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Towards an ecological transition in the construction sector through the production of new eco-efficient products

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Abstract. The economic model of the construction sector is becoming more circular by emphasizing sustainability at all stages from the design, the production phase, the installation, the use, the removal and finally its transport to landfill. This work analyses the influence of added polyurethane foam waste from refrigerated industry on the technical properties (bulk density, water vapor permeability, and reaction to fire performance). The environmental properties were also measured through a comparative Life Cycle Analysis (LCA) between the traditional gypsum ceiling tile and a new organic one. The re-use of polyurethane waste in ceiling tiles causes technical improvements. The most relevant improvements noticed are the decrease in the density (28%), reduction in thermal conductivity (27%) and A1 classification for fire reaction. The comparative (LCA) between both tiles shows that the new product that incorporates polyurethane waste has significant improvement in CO_2 (14%) and lower use of energy during the manufacturing process (14%). The following impact categories were also reduced: 9% in the case of the acidification of the ground and water, 9% for eutrophication and 31% reduction for non-hazardous waste. This work intends to reduce the carbon footprint and increase the sustainability of polyurethane gypsum products.

1 Introduction

Since the second half of the 20th century, the use of plastics (polyethylenes, polypropylenes, polycarbonates, polystyrenes, polyamides, silicones, polyurethanes, phenolic and acrylic resins, melamines, etc.) has gradually spread, being consequently very present in urban and industrial waste [1]. According to the latest report published by Plastic Europe-the Facts 2021, the demand for plastic in Europe in 2020 was 50.7 million Tn, 7.9% in the case of polyurethane (PUR), which meant an annual demand of 4.0 million Tn. Approximately 25% of this polyurethane became waste (1.000.000 Tn) and 50% of it are polyurethane foam. After being used, the plastic is collected and 32.5% is recycled, 42.6% is re-used for energy purposes (incinerated) and the remaining 24.9% is taken to a landfill [2]. Policies on sustainable construction, and the need to differentiate themselves in the market for green

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building products, as well as the high user acceptance in the field of sustainability, makes assessing and quantifying the environmental impact of building materials of great interest today [3].

The LIFE-REPOLYUSE project (REcovery of POLYurethane for reUSE in eco-efficient materials) tackles the problem of managing plastic waste such as polyurethane through the use of innovative techniques for reducing and reusing it, integrating it into a new construction material, a gypsum pre-fabricated tile for registrable ceilings, thus prolonging the useful life of the polyurethane. The development of this project follows the main objectives of the European Union to reduce the effects of the planet's climate change on human beings [4]. LIFE-REPOLYUSE expresses the idea of circular economy from the initial waste generation to the end of its life. First, polyurethane foam waste (PUW) is generated in a factory of polyurethane panels and then it’s used in the production of new ceiling tiles which are then used in a building. If this building is demolished at the end of its life, PUW can be recovered and the process can start again.

This work analyses the influence of added polyurethane foam waste from refrigerated industry on the technical properties (bulk density, water vapour permeability, and reaction to fire performance). The environmental properties were also measured through a comparative Life Cycle Analysis (LCA) between the traditional gypsum ceiling tile and a new organic one.

1.1 Raw materials

Gypsum conglomerate was used ad it is classified as A/14/3.5 in Standard EN 13279-1 [5], the specifications of which stipulate an initial setting period of over 14 min, with a compression resistance of 3.5 N/mm^2. According to the manufacturer’s specifications, this gypsum presents a purity value of 92%. (Fig. 1).

Fig. 1. Gypsum conglomerate (A/14/3.5).

The aggregate used in the mixtures was Polyurethane Foam Waste (PFW) and was taken from the waste generated in the manufacture of insulation panels in the industry of Paneles Aislantes Peninsulares (Cuenca, Spain). Following shredding, it presented itself as a dust with a granulometry of between 0 and 0.5 mm and with real density and bulk density values of 1080 kg/m^3 and of 72 kg/m^3, respectively (Fig. 2).

