Life-Cycle Assessment of Thermal Insulation Materials for External Walls of Buildings

Conference Paper · February 2011

DOI: 10.13140/RG.2.1.1756.7768

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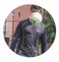

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Life-cycle assessment of thermal insulation materials for external walls of buildings

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ABSTRACT: This paper includes a review of the results of research studies regarding the life-cycle assessment (LCA) of insulation materials used in a building's external walls. The results concerning the environmental evaluation of the most common solutions are compared with the results of non-traditional solutions, namely in the issues related with production, transport and end-of-life phases.

This kind of benchmarking will evolve into a direct comparison of the environmental information of the insulation materials of each European producer when CEN TC350 - "Sustainability of construction works" - finishes its standardization work. Then, it will be possible to develop "Type III" Environmental Product Declarations (EPD) for each construction material or building assembly, which are based on LCA methodology. Nevertheless, the EPD's of insulation materials already available in international programs and listed in this paper are important to define a point of reference for the thermal performance of this group of materials.

1 INTRODUCTION

In the European Union, residential and commercial buildings represent an important part (about 40%) of the global energy consumption and CO_2 emissions, about half of the emissions not covered by the "Emission Trading Scheme", and approximately 40% of all man-made waste. All possible reduction in the impact of a building leads to significant economic, social and environmental benefits, and the reduction potential of this kind of construction is high (namely in CO_2 emissions) and has negative or low abatement costs (CIB, 1999; EC, 2008; UNEP, 2007).

The envelope is one of the main parts of a building. One of its parts, the external walls, directly influences its thermal and environmental performance through its considerable weight in the envelope's initial embodied energy, life cycle energy consumption, life cycle cost and the users comfort. Walls can represent up to 15% of the overall environmental impacts of a building over a 60-year life cycle (Bingel et al., 2006). The environmental impacts of each external wall solution result directly from the attributes of the materials used (namely the insulation materials), such as its initial embodied energy and thermal properties, and from the way the solution is designed and built.

The evaluation of the environmental impacts of buildings should be made from a life-cycle point of view. The life-cycle assessment (LCA) integrated approach is one of the most often used to achieve this goal and allows for the evaluation of the environmental impacts of insulation materials by considering their source and the resources used in their execution, the maintenance operations, the expected service life, and the end-of-life phase.

This methodology could be applied via a "cradle to grave" (including the extraction and processing of raw materials, the transport and distribution, the use, maintenance and final disposal) or "cradle to cradle" approach (also including the reuse and/or recycling) based on ISO 14040:2006 and ISO 14044:2006 international standards (ISO, 2006b, 2006c). The application of the LCA methodology must be followed by the creation of extensive and reliable Life Cycle Inventory data, namely concerning the construction materials.

The purpose of this paper is to make a review of international LCA research studies of common and non-traditional insulation materials used in external walls of buildings. The final aim is to identify the most environmentally friendly solution and find lacunas and opportunities for research development.

2 SCOPE AND METHODOLOGY

The aim of this research work is to develop cradle to cradle LCA studies of the external wall solutions used in Portugal. Even though it is imperative to use national production data (because the production technology, energetic mix and most significant environmental impact categories differ from country to country), this work started by benchmarking LCA research results concerning the materials integrated in a building's external walls. For this reason, this paper includes a review of the results of research studies made in the last decade regarding the LCA of insulation materials from the main scientific databases.

3 INSULATION MATERIAL CLASSIFICATION

Insulation materials can be grouped in 3 families according to their chemical or physical structure: mineral/inorganic; oil derived ones; and so-called "organic natural" ones. Further, these materials can have a fibrous or cellular structure which will determine to a great extent both their mechanical and thermal properties (Table 1) (Kotaji & Loebel, 2010). Mineral/inorganic materials account for 60% of the market in Europe; oil-derived ones account for about 30% (namely Extruded Polystyrene (XPS), Expanded Polystyrene (EPS) and Polyurethane/Polyisocyanurate (PUR/PIR)); and "organic natural" and other materials account for about 10% (Ardente et al., 2008). In this last group, Agglomerate of Expanded Cork (ICB) can be highlighted as Portugal is the world's largest producer and exporter. This material can be used as insulation but also as an external covering (Figure 1).More exotic materials, like transparent and dynamic insulation, 'ecological' materials based on agricultural raw materials, and gas-filled and vacuum insulated panels have found limited acceptance in the market, mainly because of their high cost (various references cited by (Ardente, et al., 2008)).

