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Comparative assessment of roof tiles' environmental performance from cradle to cradle

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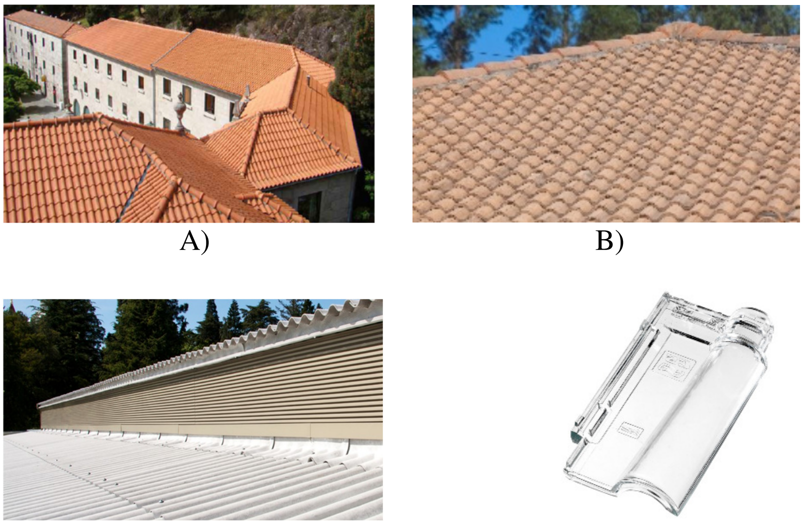
Abstract. Roof plays an important protective role in a building, and claddings are the first element to collaborate in that function. In Portuguese architecture, ceramic roof tiles are the most common claddings in pitched roofs. Concrete roof tiles are a good alternative because of their technical performance and visual similarity to ceramic ones. Both have been studied in different perspectives, but there is no updated comparison of their environmental performance in the European context. For this research work, the environmental performance of ceramic and concrete roof tiles was studied and compared, based on the Life Cycle Assessment (LCA) methodology and following international standards. A cradle-to-gate LCA was performed for the product stage of concrete roof tiles. The LCA approach applied in the comparison study was cradle-to-cradle, based on plausible and conservative scenarios. They are presented for the product stage for the respective reference flows, based on the LCA performed for concrete roof tiles within this research work, and in another recent LCA performed for ceramic roof tiles in Portugal. A comparison is then performed between the LCA results from cradle to cradle of ceramic and concrete roof tiles when applied in a building for a service life of 50 years. Ceramic roof tiles present lower environmental impacts over their life cycle in five out of seven impact categories: ADP-Elem. (different magnitude), GWP (-16%), POCP (-10%), AP (-5%) and EP (-89%). The exceptions are ADP-ff and ODP for which concrete roof tiles present a better environmental performance (-44% and -64%, respectively). For both roof tiles, it was concluded that the production stage is the most relevant, representing between 63% and 84% of life cycle impacts.

1. Introduction

The roof is a fundamental element in a building, because of its protective function [1-2], as well as its role in the energy efficiency and indoor comfort. The evolution of pitched roofs systems allowed complying with increasingly demanding functional, sustainability, aesthetic, and economic requirements. Although roofs may have different claddings, structures, geometries, and slopes, pitched roofs are a traditional aspect of Portuguese architecture, typically with a ceramic tile cladding [3-6]. The external cladding layer is crucial in ensuring several functional requirements, namely: safety, watertightness, and durability, as well as sustainability requirements which must be met by each material (Regulation (EU) No 305/2011 of March 9, 2011 [2; 8].

There are in the market many alternative solutions of claddings for pitched roofs. In terms of the nature of these materials, they can be organic, natural stone, artificial stone (ceramics, concrete, and fibre cement), metals, bituminous, plastics or mixed materials (including metallic of fibre cement sandwich panels) [9-10].

Artificial stone claddings (Figure 1) are the most used in pitched roofs in Portugal. For residential buildings, particularly, ceramic, and concrete tiles are the most common solution, as fibre cement and glass solutions present less appropriate characteristics. Fibre cement sheets are usually applied in the roofs of industrial, school, agricultural and sports buildings. As a single roofing system, it is generally associated with buildings that have lower levels of functional demand or provisional character [5]. Glass tiles may be used alone, but they are most often used combined with ceramic or concrete tiles, allowing natural light to pass to the interior of the roof. Transparency is the most relevant characteristic that justifies the use of glass tiles, considering the fragility of the material [7].



A) B)

C) D)

Figure 1. Examples of artificial stone claddings in Portugal: A) Ceramic tile roof [11]; B) Concrete tile roof [12]; C) Fibre cement roof (school) [13]; Glass tile example - “Telha lusa” [14]

Ceramic tiles are part of the Portuguese architectural heritage [6-7]. This tile is the cladding material most applied in pitched roofs of Portugal, mainly due to the low technological level associated with the manufacture of tiles, but also to the low cost and abundance of raw materials [5]. The main advantages of ceramic tiles are related to their aspect (architectural tradition), good performance, high dimensional accuracy, low cost, and durability. It is also a non-toxic, and renewable product. The main disadvantages are related to the generation of waste, characteristics of the application process (time-consuming and labour-dependent process, very prone to human error), dependence on the design and detail of the singular points and need to be complemented with other materials/elements (thermal insulation, complementary watertight barriers, flashings, downspouts, draining pipes, vapour barriers, etc.) [5].

Concrete tiles are currently an alternative to ceramic tiles, in practically all their fields of application, with very good performance, particularly in terms of dimensional stability, tightness, mechanical resistance and reduced sensitivity to thermal variations. They are produced with the same formats as ceramic tiles, sharing most of its advantages and disadvantages. One advantage compared to ceramic tiles is the possible colour range, which can be adapted to the thermal needs of specific locations (heat absorption or reflection) However, they are heavier than ceramic tiles and do not maintain the traditional architecture characteristics [7].

1.1. Review on LCA of roof tiles

Available information on concrete and ceramic tiles LCA is limited. A systematic review was performed in Scopus, Web of Science and Google Scholar databases. The studies found, related to this theme are summarised in Table 1.

It is possible to conclude that the existence of distinct methodological variables (boundaries, functional units and LCIAM, among others) make it difficult is difficult to use these studies to create a benchmark or compare the results obtained.

In the cradle-to-grave studies, the end-of-life scenarios are very diverse, depending on the location of the construction work and even national policies. Thus, the scenario of landfilling was selected in most cases [15-16], although in the United Kingdom a scenario of 95% recycling/reuse and 5% landfill was studied [17].

Cellura *et al.* [18] performed an LCA of “Sicilian tiles”, typical roof tiles used in the rehabilitation of old buildings in the Mediterranean area. The authors identified the most relevant sources of uncertainty of the LCA study. Then, a sensitivity analysis was performed to estimate the effects of different secondary input data and of the chosen methods for the environmental impact assessment on the tile eco-profile.

Souza *et al.* [16] compared the life cycle impacts of ceramic and concrete tiles covering 1 m^2, for a lifetime of 20 years in Brazil. The authors concluded that ceramic tiles present less impact on Climate Change, Resource Depletion and Water Withdrawal, while for Human Health and Ecosystem Quality, the two alternatives presented very similar results.

When comparing different solutions, Le *et al.* [19] concluded that clay tiles have the lowest carbon footprint (4.4 t CO_2 eq.) and embodied energy (52.7 MJ) per 100 m^2, most of it related to the manufacturing. Aluminium metal sheet roofing presented the highest carbon footprint (9.85 t CO_2 eq.), while concrete roof tiles showed the highest embodied energy demand (83 MJ).

