Cardboard-Based Packaging Materials as Renewable Thermal Insulation of Buildings: Thermal and Life-Cycle Performance

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ABSTRACT: Cardboard-based packaging components represent a material that has significant potential as a renewable source for exploitation in buildings. This study presents the results of thermal and environmental analyses of existing packaging materials compared with standard conventional thermal insulations.

Experimental measurements were performed to identify the thermal performance of studied cardboard packaging materials. Real-size samples were experimentally tested in laboratory measurements. The thermal resistance and conductivity of all the analyzed samples were measured according to the procedure indicated in the ISO8032 standard. A life-cycle assessment according to ISO 14040 was also performed to evaluate the environmental impacts related to the production of these materials. The results show that cardboard panels are a material with thermal and environmental properties on par with contemporary thermal insulations. Depending on their structure, the measured thermal conductivity varies from 0.05 to 0.12 $W \cdot m^{-1} \cdot K^{-1}$ and their environmental impacts are much lower than those of polyisocyanurate foam or mineral wool.

KEYWORDS: Cardboard, thermal insulation, thermal performance, environmental impacts, life-cycle assessment, packaging industry

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1 INTRODUCTION

Currently, building energy efficiency is being emphasized in developed countries around the world as one of the ways for reducing climate change. One of the newest legal documents striving to support climate change mitigation is the recently ratified Paris Agreement [1], which demonstrates a global commitment to move towards a low carbon economy [2]. A key document in this regard in the European Union (EU) is Directive 2010/31/EU [3], which denotes that buildings in the EU should be built or renovated as near-zero energy buildings [4] with lowest possible environmental impacts after 2020 [5]. One of the simplest ways of complying with these requirements is by reducing heat loss through the building envelopes, which is synonymous with improving the thermal properties of the building envelopes. This can be achieved by adding a sufficient amount of thermal insulation. Many types of insulation materials are currently available in the building sector [6]. Generally the public focus is on common thermal insulation systems that are often promoted by various subsidy programs, like Czech New Green Savings [7]. However, at the same time, the field of novel building materials with above average insulation properties is developing rapidly. In order to find new ways to optimize energy consumption and mitigate the environmental impacts of structural solutions and building materials, attention is being focused on the exploitation of recent interdisciplinary findings.

The starting point for the presented analysis was the fact that the contemporary packaging industry offers materials with interesting features: simplicity of production, thermal and acoustic properties and presumably also low environmental impacts related to the reuse of paper waste and recyclability of cardboard-based materials (CBMs). These features make corrugated fiberboard (CFB) or honeycomb fiberboard (HFB) an attractive alternative to commonly used thermal insulation materials. The potential use of CBMs in the construction industry has already been addressed in recently published works of several authors. This study follows the works of Asdrubali *et al.* described

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in [8] and [9], who evaluated the thermal, acoustic and environmental performance of single- and multilayer CFB and cellulose samples. Also related is the work of Secchi *et al.* [10], who investigated the acoustic and environmental performance of several cardboard- or cellulose-based acoustic panels. These three works show that CBMs are an interesting alternative to the common insulation materials. However, there is another approach regarding the evaluation of environmental impacts that has been implemented, which is detailed in this study.

The aim of this article is the evaluation of the thermal and environmental performance of selected CFB and HFB samples and their comparison with contemporary common insulation materials. Polyisocyanurate foam (PIR), expanded polystyrene (EPS) and mineral wool (MW) were selected as representatives of common contemporary insulation materials for the comparison.

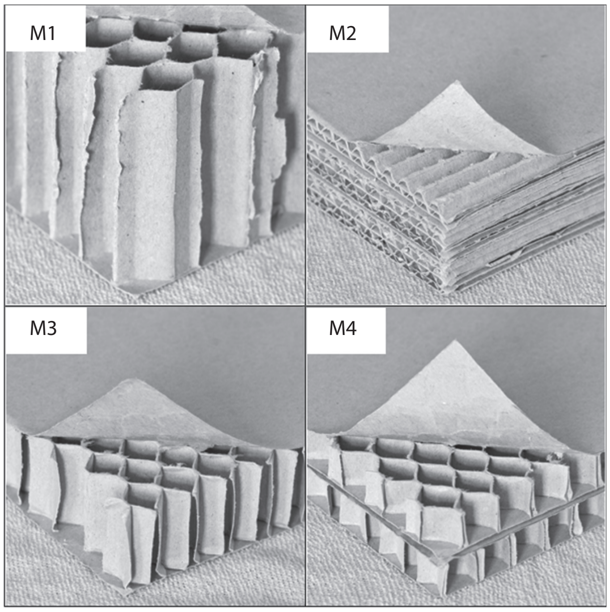

Figure 1 CFB and HFB samples M1 to M4 used in the thermal analysis.

