varies linearly with changes in T_m. Thermal conductivity increases as the mean temperature increases. As a material's density increases, it becomes less susceptible to thermal conductivity changes with changes in temperature gradients [29]. The values,

TABLE 1. INSULATION MATERIAL ATTRIBUTES CONSIDERED FOR COMPARATIVE ANALYSIS AMONG EIGHT DIFFERENT PRODUCTS.

Material	ρ	δ	k	$\frac{\Delta k}{\Delta T_m}$ †[c]	H_2O SORP ‡[c]	$\frac{\Delta k}{\Delta H_2O}$ ∗	H_2O PERM ‡[c]	Air PERM[c]	FSI	SDI	$\dot{Q}''_{peak}$ #	Cost ⋆[g]	Energy Use ⋆	Water Use ⋆	Climate Change ⋆	NRC
	kg/m³	mm	W/m-K	1/K	kg/kg	1/%wt	10^{-10} kg/m-s-pa	10^{-7} kg/m-s-pa	N/A	N/A	kW/m²	USD	MJ	kg	kg CO_2e	N/A
FG-C	21	89	0.039	0.006	0.0075	0.003[r]	1.72	2500	25	50	20[o]	$2.83	19.5[h]	9.7[h]	0.76[h]	1.00
FG	21	89	0.039	0.006	0.0075	0.003[r]	1.72	2500	25	50	20[o]	$2.83	9.9[i]	4.8[i]	0.62[i]	1.00
FG-KF	21	89	0.039	0.006	0.0075	0.003[r]	1.72[d]	2500[d]	70[d]	500[d]	200[p]	$2.83	16.7[j]	15.2[j]	0.75[j]	0.90
RW	32	89	0.034	0.003[a]	0.0075[d]	0.001[r]	1.72[d]	2500[d]	0	0	10[o]	$3.86	25.2[u]	6.3[u]	1.81[u]	1.00[d]
SC	25	89	0.040	0.004	0.2400	0.005[s]	1.78	2900	15	10	80[p]	$5.02	26.2[l]	0.8[l]	7.83[l]	0.80
SPF-OC	8	89	0.039	0.004	0.0160	0.003[d]	0.875	0.0420	70[e]	500[e]	200[q]	$8.28	52.1[m]	457.0[m]	2.40[m]	0.70
SPF-CC	30	89	0.021	0.004[b]	0.0200	0.003[t]	0.0322	0.0001	70[e]	500[e]	200[q]	$9.71	97.5[m]	761.0[m]	25.65[m]	0.20
XPS-CC	21	76	0.029	0.005	0.0040	0.001[t]	0.0122	0	110[f]	500[f]	300[o]	$14.06	80.7[n]	37.9[n]	60.80[n]	0.20[d]

All values from manufacturer's product specifications, unless otherwise noted. N/A = Not Applicable.

† Mean Temperature Effect on Thermal Conductivity ($\frac{\Delta k}{\Delta T_m}$)/($k$ @ 24°C).

∗ Moisture Effect on Thermal Conductivity ($\frac{\Delta k}{\Delta H_2O}$)/($k$ @ 0%wt).

‡ Water Vapor Sorption and Permeability @ 23°C. H_2O SORP @ 88% RH; H_2O PERM @ 90% RH.

Representative, Rounded, Peak Heat Release Rate @ 75 kW/m^2 Irradiance in Cone Calorimeter.

⋆ For 1 m^2 @ R_{SI} = 1 m^{2}K/W.

[a] [29]; [b] [30]; [c] [31], unless otherwise noted; [d] No data available. See related section for explanation of value assigned;

[e] [32]; [f] [33]. Values are those calculated with inclusion of ignition of molten residue on furnace floor;

[g] [34]. Installed; [h] [35]; [i] [36]; [j] [37]; [l] [38]. Climate Change value extrapolated; [m] [39]; [n] [40]; [o] [41]; [p] [42]; [q] [43]; [r] [44]; [s] [45]; [t] [46]; [u] [47].

listed as $\frac{\Delta k}{\Delta T_m}$, represent the mean temperature effect on thermal conductivity, relative to k at 24°C.