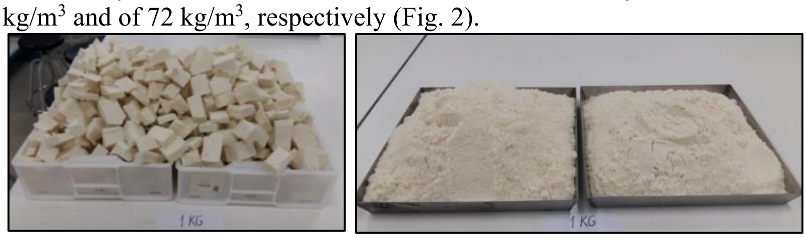

Fig. 2. Polyuretane foam waste (PUW).

Glass fibres were used to reinforce the matrix of both products supplied in individual roll with 24 µm diameter and 0.55 %mass loss of ignition. The fluidizer used was a Melamine-based water-reducing superfluidizer with chloride-free.

The two products compared in this comparative statement are two gypsum tiles: Standard gypsum ceiling tile and PU-gypsum ceiling tile with nominal dimensions of 593x593x15 mm (+-2 mm). Both gypsum tiles are installed in partitions, linings and interior ceilings, forming systems that provide the acoustic insulation, thermal resistance and fire resistance required in each case (Fig. 3).

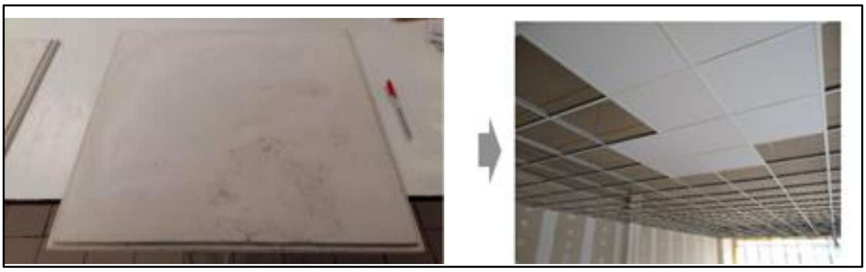

Fig. 3. Gypsum ceiling tile test piece (left), Gypsum ceiling tile installed in a ceiling (right).

The main difference between both models of gypsum tiles is the incorporation of polyurethane residue in one of them by progressive substitution of one part of gypsum with 1.5 parts of polyurethane foam waste (PFW) by volume [6]. The composition of both gypsum ceiling tiles is shown in Table 1.

Table 1. Composition per square metre of PU-Gypsum ceiling tile and the Standard Gypsum tile

Raw materials	PU-GYPSUM TILE	STANDARD GYPSUM TILE
Polyurethane (Kg/m^2)	0.35	0.00
Gypsum (Kg/m^2)	4.23	6.19
Water (Kg/m^2)	6.09	8.19
Fibres (Kg/m^2)	0.06	0.06
Fluidizier (Kg/m^2)	0.04	0.00

1.2 Methodology

Gypsum ceiling tiles were characterized by their bulk density, maximum breaking load under flexion stress, thermal conductivity, and reaction to fire performance. The tests followed the instructions in Standards 14246:200622 [7], which establish the specifications and the test methods for gypsum plasterboard and tile for internal ceilings and UNE-EN ISO 1716:2011 [8] that establishes the fire reaction. The methodology for the determination of water vapour permeability in a stationary state in stucco and plaster mortars is defined in Standard EN 1015-19 [9]. The Standard specifies that to find the permeability value, it is first necessary to calculate the permeance, which is the water vapour flow that passes through one area unit under equilibrium conditions for each unit of vapour pressure difference on both sides of the plaster. Subsequently, water vapour permeability is calculated as the result of multiplying permeance by the thickness of the test specimen. After establishing the characteristics of the new material, manufacturing of the tiles was performed on an industrial scale at Yesyforma Europa manufacturing plant in Zaragoza, Spain.