The study performed by the World Steel Association [20], compared six different designs for a typical Scandinavian roofing, including one design based on concrete tiles. The results show that for the steel and concrete solutions, the construction materials have the biggest contribution, contributing more than 70% in terms of GWP.

In their production process analysis, Octavia *et al.* [21] concluded that the analysed company was causing high environmental impacts, and had a significant saving potential, and drew recommendations for the company to improve its environmental performance. The most relevant impact categories of the analysed concrete roof tile production process are natural land transformation, marine eco-toxicity, freshwater eutrophication, and freshwater eco-toxicity, where those impact categories represent an average of 75% of the overall normalised impacts, according to a Pareto analysis for concrete tile..

In Portugal, ceramic roof tiles are an important element of traditional architecture and have been the object of several studies, namely two theses dedicated to either this specific product [22] or to the ceramic industry, including roof tiles [25] and one peer reviewed paper [23].

Vieira [22] developed a PEF for a square meter of ceramic roof tile produced in Portugal, according to the first version of the PEF method [27]. Since there was no PEFCR available, it was performed only for the product stage and secondary data do not comply with PEF requirements. The author concluded that manufacturing is the stage that most contributes to most of the impact categories, except for human toxicity - non-carcinogenic, ionising radiation, eutrophication (fresh water) and ecotoxicity (freshwater), where packaging represents 78%, 52%, 68 and 70% of the impacts, respectively.

Table 1. LCA studies concerning ceramic and concrete tiles considered in the literature review.

Reference	Boundaries	Object of the assessment (region)	Declared unit	LCIA method: LCA impact categories

[15]	Cradle-to-grave (Distrib.: 100 km)	Generic ceramic tile (Spain)	1 kg	CED: NRPE; IPCC 2007: GWP; Eco-Indicator 99: water footprint
[18]	Cradle-to-grave (Distrib.: 100 km)	Sicilian tiles (used in building rehabilitation)	1000 kg	CED: NRPE; CML 2 (2000): GWP; AP; EP; ODP; POCP
[17]	Cradle-to-grave	Average tile from 10 producers (Belgium)	1000 kg of tiles over 150 years	CML2001: all impact categories (according to EN 15804+A1)
[24]	Cradle-to-gate	Local data from one producer	1 ft^2 over 100-years	Eco-indicator 99
[16]	Cradle-to-grave (distribution 120 km)	Comparison of ceramic and concrete tiles (Brazil)	1 m^2 (38.4 kg) of tile over a 20-years' service life	Impact 2002+:all categories; ReCipe: all categories
[22]	Cradle-to-gate	One ceramic roof tile (Portugal)	1 m^2 over a 35-years' service life	ILCD 2011 Midpoint + (PEF 2013 method): all categories
[21]	Gate-to-gate, only focused on the process	Concrete flat roof tiles		ReCipe Water footprint
[25]	Cradle-to-grave + distribution (120 km)	Average ceramic tile considering two producers (Portugal)	1 m^2 of ceramic tile over 50 years	CML-IA and ILCD: all categories
[19]	Cradle-to-grave	Roof-covering materials (clay tile, concrete tile, and metal sheet; West Australia)	100 m^2 (roof covering+ wood supporting structure)	IPCC 2007: GWP; CED: NRPE
[20]	Cradle-to-grave	Generic concrete tile (EU-28)	The functional unit is a roof of 150m^2 for 60 years. The key roofing materials considered are	ADP elements, ADP fossil, AP, (EP), Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.); GWP 100 years; GWP 100 years, excluding biogenic carbon, ODP, steady state, POCP; CED: RPE and NRPE
[26]	Cradle-to-grave	One tile from one producer (Serbia)	1 t of clay roof tile for 50 years	CML2001: all impact categories
[23]	Cradle-to-grave	Two ceramic roof tiles produced by two producers (Portugal)	1 m^2 of ceramic roof tile for 50 years	CML2001: all impact categories (according to EN 15804+A1)

Fernandes [25] provided an LCA study according to EN 15804:2011+A1 2013. The author applied both the CML-IA and the ILCD impact assessment methods and concluded that the product stage is the most influential for all impact categories assessed, except for human toxicity - non-carcinogenic and ecotoxicity, for which transport presents the highest contribution.

Analysing the results of the developed Environmental Product Declaration for clay roof tiles, Drpi *et al.* [26] concluded that manufacturing stage (module A3), transport to the building site (module A4), waste transportation (module C2) and raw material extraction and processing (module A1), generally present the most significant impacts. Primary energy and GWP are highly influenced by the high energy consumption during the roof tile production, as well the transportation of the finished products to long distances. Considering the benefits of end-of life recycling and reuse presents a relevant contribute to a global decrease in the environmental impacts.

Quinteiro *et al.* [23] assessed the environmental performance of ceramic tiles from two Portuguese manufacturers, over a period of 10 years. They conclude that, despite the differences between the roof tiles assessed, there was an overall improvement in their environmental performance for all impact categories over the 10-year period. This resulted from a consolidated effort to implement more sustainable technological and energy solutions in the manufacturing processes.

Considering the significance of pitched roofs in Portuguese (and European) architecture, it is important to have updated and specific data on the environmental performance of the most relevant cladding materials used for that building assembly. This paper answers such question through four chapters: introduction methodology, results and discussion, and conclusions.

2. Methodology

The environmental assessment performed during this work applied the Life Cycle Assessment (LCA) internationally standardised method (ISO 14040 series). This, allows the (environmental) performance assessment of goods or services ("products"), based on the quantification of all relevant emissions and resources consumed and the calculation of related potential environmental and health impacts and resource depletion issues over their life cycle [28].

2.1. Environmental life cycle assessment

To perform a study on the environmental performance of concrete and ceramic tiles from cradle to cradle, they were considered installed in a habitational building with an implementation (and roof) area of 100 square meters. The default location for this study is Lisbon because it is the national metropolitan area with the highest building density. To account for the cladding materials in the pitched surfaces, a two-pitched roof was assumed with plan sizes between 6 and 10 meters and located in a regular zone (not too exposed nor protected). Under these conditions, manufacturers advise a minimum recommended slope of 31%, which was used for both studied solutions. This results in 12 tiles per square meter for ceramic tiles and slightly less (11 tiles per square meter) for concrete tiles.

2.2. The Impact Assessment Method (IAM) selected for this research work was CML-IA baseline, the method complying with EN 15804+A1:2013 (CEN/TC 350, 2013). This is justified by the possibility to perform benchmarks and use existing environmental profiles, collected by research studies and EPDs developed before the recent update of the standard. The impact categories assessed were: Abiotic resource depletion potential for energy resources and for non-energy resources (ADP-f.f. and ADP-Elem.), global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), Acidification potential (AP), and Eutrophication potential (EP). Moreover, the cumulative energy demand (CED)(low heating value) method was also applied, to calculate non-renewable primary energy (NRPE) and renewable primary energy (RPE) associated to the products assessed. Scope of the assessment - Functional or declared unit

The functional unit defined for this LCA study "the cladding of one square meter (in horizontal projection) of pitched roof, ensuring watertightness and further required services for 50 years". The time span selected was 50 years because it is the usual service life considered for a building at the design stage [29].

2.3. Scope of the assessment - Boundaries

The system boundaries define the unit processes to be included in the system model. The modular approach of LCA studies applied to construction products (as defined in EN 15804) allows the use of data packages throughout the life cycle of the product [30-31]. The modules assessed in this research work are marked in bold in Table 2.