As with fire, air infiltration into the cavity is a significant factor for thermal performance. However, if the cavity has been properly and completely sealed, the thermal performance of the insulation is not affected by the material type [30]. Again, proper installation and complete sealing of the space is required. Otherwise, the effective R-value of the insulation will be reduced by heat convection with air flow through the cavity. ASHRAE report RP-1018 lists air permeability for all of the materials sampled, except RW and FG-KF [31]. A separate study found no difference in air permeability between FG and FG-KF, therefore the value from ASHRAE RP-1018 for FG has also been used for FG-KF [30]. No additional data could be found for air permeability of RW, therefore it was assumed to be the same as FG, due to similarity in material type (both mineral wools). Air permeability is denoted as Air PERM in Table 1.

Finally, moisture content can change thermal properties. Increased moisture decreases thermal resistance. Although this relationship is not necessarily linear for all insulating material types and densities, prior work in [44] indicates that it may be approximated as such for the products and material densities sampled, under likely operating conditions. Again, proper sealing of the cavity with moisture barriers can mitigate the inherent susceptibility of the insulation to moisture effects. Density will affect moisture's impact on thermal conductivity. The values given in Table 1, denoted as $\frac{\Delta k}{\Delta H_2O}$, are at or near the material densities of the samples and are relative to k at 24°C. No data could be found for SPF-OC, therefore it was assumed to behave the same as SPF-CC. It should be noted that SPF-OC and SPF-CC have very different densities, which has been demonstrated to affect the sensitivity of thermal conductivity change with moisture changes for other materials [44]. Additional data is needed to confirm that SPF-OC does indeed exhibit similar behavior as SPF-CC, in this regard.

All insulation materials have been evaluated based on an

ASTM test method, specific to their material type, for their moisture absorption. The type of test falls into two categories. The first is performed at very high relative humidities (RH) of 90% or 95% for 24 or 96 hours and an elevated temperature of 49°C (CB & SC, RW & FG) [49, 50]. The second is an immersion in water at 23°C for 24 or 96 hours (XPS & SPF) [51, 52]. As one might imagine, the disparate test methods result in incomparable values. Therefore, results from ASHRAE RP-1018 have been used instead. These values give an indication of the material's moisture uptake (denoted in Table 1 as H_2O SORP) under steady state conditions of 88% RH and 23°C [31]. No additional data could be found for moisture sorption of RW, therefore it was assumed to be the same as FG, due to material type similarity. When coupled with the material's thermal response to moisture, one can gain insight into the material's likely thermal conductivity change during extreme humidity events.

Acoustic Damping

Insulation may also serve as a barrier to sound transmission. ASTM C423, *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*, measures the sound absorption coefficient (α) at multiple frequencies for a certain material thickness and mounting condition [53]. Typically, the absorption coefficients at the 1/3 octave band center frequencies of 125, 250, 500, 1000, 2000, and 4000 Hz are measured. The Noise Reduction Coefficient (NRC) is the arithmetic mean, rounded to the nearest 0.05, of the sound absorption coefficients at four of these frequencies (250, 500, 1000 and 2000 Hz). This singular value gives an indication of the sound absorption capabilities of the material in a typical room environment (eg. human speech). Although a value of 1.00 indicates 100% sound absorption, often the NRC can be higher due to the specimen thickness [54]. All NRC values listed in Table 1 were calculated from mounting type A (ASTM E 795) test configurations [55]. NRC is the prior standard, and was recently replaced by the Sound Absorption Average (SAA). The SAA is more inclusive than the NRC, as it averages twelve sound absorption coefficients at the 1/3 octave frequencies from 200 to 2500 Hz. The SAA is also more precise, as it is rounded to the nearest 0.01 [54]. However, material data has not adapted to the new SAA standard, therefore this paper reports NRC values. Values listed are for the material thickness of the samples. The specific RW product selected did not have any acoustic data available, therefore the value listed in Table 1 is a reasonable estimate, based on other RW products NRC data from the same manufacturer (with similar density, composition, and thickness). The XPS-CC product did not list acoustic data either. This is most likely because polystyrene is not generally regarded as a good acoustic insulator, therefore it is not tested or advertised as such. The NRC value for XPS-CC was taken from a similar (in density, composition, and thickness) closed-cell expanded polystyrene, made by a different manufacturer [56].