The design of mixtures was carried out by substituting different amounts of gypsum with PU waste and optimizing and testing the mixtures in order to discover their technical qualities. In the manufacturing plant, the PUW waste is placed into an industrial shredder. The powder obtained is mixed with gypsum and other components in order to produce the new ceiling tile (Fig. 4).

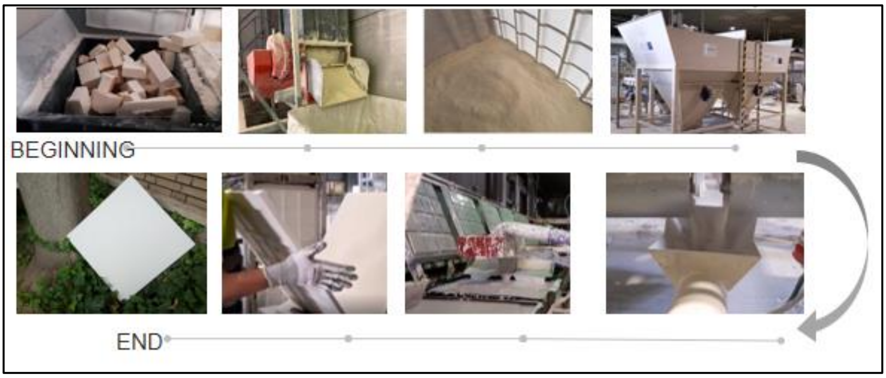

Fig. 4. Industrial manufacturing process of PU-Gypsum ceiling tile.

In order to calculate the environmental impact of the production of each type tile, a comparative environmental analysis using the Life Cycle Assessment (LCA) methodology was carried out using the standards ISO 14040:2006 and ISO 14044:2006 [10], [11].

2 Results and discussion

2.1 Bulk density

The results of the bulk density test are shown in Table 2 for both types of tiles. It may be seen that, as the volume of PU in substitution of gypsum increases, there is a drop in density at 15% in the PU-Gypsum tile (1 part gypsum and 1.5 PUW). This fact fundamentally occurs because of the replacement of the gypsum matrix (2960 kg/m3) by PU (1080 Kg/m3). In addition, PU requires high quantities of water to arrive at an acceptable workability according to EN-13279, which implies a high volume of pores and, in consequence, a reduction in the density of the material [12]. It translates into a reduction of (31.6%) in gypsum.

Table 2. Bulk density results of PU-Gypsum ceiling tile and the Standard Gypsum tile

Parameter	PU-GYPSUM TILE	STANDARD GYPSUM TILE
Bulk density (Kg/m^3)	773	900
Reduction of gypsum (%)	31.6	-

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2.2 Fire reaction test

The results of the non-combustibility test confirmed that the tile that incorporated PU in their composition, presented flaming times of less than 20 s with a temperature increase of below 50ºC and a loss of mass of less than 50% (Table 3). The superior calorific value was 1.0477 MJ/Kg. This result indicates that its composition corresponded to Euroclass A1 (non-combustible), in accordance with the European fire reaction classification of building materials for homogeneous products.

Table 3. Fire reaction test of the PU-Gypsum ceiling tile

Parameter	PU-GYPSUM TILE
Temperature rise of furnace (ºC)	16.6
Duration of sustained flaming (s)	<5
Loss of mass (%)	26.63
Euroclass clasification	A1
CTE-D-SI	B-s2-d0
Superior Calorific Value	1.0477

2.3 Water vapor Permeability test

Table 4 shows the water vapor permeability of the standard and PU-Gypsum tiles. The results show that the PU-Gypsum ceiling tile (Fig 5, Fig. 6) presents a progressive increase in permeability due to the fact that polyurethane is a porous material, which means that it has relatively high mean diameters in the capillary network, which in turn eases the passage of water vapour [13]. All these factors allow to consider these products as lightweight materials free of condensation in the form of liquid water in practically any climatic condition, which perform well with respect to water vapour diffusion.