The product stage (A1-A3) is fully considered in the life-cycle assessment sections 2.4 and 2.5. No reliable information was found for the construction stage process A5. Thus, only A4 (transport to the building site) was considered. Within the use stage, B2-B4 are considered based in scenarios considering the reference service life of the tiles. The use or application and the refurbishment (B1 and B5) are not accounted for. Thermal performance and water use are not significant characteristics of the assessed claddings, so B6 and B7 are excluded from the assessment. For the end-of-life stage, only the C2, C3, C4 and D modules were accounted for. In brief, for modules A5, B1, B5, B6, B7 and C1 either there was no reliable information, or the available information would be similar in the assessed alternatives, so they were excluded from the performed assessment.

Table 2. Life cycle stages of construction materials, according to the European standards - in bold the modules included in this study) [29-30].

LCA boundaries			**Life cycle stages / LCA information modules**	**Life cycle stages designation and description**	
Cradle-to-cradle	Cradle-to-grave	Cradle-to-gate	***Product stage (A1-A3)***	***A1***	***Raw material extraction and processing***
				A2	***Transport to the manufacturer***
				A3	***Manufacturing***
		Gate-to-grave	Construction process stage (A4-A5)	***A4***	***Transport to the building site***
				A5	Installation into the building
			Use stage - Information modules related to the building construction/manufacture (B1-B5)	B1	Use or application of the installed product
				B2	***Maintenance***
				B3	***Repair***
				B4	***Replacement***
				B5	Refurbishment
			Use stage - Information modules related to the building operation (B6-B7)	B6	Operational energy use
				B7	Operational water use
			End-of-life stage (C1-C4)	C1	De-construction, demolition
				C2	***Transport to waste processing***
				C3	***Waste processing for reuse, recovery and/or recycling***
				C4	***Disposal***
			Benefits and loads beyond the system boundary (D)	***D***	***Reuse, recovery and/or recycling potentials***

After the calculation of specific impacts for the product stage, the environmental performance of the roof tiles was assessed from cradle to cradle according to the requirements of the LCA international standards (ISO 14040 and ISO 14044) [28; 31], and the specific standards applicable to buildings' LCA: EN 15978- Assessment of environmental performance of buildings - Calculation method and EN 15643-2 - Assessment of buildings - Part 2: Framework for the assessment of environmental performance:

- The results of the assessment are organised into three main groups according to the life cycle stages (Table 2): A1-A4, B2-B4, and C2-C4 and D;
- The benefits and loads beyond the building life cycle (e.g. impacts resulting from further reuse, recycling potential and energy recovery or others), are calculated, because they may be important to the promotion of more sustainable end-of-life solutions for buildings and assemblies;
- The default value for the reference service life of **the assembly** shall be the one required for the building. The estimated service life should consider the rules and guidelines included in ISO 15686 standards (parts 1, 2, 7 and 8). Thus, the analysis of the assembly includes the maintenance and replacement of the tiles according to the information on durability and maintenance from the manufacturer or from literature sources (described in section 2.7).

The methodology for the product stage assessment (A1-A3) of each tile is described in sections 2.4 for concrete tiles and 2.5 for ceramic tiles. The remaining stages of the life cycle are explained for both tiles in sections 2.6 (Transport to the building site), 2.7 (Use stage – Maintenance, Repair, Replacement), and 2.8 (End-of-Life), based on the described scenarios. These scenarios (for all stages after the manufacturing) were developed according to the European Standards, with generic LCA data as close as possible to the current or anticipated situation [32].

2.4. Product stage LCA - Concrete tiles

Concrete roof tiles are made of cast and pigmented concrete. The tile body consists of around 4.2 kg of concrete, and is made from sand, water, cement, and a small percentage of iron oxide pigment. Concrete roof tiles are a cladding material subject to standard "EN 490 - Concrete roofing tiles and fittings for roof covering and wall cladding - Product specifications". Table 3 presents the technical characteristics of the concrete roof tiles studied.

The LCA study of concrete roof tiles was performed within this research work, to provide site-specific and scientifically validated data for a material that may be used as cladding in pitched roofs. These data are to be used also as a contribution to the development of a National LCA database in the construction sector.

The time boundary of this study was the year 2017. The LCA was performed complying with applicable international LCA standards (namely ISO 14000 series), and with EN 15804. The data used and simulated were collected at the production unit located near Braga.

Table 3. Summary of the technical characteristics of studied concrete tiles.

Characteristics	Specifications	Value	Unit
Length	-	420	mm
Width	-	332	mm
Wave height	-	37	mm
Usable width	± 5 mm	300	mm
Length over stud	± 4 mm	395	mm
Mass	± 10%	4.2	kg
Fire resistance	-	Incombustible	-
Fire reaction	-	A1	Euro Class
Water tightness	No drip in 20 hours	Complies	-
Durability (freeze-thaw resistance)	25 cycles	Complies	-
Flatness	3 mm	0	
Resistance to transversal bending	Before 28 days: ≥ 1600 At 28 days ≥ 2000	2000	N
Release of hazardous substances	-	Not determined	

The unit of analysis of the LCA study was one concrete tile with the previously declared dimensions at the out gate of the production unit, ready to be sent to the construction site.

The manufacturing process of the concrete roof tiles starts with the selection of raw materials such as washed graded sand, Portland cement, inorganic pigments, and water. These raw materials are mechanically mixed in the concrete mixer. Then, the concrete in the fresh state is extruded under pressure into the tile moulds that give them the desired shape. These fresh tiles are then placed into racks and taken to a curing/hardening area. The curing process is based on steam produced in a boiler. After this, the tiles are demoulded and subject to a quality control process. Tiles are then packed into pallets and prepared for shipping.

In the production of concrete tiles, there are no co-products, thus no allocation was performed.

All data on primary processes (controlled by the manufacturer, at the plant) were collected at the plant, based on the internal records. For secondary data, the Ecoinvent and ELCD databases were the main source of information. For the estimation of fuel consumption (diesel) emissions in internal processes, for which the amount of spent diesel was known, emission factors were used applying processes from the Ecoinvent database.

The main input and output flows in the production of ready-mixed concrete are summarised in Table 4 and Table 5. Besides raw materials, there are inputs of electricity, diesel used in the machinery that supports internal transport of raw materials, as well as the fuel oil used in the boiler for the curing process.

On the output side, the main waste flow is related to the non-compliant tiles and concrete slurry generated during the production. The main raw materials are supplied in bulk. However, there is packaging waste from the pigments and from the packaging materials used in the product. Further output is the final product at the out gate of the unit. There are no emissions to water or soil during the production process. Both air emissions and wastes were accounted for based on internal and official reports.

Table 4. Input flows for ready-mixed concrete product system.

Production stages	Material flow	Energy flow
Reception and storage of raw materials	-	Diesel
Mixing	Aggregates; cement; pigments; water	Electricity
Extrusion/moulding	Demoulding oil	Electricity
Cure/hardening	-	Fuel oil; electricity
Packaging and expedition	Packaging materials: PP string, LDPE film and bags; wood pallets	Electricity

Table 5. Output flows for ready-mixed concrete product system.

Production stages	Output flow
Reception and storage of raw materials	Packaging waste (pigments); air emissions
Mixing	-
Extrusion/moulding	-
Cure/hardening	Gas emissions
Demoulding and quality control	Noncomplying product for waste
Packaging and expedition	Final product packed; packaging materials waste

The manufacturing plant where the concrete tiles are produced also produces the respective accessories. The only difference for the tiles is the mould used, so there was no need to use an allocation methodology for the inputs and outputs. These were associated with the total amount (mass) of products and then, to the average mass of one tile and of one square meter of tiled roof.

2.5. Product stage LCA - Ceramic tiles

Ceramic tiles are manufactured by forming (extrusion and/or pressing), drying and firing the prepared clay, with or without additives (EN 1304:2013 - Clay roofing tiles and fittings. Product definitions and specifications" [33].

