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Integrated Evaluation of the Performance of Composite Cool Thermal Insulation Materials

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Abstract

A family of composite cool thermal insulation materials has been developed as part of the DICOM research project, in order to provide building materials optimized for the retrospective insulation of existing buildings, which contribute in particular to the reduction of cooling loads in summer. An integrated evaluation of the materials was carried out in 2013-2014, by means of in vitro and in situ measurements, in order to determine and evaluate the materials' performance and the thermal comfort conditions before and after the retrofitting. Finally, a Life Cycle Analysis was carried for the materials, in order to evaluate their environmental impact.

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Keywords: Composite, cool, thermal insulating materials, measurements

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1. Introduction

The use of cool materials constitutes an appealing idea, in order to achieve the reduction of the cooling loads, especially in horizontal building elements, a goal that it is prerequisite for achieving the Nearly Zero Energy Buildings goal set by the Energy Performance of Buildings Directive 2010/31/EC [1].

In this frame a national research project was carried out, concerning the development and application of composite cool thermal insulating material. During this project two composite materials were developed, to be used in flat roofs and in vertical construction elements. The base of those materials is an improved generation of extruded polystyrene (XPS); in the case of the flat roof the final coating is a ceramic tile with high reflectivity to solar radiation (SR=58%), while in the vertical construction elements as final coating a photocatalytic plaster (SR=71%) is used. In both cases SR are higher up to 25% compared to the traditionally used materials. The XPS used, is a new generation of material, characterized by an improved water vapour permeability expressed by a low water vapour diffusion coefficient μ up to 17% and a thermal conductivity coefficient around 0.034 W/(mK). A pilot implementation of those materials took place in an existing building in the area of Thessaloniki, Greece, as part of its refurbishment and a series of measurements were conducted in order to be evaluate the materials [2].

Finally, a Life Cycle Analysis (LCA) of the new materials was carried out at the production process, in order to evaluate their environmental impact, together with an appraisal of their feasibility, so as to assess their competitiveness on the market. LCA is a popular environmental tool that has been applied since the early 1980s to a plethora of products and processes, examining the environmental performance of the selected reference systems from ‘cradle to grave’ or ‘cradle to gate’ [3].

2. Measurements

In order to achieve an integrated evaluation of the composite materials a variety of in vitro and in situ measurements were carried out for over two years. The parameters evaluated by the in vitro measurements, were the thermophysical properties of the new composite materials and specifically the thermal conductivity, the vapour diffusion, their emissivity and their reflectivity. The in situ measurements took place in a multi-family residential building constructed in 1987 in Thessaloniki which was built according to the Greek Regulation of Building Insulation of this period. The thickness of insulation used, was approximately 3cm for both horizontal and vertical construction elements while the insulation thickness of the new materials are 7cm and 10cm for the vertical and horizontal construction elements respectively after taking into consideration the existing legislation. The parameters measured were the local microclimate, the surface temperature in the consecutive layers of the building elements with a HOBO UX120-006M and the air temperature and relative humidity in the interior with HOBO U14 and UX100. The measurements were done by means of surface and embedded sensors, thermo- and hygrometers, as well as an infrared camera to document and visualize the surface temperature distribution values. The embedded sensors were placed between the existing construction and the new composite materials.

