JRC SCIENCE FOR POLICY REPORT

Revision of European Ecolabel Criteria for hard coverings products

Preliminary report

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List of abbreviations

AHWG	Ad-hoc Working Group meeting
AP	Acidification potential
A.St.A	Agglomerated Stone Association (Engineered Stone manufacturers Association)
BAT	Best Available Technology
B2B	Business-to-business
BREEAM	Building Research Establishment Environmental Assessment Method
BREF	Best Available Techniques Reference Document
CLP	Classification, Labelling and Packaging
CNC	Computer Numerically Controlled
CO_2	Carbon dioxide
DWC	Diamond wire cutting
EMAS	Eco Management and Audit Scheme
EN	European Norm
EP	Eutrophication potential
EU	The European Union
EUEB	The European Union Eco-labelling board
GWP	Global warming potential
IPPC	Integrated Polution Prevention and Control
ISO	International Standardisation Organisation
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
MBM	Meat and Bone Meal
MSW	Municipal solid Waste
NGO	Non-governmental organizations
NOx	Nitrogen Oxides
POCP	Photochemical ozone creation potential
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RDF	Refuse derived fuel
SO_2	Sulphur Dioxide
VOC	Volatile Organic Compound

Abstract

The objective of this project is to revise the existing EU Ecolabel criteria for hard coverings products The Commission Decision of 9 July 2009 establishes the ecological criteria for the award of the EU Ecolabel for hard coverings (Commission Decision 2009/607/EC[1]). The current criteria and the related assessment and verification requirements currently in force are valid until 31 June December 2021.

This preliminary report inteds to provide the background information for the revision of the EU Ecolabel criteria. The study has been carried out by the Joint Research Centre-Directorate B, Innovation and Growth (JRC-Seville) with technical support from Life Cycle Engineering. The work is being developed for the European Commission's Directorate General for the Environment.

An important part of the process for developing or revising Ecolabel criteria is the involvement of stakeholders through publication of and consultation on draft technical reports and criteria proposals and through stakeholder involvement in working group meetings. This document provides the background information required for the first Ad-hoc Working Group (AHWG) meeting, scheduled to take place in December 2018.

This preliminary report addresses the requirements of the Ecolabel Regulations No 66/2010 for technical evidence to inform criteria revision. It consists mainly on the following sections: an analysis of the scope, definitions and description of the legal framework; an economic and market analysis; and an overview of existing technical lifecycle assessment studies, revealing the significant environmental impacts. Combined with input from stakeholders, this information will be used to present an initial set of criteria proposals (1st Technical Report).

The following chapters present the state-of-the-art for each of the product type included in the scope of the Ecolabel criteria,namely, natural stones, agglomerated stones, concrete paving units, terrazzo tiles, ceramic tiles and clay tiles. The following aspects have been investigated

- **Terminology and classification**: this includes a review of the specific legislation (if any), European standards, other voluntary schemes, etc.
- **Economic and market analysis**. Market data presented in this report has been mainly taken from published reports and official statistics.
- **Review of production technologies**, including environmental technical analysis
- **Improvement and innovation** potential of proposed measures and /or criteria.

[1] COMMISSION DECISION of 9 July 2009 establishing the ecological criteria for the award of the Community eco-label to hard coverings (notified under document C(2009) 5613) (Text with EEA relevance) (2009/607/EC), available from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009D0607

1 SCOPE AND DEFINITION

1.1 Introduction

The overall purpose of this chapter is to provide a background to the legal, policy and technical framework in which Hard Coverings products lie as well as comparing the existing EU Ecolabel scope and definition for this product group with those of industry and other ecolabel schemes.

The chapter is split into the following sections:

- Existing EU Ecolabel and definition
- Review of national and third country voluntary schemes
- Relevant European Legislation and Policies
- Review of information in EPDs
- Summary of feedback for scoping questionnaire

1.2 Existing EU Ecolabel scope and definition

The current EU Ecolabel criteriaon hard coverings define the current product scope as:

The product group 'hard coverings' shall comprise — for internal/external use, without any relevant structural function — natural stones, agglomerated stones, concrete paving units, terrazzo tiles, ceramic tiles and clay tiles. For hard coverings, the criteria can be applied both to floor and wall coverings, if the production process is identical and uses the same materials and manufacturing methods.