For this research work, specific information for the product stage of ceramic tiles was used from the recent and thorough LCA study performed for Portuguese ceramic tiles by Fernandes [25]. The methodology of the study is detailed in the original publication by Fernandes [25]. A summary of this methodology is presented to frame the study.

For the LCA of ceramic roof tiles, two case studies over time (from 2005/2006 to 2014) were considered, representative of two national ceramic tile manufacturers. The unit of analysis of the LCA study was 1 m^2 of red ceramic tile (Lusa tile) produced in Portugal, to cover a pitched roof over a period of 50 years. The tiles considered presented a mass value of 3.4 and 3.8 kg respectively [25].

The main input and output flows in the production of ready-mixed concrete are summarised in Table 6 and Table 7. Besides raw materials, there are inputs of electricity, diesel used in the machinery, as well as the natural gas used in the kiln for the firing process. On the output side, there are emissions of wastewater for the municipal wastewater collection system, air emissions, oils and fats, hydrocarbons, and solid waste. Further output is the final product at the out gate of the unit. There are no emissions to water or soil during the production process.

Table 6. Input flows for ceramic tile product system (adapted from [25]).

	Material input flow	**Energy input flow**
Production	Clay	Electric energy
	Sand	
	Calcium carbonate	
	Dolomite	
	Dyes	Natural gas
	Wire	
	Lubricating oil	
	Water (natural source/supplied)	
Packaging	Wood; plastic film; plastic strap; metals	Diesel

Table 7. Output flows for ceramic tile product system (adapted from [25]).

Output flow
Air emissions
Wastewater-
Oils and fats
Hydrocarbons
Recyclable Waste
Non-Recyclable Waste
Hazardous waste
Noncomplying product for waste
Final product packed

2.6. Construction process stage (A4) for concrete and ceramic tiles

The construction process stage (A4-A5) includes transporting the product from the production unit gate to the site, and its application. In this study, only transport (A4) to the building site was considered. For that purpose, the transport distances were considered from the production sites to the default site location in Lisbon. All transportations (by road) to and from the construction site are carried out by trucks, and the following assumptions were considered:

- To be conservative, in the absence of real information, the trucks were considered Euro 3 type assuming that they were built after 1999;
- Environmental loads associated with infrastructure (vehicle manufacturing, road maintenance, etc.) were not accounted for, as a methodological choice for this study;
- In the cases where the truck returns empty, it is assumed that the return journey is also caused by the products primarily transported. Thus, the distance allocated to the transport of the product is 1.7 times the distance travelled to the manufacturer [29]. When the distance of the trip is longer than 200 km, the full return of the trucks was always assumed and allocated to another system. When the truck transports another product/material on the return journey, only the distance between the supplier and the construction site is considered.

Transport distances were calculated/estimated based on google maps information for the better path between the source and destination points.

2.7. Use stage - Maintenance, repair and replacement for concrete and ceramic tiles

This life cycle stage quantifies the environmental impacts of the materials used in the maintenance, repair, or replacement operations over the life cycle of the assembly (including the waste generated), in the year they occur. It does not include other impacts resulting from these operations (e.g. water for cleaning, energy for operating equipment, etc.) due to their unpredictable nature. The interventions were determined based on literature references, since estimated service lives declared by the manufacturers were similar to the expected service life of the assembly. Nevertheless, maintenance, repair or replacement operations were considered as detailed in Table 8.

Table 8. Maintenance, repair, and replacement operations of roof elements for 50 years (adapted from [29; 34-36]).

Roof materials/solution	Maintenance/repair/replacement operations
Ceramic or concrete roof tiles	Repair of 20% of the area every 25 years

2.8. End-of-life stage (C2-C4) and benefits and loads beyond the system boundaries (D) for concrete and ceramic tiles

End-of-life is complex to model in the construction sector because of the uncertainty related to very long expected service life [29; 37], as well as the uncertainty about the available end-of-life technological solutions at that time.

The current product system includes waste processing for reuse, recycling and/or energy recovery (sub-step C3), as well as the collection and transport processes of materials that leave the system (in the form of secondary materials or fuels) before reaching the end-of-waste status. This point is the boundary of the following product system that will use the secondary material. After reaching the end of waste status, further processing may be required to replace a primary material or primary fuel in the next system. These processes are beyond (current) system boundaries and are declared in module D (declared beyond this system boundary and accounted for in the following system) [30].

The LCA of the end-of-life stage was supported by realistic and representative scenarios. Additionally, a conservative approach leads to the use of waste treatment processes compatible with current practices [30].

A selective demolition was considered as a basis to estimate the impacts of transport and waste treatment and disposal in proper sites [38]. According to that assumption, roof tiles can be physically separated. The environmental impacts of the demolition process (C1) were not accounted for because they would be similar for both types of tiles. The calculated impacts for stage C include C2 (transport to waste processing), C3 (waste processing for reuse, recovery and/or recycling) and C4 (disposal, including pre-treatment and disposal site management).

The environmental impacts generated by each product were calculated considering the most likely CDW manager/recycler (considering the available solutions in the geographical area) and the destination of CDW. Ecoinvent (version 3) datasets were used to model the disposal scenario. The scenarios considered were recycling for both concrete and ceramic tiles ("Waste brick {RoW}| treatment of waste brick, recycling" for ceramic tiles and "Waste concrete, not reinforced {Europe without Switzerland}| treatment of waste concrete, not reinforced" for concrete tiles). A benefit was calculated for the avoided impacts of virgin aggregates which may be replaced with the recycled materials.

3. Results and discussion

3.1. Product stage LCA - Concrete tiles

The LCIA results for stages A1-A3 (from extraction and processing of raw materials to the gate of the production unit) for concrete roof tiles are presented in Table 9 in absolute values, and in Figure 2 in relative contribution of each life cycle stage.

It is possible to observe in Figure 2 that, for most impact categories, raw materials (stage A1) represent the highest contribution for the calculated potential environmental impacts. This is mainly due to the high environmental impacts from the production of cement. The most visible case is ADP-elem. for which stage A1 represents 99% of the impact, followed by GWP.

In the case of NRPE, stage A1 is responsible for 53% of the impacts, followed by stage A3.2 with 31%, due to the amount of electricity and fossil fuels used in the manufacturing process. For RPE, the main contributor is packaging (A3.1), followed again by the production stage. This result can be influenced by the use of a high amount of wooden pallets (renewable energy resources used as material), as well as for the high share of renewable energy in the Portuguese electricity mix, although in absolute values RPE is less than half of the NRPE amounts.

Table 9. LCIA results for 1 concrete tile (with 4.2 kg).