2 EVALUATED MATERIALS

The main focus of this article lies in the evaluation of the thermal and environmental properties of the CBMs. This material is already well known in the packaging industry. Applications in the building industry also exist. CBM panels can be lightweight and structurally sound. They are commonly used for production of furniture, door wings or as a lightweight load-bearing substructure for decorative elements. Asdrubali *et al.* [8] propose their use as acoustic insulation.

The CBMs exist in different forms. This article evaluates samples of the two most common forms. The first is called corrugated fiberboard (CFB) or pleated cardboard. It consists of a fluted corrugated sheet, which provides structural stiffness. This sheet can be covered with flat cardboard sheets on one or both sides. The CFB has been in use for a long time. It was patented in the 19th century [11]. The other evaluated form is honeycomb fiberboard (HFB). It uses a honeycomb structure with tubular or hexagonal shaped cells. Again, it can be covered with flat cardboard sheets. The sandwich structure with air cavities enclosed in the cardboard is essential for the CBMs thermal and acoustic properties. From an environmental point of view, the CBMs are interesting due to the possible use of secondary raw materials for their production. Recycling of CBMs is also rather simple. Such avoided depletion of primary raw materials should lead to a relatively low environmental profile of the material [10].

The analysis described in this article evaluates the thermal and environmental properties of seven CBM samples (M1 to M7) and compares them with PIR (sample M8), EPS (sample M9) and MW (sample M10). All samples are shown in Figures 1 and 2.

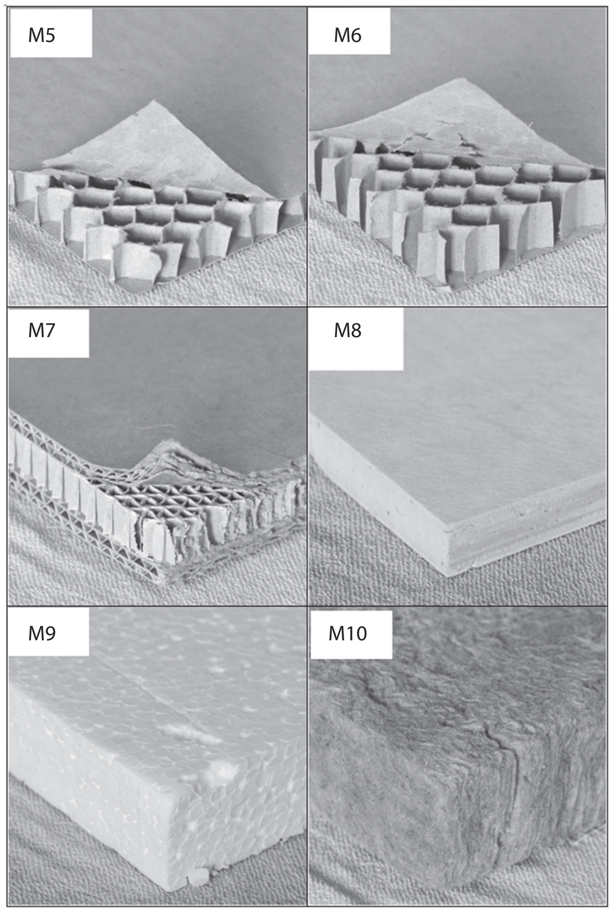

Figure 2 CFB and HFB samples M5 and M6 used in the thermal analysis, HFB sample M7, and conventional thermal insulation samples M8 (PIR), M9 (EPS) and M10 (MW).

Sample M1 is a HFB with hexagonal cells 68 mm high and 16 mm wide covered by flat cardboard sheet on both sides. Sample M2 is a combination of ten layers of CFB. Individual layers are 2 or 4 mm thick with alternating sequence: the orientation of CFBs rotates by 90° between layers. Sample M3 is a HFB with hexagonal cells 29 mm high and 14 mm wide covered by flat cardboard sheet on both sides. Sample M4 is made of two layers of HFBs with hexagonal cells 17 mm high and 14 mm wide covered by flat cardboard sheet on both sides. Sample M5 is a HFB with hexagonal cells 12.5 mm high and 13 mm wide covered by flat cardboard sheet on both sides. Sample M6 is a HFB with hexagonal cells 17 mm high and 14 mm wide covered by flat cardboard sheet on both sides. Sample M7 is a combination of 14 mm thick CFB panel placed perpendicular to two layers of 3 mm thick covering CFB. All evaluated CBM samples were obtained as waste products from the packaging industry.

