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Comparative environmental life cycle assessment of thermal insulation materials of buildings

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ABSTRACT

Insulation is a relevant technical solution for cutting energy consumption in buildings. The aim of this paper is to evaluate the environmental impacts and the consumption of renewable and non-renewable primary energy on the production of conventional thermal insulation materials: extruded and expanded polystyrene, polyurethane, expanded cork agglomerate and expanded clay lightweight aggregates. The comparison per functional unit of the innovative and up-to-date environmental performance of expanded cork and clay with the most common insulation materials used in Europe (the remaining three), and for the environmental categories and life-cycle stages defined in recent European standards, is presented for the first time. These results have been based on site-specific data from companies whose quality was fully characterised, and achieved through a consistent methodology that is fully described, including the modelling of energy processes and a sensitivity analysis of the allocation procedures. These "cradle to gate" results are scientifically sound since they were achieved by following the International standards for Life Cycle Assessment and recent European standards on the environmental evaluation of buildings.

1. Introduction

The consumption of energy in the world today contributes to pollution, environmental degradation and global greenhouse emissions [1]. The four sectors that contribute the most to energy consumption are the industrial, building (residential/commercial), transportation and agriculture sectors, a large fraction of it being accounted for by the construction and operation of buildings. In the European Union (EU), the building sector is responsible for over 40% of overall energy consumption, making a significant contribution to CO_2 emissions [2–4]. Sustainability is now a relevant focus of the construction industry, and, in particular, environmental concerns related to buildings are growing among the general public and potential building buyers [5].

In Europe, the Energy certification of buildings [6] has already had positive consequences, not only in terms of buildings' thermal performance. If buildings are properly designed and operated, significant energy savings can be achieved. Hence, building designers can play a major part in solving the energy problem by making the appropriate design decisions, at an early stage, for the selection and integration of building components [7]. Thermal insulation materials have an important role and their use is a logical first step to reducing the energy required to keep a good interior temperature and therefore achieve energy efficiency [8].

With the minimisation of carbon emissions resulting from the use of buildings, largely due to the progress made towards low- or near-zero energy buildings, the relative importance of a building's life-cycle stages is changing ([9] cited by [10]). Thus, measures to control and reduce the environmental impacts of the entire production chain of construction have become a priority, in particular the production of building materials. The increased investment in near-zero buildings is also promoting the use of passive solutions for the envelope, resulting in increased insulation thicknesses in buildings all over the world. Thus, the contribution of these materials to the life cycle environmental impact of buildings is also gaining momentum. This paper therefore presents the following original aspects:

- The evaluation of the environmental impacts of the production of conventional thermal insulation materials: extruded and expanded polystyrene (XPS and EPS, respectively), polyurethane (PUR), expanded cork agglomerate (ICB) and expanded clay lightweight aggregates (LWA);

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List of symbols and acronyms:

A	Area (m^2)
λ	Thermal conductivity (W/(m K))
ρ	Density of the insulation product (kg/m^3)
ADP	Abiotic depletion potential
AP	Acidification potential
C2C	Cradle to cradle
CED	Cumulative energy demand
CFC	Chlorofluorocarbons
EIAM	Environmental Impact Assessment Method
EP	Eutrophication potential
EPD	Environmental Product Declarations
EPS	Expanded polystyrene
ETICS	External thermal insulation composite system
EU	European Union
f.u.	Functional unit
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbons
ICB	Expanded cork agglomerate
LCA	Life Cycle Assessment
LWA	Expanded clay lightweight aggregates
ODP	Ozone depletion potential
PCR	Product Category Rules
PE	Polyethylene
PE-NRe	Consumption of primary energy, non-renewable
PE-Re	Consumption of primary energy, renewable
POCP	Photochemical ozone creation potential
PP	polypropylene
PUR	polyurethane/polyisocyanurate
R-value	Thermal resistance (m^2.K/W)
U-value	Thermal transmittance (W/m^2 K)
XPS	Extruded polystyrene

- The comparison per functional unit of the innovative and up-to-date environmental performance of LWA and ICB with the most common insulation materials used in Europe (XPS, EPS, PUR), for the environmental categories and life-cycle stages defined in recent European standards;
- Results based on site-specific data from companies which quality was fully characterised, and achieved through a consistent methodology that is fully described, including the modelling of energy processes and a sensitivity analysis of the allocation procedures;
- "Cradle to gate" results achieved by following the International standards for Life Cycle Assessment and recent European standards on the environmental evaluation of buildings.