Table 1. Classification of insulation materials by chemical and physical structure

	Fibre	Cellular	Granular
Mineral "Inorganic"	Mineral wool - MW (Glass/ Stone wool - GW and SW)	Foam glass	Expanded perlite; expanded vermiculite; LECA (Light Expanded Clay Aggregate)
Oil-derived "Organic synthetic"	-	EPS; PUR/PIR; XPS	
Plant / animal derived "Organic natural"	Cellulose; Wood wool; Cotton/Sheep wool; Duck feathers; Flax; Hemp; Straw bale; Recycled paper or denim	ICB; Recycled paper	Cork granulate; Recycled paper

Figure 1. Images from the Portuguese Pavilion at the Xangai exhibition (from http://www.stylepark.com and http://corticeira-amorim.blogspot.com)

3.1 *Thermal performance of insulation materials*

The U-value or thermal transmittance is defined as the thermal conductivity of the insulation material divided by its thickness. To achieve the same U-value (0.4 W/(m^2.ºC), for example), different thicknesses are needed for each insulation material: 9.3 cm for EPS and XPS, 10 cm for PUR/PIR, GW and SW, 11.3 mm for ICB and 40 cm for LECA.

Along with the thermal performance, other characteristics have to be taken into account when an insulation material is chosen for a specific use in a building, namely for external walls, as very few are capable of performing all functions (CIB, 2010). The absorption of water, the durability, the mechanical and fire resistance, the sound absorption, and the release of hazardous substances, namely during a fire, are some of the characteristics that have to be evaluated along with the environmental performance to make a conscientious choice of the adequate solution possible (Al-Homoud, 2005). The environmental performance will be described in detail for some types of insulation materials in the next section of the paper.

4 LCA OF THERMAL INSULATION MATERIALS USED IN A BUILDING'S EXTERNAL WALLS

In order to benchmark the environmental performance of different insulation materials, this section of the paper presents a review of the results of different research works regarding the LCA of insulation materials used in a building's external walls. This review also includes some considerations about important environmental impacts of these materials, namely in the following life-cycle phases: production, transport and end-of-life.

4.1 *Benchmarking of LCA research results*

PU-Europe, the "European association of rigid polyurethane foam insulation manufacturers", ordered from the UK "Building Research Establishment", a LCA study of a building with different insulation materials in the envelope, including the production of construction materials and the energy use considering the same U-value in walls, roof and ground floor (Kotaji & Loebel, 2010). The main conclusions were that: there are not enough LCA data available to the public on "natural" plant or animal derived insulation materials to perform meaningful LCA comparisons; PUR and MW and GW have similar environmental performance and the building's energy use dominates the Global Warming Potential (GWP). In terms of the production of construction materials, Acidification, Photochemical ozone creation and Eutrophication dominate the potential impacts.

A LCA study in Greece collected information about raw materials and energy flows from material manufacturers, and emissions from production, transportation and installation from SimaPro (a LCA software). The results presented in Figure 2 are dimensionless and compare the scale of CO_2 emissions (GWP) between the materials (PUR, MW, XPS and EPS) considering the same U-value. The results for embodied energy are similar, but in this case the environmental performance of PUR and MW are significantly different (Anastaselos et al., 2009).

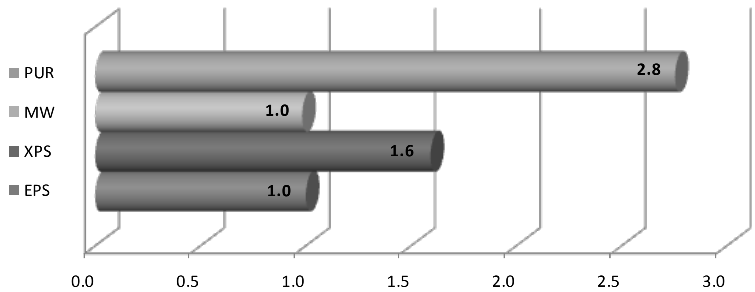


Figure 2. Dimensionless results for Global Warming Potential from production, transportation and installation of four insulation materials, considering the same U-value (Anastaselos, et al., 2009)

Also in Greece, a cradle-to-gate LCA included SW (mattress) and XPS production. XPS has 2.3 times more GWP than SW per functional unit (m^2 of insulated surface), greater than the 1.6 value of the previous study, where the thermal conductivity considered for the MW was just 6% lower than the one considered for the SW of this study (Papadopoulos & Giama, 2007).