The other three samples serve as a reference and are representative of the common contemporary thermal insulations. Sample M8 is made of PIR, which is a high performance thermal insulation in the building industry. Sample M9 is made of EPS and sample M10 is made of MW.

Basic parameters of the samples are described in Table 1. Thermal parameters were determined by measurements which are described in Section 3. The thermal conductivity of hydroscopic materials strongly depends on moisture. The moisture content of samples presented in Table 1 is so small that the samples are practically dry.

3 THERMAL ANALYSIS

Common homogenous materials have thermal transfer mainly caused by thermal conduction. Tested CBMs combine convection and radiation in closed air cavities. This thermal analysis is focused on measuring real thermal properties of the samples presented in Figures 1 and 2. These properties have been determined from measured heat flow under known boundary condition. Based on these measurements, the equivalent thermal resistance and thermal conductivity were determined.

Table 1 Table of measured materials.

Sample	Type	Thickness [mm]	Bulk density [kg·m^{-3}]	Moisture ratio [kg·kg^{-1}]
M1	HFB	69.662	24.50	2.60%
M2	CFB	34.007	89.52	2.82%
M3	HFB	30.400	37.35	3.98%
M4	HFB	26.810	47.93	3.48%
M5	HFB	13.268	48.25	1.43%
M6	HFB	18.130	38.72	1.69%
M7	CFB	28.625	129.02	3.89%
M8	PIR	20.084	52.33	n/a
M9	EPS	19.736	13.74	n/a
M10	MW	25.808	99.75	n/a

Thermal resistance of tested samples was measured using guarded hot plate method in accordance with ISO 8302 [12]. A TLP 300 DTX-1 thermal conductivity measuring device from Taurus Instruments was used (Figure 3). This device can determine thermal resistance of samples with thickness from 20 mm to 80 mm. Maximum dimension of the measured samples is 300 mm × 300 mm and protected measured field represents an area of 100 mm × 100 mm. Upper and lower surfaces of the tested sample have a set temperature difference which is maintained to activate heat flow within the tested sample. Temperatures are controlled by Peltier elements. The total power of the elements is maintained to achieve one-dimensional steady-state heat transfer. Temperature difference on the sample's surfaces is measured applying two batteries of thermocouples on each side. In terms of the equation (Eq. 1), the thermal resistance is calculated from heating power Q through measured area A and temperature difference between sample surfaces ΔT.

$$R = \frac{\Delta T \times A}{Q} \ [\mathrm{m^2.K.W^{-1}}] \qquad (1)$$

3.1 Thermal Measurement Procedure

Although the TLP 300 DTX-1 device implements the system for estimating the thickness of the sample, the sample thickness could be distorted by applying the contact mat. Therefore, before testing each sample,

Figure 3 The TLP 300 DTX-1 thermal conductivity measuring device.

its own measurements, weight and overall thickness have to be measured separately. The sample is placed between plates with upper and lower surface covered by contact mat with a thickness of 3 mm. The plastic foil with thermocouple batteries is installed between the contact mat and surface of sample. The higher plate is slowly lowered until the pressure on the sample reaches a predefined level. Considering 10 K temperature difference of both sample sides, testing may have several point measurements, which means various temperatures in the middle of the sample. The measurement process starts by cooling and/or warming plates at a predefined temperature in the measurement point. The top Peltier plate monitors voltage and electric current, whose values are used for determination of overall heating power. Finally, as demonstrated above, the thermal resistance of tested sample is calculated according to Equation 1. The time varying power is managed by microprocessor control system according to the surface temperatures of sample. It has mainly decreasing behavior until it reaches steady state corresponding to Fourier's law. Measurement is completed if the time is over or stability criteria are reached. At the end the equivalent thermal conductivity coefficient λ_{ekv} is calculated based on material thickness.