Impact category	Unit	LCIA results					
		A1-A3	**A1**	**A2**	**A3.1**	**A3.2**	**A3.3**
NRPE	MJ	6.65E+00	3.54E+00	2.50E-01	7.37E-01	2.11E+00	1.60E-02
RPE	MJ	2.91E+00	2.21E-01	2.82E-04	2.28E+00	3.91E-01	1.31E-02
ADP-elem	kg Sb eq	2.71E-05	2.70E-05	7.04E-10	9.50E-08	1.61E-08	1.29E-09
ADP-ff	MJ	6.00E+00	2.97E+00	2.48E-01	6.72E-01	2.09E+00	1.37E-02
GWP	kg CO_2 eq	8.84E-01	7.80E-01	1.77E-02	3.49E-02	5.06E-02	1.11E-03
ODP	kg CFC^{-11} eq	4.87E-08	2.52E-08	3.58E-11	2.89E-09	2.04E-08	9.58E-11
POCP	kg C_2H_4 eq	1.25E-04	8.03E-05	5.64E-06	1.59E-05	2.31E-05	2.80E-07
AP	kg SO_2 eq	2.99E-03	2.20E-03	7.94E-05	1.63E-04	5.41E-04	6.23E-06
EP	kg PO_4^{3-} eq	3.72E-04	2.60E-04	1.81E-05	2.61E-05	6.73E-05	8.91E-07

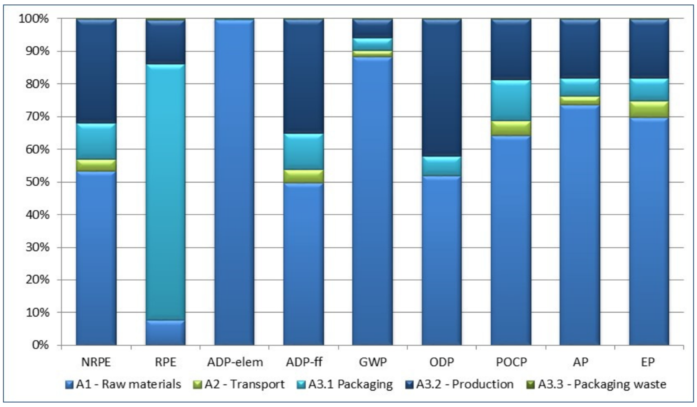


Figure 2. Relative contribution of each life cycle stage for potential impacts of concrete tiles.

In the impact category ADP-ff, stage A1 represents 50% of the impacts, strongly influenced by the impacts of cement, followed by the production stage (A3.2), due to the amount of energy used in the manufacturing process. Raw materials represent 88% of the GWP impacts, followed by the production stage with 6% and packaging with 4%.

For ODP, POCP, AP and EP, the raw materials are responsible for around 52%, 64%, 73 and 70% of the obtained impacts, respectively. In the same impact categories, the production stage represents the second most important contribution with 42% for ODP and around 18% for the other ones.

To assess plausibility of the results, a benchmark was performed for the concrete tile LCA. As no other comparable sources were found, the comparison was performed only with the Ecoinvent dataset “Concrete roof tile {GLO}|production| Cut-off” and is presented in absolute values for the most relevant categories in Figure 3 and in relative values in Figure 4.

In the presented comparisons, it is possible to observe that the Ecoinvent dataset presents much lower impacts than the assessed concrete tile for RPE and for ADP elements. For RPE, this can be explained by the share of renewable energy in the Portuguese electricity mix and the use of many renewable energy resources as materials in packaging. Although in Figure 4 the difference looks very significant (in percentage), in absolute terms it is not so significant (results are within the same magnitude). The total energy resources for the Ecoinvent dataset are, however, slightly lower than those for the assessed Portuguese tile. For ADP-elem., the Ecoinvent dataset presents a result surprisingly low. For this impact category, both cement and pigments present a significant contribution in the analysed concrete tile. It was found that pigments are inexistent in the Ecoinvent dataset, which explains a much lower result for ADP-elem.

The analysed concrete tile presents slightly lower results for NRPE. However, for GWP the Ecoinvent dataset presents a lower impact, which can be explained with higher efficiencies on fuels use or in pollutants retention.

For ODP, AP and EP, the results are very similar for both tiles. For POCP, the difference looks very significant in Figure 4, with the Ecoinvent dataset presenting around 50% more impact. However, in absolute values, it is not that much significant, with the results within the same magnitude.

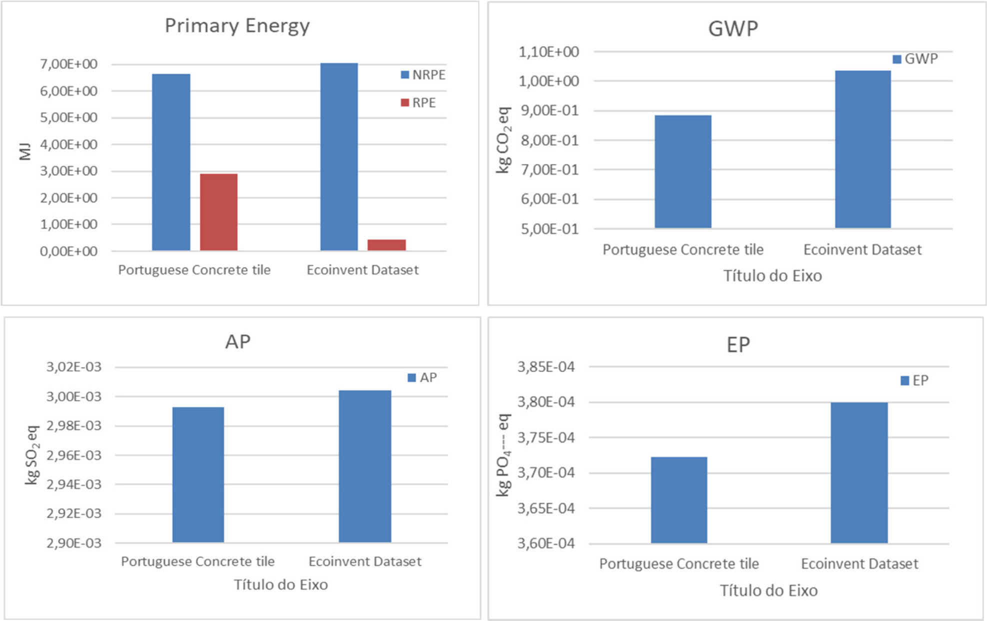


Figure 3. Comparison of the cradle-to-gate potential environmental impacts, between the studied concrete tile and selected alternative datasets.

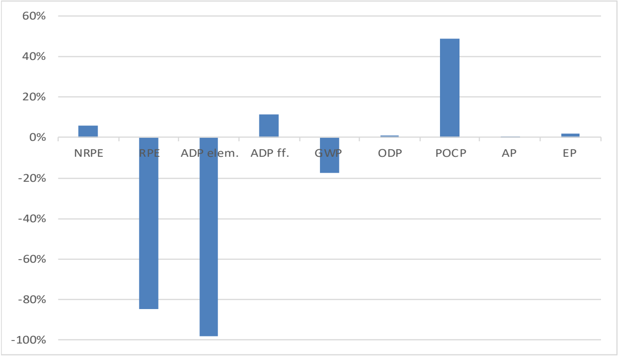


Figure 4. Environmental impacts from cradle to gate of the Ecoinvent dataset in relation to the obtained impacts for Portuguese concrete tile.

In general, the results obtained for the Portuguese concrete tile assessed are plausible, within the same magnitude of those in the generic dataset.

3.2. Product stage LCA - Ceramic tiles

Roof ceramic tiles were thoroughly studied by Fernandes [25]. Within her thesis, this researcher performed the LCA of two types of ceramic tiles from Portuguese producers. The results were benchmarked to existing literature results and differences were dully discussed and justified. No other EPDs were found for this material. Considering the specificity of the data, the average results obtained for the two national ceramic roof tiles were considered appropriate to be used as National Reference Value (ReVa) for this study and the results are presented in Table 10.

Moreover, it was concluded that the production stage (A.3.1) is the most relevant in almost all the impact categories, especially due to the consumption (and combustion) of natural gas in the kiln and to the electricity consumption.

Table 10. LCA data selected for product stage (A1-A3) of ceramic roof tile.