In Canada, a study was devoted to the energy associated with the manufacture of four insulation materials. The production of EPS or PUR can consume more than 40 times the energy of the production of cellulose insulation (Figure 3) (Harvey, 2007).

Kenaf (*Hibiscus cannabinus*) is a plant cultivated in Italy and other Mediterranean countries and mainly used in the thermal insulation field and in pulp production. The life-cycle impacts of production and end-of-life of kenaf-fiber insulation boards have been compared to the performances of their competitors (SW - natural minerals and recycled post-production waste materials, mixed with binder and impregnation oil; paper wool; flax rolls; PUR; GW; MW derived from basalts and dolomites). The introduction of recycled materials into the manufacturing process or incineration with energy recovery and electricity production could decrease the energy requirements of the kenaf-fiber insulation. The results also show that the lowest energy consumption is ascribed to MW. Regarding the other environmental categories, paper wool has the best performance. PUR has the largest impact in terms of consumed energy and air releases due to the large use of fossil fuels during the production process. The environmental impacts of insulation boards are also largely due to the employment of oil derived resins and binders during the production, even in natural-fibre based products (Ardente, et al., 2008).

LCA from cradle-to-gate (Europe), including packaging and end-of-life, were applied to SW, flax and recycled cellulose. The results (Figure 4) show that a large consumption of non-renewable materials (e.g. binders and flame retardants) in the production of flax insulation adds a significant contribution to GWP and energy consumption (Schmidt et al., 2004a).

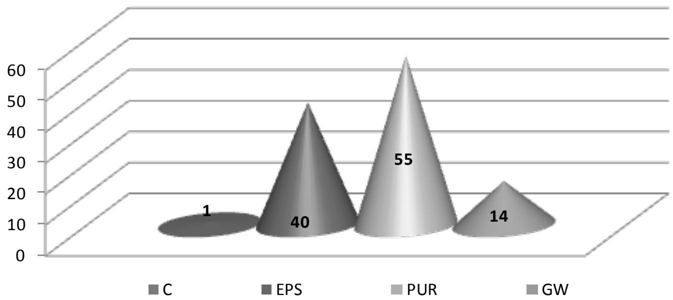


Figure 3. Dimensionless results for the energy associated with the manufacture of four insulation materials, considering the same U-value (Harvey, 2007)

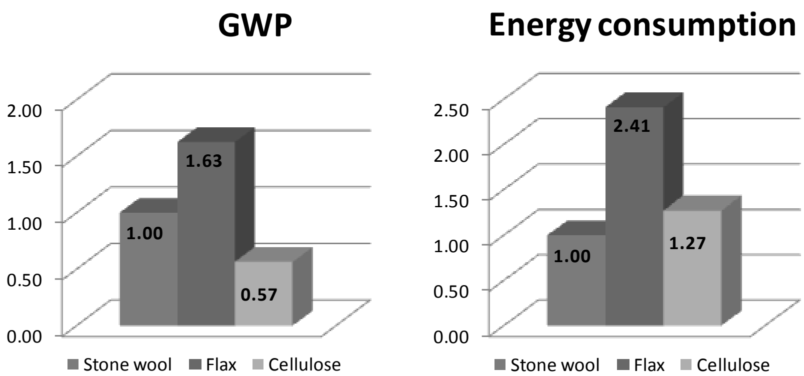


Figure 4. Dimensionless results of the Global Warming Potential and Energy Consumption from cradle-to-gate, including packaging, and end-of-life, considering the same U-value (Schmidt et al., 2004b)

4.2 *The production of insulation materials*

The influence of the production phase can be crucial to the energy and components embodied in each insulation material. To decrease the consumption of raw materials, a solution is to use a significant quantity of recycled materials, e.g. insulation made of natural denim and cotton fibres (90% post-consumer) (Figure 5) and paper insulation made from cellulose from waste paper, which is available in the form of a board or filling type particles (Figure 6).