3.2 Thermal Measurement Results and Discussion

The testing of each sample included repeated measurements at different mean temperature levels: 10 °C, 20 °C and 30 °C respectively. The load force of 200 N was applied on the samples through the top plate during the measurements. The temperature dependency between thermal resistance and mean temperature of sample was recorded. Thermal resistance approximated by linear function indicates a similar tendency of the slope; the higher the temperature difference, the lower the thermal resistance of all tested samples.

Thermal conductivity of all materials described in Section 2 was measured. Thermal conductivity parameters at three different measurement points are presented in Figure 4.

The PIR has the lowest thermal conductivity. It is undoubtedly the best performing of all tested materials. Next, and relatively close to each other, are MW and EPS. Their thermal conductivity is approximately two times higher than the PIRs.

The CBM samples reached various results. In general, it can be said that (logically) samples with more layers had better thermal conductivity. Supposedly the division of the air cavities eliminates the prevailing effect of convection. Samples with undivided air cavities reach worse results as the height of the cavities increases. It is therefore logical to further develop materials with smaller and more numerous air cavities.

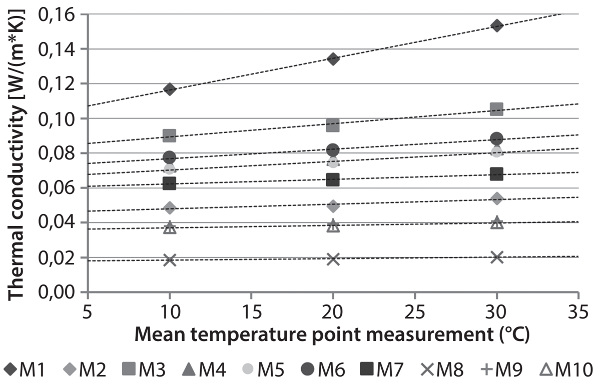

Figure 4 Thermal conductivity at mean temperature.

4 LIFE-CYCLE ASSESSMENT

An inseparable part of the research presented in this article is a life-cycle assessment (LCA) that evaluates and compares the environmental impacts of the individual materials. LCA is an analytical method for evaluation of the environmental impacts of products from the extraction of necessary raw materials for waste management. The method originated in the 1960s [13]. Currently the LCA framework is well established thanks to international standards like ISO 14040 [14]. This standard describes the general principles and gives the users a general framework for the evaluation. Specifics of the building industry have led to the creation of European standards, like EN 15804 [15] or EN 15978 [16], that address evaluation of building elements, materials or even whole buildings. Product category rules (PCR) [17] for Environmental Product Declarations are also considered in the presented evaluation. This PCR further specifies the evaluation methodology for thermal insulations; for example, it defines recommended boundary conditions and impact categories.

4.1 Goal and Scope of the LCA

The goal of the presented LCA is to estimate the environmental impacts of the CBM samples and compare them with the environmental impacts of more common insulation materials. The application of the cardboard in building structures is not yet fully addressed. Thus only the product stage defined in EN 15804 [15] is considered in the assessment. This approach is also known as cradle-to-gate LCA in the literature, e.g. [18]. It means that only the environmental impacts related with the production of the assessed materials are included in the LCA; for example, extraction of raw materials, transport of the raw materials to the production facilities and the production process.

The results of individual materials should be compared on the basis of a "functional unit." This reference unit should be common to all assessed samples. The functional unit for evaluation of the environmental impacts of thermal insulations is defined in the PCR as the mass (weight) of the insulation necessary to provide thermal resistance R = 1 $m^2\cdot K\cdot W^{-1}$ [17]. Asdrubali *et al.* [9] also used this approach in their work. This approach is suitable for comparison of homogenous thermal insulations with small air cavities like PIR, EPS, MW or foam glass. However, it is not suitable for the calculation of the environmental impacts of the described CBM samples. None of these samples has the thermal resistance R = 1 $m^2\cdot K\cdot W^{-1}$. It would be necessary to either stack several layers together or to increase the thickness of the samples. Either solution would distort the results. Stacking up several layers of the described CBMs is a simple solution for increasing the thermal resistance. However, the thermal resistance of the stacked CBM layers would still not be equal to 1 $m^2\cdot K\cdot W^{-1}$. Increasing the thickness of one layer would increase the thermal resistance as well as mass, but the increase will not be linear. The thermal resistance of the described CBM samples is related to their shape, especially to the dimensions of the air cavities. Increasing the thickness would reduce the ratio between the samples' thermal resistance and mass. Therefore, we decided to use mass of 1 m^2 of a cardboard sample as a functional unit in this work. Secchi *et al.* used a similar approach [10]. However, they did not sufficiently address the fact that individual samples have different physical properties. According to the measurements presented in the previous sections, each CBM sample has different mass and thermal resistance. Therefore, direct comparison of the environmental impacts of the samples is impossible with the specified functional unit. Still, each CBM sample can be separately compared with the mass of the PIR, EPS and MW necessary to reach the same thermal resistance at 20 °C (see Table 2). The results of such partial LCAs should still be sufficient to indirectly identify the most environmentally friendly CBM sample.