Table 4. Results of the water vapor permeability test

Series no.	Permeability (kg/m s Pa) x 10^{-11}
STANDARD GYPSUM TILE	6.55
PU-GYPSUM TILE	7.89

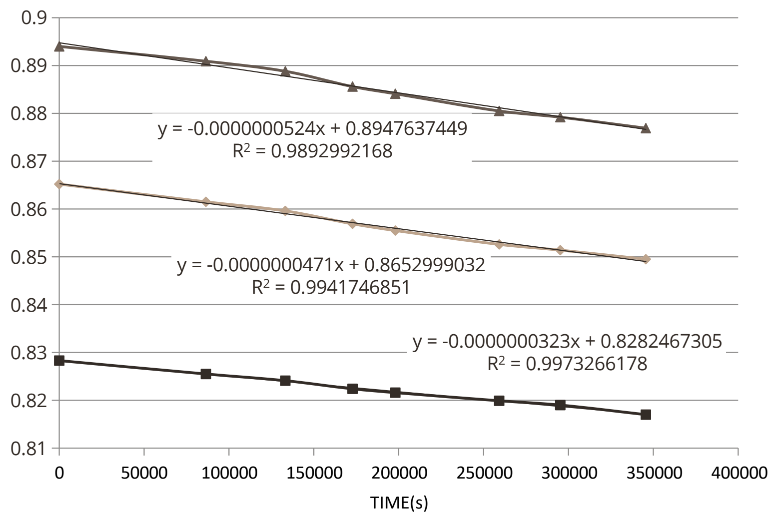

Fig. 5. Permeance of Standard-Gypsum ceiling tile.

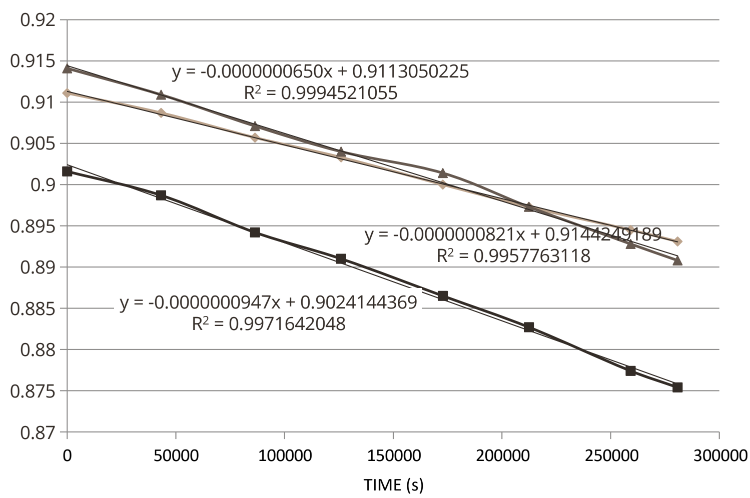

Fig. 6. Permeance of PU-Gypsum ceiling tile.

2.4 Life Cycle Assessment (LCA)

The process was not carried out from cradle to cradle due to the fact that the manufacturer has not recovered the PU and the gypsum waste yet [14]. The assessment was carried out at the Yesyforma Europe manufacturing plant from 2018 to 2020. The functional unit used in the system was 1 square metre. Table 5 shows the LCA information.