Table 1. Product group classification

<table>
<tr><td rowspan="3">Natural Product</td><td rowspan="3">Natural stone
CEN TC 246</td><td>Marble</td></tr>
<tr><td>Granite</td></tr>
<tr><td>Other</td></tr>
<tr><td rowspan="5">Processed Product</td><td rowspan="3">Hardened Product</td><td>Agglomerated stone
JWG 229/246 EN 14618</td></tr>
<tr><td>Concrete paving units
CEN TC 178</td></tr>
<tr><td>Terrazzo tiles
CEN TC 229</td></tr>
<tr><td rowspan="2">Fired Product</td><td>Ceramic tiles
CEN TC 67</td></tr>
<tr><td>Clay tiles
CEN 178</td></tr>
</table>

1.3 Review of relevant national and international voluntary "green schemes"

Hard coverings products are covered under a number of other environmental initiatives. This section introduces each of the main initiatives and identifies the hard coverings scope and products categorization approach used within each. On the European market, both the Nordic Swan and Germany's Blue Angel have criteria for "floor coverings", but the scopes of these product groups are different than the one set out in the EU Ecolabel for Hard Coverings. The Nordic Swan scope covers wooden, textile and plastic flooring materials. The Blue Angel criteria applies to resilient (i.e. plastic, resin, cork) floor coverings (DE-UZ 120 and textile floor coverings (DE-UZ 128).

Korea Ecolabel

Korea eco-label is a voluntary program operated by the Korea Environmental Industry and Technology Institute (KEITI) and supervised by the Ministry of Environment (MOE). Korea eco-label is used for life-cycle assessment of products. It indicates whether products were manufactured with a low emission level of environmental pollutants or with conservation of resources in each production step (raw material acquisition production distribution application disposition).

The following criteria[2] are relevant for the hard coverings product group:

Block, tiles and panels (EL745).This standard describes a method to verify if the blocs, tiles and board materials formed by using inorganic waste materials, including waste, lime waste, plaster waste casting, and sand waste lime powder generated in the manufacturing process of waste ceramic materials such as inorganic civil engineering construction waste material, waste glass, waste ceramic waste tile incineration residue, inorganic sludge, and other products are in compliance with the eco-label certification standard. However, products complying with other designated certification criteria shall be excluded.

Recycled Construction Materials (EL 743) This standard describes the method of verifying the civil engineering construction materials made by using inorganic waste materials including waste lime, waste plaster, waste casting sand, waste lime powder that is generated in the manufacturing process of waste ceramic materials -such as construction waste material, waste glass, waste ceramic, waste tile -incineration residue, inorganic sludge and other products is in conformity with the Eco Mark Certification Standard.

The waste material usage rate shall satisfy the one of the following criteria.

a. The use rate of waste material shall be more than 40 weight% in case of firing processing products.

b. The use of waste material shall be more than 50 weight% in case of non-firing processing

Aggregate and Fine Powder (EL746). This standard specifies the method to confirm the civil engineering-construction materials made by using inorganic waste materials including waste lime waste plaster-waste casting sand-waste lime powder that is generated in the manufacturing process of waste ceramic materials -such as inorganic civil engineering construction waste material, waste glass, waste ceramic waste tile -incineration residue, inorganic sludge and other products is in conformity with the Eco Mark Certification Standard. However, the product for which separate certification

Good Environmental Choice Australia

The Good Environmental Choice Australia (GECA) program follows the ISO 14024 standard and offers global best practice in product certification and ecolabelling to the Australian market.

A prerequisite for certification under the GECA ecolabel is to satisfy the relevant Australian or International Standard, where it is required by law. However, Australian

[2] KEITI Ecolabel criteria . The criteria can be downloaded from this link.

Standards typically define "fit-for-purpose" criteria and usually do not provide assurance of environmental preferability. GECA ecolabelling standards go beyond Australian Standards and define an environmental benchmark for the product category. GECA standards are rigorous, scientific and relevant to key Australian industries.