Table 2 Thermal resistance at mean temperature.

Sample	Thickness [mm]	Equivalent thermal resistance at specific mean temperature [$m^2\cdot K\cdot W^{-1}$]		
		10 °C	20 °C	30 °C
M1	69.662	0.5969	0.5195	0.4544
M2	34.007	0.6997	0.6870	0.6309
M3	30.400	0.3382	0.3177	0.2892
M4	26.810	0.3688	0.3505	0.3246
M5	13.268	0.1879	0.1781	0.1646
M6	18.130	0.2345	0.2222	0.2056
M7	28.625	0.4587	0.4438	0.4222
M8	20.084	1.0856	1.0571	0.9943
M9	19.736	0.5194	0.5048	0.4837
M10	25.808	0.6938	0.6738	0.6452

Table 3 Thermal resistance at mean temperature.

Sample	Thickness [mm]	Equivalent thermal conductivity coefficient at specific mean temperature [$W\cdot m\cdot^{1}\cdot K\cdot^{-1}$]		
		10 °C	20 °C	30 °C
M1	69.662	0.1167	0.1341	0.1533
M2	34.007	0.0486	0.0495	0.0539
M3	30.400	0.0899	0.0957	0.1051
M4	26.810	0.0727	0.0765	0.0826
M5	13.268	0.0706	0.0745	0.0806
M6	18.130	0.0773	0.0816	0.0882
M7	28.625	0.0624	0.0645	0.0678
M8	20.084	0.0185	0.0190	0.0202
M9	19.736	0.0380	0.0391	0.0408
M10	25.808	0.0372	0.0383	0.0400

4.2 Life-Cycle Inventory and Impact Assessment

Individual materials are represented by generic data from ecoinvent 2.0 database [19] in this LCA. These generic data describe production of PIR, EPS and MW from primary raw materials. It should be noted that the description of the cardboard in the used dataset mentions the use of recycled secondary raw materials, but with no specifications. The assessment itself is conducted by a GaBi software tool.

The assessed mass of the materials considered in the LCAs is specified in Table 4. It is calculated based on the samples' densities specified in Table 1 and thermal resistances at 20 °C specified in Table 2. The first column in the table specifies mass of the CBM samples according to data from the aforementioned tables. The other columns in each row specify the equivalent mass of the PIR, EPS and MW necessary to provide the same thermal resistance as the CBMs in the first column.

Table 4 Mass of the insulation materials used as a basis for the LCAs.

CBM sample	Mass [kg]	Equivalent mass of common insulation materials [kg]		
		PIR (M8)	**EPS (M9)**	**MW (M10)**
M1	1.7067	1.4308	0.1826	1.3530
M2	3.0443	1.8921	0.2414	1.7892
M3	1.1354	0.8750	0.1116	0.8274
M4	1.2850	0.9654	0.1232	0.9129
M5	0.6402	0.4905	0.0626	0.4639
M6	0.7020	0.6120	0.0781	0.5787
M7	3.6932	1.2223	0.1560	1.1558

It is obvious that the EPS is the material with the best ratio between thermal insulation and mass in the presented comparison. The mass of the EPS necessary to provide the same thermal resistance as the CBMs varies between 4% (compared with CBM sample M7) and 11% (compared with CBM sample M1) of the CBMs mass. The necessary mass of PIR and MW is significantly larger, with MW being slightly more efficient in this regard. The mass of PIR varies between 35% (compared with CBM sample M7) and 87% (compared with CBM sample M6) of the CBMs mass. The mass of MW between 35% (compared with CBM sample M7) and 82% (compared with CBM sample M6).