Fire Performance

Concealed insulation in a wall or floor assembly must only meet a minimum standard for flame spread and smoke development through a Steiner Tunnel test, typically ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials* or UL-723 [57, 58]. The results of this test are a Flame Spread Index (FSI) and Smoke Developed Index (SDI) for the material. These indices are on a relative scale; asbestos-cement board having a value of 0 and red oak wood having a value of 100. Although this is the only fire test universally performed on individual materials, there are several critiques of the method. The test is performed, as the name implies, in a horizontal tunnel. If the specimen easily melts, such as thermoplastics (e.g. polystyrene), or is very thin, the results of the test may be mis-representative of actual fire scenarios [59].

The whole wall/floor assembly may be required to undergo the ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*, the consensus being that the exterior flame retarding wall (typically gypsum board in the USA) will provide a sufficient barrier between the heat of the flames and the concealed space contents [60]. In fact, some insulation is not required to meet the standard maximum threshold FSI of 25 or SDI of 450 if it is installed abutting the thermal barrier (e.g. kraft faced fiberglass). This test gives no indication of the insulation's impact in concealed space fires.

A more robust assessment of a material's combustibility and contribution in fire is the heat release rate per unit area ($\dot{Q}''$), given in Equation 2. Using the standard test method ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, one is able to measure a peak heat release rate ($\dot{Q}''_{peak}$), as well as many other properties in fire. The rate of heat release is a function of the mass flux of vaporized fuel ($\dot{m}''_F$) and the heat of combustion of the fuel (Δh_c) [61]. Some representative values have been added to assess the materials studied in this paper. These values assume a fuel-lean environment, where oxygen supply is not limited because the cone calorimeter test is in such an environment. However, if a fire were to occur in a concealed space, the likely scenario would be a fuel-rich environment, in which $\dot{Q}''$ is limited by the air supply to the cavity. Therefore, the $\dot{Q}''_{peak}$ values provided are conservative. Further, these values include the presence of flame retardants (if applicable) in the materials. Unlike FSI and SDI, values for heat release rate can be used to model impacts of fuel sources in fire events [59]. However, there has been no requirement for product manufacturers to test for or publish such data. The FG-KF did not undergo the ASTM E84 test, hence the values listed in Table 1 for FG-KF FSI and SDI are assumed to be the same as SPF. This assumption is based on the similarity between $\dot{Q}''_{peak}$ for FG-

KF and SPF, which suggests that they would exhibit similar FSI and SDI. Assuming these values for FG-KF is a conservative estimate.

$$\dot{Q}" = \dot{m}_F" \Delta h_c \tag{2}$$

Miscellaneous

Cost. Although there are many attributes that can be considered in material selection, cost is always a factor. The relative cost of thermal insulation can be weighed as the price per unit area and R-Value. The costs listed in Table 1 are installed costs, based upon estimates for the Northeastern United States. Additional costs associated with air barrier installation are not included. Further, although the thickness required for the same R-Value may influence the costs of other materials, such as the framing materials, it is not considered here.

Durability. Commercially available insulation has been tested under various ASTM standards to meet minimum requirements of durability. Acceptable levels of corrosiveness, moisture absorption, microbial growth, vermin hospitality, etc. must be met. The reporting method for these tests is pass/fail, therefore it is hard to assess the variance in quality among materials. The National Association of Home Builders (NAHB) reports expected durability of all types of insulating materials will last or exceed the lifetime of the building [62].

Water vapor permeability (H_2O PERM) of the insulation may affect the durability of adjacent materials and the humidity of the indoor environment, however. This data has been added to provide some insight. Rockwool and FG-KF were not reported in the study, therefore these materials were assumed to behave the same as FG. This assumption is most likely conservative, in that FG-KF is more likely to prevent water transport (due to the facing) and RW is denser that FG (again preventing transport). However, it is unlikely that the true value for either varies that much from the FG data (e.g. relative to the values for the plastics). Future work may include more emphasis on durability differences (e.g. compression degradation, decomposition, etc.), but is not considered here in full.