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Table 5. Information of the system

FUNCTIONAL UNIT / DECLARED UNIT	1 m2 of gypsum ceiling tile (both models)
LIMITS OF THE SYSTEM	From the cradle to the grave
REFERENCE LIFETIME	30 years
ASSIGNMENTS	Production data. The recycling, emission, energy and waste data have been calculated based on the surface of the product (functional unit)
DATA QUALITY	Product data has been obtained from information from the production center of Yesyforma during the 2018 and 2019 period. The electric mix considered corresponds to the year 2018.
SUPPORT DATA	All the main data has been obtained from Yesyforma. Secondary data has been obtained using SIMAPRO software. The impact model used corresponds to CML 2.001. Other bibliographic sources that are detailed in the "bibliography" section of this report have also been used.
GEOGRAPHICAL COVERAGE PERIOD	Production center of Yesyforma located in Crta. Zaida a Sástago, Pol. Ind. Nº 1, 50780, Sástago, Zaragoza (Spain) 2018-2019-2020.

The product system has been studied taking directly into the Yesyforma plant where the "traditional" gypsum ceiling tile and the new “ecological” have been manufactured. Therefore, the diagrams of both systems are shown below (Fig. 7, Fig. 8). Both product systems are very similar, although they present some differences based on the incorporation processes of the recycled materials in the case of the “ecological” tile such as the shredding and drying processes. Each unit process has its own product flow and its own inputs and outputs.The inputs are the raw materials and the energy. And the outputs are waste and the emissions which are given off from each unit process.

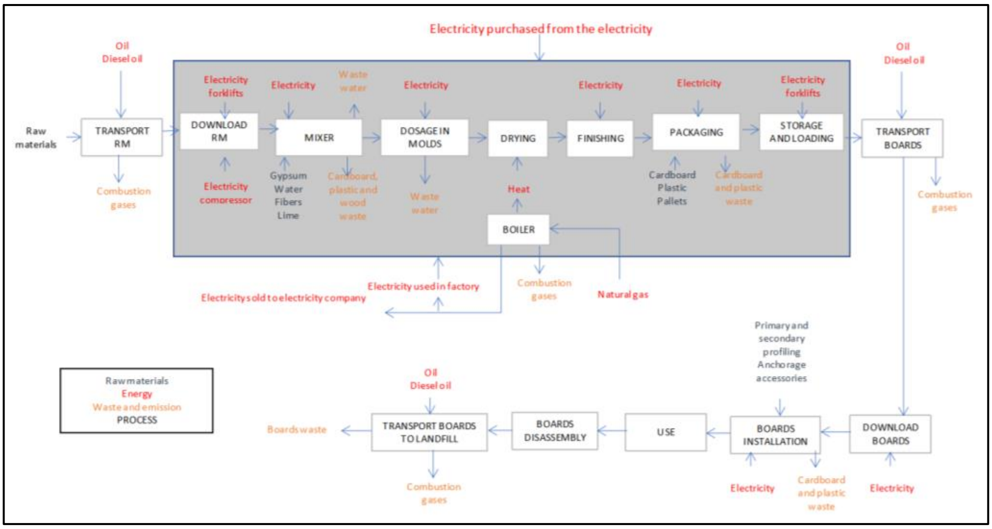

Fig. 7. "Traditional" Gypsum Ceiling tile Product System (Standard)