The resulting environmental impacts are calculated using CML 2001 method developed by the Institute of Environmental Sciences in Leiden, Netherlands [20], with impact categories and characterization factors in version Nov 10. This method uses 12 "impact categories" to describe the environmental impacts of products. Only seven impact categories mandatory according to EN 15804 [15] and EN 15978 [16] standards are used in the LCAs presented in the following section: Abiotic Depletion Potential with regard to fossil fuels (ADP-fos.) and scarce resources (ADP-el.), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (ODP) and Photochemical Ozone Creation Potential (POCP). Results in each impact category are represented by "equivalent units." These units express the harm that the assessed product system causes to the environment by comparing it to damage caused by defined reference substance. For example, in GWP impact category the environmental impacts of the assessed product system are expressed by the amount of CO_2 emissions that would cause the same damage if released into the atmosphere [18]. Results in individual impact categories can be confusing for the general reader. Also, individual categories have different equivalent units. This makes direct evaluation and comparison between them impossible. A method known as "normalization" can be used to overcome this problem and increase the clarity of the results [18]. Normalization transforms the results in individual impact categories into dimensionless quantities that can be easily compared either separately or as a sum. It is, for example, used to compare the share of individual impact categories on total results. CML2001 EU25+3 normalization factors in version Nov 10 are used in this work.

4.3 LCA Results

Table 5 shows calculated environmental impacts related to production of 1 kg of each assessed material: CBMs (representing samples M1 to M7), PIR (sample M8), EPS (sample M9) and MW (sample M10). Table 6 shows normalized environmental impacts related to the production of 1 kg of these materials.

Figures 5 to 11 present the comparison of normalized environmental impacts (vertical axis) related to the production of each CBM as well as the environmental impacts related to the production of comparable mass of PIR, EPS or MW. Share of the

Table 5 Environmental impacts related to the production of 1 kg of the assessed materials.

Impact cat.	Unit	CBM	PIR	EPS	MW
ADP-el.	10^{-6} kg $Sb_{\text{-Eq.}}$	1.7	22.6	0.6	3.6
ADP-fos.	10^{-2} MJ	1.5	6.5	6.8	2.6
AP	10^{-3} kg $SO_{2\text{-Eq.}}$	2.9	17.8	15.0	8.4
EP	10^{-3} kg Phs-$_{\text{Eq.}}$	1.1	3.1	1.4	1.1
GWP	10^{-1} kg CO_2-$_{\text{Eq}}$.	7.8	43.1	42.0	14.6
ODP	10^{-8} kg R11-$_{\text{Eq.}}$	9.8	2.0	13.1	6.5
POCP	10^{-4} kg eth-$_{\text{Eq.}}$	3.9	35.7	89.9	7.3

Table 6 Normalized environmental impacts related to the production of 1 kg of the assessed materials.

Impact cat.	Unit	CBM	PIR	EPS	MW
ADP-el.	10^{-13}	2.9	37.5	1.0	6.0
ADP-fos.	10^{-16}	4.3	18.7	19.3	7.4
AP	10^{-13}	1.7	10.6	8.9	5.0
EP	10^{-14}	5.8	16.5	7.5	5.7
GWP	10^{-13}	1.5	8.3	8.1	2.8
ODP	10^{-15}	9.7	2.0	12.8	6.3
POCP	10^{-13}	2.2	20.6	52.0	4.2

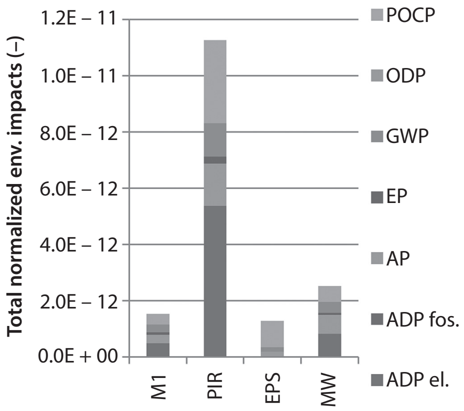

Figure 5 Total normalized environmental impacts related to production of CBM M1 and equivalent mass of PIR, EPS and MW.

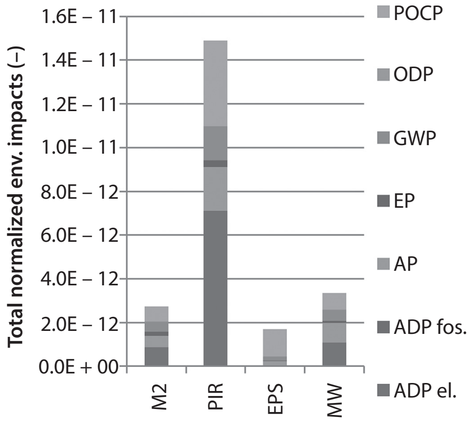

Figure 6 Total normalized environmental impacts related to production of CBM M2 and equivalent mass of PIR, EPS and MW.