Impact category	**Unit**	**LCIA Results**
		Ceramic tile (per kg)
ADP-elem.	kg Sb eq	8.27E-09
GWP	kg CO_2 eq	2.48E-01
ODP	kg CFC^{-11} eq	3.86E-08
POCP	kg C_2H_4 eq	4.11E-05
AP	kg SO_2 eq	9.52E-04
EP	kg PO_4^{3-} eq	7.07E-05

3.3. Life Cycle Environmental performance - Assessment results

After concluding the assessment of the product stage for concrete and ceramic tiles, the cradle-to-cradle (C2C) LCA results for the two cladding materials assessed are presented in Figures 5 and 6, with no weighting or aggregation (with exception for ADP-elem. For which comparison is not within the same magnitude).

It is possible to observe in Figure 5 that, generally, ceramic tiles present lower global impacts, except for ADP-ff., and ODP.

ADP-elem. is not represented in the figure because the results obtained for ceramic tiles are three orders of magnitude lower than those obtained for concrete tiles, thus the visual representation would not be clear. For both tiles, ADP-elem. is mainly influenced by the extraction of raw materials and the packaging materials. Concrete tiles present much higher impacts due to the extraction of raw materials related to the production of cement, adjuvants, and pigments.

For ADP-ff. concrete tiles present impacts 44% lower than ceramic tiles, despite the high impacts of cement production for concrete. This is mainly due to the burning of natural gas during firing of the ceramic tiles, and to the substitution of fossil fuels by other types of fuels in the production of cement, e.g. RDF (residue derived fuels). Also, for ODP potential impacts calculated are lower (-64%) for concrete tiles than for ceramic ones. This is also explained by the high consumption of natural gas in the latest.

Concrete tiles' GWP impacts are 16% higher than those of ceramic ones. This is mainly influenced by the high GWP impacts of cement production that represent around 80% of product stage GWP impacts for concrete tiles. The same happens for POCP (10%), AP (5%) and EP (89%).

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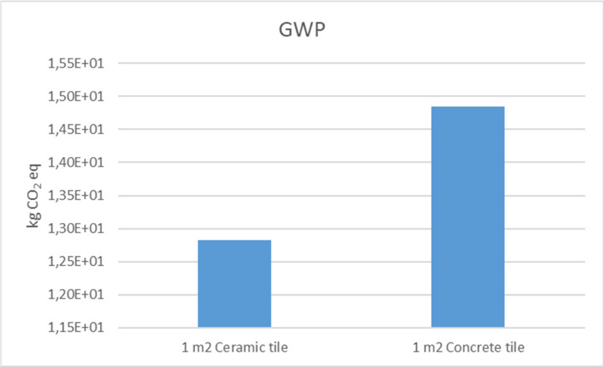
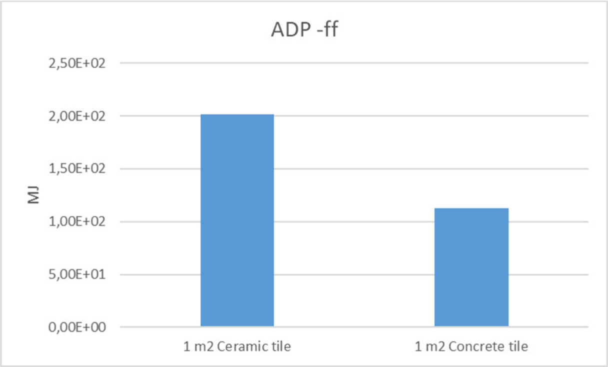
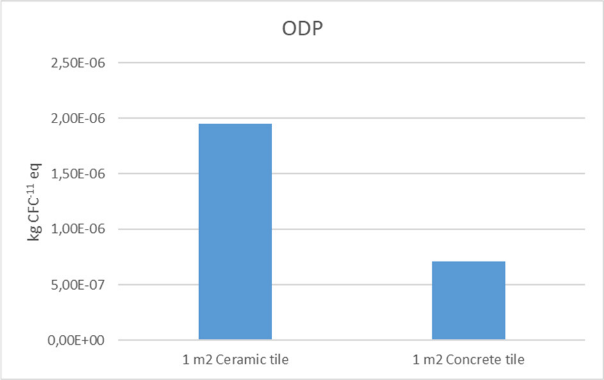
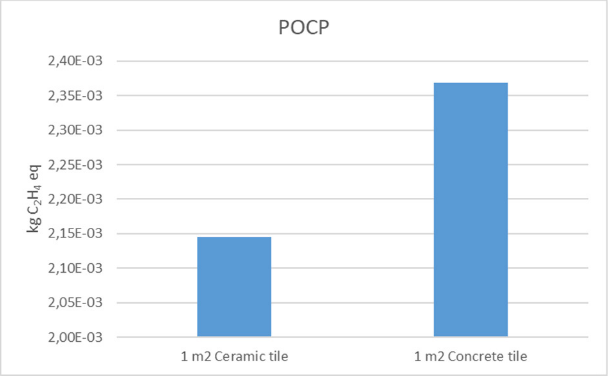
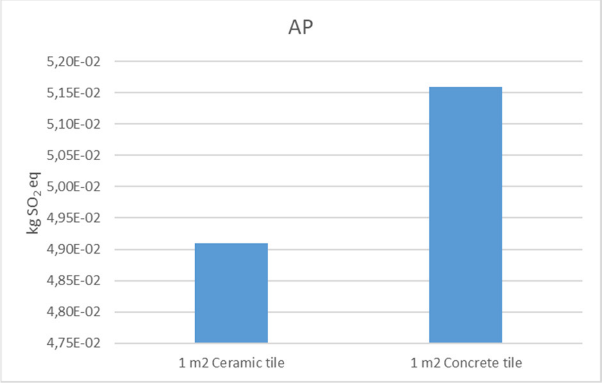
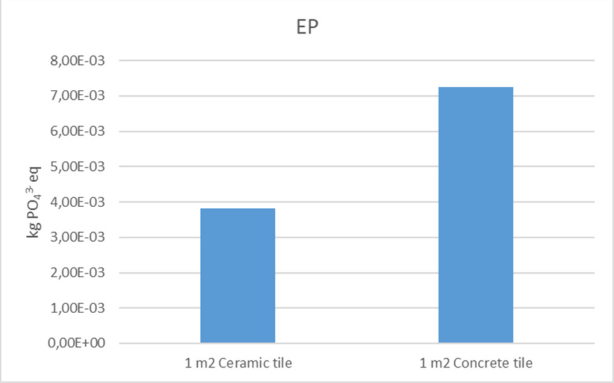

GWP
kg CO$_2$ eq
1,55E+01
1,50E+01
1,45E+01
1,40E+01
1,35E+01
1,30E+01
1,25E+01
1,20E+01
1,15E+01
1 m2 Ceramic tile
1 m2 Concrete tile


ADP -ff
MJ
2,50E+02
2,00E+02
1,50E+02
1,00E+02
5,00E+01
0,00E+00
1 m2 Ceramic tile
1 m2 Concrete tile


ODP
kg CFC^{-11} eq
2,50E-06
2,00E-06
1,50E-06
1,00E-06
5,00E-07
0,00E+00
1 m2 Ceramic tile
1 m2 Concrete tile


POCP
kg C$_2$H$_4$ eq
2,40E-03
2,35E-03
2,30E-03
2,25E-03
2,20E-03
2,15E-03
2,10E-03
2,05E-03
2,00E-03
1 m2 Ceramic tile
1 m2 Concrete tile


AP
kg SO$_2$ eq
5,20E-02
5,15E-02
5,10E-02
5,05E-02
5,00E-02
4,95E-02
4,90E-02
4,85E-02
4,80E-02
4,75E-02
1 m2 Ceramic tile
1 m2 Concrete tile