They are designed to reward top performing products and services, and are internationally recognised through GECA's membership of the Global Ecolabelling Network (GEN).

Two standards cover products currently under the scope of the EU Ecolabel for hard coverings products

Cement, concrete and concrete Products[3].It covers 3 distinct sub categories: cement and supplementary cementitious materials (such as blended cements and alternative non-Portland cements), concrete (including ready-mix and concrete manufactured in temporary batching plants on site) and concrete products (such as masonry, precast concrete, pipes, roof tiles, and autoclaved cellular concrete).

Hard Surfacing[4].Applicable to hard surfacing products for interior or exterior use that do not provide any structural function. Hard surfacing categories include, but are not limited to: Natural stone, agglomerated stones, concrete paving units, terrazzo tiles, ceramic tiles, clay tiles and glass tiles.This standard excludes roof tiles, exterior building cladding, hybrid and composite products and products containing materials not directly specified in the scope of this standard.

New Zealand Environmental Choice

Environmental Choice New Zealand (ECNZ) is an environmental labelling programme managed by the New Zealand Ecolabelling Trust (the Trust). ECNZ operates to the ISO 14024 standard "Environmental labels and declarations - Guiding principles".

ECNZ has established two criteria of relevance for the hard covering product group:

Portland cement and Portland cement blends (EC 42-10)[5]. This includes Portland cement and inter-ground or blended mixtures of Portland cement with other materials, which may include fly ash, slag or naturally occurring pozzolanic materials. The criteria addresses the most significant potential impacts on the environment for cement manufacture, namely, quarrying raw materials, discharges to air from the kilns such as products of combustion including particulate, sulphur dioxide and nitrogen dioxide, energy consumption and carbon dioxide emissions.

Concrete: Ready Mixed Concrete, Pre-cast Concrete, Concrete Products and Dry Bagged Mortars (EC-43-18)[6]. This specification covers ready mixed concrete, precast concrete such as tilt slab panels, premixed (dry bagged mortar), and concrete products such as concrete roof tiles and blocks. The criteria cover the most important adverse impacts on the environment: quarrying of raw materials, dust discharges, and discharges of high pH water to waterways, energy requirements and carbon dioxide emissions.

SCS Floor Score

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3 Good Environmental Choice Australia , GECA 40-2008 Hard Surfacing http://www.geca.org.au/products/standards/65/

4 Good Environmental Choice Australia , GECA 40-2008 Hard Surfacing v1.1http://www.geca.org.au/products/standards/37/

5 https://www.environmentalchoice.org.nz/assets/Specifications/ec-42-10-portland-cement-and-cement-blends-specification.pdf

6 https://www.environmentalchoice.org.nz/assets/Specifications/EC-43-18-Concrete.pdf

FloorScore is a certification for commercial and residential hard-surface flooring products and flooring adhesives. Developed in conjunction with the Resilient Floor Covering Institute, products must comply with indoor air quality and VOC emission requirements set by California Section 01350, and meet rigorous quality management standards in manufacturing. Certification and documentation help products qualify for credits within the LEED rating systems.

Leadership in Energy & Environmental Design (LEED)

LEED is a green building rating system established by the US Green Building Council that is nationally accepted as a benchmark for the design, construction and operation of high performance green buildings. LEED gives building owners and operators the tools they need to have an immediate and measurable impact on the building performance. LEED promotes a whole building approach to sustainability by recognizing performance in 5 key areas of human and environmental health: sustainable site development, water savings, energy efficiency, material selection and indoor environmental quality.