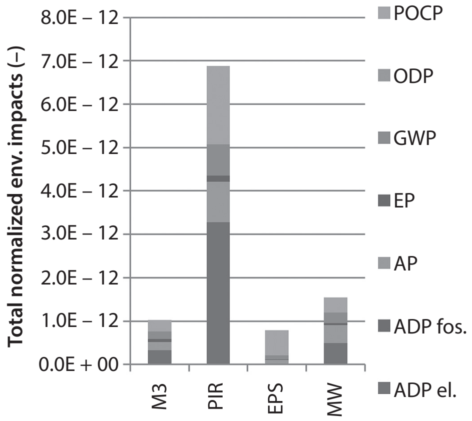

Figure 7 Total normalized environmental impacts related to production of CBM M3 and equivalent mass of PIR, EPS and MW.

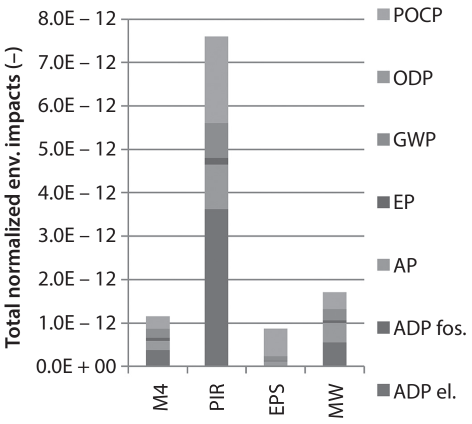

Figure 8 Total normalized environmental impacts related to production of CBM M4 and equivalent mass of PIR, EPS and MW.

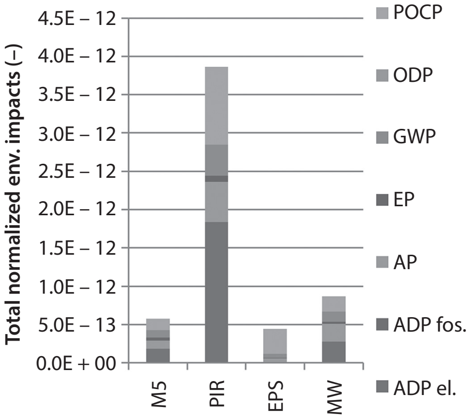

Figure 9 Total normalized environmental impacts related to production of CBM M5 and equivalent mass of PIR, EPS and MW.

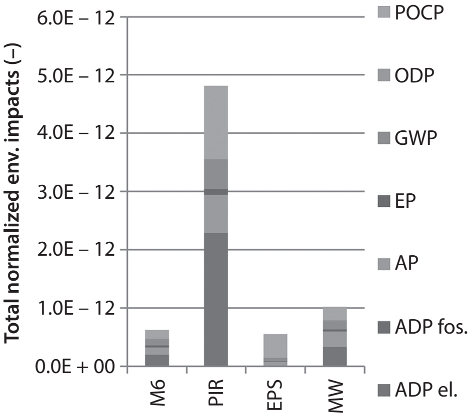

Figure 10 Total normalized environmental impacts related to production of CBM M6 and equivalent mass of PIR, EPS and MW.

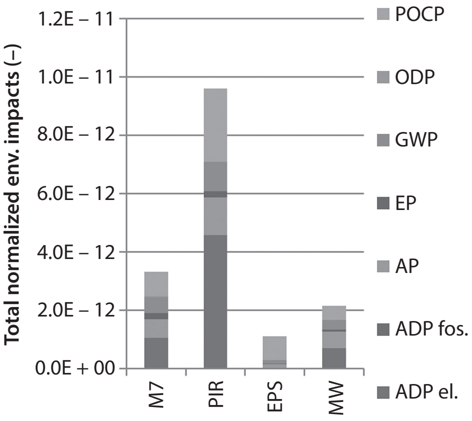

Figure 11 Total normalized environmental impacts related to production of cardboard M7 and equivalent mass of PIR, EPS and MW.

individual impact categories on the normalized environmental impacts is highlighted by different colors. We can see that the consumption of natural resources represented by ADP-el. (excluding fossil fuels) has the highest share of the results in the case of PIR (48%), MW (32%) and CBMs (32%). The only exception is EPS (13%), which is probably due to its very low density and thus low consumption of raw materials. The second most important category in regard to its share on total results is the POCP. It has a 73% share on normalized environmental impacts of EPS and 26% to 22% share on environmental impacts of PIR, MW and CBMs. The environmental impacts in these two categories alone represent 75% (EPS), 74% (PIR), 57% (CBMs) and 55% (MW) of total normalized environmental impacts of the assessed materials.