This paper comprises six sections, including this introduction. The scope section sets out the object of this study, including the state of the art of similar approaches. The Life Cycle Assessment (LCA) methodology used is described in detail in the third section, including the modelling of energy processes and a sensitivity analysis of the allocation procedures. The resulting graphs are presented and analysed in section four. Section five presents a discussion of the methodology used in this paper, and the paper ends by drawing conclusions that summarize the main findings of the work.

2. Scope

A range of thermal insulation materials are available on European markets. Mineral/inorganic materials account for 60% of the market in Europe; oil-derived materials account for about 30% (particularly extruded polystyrene (XPS), expanded polystyrene (EPS) and polyurethane/polyisocyanurate (PUR/PIR)); and "organic natural" and other materials account for about 10% [11]. In this last group, expanded cork agglomerate (insulation cork board-ICB) is highlighted since Portugal is the world's largest producer and exporter of cork-based materials. This group of materials is of unquestionable significance in the energy, environmental and economic performance of the building envelope [12], and therefore an interdisciplinary research project was carried out to provide the environmental life cycle assessment of the main thermal insulation materials of buildings [13,14].

The insulation materials selected for this study are those most often used in Portugal. They include XPS, EPS, PUR, ICB and expanded clay lightweight aggregates (LWA). A number of studies on the potential environmental impacts of producing some of these materials have already been performed (Table 1). Nevertheless, very few international studies have been published on the environmental impacts generated by the manufacture of LWA and ICB. This paper can help to fill this gap and provide a detailed environmental impact assessment of the thermal insulation materials proposed, based on real data obtained from Portuguese manufacturers and also including the primary energy consumption in the production of each of these materials. Since Portugal is a major manufacturer and exporter of cork-based products (in particular ICB boards), the environmental impact analysis of ICB should yield significant results through comparison with the alternatives.

2.1. State of the art on the environmental performance of thermal insulation materials

One of the most important properties of a thermal insulation material is thermal conductivity. Ideally, if a thermal insulation material has low thermal conductivity (W/(m K), it is possible to obtain relatively thin building envelopes with a high thermal resistance *R-value* (m^2 K/W) and a low thermal transmittance *U-value* (W/m^2 K) [15]. Therefore, the service provided by these materials is their thermal insulation, with a specific performance level in a specific area (e.g. a square meter), and the parameters of this functional unit should be defined in order to compare different types of insulation materials.

Various life cycle assessment (LCA) studies of insulation solutions have already been performed. In most of these studies the functional unit (f.u.) was defined as the mass (kg) of insulation board that provides a thermal resistance *R* of 1 (m^2 K/W) [11]:

$$f.u. = R\lambda\rho A, \quad (1)$$

where *R* represents the thermal resistance as 1 (m^2 K)/W, λ is the thermal conductivity measured as W/(m K), ρ corresponds to the density of the insulation product in kg/m^3 and *A* is the area as 1 m^2. This f.u. provides information on the volume of insulation material necessary to provide a given thermal resistance throughout the insulation life span, focusing only on the insulating and environmental properties of the material under study [11].

Many research studies already analysed the thermal and economic performance of insulations materials in buildings [16–30]. These papers highlight the important role of insulations materials in the thermal efficiency, and also in the environmental performance, of buildings. However, none of them considers the environmental impacts or the consumption of primary energy (renewable or non-renewable) in the production of each insulation material, but only the thermal conductivity and/or initial cost of each of these materials. In fact, only one of these papers considers the embodied energy of the insulation material, but based on literature and not singling out their renewable and non-renewable fractions [28].

The main characteristics of LCA research studies of thermal insulation materials conducted worldwide are presented in Table 1,