Life Cycle Assessment. Although an extensive list of accounting can be performed, three factors of environmental impact are considered here. These factors are considered from cradle-to-grave, with 100% landfill disposal as the last stage of product life. Total energy and water consumption, as well as equivalent CO_2 emissions are quantified for each material. Where available, these data are drawn from the specific product; otherwise, they are from a generalized study of a similar product (e.g. rockwool in the European market). The Functional Unit (FU) is based on 1 m^2 of insulation with an R_{SI} = 1 m^2-K/W. No integration of risk in the LCA has been done here.

Indoor Air Quality. It has been found that indoor air quality (IAQ) can be adversely affected by emissions from concealed materials [63]. Although material composition has been listed, further consideration of impacts to IAQ are not included in this assessment.

METHODOLOGY

The data values (X) gathered for each attribute category (i) were normalized (X') relative to the range of values over the materials sampled (j). Equations 3 and 4 provide the normalization equations, on a scale from 0 to 1, with 1 being the best material in that attribute category. Equation 3 was used if a higher attribute value was preferable (e.g. NRC) and Equation 4 if a lower value was preferable (e.g. FSI).

$$X'_{i,j} = \frac{X_{i,j} - X_{i,min}}{X_{i,max} - X_{i,min}} \tag{3}$$

$$X'_{i,j} = \frac{X_{i,max} - X_{i,j}}{X_{i,max} - X_{i,min}} \tag{4}$$

Each category was then weighted based on the relative importance given to that attribute, with all weights (w) summing to 1. Table 2 gives the chosen weights for each attribute. These weights may change based on the particular desires or needs for the specific project. As such, these weights may be altered and used in the weighted mean equation (Eqn. 5) to find the overall rating ($\bar{x}$) of each insulation sample. Four different weighting scenarios were chosen as a demonstration. The first is with a high emphasis on cost, the second with a high emphasis on fire, the third with a high emphasis on LCA, and the fourth emphasis is on superior thermal performance (Wt Thermal). In each of these scenarios, a total of $w = 0.5$ was assigned to the emphasized attribute(s). For example, in the fire emphasized case, the 0.5 weight was evenly distributed between FSI, SDI, and $\dot{Q}"_{peak}$. Finally, the remaining weight was then evenly distributed among the other attributes. Exceptions are H_2O SORP and $\frac{\Delta k}{\Delta H_2O}$, which were counted as one combined attribute due to their interdependence (each receiving half the weight) and k counted as two attributes due to its significant role in insulation quality (receiving double the weight). The weighting scheme presented herein is somewhat subjective, although future work will benefit from incorporation of statistics to determine more appropriate relative weighting of insulation attributes.

TABLE 2. WEIGHTED INSULATION MATERIAL ATTRIBUTES WITH FOUR WEIGHTING SCENARIOS. EACH SCENARIO INCREASES THE RELATIVE WEIGHT OF A CERTAIN SET OF ATTRIBUTES TO EMPHASIZE EITHER COST, FIRE, LCA, OR THERMAL.