The measurements were conducted both in summer and winter, before and after the application of the new composite materials at the construction. During the summer period and after the application of the materials (12.07. -31.08.2014) 25% of the temperature values which were mentioned, were over 31°C and 34.8°C while the maximum were 36.88°C and 44.73°C with a maximum temperature difference between indoor and outdoor conditions up to 6.52K and 15.22K for the vertical construction elements and the flat roof, respectively. It is obvious from Fig.1a that despite the intense temperature range during the day, the indoor temperature during the summer and after the placement of the new materials, remains on low levels taking into consideration that the country is characterized of a temperate climate and also improves greatly the thermal comfort sensation of the users. Moreover, for a period of 17 days (12.07-28.07.2014) measurements have been carried out at the construction before (2013) and after (2014) the application of the materials. Sensor-loggers were used to determine the indoor conditions of three areas of the house (Bedroom (BR), Living room (LV) and Office (OF)) while the outdoor conditions were set through a weather station. All the under evaluation areas have a southwest surface, except from the office and living room areas which have a southeast and a northwest surface respectively. From the collected measurements (Fig. 1b) a reduction of 2.3K and 2.6K is observed in case of the office area and the living room-bedroom areas, respectively. Generally, a 12% reduction of the indoor temperature is mentioned after the placement of the new composite materials in the construction. This temperature reduction contributes to a minimization of the cooling cost of the areas during the summer and an improvement of the indoor living conditions for the users [4, 5].

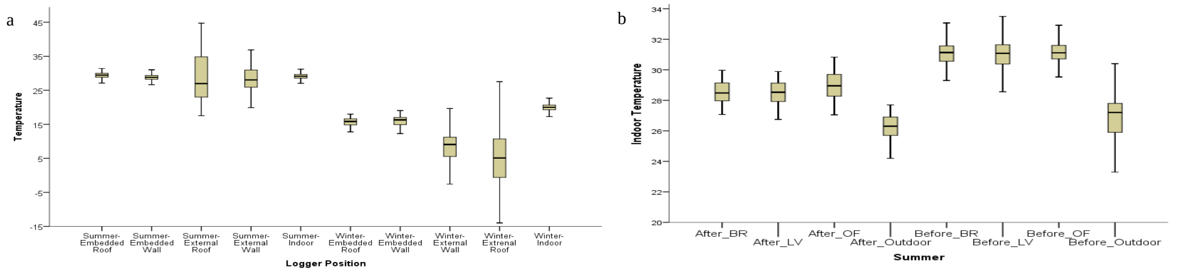

Fig. 1. (a) Temperature values specified by a variety of loggers sensors (in the surface and embedded) after the application of the materials during winter and summer; (b) Indoor temperature values during summer before and after the application of the new composite materials.

This temperature reduction is very important but in order to achieve a better evaluation of the results a statistical analysis was conducted, taking into account the temperature difference between the indoor areas of the house and the outdoor conditions before and after the placement of the new materials. From the nonparametric Wilcoxon analysis depicted in table 1, it can be deduced that the new composite materials affects the temperature in the areas of the house in correlation to the outdoor temperature with confidence interval of 99% (p-value<0.001).

Table 1. Correlation values among the parameters that have taken into consideration.

Temperature Difference	Sig. (2-tailed)
Bedroom-External air	0.000000454
Living Room-External air	0.000000645
Office-External air	0.000000398

During the winter period (Fig.1a) and after the application of the materials (11.12.2014-17.01.2015) the sensor-loggers specified that 50% of the temperatures were below 9.1°C and 5.1°C while the minimum were -2.6°C and -14.0°C. Also, the temperature differences between the indoor and outdoor conditions were very wide as the maximum were up to 22.72°C and 32.75°C for the vertical construction elements and flat roof, respectively. It is clear from Fig.1a that despite the great temperature range of the outdoor temperature of the horizontal and vertical construction elements, the indoor temperature were not affected and the thermal comfort sensation of the users is very high.

Except from the data collected by the sensor-loggers, a thermal camera (FLIR E40) was used to determine the temperature difference among the different types of final coating in case of the flat roof (Fig.2). As expected the flat roof constructed with the new composite material has cooler surface temperature in contrast to the one with a conventional material as well as the one with the asphalt topcoat. Specifically, the surface temperature at the new composite material has decreased up to 15% compared to the conventional flat roof and 21% when asphaltic membrane is used as final coating.