EP
kg PO$_4$$^{3-}$ eq
8,00E-03
7,00E-03
6,00E-03
5,00E-03
4,00E-03
3,00E-03
2,00E-03
1,00E-03
0,00E+00
1 m2 Ceramic tile
1 m2 Concrete tile

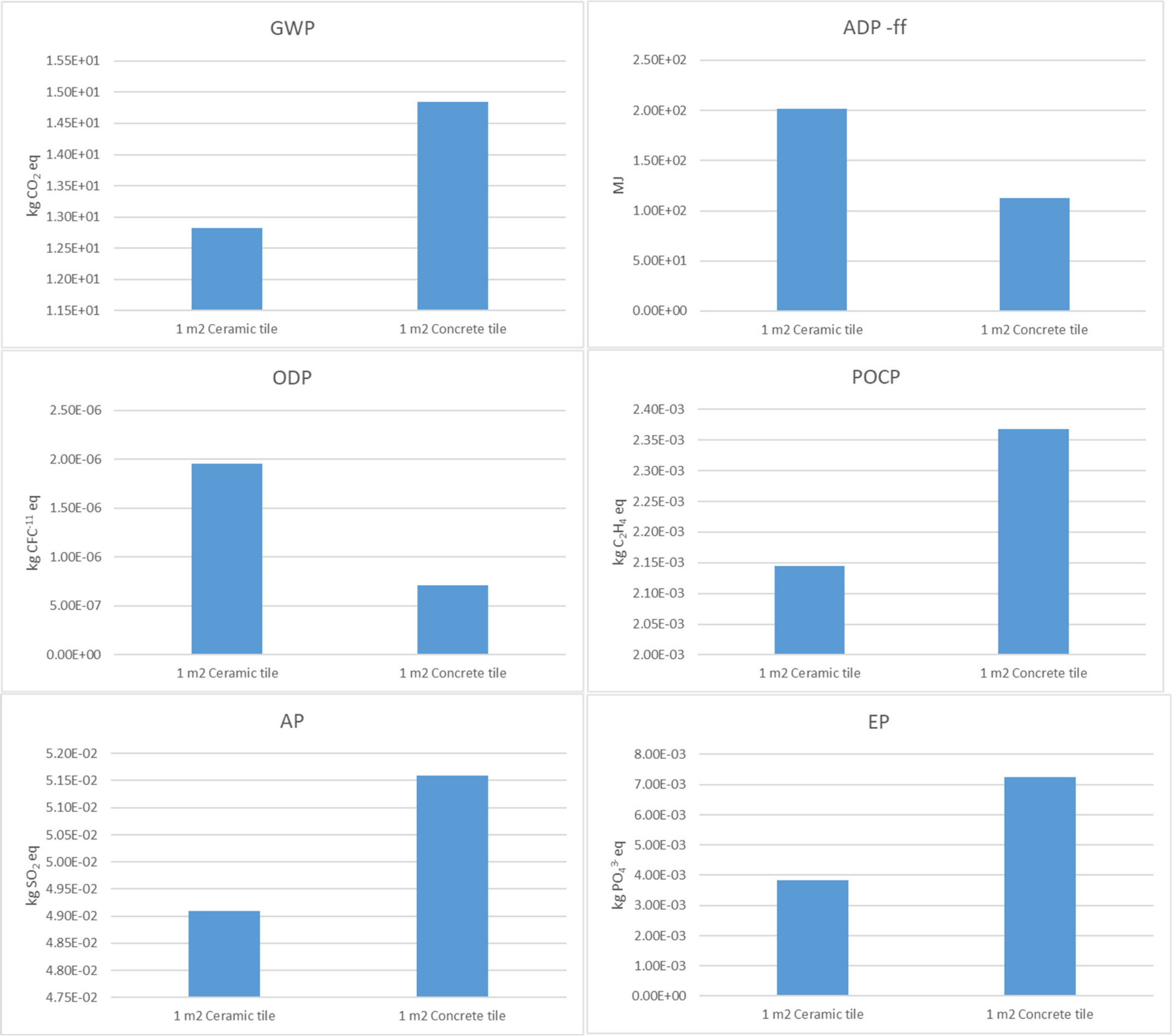


Figure 5. Absolute results of the environmental assessment of ceramic and concrete tiles over their life cycle, from cradle to cradle.

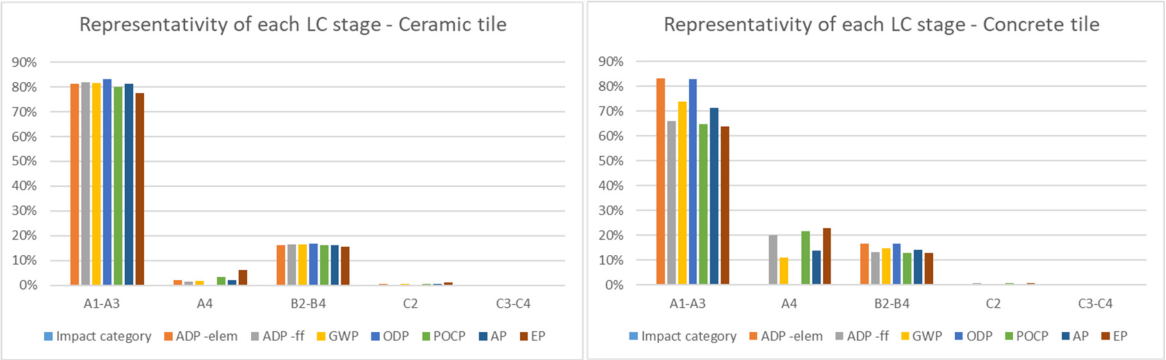


Figure 6. Relative results per stage of the environmental assessment of ceramic and concrete tiles over their life cycle, from cradle to cradle.

4. Conclusions

Ceramic tiles generally present lower cradle-to-cradle environmental impacts. This trend is found in five out of seven impact categories: ADP-Elem. (different magnitude), GWP (-16%), POCP (-10%), AP (-5%) and EP (-89%). For ADP-ff and ODP, concrete tiles present a better environmental performance (-44% and -64% respectively), justified by the use of natural gas in ceramic tiles' production. For both tiles, it was concluded that the production stage is the most relevant, representing between 63% and 84% of life-cycle impacts. For concrete tiles, the most important contribution to the product stage potential environmental impacts comes from raw materials, mainly cement.

Although the impact assessment methods are distinct in previous studies comparing ceramic and concrete tiles, for some impact categories it is possible to benchmark conclusions, if not results:

- GWP - both Souza *et al.* [16] and Le *et al.* [19] concluded that ceramic tiles presented the lower impact than concrete tiles;
- Resource depletion - Souza *et al.* [16] also concluded that ceramic tiles presented lower impacts than concrete tiles;

Analysing the distribution of environmental impacts from cradle to cradle, for both types of tiles, the product stage is the most representative, weighting between 63% and 84%. For ceramic tiles, the variability is lower, with the product stage A1-A3 representing between 77% and 84% of the global impacts. Stage B is the second most representative due to the substitution of material that was considered during required maintenance. Together, stages A1-A3 and B2-B4 represent between 76% and 99% of the global environmental impacts. This means that the production of both ceramic and concrete tiles causes high environmental impacts when compared to the needs of transport and end of life processes associated to the whole product life cycle.

The LCA results of concrete tiles were obtained through a consistent and coherent methodology in line with the European standards in force in this area of knowledge. The results obtained for cradle to cradle life cycle are also according to applicable standards. It represents an important input for building designers and other construction actors since the information provided directly compares the two most used solutions for pitched roofs claddings in Portugal.