LEED v4 was released in October 2016 and can be applied to the following project types and scopes:

- <u>LEED for Building Design and Construction (BD+C):</u> Can be applied to New Construction, Core and Shell, Schools, Retail, Healthcare, Data Centres, Hospitality, Warehouses and Distribution, Homes and Multifamily/midrise buildings.
- <u>LEED for Interior Design and Construction (ID+C):</u> Can be applied to Commercial Interiors, Retail and Hospitality.
- <u>LEED for Building Operations and Maintenance (O+M):</u> Can be applied to Existing Buildings, Data Centers, Warehouses and Distribution, Hospitality, Schools and Retail.
- <u>LEED for Neighbourhood Development (ND):</u> Can apply to plans as well as built projects for Cities/Communities is a pilot rating system that addresses performance in existing cities and communities for (i) smart location and linkage, (ii) neighbourhood pattern and design and (iii) green infrastructure and buildings.

The LEED rating systems are made up of prerequisites and credits. Prerequisites are required elements or green building strategies that must be included in any LEED-certified project. Credits are optional elements that projects can pursue to gain points toward LEED certification. Although the organization of prerequisites and credits varies slightly depending on the building type and associated rating system, LEED is generally organized by the following broad concepts:

- LT: Location and Transportation
- SS: Sustainable Sites
- WE: Water Efficiency
- EA: Energy and Atmosphere
- MR: Materials and Resources
- EQ: Indoor Environmental Quality
- IN: Innovation
- RP: Regional Priority

Achieving LEED certification requires satisfying all prerequisites and earning a minimum number of credits. Reference guides, designed to help project teams, explain credit criteria, describe the benefits of complying with the credit and suggest approaches to achieving credit compliance. A total of 110 points are possible (100 base points, 6 innovation points and 4 regional priority points). The levels of certification follow these thresholds (see **Figure 1**):

Figure 1. LEED certification levels

The exact weighting given to different credits will evolve in subsequent versions and depends on its ability to contribute to LEEDs system goals, which are:

- To reverse contribution to global climate change (35% of weighting in v4).
- To enhance individual human health and well-being (20% of weighting in v4).
- To protect and restore water resources (15% of weighting in v4).
- To protect, enhance and restore biodiversity and ecosystem services (10% of weighting in v4).
- To promote sustainable and regenerative material resource cycles (10% of weighting in v4).
- To build a greener economy (5% of weighting in v4), and
- To enhance social equity, environmental justice and community quality of life (5% of weighting in v4).

For Building Design and Construction (BD+C) projects, the scoring is weighted as follows:

Table 2. Cross-check of LEED v4. credits with hard covering type product aspects.

Category / Goal	**Requirement / credit name**	**Design?**	**Constrc.?**	**Exemplary?**	**Comments about potential relevance to EU Ecolabel hard covering products**
Project	Integrated Project Planning and Design	n/a			
	Integrative Process	1			
LT Location and Transport	LEED for Neighborhood Development Location	16			
	Sensitive Land Protection	1			
	High Priority Site	2		Y	
	Surrounding Density and Diverse Uses	5			
	Access to Quality Transit	5		Y	

	Bicycle Facilities	1			
	Reduced Parking Footprint	1		Y	
	Green Vehicles	1			
SS Sustainable Sites	Construction Activity Pollution Prevention		Req.		
	Environmental Site Assessment	n/a			
	Site Assessment	1			
	Site Development—Protect or Restore Habitat	2		Y	
	Open Space	1			
	Rainwater Management	3		Y	Outdoor paving blocks, tiles or flags that are designed to be installed with permeable joints.
	Heat Island Reduction	2		Y	Light coloured outdoor blocks, tiles or flags with initial Solar Reflectance value (albedo) >0.33
	Light Pollution Reduction	1			
	Site Master Plan	n/a			
	Tenant Design and Construction Guidelines	n/a			
	Places of Respite	n/a		Y	
	Direct Exterior Access	n/a			
	Joint Use of Facilities	n/a			
WE Water Efficiency	Outdoor Water Use Reduction	Req.			
	Indoor Water Use Reduction	Req.			
	Building-Level Water Metering	Req.			
	Outdoor Water Use Reduction	R??			
	Indoor Water Use Reduction	6			
	Cooling Tower Water Use	18			
	Water Metering	1			
EA Energy and Atmosphere	Fundamental Commissioning and Verification		Req.		
	Minimum Energy Performance	Req.			
	Building-Level Energy Metering	n/a			
	Fundamental Refrigerant Management	5R?			
	Enhanced Commissioning		2		
	Optimize Energy Performance	2		Y	
	Advanced Energy Metering	2			
	Demand Response		n/a		
	Renewable Energy Production	n/a		Y	
	Enhanced Refrigerant Management	n/a			
	Green Power and Carbon Offsets		n/a		
MR Materials and Resources	Storage and Collection of Recyclables	Req.			
	Construction and Demolition Waste Management Planning		Req.		
	PBT Source Reduction--Mercury	n/a			
	Building Life-Cycle Impact Reduction		5	Y	Environmental data to calculate GWP, ODP, AP, EP, POCP and fossil energy resource depletion for the construction products could contribute considerably to the building LCA.
	Building Product Disclosure and Optimization-- Environmental Product Declarations		2	Y	Recognition of plant specific EPDs (x1.0) and sector average EPDs (x0.5) but not currently any Type I ecolabel.
	Building Product Disclosure and Optimization—Sourcing of Raw Materials		2	Y	Values post-consumer recycled content (x1.0), pre-consumer recycled content (x0.5) and products sourced within 100 miles of the construction site (x2.0).
	Building Product Disclosure and Optimization—Material Ingredients		2	Y	Declare the ingredients, including chemicals, which account for at least 99% of the product weight.