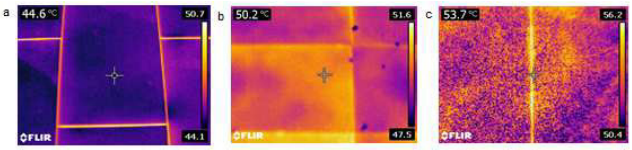

Fig. 2. (a) Flat roof with the new product (XPS with cool ceramic tile); (b) flat roof with a conventional material (XPS – cement tiles); (c) a conventional flat roof with asphalt topcoat membrane.

3. Environmental evaluation: Methodological approach and results

The concept of LCA is based on (a) the consideration of the entire life cycle which includes raw material extraction and processing, the production, the use of the product, up to the recycling and/or disposal, (b) the coverage of all environmental impacts connected with the products' life cycle, such as emissions to air, water and soil, waste, raw material consumption or land use and (c) the aggregation of the environmental effects in consideration of possible impacts and their evaluation in order to give oriented environmental decision support. LCA therefore offers a comprehensive analysis which links actions with environmental impacts. At the same time it provides quantitative and qualitative results and taking into consideration the link between system's functions and environmental impacts it is easy to identify the issues that need improvement. Necessary input data, namely raw materials and energy flows, were by monitoring the production process of the materials. For the output data, namely emissions from mining, production, packaging, storage and transportation at the inventory phase, two software tools were used for the results' reliability control: the SimaPro LCA software, which is a life-cycle analysis model with embodied EcoInvent LCA database [6] and the Global Emission Model for Integrated Systems (GEMIS) [7]. At the environmental impact assessment phase (normalization and weighting) two set of indicators were used, one derived from CML 2 baseline 2000 m method [8] and the other from Eco Indicator 95 method [9]. The functional unit selected for the materials' environmental evaluation is kg emission/kg building material and MJ/kg building material for the embodied energy.

The system boundaries studied for extruded polystyrene, consisted of two main subsystems: production processes of the material, including the extraction of raw materials and energy use, auxiliary activities, product's packaging, storage and transportation. The system boundaries defined a "cradle to gate" approach for the LCA implementation [10, 11] which means the use of a simplified reference system that consists of mining, production, packaging and transport processes. The reason for choosing a "cradle to gate" approach has to do with the quality and reliability of the initial data used for the inventory analysis. In order to determine the electricity generation emission factors, the total annual electricity generation mix was taken into account. It was based on the energy mix of the Greek electrical systems, which consists of lignite, oil, natural gas and renewables and is published every month by the Hellenic Electricity Market Operator [12, 13]. The output data provided information about specific air emissions from raw materials extraction, production processes, transportation and storage procedures such as CO_2 equivalent, SO_2 equivalent, PO_4 equivalent, SPM equivalent, C_2H_4 equivalent and environmental impacts like climate change, acidification, eutrophication.

The extruded polystyrene's production process consists of the following steps: supplying the production line, which consists of two extruders, supply the first extruder with styrol and additive substances, mixing and increasing the mixture's viscosity, infuse the mixture under high pressure condition and temperature (200°C), mixture's diffusion, complete additives diffusion in the polymer's mass and control progressive refrigeration of the mixture in the second extruder, change the material's flow from cylindrical to flat form in the head drawing, mixture's exit in atmospheric pressure conditions, mixture's expansion at the appropriate thickness to form the forming plates, cutting and freezing the final product at ambient temperature, product's packaging and temporary storage and product's transport. The environmental evaluation process pointed out the procedures which cause the most significant environmental impact. Based on the LCA evaluation, which is depicted in Fig. 3, results the production procedures contribute mainly to air emissions and more specific to CO2 production.