Material	k	$\frac{\Delta k}{\Delta T_m}$	H_2O SORP	$\frac{\Delta k}{\Delta H_2O}$	H_2O PERM	Air PERM	FSI	SDI	$\dot{Q}''_{peak}$	Cost	Energy Use	Water Use	Climate Change	NRC
FG-C	0.0	0.0	1.0	0.4	0.0	0.1	0.8	0.9	1.0	1.0	0.9	1.0	1.0	1.0
FG	0.0	0.0	1.0	0.4	0.0	0.1	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0
FG-KF	0.0	0.0	1.0	0.4	0.0	0.1	0.4	0.0	0.3	1.0	0.9	1.0	1.0	0.9
RW	0.3	1.0	1.0	1.0	0.0	0.1	1.0	1.0	1.0	0.9	0.8	1.0	1.0	1.0
SC	0.0	0.5	0.0	0.0	0.0	0.0	0.9	1.0	0.8	0.8	0.8	1.0	0.9	0.8
SPF-OC	0.0	0.5	0.9	0.5	0.5	1.0	0.4	0.0	0.3	0.5	0.5	0.4	1.0	0.6
SPF-CC	1.0	0.6	0.9	0.5	1.0	1.0	0.4	0.0	0.3	0.4	0.0	0.0	0.6	0.0
XPS-CC	0.6	0.3	1.0	0.9	1.0	1.0	0.0	0.0	0.0	0.0	0.2	1.0	0.0	0.0
Wt Cost	0.078	0.038	0.019	0.019	0.040	0.038	0.038	0.038	0.038	0.500	0.038	0.038	0.038	0.040
Wt Fire	0.092	0.045	0.023	0.023	0.045	0.045	0.167	0.167	0.167	0.046	0.045	0.045	0.045	0.045
Wt LCA	0.092	0.045	0.023	0.023	0.045	0.045	0.045	0.045	0.045	0.046	0.167	0.167	0.167	0.045
Wt Thermal	0.200	0.100	0.050	0.050	0.052	0.100	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056

$$\bar{x}_j = \sum_{i=1}^{n} w_i X'_{i,j} \tag{5}$$

RESULTS

The overall ratings for each material under the four weighting scenarios can be seen in Figure 1. Rockwool was the best performer, regardless of which scenario of weights was chosen. When cost was emphasized, close contenders were the fiberglass materials. Unfaced fiberglass and cellulose faired well when fire safety or LCA was emphasized, while closed-cell spray polyurethane foam performed well with thermal performance emphasis. The extruded polystyrene did not perform well in any scenarios. Although these results may seem counterintuitive to industry preferences, part of the disparity can be explained by the inclusion of both LCA and fire safety in all weighting scenarios herein demonstrated. These two factors, frequently overlooked, can be seen here to have a fairly significant impact on the insulation of choice. However, this is only because of the import placed on these factors, which may not be justified in all building projects.

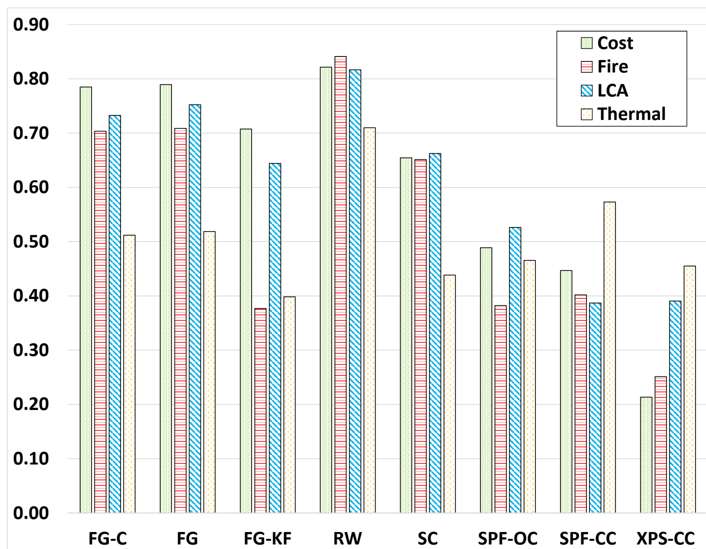

FIGURE 1. OVERALL INSULATION RATING, 0 TO 1, WITH 1 BEING BEST. WEIGHTED WITH COST, FIRE, LCA, OR THERMAL EMPHASIS.

CONCLUSION

Several thermal insulating products were selected and assessed relative to one another based on their performance characteristics. Attributes, such as thermal conductivity and NRC, were normalized and subsequently weighted relative to each other in four different scenarios. Each scenario emphasized a performance area: cost, fire, LCA, and thermal. Based on the extensive, but not exhaustive, list of attributes considered, rockwool was the best performer across the board. Unfaced fiberglass (FG-C & FG) faired well in all scenarios, although only marginally so in thermal performance. Closed-cell polyurethane foam (SPF-CC) performed well when thermal performance was emphasized. The extruded polystyrene (XPS-CC) was typically the weakest performer in all scenarios.

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