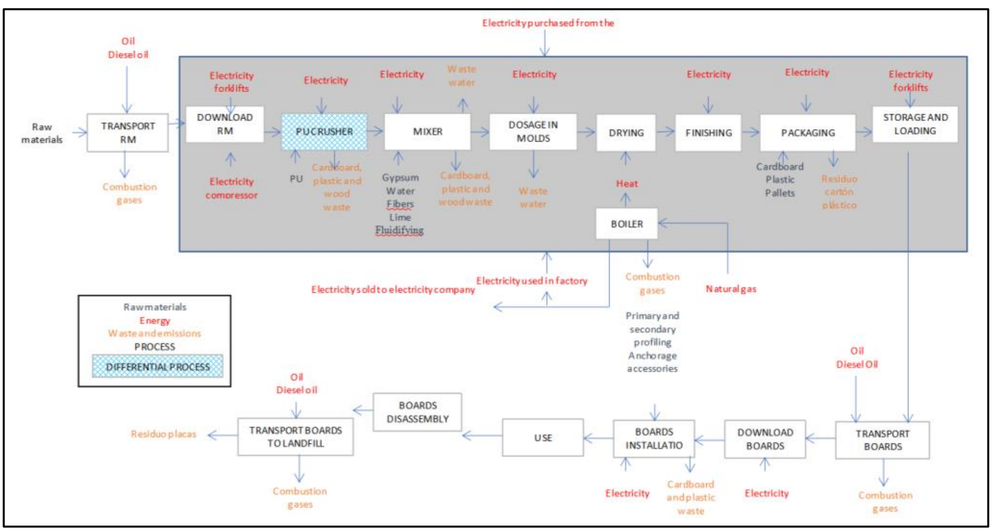

Fig. 8. Product system of the "ecological" PU-Gypsum ceiling tile

Table 6 shows the results obtained from the LCA for each impact category and indicates the percentage of difference found between both tiles, using the standard gypsum as a reference.

In the case of the "Global warming"impact category, the PU-gypsum ceiling tile has a significant reduction in CO2 emissions compared to the standard model. This difference is mainly due to two reasons: the lower consumption of natural gas necessary for drying due to the new product drying more quickly. The other reason, is because of the lower consumption of fuel for transport. This is down to the lighter weigth of the new ceiling tile.

In the case of "Acidification of the soil and water", the PU-gypsum ceiling tile indicates a 9.52% reduction of emissions equivalent to Kg SO2 eq / m2 (kilogram sulpher dioxide per square metre) and in the case of "Eutrophication impact" the PU-gypsum ceiling tile indicates a 8.95% reduction of emissions equivalent to Kg (PO4)3- eq/m^2 (kilogram phosphoric acid per square metre), in both cases compared with the standard gypsum ceiling tile. This decrease is based on the lower consumption of natural gas necessary for the drying of PU-gypsum tile, as well as the lower consumption of fuel for transport.

Table 6. Impact category for PU-Gypsum and Standard system

Impact category (Unit)	Model of tile	TOTAL	% difference between models
Global warming (kg CO_2 eq/m^2)	Standard	6.488	-13.98%
	PU-gypsum	5.581	
Soil and water acidification (Kg SO_2 eq/m^2)	Standard	1.68×10^{-3}	-9.52%
	PU-gypsum	1.53×10^{-3}	
Eutrophication (Kg $(PO_4)^{3-}$ eq/m^2)	Standard	3.12×10^{-4}	-8.65%
	PU-gypsum	2.85×10^{-4}	
Photochemical ozone formation (Kg C_2H_2 eq/m^2)	Standard	1.05×10^{-5}	+19.05%
	PU-gypsum	1.25×10^{-5}	
Abiotic resource depletion (ADP-elements) (Kg Sb eq/m^2)	Standard	0.48737	-11.79%
	PU-gypsum	0.42989	
Abiotic resource depletion (ADP-fossil fuels) (MJ/m^2)	Standard	94.0797	-13.83%
	PU-gypsum	81.0671	
Use of renewable primary energy excluding resources used as raw material (MJ/m^2)	Standard	0	--%
	PU-gypsum	0	
Non-renewable primary energy use excluding resources used as raw material (MJ/m^2)	Standard	94,0797	-13.83%
	PU-gypsum	81.0671	
Net use of fresh water (L/m^2)	Standard	8.328	-25.22%
	PU-gypsum	6.228	
Disposed / discharged hazardous waste (Kg/m^2)	Standard	0	--%
	PU-gypsum	0	
Non-hazardous waste disposed / discharged (Kg/m^2)	Standard	10.1452	-31.18%
	PU-gypsum	6.9816	
Materials for recycling (Kg/m^2)	Standard	0.220212	+1.08%
	PU-gypsum	0.222600	
Exported energy (MJ/m^2)	Standard	30.458	-21.75%
	PU-gypsum	23.832	

Under the impact category “Photochemical ozone formation” the new ceiling tile shows an increase in acetelyne of 19.05% compared with the standard gypsum ceiling tile. Although the difference in percentage seems greater, the difference is only 0.000002 Kilogram of acetelyne per square metre, so the different is very low.