	PBT Source Reduction--Mercury	n/a			
	PBT Source Reduction--Lead, Cadmium, and Copper		n/a		
	Furniture and Medical Furnishings		n/a	Y	
	Design for Flexibility	n/a			
	Construction and Demolition Waste Management		2	Y	
EQ Indoor Environmental Quality	Minimum Indoor Air Quality Performance	Req.			
	Environmental Tobacco Smoke Control	Req.			
	Minimum Acoustic Performance	n/a			
	Enhanced Indoor Air Quality Strategies	2		Y	
	Low-Emitting Materials		3	Y	Hard coverings are inherently compliant with this.
	Construction Indoor Air Quality Management Plan		1		
	Indoor Air Quality Assessment		2		
	Thermal Comfort	1			
	Interior Lighting	2			
	Daylight	3			
	Quality Views	1		Y	
	Acoustic Performance	1			
IN Innovation	Innovation	5			Low CO2 cement is one example of relevant innovation that has been recognised.
	LEED Accredited professional	1			
RP Regional Priority	Regional Priority	4			

Building Research Establishment Environmental Assessment Method (BREEAM)

The BREEAM assessment scheme, developed by BRE Global, is the generally considered as the first sustainability assessment method to have been developed for buildings. As of October 2018, over 2.2 million buildings have been certified in 77 countries. The BREEAM scheme consists of a "family" of other assessment methods, including the HQM (the UK-based Home Quality Mark), CEEQUAL (an assessment method specifically for civil engineering, infrastructure, landscaping and public realm projects) and QSAND (a free-to-use self-assessment tool for assessing the sustainability and resilience of shelters and settlements in the aftermath of natural disasters). Specific assessment methods and scoring have been developed for:

- Communities (for masterplanning of new communities or regeneration of existing ones)
- Infrastructure (soon to be relaunched as CEEQUAL 2018)
- New construction (for various types of residential buildings, commercial buildings, education buildings and shell and core projects - the latest international standard was published in 2016 and the UK standard in 2018)
- In Use (for operating commercial buildings that is split into three parts: asset performance; building management and occupier management – this last part being only for office buildings)
- Refurbishment and fit-out (for domestic and non-domestic buildings).

The BREEAM assessment methodology includes some minimum standards which must be met and a series of credits that can be gained via compliance with certain criteria or conditions that are set against established benchmarks. Although the organization of minimum requirements and credits may vary slightly depending on the building type and national scheme operator, BREEAM credits are generally organized by the following broad concepts and weightings:

MAN (Management): 11.5 to 15.0% - Responsible management practices are encouraged to ensure that sustainability objectives are followed throughout the operation of the building. Sustainability should be embedded from the initial design stage through to the appropriate provision of aftercare.