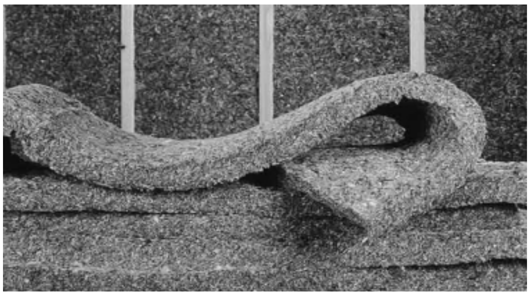
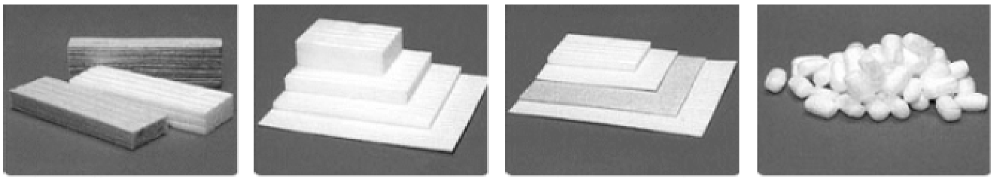


Figure 5. Insulation that consists almost entirely of natural denim and cotton fibers (90% post-consumer) that are 100% recyclable (from http://www.bondedlogic.com/ultratouch-cotton.htm)



a) Low density board b) Medium density c) High density d) Filling particles

Figure 6. In South Korea, paper insulation can be found in the form of a board or filling type particles: the cellulose from waste paper is mixed with starch and polypropylene resins; then undergoes a process of expansion using steam and a press moulding process (Kang et al., 2008)

The environmental characterization of the production phase of some insulation materials is already detailed in “Environmental product declarations” (EPD). EPD’s are voluntarily developed documents that present quantified environmental information about the life-cycle of a product, thus allowing comparisons among functionally equivalent products. EPD’s correspond to Type III environmental declarations which are defined in detail in the international standard “ISO 14025:2006 - Environmental labels and declarations - Type III environmental declarations - Principles and procedures” (ISO, 2006a). Table 2 includes the EPD’s of insulation materials already available in international EPD programs.

Table 2. EPDs of insulation materials already available in international EPD programs

EPD Program	Country (Organization; website)	Insulation materials with EPD
Programme de Déclaration Environnementale et Sanitaire pour les produits de construction	France (*Centre Scientifique et Technique du Bâtiment”; www.inies.fr)*	147 EPDs of insulation materials - cotton wool; duck feathers; EPS; expanded perlite; foam glass; hemp; MW; PUR; wood wool
Umwelt-Deklarationen (EPD)	Germany (*Institut Bauen und Umwelt; bau-umwelt.de/ hp421/Declarations.htm)*	Foam glass and MW
EcoLeaf	Japan (Japan Environmental Management Association For Industry - JEMAI; *www.jemai.or.jp/english/ecoleaf*)	EPS and XPS
International EPD System	(Non-profit international organization; *www.environdec.com/*)	PUR and XPS
Declaración Ambiental de Produto (DAPc)	Spain (*Col·legi d´Aparelladors, Arquitectes Tècnics i Enginyers d'Edificació de Barcelona* e *Generalitat de Catalunya; es.csostenible.net/dapc/ el-sistema-dapc/*)	MW

4.3 *The transport of insulation materials*

Despite being low-density materials, the transport phase of insulation products can be significant in a LCA study because of the volume they can reach.

Following the study (Harvey, 2007) already described, another one in Ireland analyzed the energy for transport of insulation materials from the producers (GW from Germany; others from the UK) and concluded that the delivery of cellulose insulation needs slightly more energy than its production (Collins et al., 2010).

In Thailand, insulation boards are produced from agricultural waste: bagasse (the waste from sugar production), coconut coir and rice hull. Ongoing research in this country aims at reducing the thermal conductivity between 80 % - bagasse - and 5 % - rice hale (coconut coir - 15%) to make these solutions almost as intensive in energy as Cellulose or GW imported from Los Angeles, USA (Panyakaew & Fotios, 2009).

4.4 *The end-of-life of insulation materials*

In the study made in Europe, LCA from cradle-to-gate, including packaging, and end-of-life with different scenarios were made of SW, flax (crop grown) and cellulose (recycled) (Schmidt, et al., 2004b). The reference case was “100% recycling” in low-grade applications; but the best end-of-life option may be unavailable due to technical or economic constraints.

The end-of-life of insulation materials continues to be a problem and not even the new European Laws contribute to ease its resolution. The targets for reduction of quantities, recycling or reuse of construction and demolitions wastes (CDW) are all defined in weight (EP, 2008) and, consequently, the insulations materials become dispensable or forgotten in the process of CDW, and the most probable destiny is landfill. If this criterion is changed in order to define the importance of CDW in volume when they have a density of less than 300 kg/m^3, reality would look different for the end-of-life of insulation materials.