4.4 LCA Discussion

The results of individual LCAs in Figures 5 to 11 show that environmental impacts related to the production of the CBMs are comparable with environmental impacts of other common insulation materials.

The worst environmental impacts in all seven LCAs are related to PIR insulation. It has environmental impacts that are three (compared with M7) to eight (compared with M6) times higher than the tested CBMs. This is due to the very demanding production process of the PIR (see the normalized environmental impacts related to ADP-el.). This category represents the consumption of resources (excluding fuels). Environmental impacts related to the production of PIR in this category alone are higher than the total normalized environmental impacts of any other assessed material.

The environmental impacts of MW are worse than CBMs M1 to M6. Only the environmental impacts of sample M7 are 54% higher than those of MW. The reason why MW has higher environmental impacts than six out of seven tested CBMs lies in the combination of its relatively high density and environmental impacts per 1 kg. Table 4 and the accompanying text in Section 4.2 have already explained the small difference between the compared mass of MW and CBMs. This is combined with the fact that environmental impacts of the production of MW are twice as high as environmental impacts of the production of CBM (see Tables 5 and 6). The resulting comparison is a fine example of the necessity of complex multi-criteria evaluations: it proves that even if a material has worse physical properties, it can still be potentially better than others overall.

EPS has lower environmental impacts than any assessed CBM. The difference varies between 12% (in the case of HFB M6) and 63% (in the case of CFB M7). CBMs have lower environmental impacts per 1 kg than EPS (see Tables 5 or 6). However, the EPS has higher thermal resistance and lower density than any assessed CBM sample. Therefore, the compared masses of EPS and CBMs differ greatly, which favors the EPS overall.

The obtained results correspond with the findings of Asdrubali *et al.* [9]. The results of their LCA also show that the CBMs have environmental impacts similar to EPS and MW.

5 CONCLUSION

This paper introduces a potential novel thermal insulation material for buildings—CBM. In general, the results show that when compared by thickness the thermal properties of the CBMs are almost two times worse than those of more common insulation materials. Depending on their internal structure, the measured thermal conductivity varies from 0.05 to 0.12 $W{\cdot}m^{-1}{\cdot}K^{-1}$. This basically corresponds to the results achieved by Asdrubali *et al.* [8], who measured the thermal conductivity of cardboard-based panels to be around 0.055 $W{\cdot}m^{-1}{\cdot}K^{-1}$. However, there is further potential for improvement. The results show that thermal properties of CBMs are directly dependent on the size and shape of air cavities enclosed in the CBMs' structure. Modifications of these air cavities could improve the thermal properties of CBM to levels comparable with common thermal insulation materials. Based on this study we can say that CFBs appear to have the best thermal performance. In particular, sample M2 combining multiple layers of CFB has thermal parameters comparable with contemporary common thermal insulations.

The presented LCAs show that from an environmental point of view the CBMs are an interesting option comparable with other contemporary thermal insulations. Based on the results we can conclude that CBMs have significantly better environmental impacts than PIR. Most of the tested samples also achieved lower environmental impacts than MW, although the differences are lower compared to PIR: between −38% (sample M3) and +67% (sample M7). On the other hand, we have to highlight the fact that none of the tested CBMs have lower environmental impacts than EPS. The difference is between 12% (sample M6) and 67% (sample M7).

Further research and development in the field of CBM insulations should focus on multilayer sandwich structures with smaller air cavities. These proved to have the best thermal properties. However, the increased number of layers should not cause a significant increase of environmental impacts. The use of recycling and secondary raw materials should be promoted as most of the environmental impacts are related to the consumption of natural resources. Case studies created in cooperation with producers of CBMs are necessary. Such case studies will improve the accuracy of existing results. The case studies should also address the topic of additives that can improve the properties of the CBMs: fire resistance, water resistance, durability and load-bearing capacity. A cost analysis is also necessary to address the question of return on possible investments. Equilibrium between improving the properties of the CBM, its environmental qualities and costs should be the final aim of all further works.

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