HEA (Health and Wellbeing): 8.0 to 15.0% - This category encourages the increased comfort, health and safety and quality of life of occupants, visitors and others in the vicinity.

ENE (Energy): 18.5 to 22.0% - Sustainable and efficient energy use should be used throughout building developments. BREEAM Credits are awarded for steps taken to improve the management of the energy efficiency of the building, including reduced energy use and carbon emissions.

TRA (Transport): 6.5 to 11.0% - Building developers and designers are encouraged to provide access to sustainable means of transport, including public transport and alternative solutions such as cyclist facilities. This supports the reduction of congestion and carbon emissions.

WAT (Water): 3.0 to 6.5% - Sustainable water use in the operation of the building and its site is rewarded. BREEAM assesses the building development's water monitoring including consumption, leak detection and the use of efficient equipment.

MAT (Materials): 9.0 to 16.5% - This category encourages steps to reduce the impact of construction materials throughout design, construction, maintenance and repair. Where possible, materials should be durable, resilient, sourced responsibly and have a low embodied impact throughout extraction, processing, manufacture and recycling.

WST (Waste): 6.0 to 8.5% - Construction waste and maintenance and repair waste of the building should be sustainably managed. Developments should aim to reduce waste, divert away from landfill and consider climate changes throughout the design to reduce the need to make wasteful future amendments.

LE (Land use and Ecology): 8.5 to 13.0% - Credits will be awarded for sustainable land use, habitat and ecological protection and long-term biodiversity improvement for the building and its surrounding land.

POL (pollution): 1.0 to 7.0% - This category encourages the prevention and control of pollution and surface water run-off. The building should have a reduced impact on light pollution, noise pollution, flooding and emissions to surrounding air, land and water.

INN (Innovation): 10% (fixed) - There are opportunities throughout a BREEAM assessment for exemplary performances and innovations that go beyond, or are not included within, the credit criteria requirements to be recognised for extra credit.

**The weightings included above apply to new construction projects for residential and non-residential buildings.*

Achieving BREEAM certification requires satisfying all minimum requirements and earning a minimum number of credits. The minimum requirements become more stringent as the target level of certification increases. The total number of credits obtained can be considered as a means to broadly benchmark the sustainability of the building. A total of

100 credits are possible (plus 10 for innovative aspects) and the levels of certification possible are as follows:

Outstanding: ≥ 85 points (top 1% of buildings – innovator)

Excellent: ≥ 70 points (top 10% of buildings – best practice)

Very Good: ≥ 55 points (top 25% of buildings – advanced good practice)

Good: ≥ 45 points (top 50% of buildings – intermediate good practice)

Pass: ≥ 30 points (top 75% of buildings – standard good practice)

Unclassified: <30 points

In order to better understand which aspects of BREEAM are of greatest relevance to hard covering products, each requirement or credit is listed below and any relevant aspects commented upon.

Table 3. Cross-check of BREEAM International New Construction (Ver. sd233 1.0) credits with hard covering type product aspects.

Category / Goal	**Requirement / credit name**	**Minimum requirement? (Y/N) and No. credits**	**Comments about potential relevance to EU Ecolabel hard covering products**
Management	Man 01. Project brief and design	4	n/a
	Man 02. Life cycle cost and service life planning	4	n/a
	Man 03 Responsible construction practices	6	n/a
	Man 04 Commissioning and handover	4	n/a
	Man 05 Aftercare	3	n/a
Health and wellbeing	Hea 01. Visual comfort	Up to 6	n/a although there is an indirect effect of lighter coloured floor and wall coverings on minimum daylighting achieved in a particular building area.