There are other problems which prevent the best end-of-life option for insulation materials. One of them is the inclusion of brominated flame retardants in EPS and XPS production, components whose risk assessment results are already available but are not conclusive or contradictory. Alternative solutions for these compounds are being introduced, but there are still a lot of insulation materials in buildings with them (BuildingGreen, 2009; EPSMA, 2009; IARC, 1990; SFT, 2003). Selective demolition methods may allow collecting a significant quantity of plastic insulation products in old buildings. Nevertheless, these products contain fire retardants that are economically unfeasible to characterize in detail. The knowledge about the behaviour of these compounds during recycling is still low and does not advise this procedure. Therefore, these problems jeopardize any possible recycling process and the disposal of plastic insulation products normally takes the form of incineration with energy recovery (Brandrup et al., 1996). Regarding CFC’s, these compounds where banned from PUR (CFC-11) and XPS (CFC-12) production. However, the recycling of these products, when recovered from an old building, has the same problems as foams with fire retardants, and also has the potential of releasing CFC’s (Andersen & Sarma, 2002; Harvey, 2007).

MW is also a group of insulation materials that represents a concern for anyone that works in their production, installation or recovery in demolition processes, but the conclusions about its effects on health are still limited (IARC, 1998, 2002). The same observation applies for insulation materials made from flax or paper fibres due to the exposure to the corresponding production dust (Schmidt, et al., 2004a). These concerns related with the end-of-life of insulation materials limit a cradle to cradle approach.

5 CONCLUSION AND PERSPECTIVES

In conclusion, each country has their own common construction materials and solutions for thermal insulation of buildings, as stated in the works described in this paper. The production technology, energy mix and most significant environmental impact categories also differ from country to country. Despite these differences, all LCA research studies must have a definite scope and methodological approach to compare functionally equivalent products. Some of the studies included in this paper do not follow these principles which prevents comparing their results, namely due to differences in the thermal performance considered for each material in the studies that clearly influence the final results. These problems create limitations to the interpretation of the results of the studies. However, careful and detailed readings of all the studies collected allow some partial and global conclusions that maintain the aim and justify the significance of this work. Nevertheless, a detailed study of the durability and end-of-life of all the insulation materials continues to be necessary. For these reasons, it is important to develop cradle to cradle LCA studies of the traditional external wall solutions of each region with production data from the same regional source and including the maintenance and reuse or recycling phases and the operation energy. This last feature is a powerful tool which allows the comparison of alternatives without the obligation of considering the functional equivalence of thermal performance, and enlarges the amount of solutions that the designer can consider. The LCA analysis could be complemented by a life-cycle cost calculation for each alternative, without forgetting that all these solutions must comply with the regulations and standards minimum requirements (Bingel, et al., 2006).

Regarding the production phase, the introduction of recycled materials into the composition of the products and the use of natural resins are good options to improve their environmental performance. The results related with the transport phase reveal that when choosing insulation material it is important to consider both the energy associated with manufacture and the location of the insulation production site.

From the insulation materials referred to in Table 1, only expanded vermiculite, LECA, ICB and other natural products (e.g. straw bale and recycled paper or denim) had not yet been studied in terms of environmental performance via the standard LCA methodology. This should be considered when assessing information provided by the manufacturer and not until all products have undergone LCA's will accurate comparisons be possible (CIB, 2010). Nevertheless, it must be stressed that the end-of-life phase may have a positive contribution to natural insulation materials, despite not being studied in detail in any of the works included in the review made. Health issues still prevent mineral and oil-derived insulation materials to be sent to the best end-of-life options.

This kind of benchmarking will evolve into a direct comparison of the environmental information of the insulation materials of each European producer when CEN TC350 - "Sustainability of construction works" finishes its standardization work, in 2012. Then, it will be possible to develop "Environmental Product Declarations" (EPD) of construction materials and building assemblies based on Rules for each construction Product Category. Namely, it will be possible to develop "Type III" EPD's which are based on an LCA with a definite scope and functional equivalent of each construction material or building assembly and, for this reason, are a complete, robust and scientifically validated source of information of the environmental impacts of the product being studied during their life-cycle. Nevertheless, the EPD's of insulation materials already available in international programs are important to define a point of reference for the Life-Cycle Assessment of a group of materials that is simultaneously so heterogeneous in their composition and production process and so important in their contribution to the thermal and environmental efficiency of buildings, and to promote a cradle to cradle approach.

6 ACKNOWLEDGEMENTS

The authors thankfully acknowledge the scholarship of FCT (Foundation for Science and Technology) to support the PhD study of the first author and the support of the ICIST Research Institute from IST, Technical University of Lisbon.

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