The next impact is Depletion of abiotic resources (ADP-elements), there is a 11.79% reduction of antimony which is considered very significant. This fact is mainly due to the lower demand for raw materials in the new product.

In the case of “Depletion of abiotic resources (ADP-fossil fuels)”, the new product has a 13.83% reduction of fossil fuels MJ per square meter compared with the standard tile. This is due to the same factors indicated above, i.e. Use of energy and trasnsport. In the "Use of non-renewable primary energy excluding resources used as raw material", this impact category, has the exact same results.

The next impact category is "Net use of fresh water". The new product has a 25.22% reduction of fresh water in litres per square meter compared with the standard gypsum tile. This is due to the lower water content required in the new tile.

The impact category that has the greatest difference between both ceiling tiles is “Non-hazardous waste eliminated in landfill”. There is a 31.18% reduction of waste in the PU-gypsum tile compared to the standard tile. This difference is due to two aspects: first, by reusing polyurethane waste, avoiding its disposal. Secondly, the decreased amount of gypsum waste generated due to the new tile having a lower mass than the standard gypsum tile. Figure 3 shows the results obtained from the economic assessment comparing both models. Different stages of the product life cycle are included in order to analyse those that have the most impact in the total life cycle cost. The stages included are raw materials supply and transport, production, placement, utilisation and end of life. The two last columns concern to the whole life cycle cost. The results are presented as percentages to better understand the comparison of models.

The raw materials supply and transport represents around 35% of the total cost. The new precast is 3% cheaper in this stage due to the difference in the composition of the products and in the amount of gypsum, additive and polyurethane. The packaging is also considered, but its cost is the same for both construction materials.

The production becomes approximately the 60%. The PU-Gypsum product has an extra cost in this stage regarding the crushing process and the crusher needed, however the production capacity increases for that model. Taking everything into account, the cost data express that the sustainable sample is lower-cost, the savings in these stages are around 7%. Placement and utilisation have not been taking into account therefore no influence in the cost is noticed.

The last phase is the transport of the ceiling tiles after its removing. It represents only the 5% of the cost. The PU-gypsum sample is a bit more inexpensive, but the difference is minimum. The key for the transport process cost is the weight of the materials and the new product is lighter.

The total cost is obtained adding the cost of each stage analysed. Considering the discounts mentioned before, it is concluded that the ceiling tile that includes PU foam waste in its composition is more affordable. The final cost reduction is estimated in 6% per m^2 of ceiling tile.

3 Conclusions

When comparing the new tile with the standard version, The new material is 32% lighter. The lighter weight of the PU-Gypsum tile compared with standard one allows for increased performance when laying the tiles. As they are lighter, the installer can considerably reduce the effort required for movement, which results in fewer injuries for the operator. In addition, the speed of installation is in-creased. Likewise, the weight of the material transport from the factory to the work site is lower, so the environmental impact of transport is also reduced. Its water vapour conductivity level is almost 16.9% higher and the reaction to fire classification is A1, according to Eurocode, which is the highest.

The comparative (LCA) between both tiles shows that the new product that incorporates polyurethane waste has significant improvement in CO_2 (14%) and lower use of energy during the manufacturing process (14%). The following impact categories were also reduced: 9% in the case of the acidification of the ground and water, 9% for eutrophication and 31%

reduction for non-hazardous waste. This work intends to reduce the carbon footprint and increase the sustainability of polyurethane gypsum products. In comparison with current products, PU-gypsum board is more sustainable because it uses less natural resources and it has lower carbon footprint which is caused by the gypsum manufacturing as well as it reduces the amount of PU landfill sites in a more profitable and efficient way.

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