Table 2. LCA implementation - Categorization results based on GEMIS and SimaPro software

Material	Density [kg/m3]	CO_2eq [kg]	SO_2eq [kg]	PO_4eq [kg]	C_2H_4eq [kg]	Embodied Energy [MJ]
Extruded polystyrene (GEMIS)	30	2.17	0.01303	0.00132	0.00059	24.90
Extruded polystyrene (SimaPro)		4.045	0.01646	0.00125	0.00088	92.38

The energy consumption from the production processes came up to 85-95%, from the mining process 5-10% while transportation contributes to the final energy consumption up to 6% and packaging only 0.04% based on the outputs depicted in Fig.3 and table 2. The transportation parameter was calculated taking into consideration an average of, 20km distance needed for raw materials transportation from the local sources to the factory. The normalization results at the impact assessment phase are presented in table 3. The functional unit used was 1kg of insulation material produced. In case the functional unit is changed to the mass of insulation material needed for insulating 1m^2 of surface taking into consideration the thermal resistance R of the building element the results are slightly different.

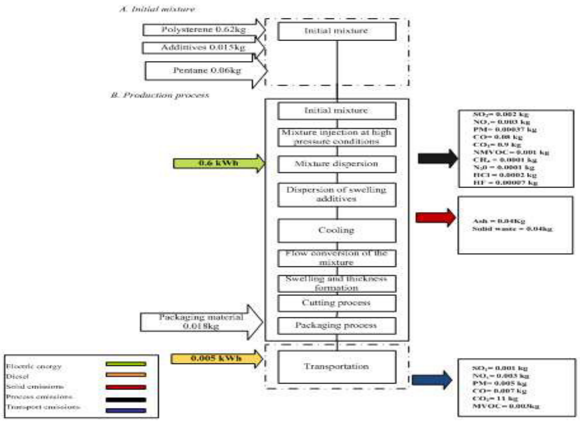

Fig. 3. Extruded polystyrene production process flow chart.

Table 3. Impact Assessment - Normalization data for Extruded Polystyrene (XPS).

	Normalization		Normalization
Impact category	Total	Impact category	Total
Abiotic depletion	2.85E-13	Human toxicity	1.33E-14
Acidification	5.09E-14	Fresh water aquatic ecotoxicity	1.61E-13
Eutrophication	9.38E-15	Marine aquatic ecotoxicity	8.99E-13
Global warming (GWP100)	9.18E-14	Terrestrial ecotoxicity	2.67E-14
Ozone layer depletion (ODP)	6.66E-17	Photochemical oxidation	8.42E-15

As it was determined by the study the use of resources is a major aspect considering the materials' environmental impact. It is therefore necessary to promote the use of best techniques available and to promote innovative solutions in the production processes in order to reduce the depletion of natural finite resources. At the same time considering the waste generated in different stages of the production process a firm commitment to reuse and recycling is beneficial in a double way namely in minimizing the use of raw materials and the production of waste. Another point that emerged from the study is the need to minimize the transport of raw materials which is responsible for significant environmental burden. In that sense promoting the use of resources locally available is one of the most important measures to reduce transport emissions and not to forget costs. The results indicate that the new materials' environmental impact is not different than that of the traditional insulation materials (conventional XPS, stonewool) and in some cases, depending on the construction process, it is even smaller, as the mass flows and the weight of the new materials is reduced [14].

4. Conclusions

A careful study of the requirements in the building envelope's thermal protection leads to the conclusion, that there is a market for materials with a double purpose: to reduce heating loads in winter and cooling loads in summer. Furthermore, given the large building stock with inadequately insulated buildings, those materials should be handy and easily adaptable to meet the necessities of deep refurbishment. The composite materials developed and produced within the frame of the DICOM project meet those requirements: They feature all the good thermal insulation properties of extruded polystyrol, which are highly effective in reducing heating loads, and at the same time they contribute significantly to the reduction of the cooling loads in summer, due to their cool material properties. This has been verified by a series of measurements, both in the laboratory and in a real building. The real world application also demonstrated that the materials are user-friendly in the construction site, which is important for their commercial success. Finally, as the Life Cycle Analysis of the products showed, their environmental impact is similar to, and in some cases better than those of conventional insulation materials.

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