5. References

[1] Gantner J, Lenz K, Horn R, von Both P and Ebertshäuser S (2018). Ökobau.dat 3.0-Quo va-dis? *Buildings*, 8(9). https://doi.org/10.3390/buildings8090129

[2] Rato V and de Brito J (2003). *Functional requirements of pitched roofs - Building construction course (in Portuguese)*. Lisboa. https://doi.org/10.13140/RG.2.1.2076.2082

[3] Carretero-Ayuso M J and García-Sanz-Calcedo J (2018). Comparison between building roof construction systems based on the LCA. *Revista de La Construccion*, 17(1), 123–136. https://doi.org/10.7764/RDLC.17.1.123

[4] de Brito J and Paulo P (2001). *Classification of pitched roofs and its claddings - Building construction course (in Portuguese).* Lisboa.

[5] de Brito J and Paulo P (2004). *Classification of pitched roofs and their coverings (in Portuguese). In Coatings on recent buildings*, Buildings notebooks (Vol. 03, pp. 63–85). Lisboa. Retrieved from https://www.researchgate.net/publication/280933485

[6] Serra e Sousa A V, Abrantes V, Silva M, Moura G I, Silva R M, Freitas V and de Sousa, H (1998). *Ceramic tiles application handbook* (APICC). *(in Portuguese)*. Coimbra: Associação Portuguesa da Industriais de Cerâmica e Construção.

[7] Lopes N M S (2009). *Technology and rehabilitation of pitched roof exterior claddings (in Portuguese).* Instituto Superior Técnico, U. Lisboa, Lisbon.

[8] Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 on the Construction Products Regulation (CPR), Pub. L. No. Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011, Official Journal of the European Union 5 (2011). European Parliament, European Union Council. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011R0305&from=PT

[9] de Brito J (2005). *Pathology and rehabilitation of pitched roof claddings - Building rehabilitation course (in Portuguese).* Lisboa. https://doi.org/10.13140/RG.2.1.1715.2489
[10] de Brito J (2015). *Cladding materials for pitched roofs*. Lisboa.
[11] Dias A B, da Silva R M, Almeida V P and Mouraz C P (2018). *Guidelines for design and application of ceramic roof tiles (in Portuguese)* (1st ed.). Coimbra: APICER.
[12] Argibetão, Retrieved from https://www.argibetao.pt/obra/moradia-cervaes
[13] Fibrolite, Retrieved from http://www.fibrolite.pt/pt/portefolio/escola-secundaria-de-penafiel
[14] MDSilva, Retrieved from https://www.mdsilva.pt/pt/telha-de-vidro-tecno-cs/p-2025
[15] Bribián IZ, Capilla, A V and Usón A (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, 46, 1133–1440.
[16] Souza D M de, Lafontaine M, Charron-Doucet F, Bengoa X, Chappert B, Duarte F. and Lima L (2015). Comparative Life Cycle Assessment of ceramic versus concrete roof tiles in the Brazilian context. *Journal of Cleaner Production*, 89, 165–173. https://doi.org/10.1016/J.JCLEPRO.2014.11.029
[17] Fachvereinigung Bauwerksbegrünung (FBB). (2012). EPD for Clay roof tiles.
[18] Cellura M, Longo S and Mistretta M (2011). Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. https://doi.org/10.1016/j.rser.2011.07.082
[19] Le A B D, Whyte A and Biswas W K (2019). Carbon footprint and embodied energy assessment of roof-covering materials. *Clean Technologies and Environmental Policy*, 21(10), 1913–1923. https://doi.org/10.1007/s10098-018-1629-9
[20] World Steel Association (2020), Life Cycle Assessment - Environmental assessment of roofing systems. Using buildLCA to assess the performance of materials in roofing systems. Available at: https://worldsteel.org/wp-content/uploads/Life-cycle-assessment-Environmental-assessment-of-roofing-systems.pdf
[21] Octavia C, Laurence and Hartono N (2018). Water footprint and life cycle assessment of concrete roof tile and brick products at PT. XYZ. *In IOP Conference Series: Earth and Environmental Science* (Vol. 109). Institute of Physics Publishing. https://doi.org/10.1088/1755-1315/109/1/012006
[22] Vieira M A B (2016). *Contribution to the assessment of environmental performance of ceramic tile through the Product Environmental Footprint*. Instituto Politécnico de Leiria, Portugal.
[23] Quinteiro P, Almeida M, Serra J, Arroja L and Dias A (2022). Life cycle assessment of ceramic roof tiles: A temporal perspective. *Journal of Cleaner Production,* 363. https://doi.org/10.1016/j.jclepro.2022.132568
[24] Kuruppuarachchi K, Ihalawatta K and Kulatunga A K (2014) Life Cycle Assessment of two different Clay Roofing Tiles. Life Cycle Assessment of two different Clay Roofing Tiles. *In Conference proceedings of Asia Pacific Roundtable on Sustainable Consumption and Production*. Bangkok, Thailand. Available at *https://www.researchgate.net/publication/302025720*
[25] Fernandes M I A (2019). *Environmental performance products in ceramic sector in Portugal (in Portuguese)*. Universidade de Aveiro.
[26] Drpi A, Spasojević-Šantić T and Radojević Z (2021). Environmental Product Declaration (EPD) For Clay Roof Tiles-Case Study: Production Plant of Clay Roof Tiles in Republic of Serbia. *In IOP Conference Series: Materials Science and Engineering* (Vol. 1196). https://doi.org/10.1088/1757-899x/1196/1/012031
[27] EC. Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations, Pub. L. No. Commission Recommendation (2013/179/EU), Brussels, Belgium 1 (2013). Official Journal of the European Union. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013H0179&from=EN
[28] ISO. Environmental management — Life cycle assessment — Principles and framework. ISO

14040:2006 + AMD 1:2020, 14040 International Standardization Organisation § (2006). Geneva: International Organization for Standardization. Retrieved from www.iso.org

[29] Silvestre J D (2012). *Life cycle assessment from cradle to cradle of building assemblies - application to external walls*. PhD Thesis in Civil Engineering. Instituto Superior Técnico, Portugal.

[30] CEN/TC 350. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. EN 15804:2012+A1:2013 (2013). Brussels: Comité Européen de Normalisation.

[31] ISO. Environmental management — Life cycle assessment — Requirements and guidelines. ISO 14044:2006 + AMD 1:2017 + AMD 2:2020, 332 § (2006). Geneva: International Organization for Standardization. https://doi.org/10.1136/bmj.332.7555.1418

[32] CEN/TC350. Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data. TR 15941:2010 (2010). Brussels: Comité Européen de Normalisation.

[33] EN 1304:2013 - Clay roofing tiles and fittings. Product definitions and specifications.

[34] Barros P M L (2008). *Technical maintenance processes of buildings - Maintenance plan of Roofs (in Portuguese)*. Engineering Scholl of Porto University, Porto. Retrieved from http://www.fe.up.pt

[35] Morgado J (2012). *Inspection and maintenance plan for current building roofs (in Portuguese)*. Instituto Superior Técnico, Lisbon.

[36] Morgado J, Flores-Colen I, de Brito J and Silva A (2017). Maintenance planning of pitched roofs in current buildings. *Journal of Construction Engineering and Management*, *143*(7). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001316

[37] Peuportier B, Herfray G, Malmqvist T, Zabalza I, Staller H and Tritthart W (2011). Life cycle assessment methodologies in the construction sector: the contribution of the European LORA-LCA project. In *SB11 Helsinki: World Sustainable Building Conference*.

[38] Coelho A and de Brito J (2011). Economic analysis of conventional versus selective demolition - A case study. *Resources, Conservation and Recycling*, *55*(3), 382–392. https://doi.org/10.1016/j.resconrec.2010.11.003

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