	Hea 02 Indoor air quality	5	Avoidance of asbestos is mandatory. One credit possible for low emissions from building products. Requirements set for "flooring materials": ≤ 0.06 mg/m3 formaldehyde (≤ 0.01 exemplary); ≤ 1.0 mg/m3 TVOC (≤ 0.3 exemplary) and ≤ 0.001 mg/m3 Category 1A/1B carcinogens. Tests are according to ISO 10580, ISO 16000-9, EN 16516 or CDPH standard method v1.1. The same emission limits and test methods are also stated for any interior adhesives and sealants used, with the extra method of EN 13999 being specified too. **Hard coverings can be deemed to automatically comply with even the exemplary performance unless organic-based coatings, binders or sealants are used in their production or finishes.* Hard coverings can potentially contribute later to one credit for low formaldehyde and low VOC concentrations in-situ post construction.
	Hea 03. Safe containment in laboratories	2	n/a
	Hea 04. Thermal comfort.	3	n/a
	Hea 05. Acoustic performance.	Up to 4	n/a
	Hea 06. Accessibility.	2	n/a
	Hea 07. Hazards.	1	n/a
	Hea 08. Private space.	1	n/a
	Hea 09. Water quality.	1	n/a
Energy	Ene 01. Reduction of energy use and carbon emissions.	15	n/a
	Ene 02 (a and b). Energy monitoring	2	n/a
	Ene 03. External lighting	2	n/a but perhaps there is an argument for light coloured outdoor paving if it means that less light is needed to reach a certain luminance level. Another benefit would be a reduction in the risk of the heat island effect.
	Ene 04. Low carbon design	1	n/a Although hard coverings could, thanks to their high thermal mass, potentially contribute to a "free cooling" credit as part of the building design.
	Ene 05. Energy efficient cold storage	3	n/a
	Ene 06 Energy efficient transport systems	3	n/a
	Ene 07. Energy efficient laboratory systems	5	n/a

	Ene 08. Energy efficient equipment	2	n/a
	Ene 09. Drying space	1	n/a
Transport	Tra 01. Public transport accessibility	Up to 5	n/a
	Tra 02. Proximity to amenities	Up to 2	n/a
	Tra 03(a + b). Alternative modes of transport	Up to 2	n/a
	Tra 04. Maximum car parking capacity	Up to 2	n/a
	Tra 05. Travel plan	1	n/a
	Tra 06. Home office	1	n/a
Water	Wat 01. Water consumption	5	n/a
	Wat 02. Water monitoring	1	n/a
	Wat 03. Water leak detection and prevention	3	n/a
	Wat 04. Water efficient equipment.	1	n/a
Materials	Mat 01. Life cycle impacts	Up to 6	Requires the use of the Mat 01 calculator where points are awarded for: Up to 8% for output indicators (if reporting CO2 plus two others); Up to 12% for number of life cycle stages covered (if including end-of-life and operational energy); Up to 10% for the level of reporting (i.e. whole building versus building element level); Up to 10% for LCA data quality: accounting for local conditions (e.g. energy mix) as per CEN/TR 15941 AND data less than 5 years old (specific) or 10 years old (generic); Up to 20% for the type of LCA methodology used (max. for EN 15804); Up to 10% for the source of LCA data (max. 10% for verified/peer reviewed data as per ISO 14025, ISO 21390 or EN 15804); Up to 30% based on the number of different elements covered by LCA analysis (most relevant being: external walls 2%, internal floor finishes 2%, internal walls and partitions 1%, stairs and ramps 1%, internal wall finishes 0.5%, hard landscaping paths and pavings 1%).
	Mat 02. Hard landscaping and boundary protection	n/a	
	Mat 03. Responsible sourcing of construction products	4	Could potentially link to the quarry criteria developed for natural stone or to quarries for limestone (for cement), aggregates (for concrete) and clay and quartz (for ceramics. Further discussion needed to see if this is something on the agenda in these sectors or if EU Ecolabel could take a lead here.
	Mat 04. Insulation.	n/a	n/a

	Mat 05. Designing for durability and resilience	1	The hard covering products are inherently hard wearing and resistance to washing (except perhaps natural marble stone), a credit possible here. Could link to fitness for use criteria perhaps.
	Mat 06. Material efficiency	1	Could potentially apply to thin format ceramic wall tiles, certain permeable paving designs and maybe to use of secondary materials in cement, ceramics and engineered stone.
Waste	Wst 01. Construction waste management	4	n/a unless it could be extended to waste at the factory for prefabricated elements.
	Wst 02. Recycled aggregates	1	If at least 25% (by weight or volume) of high grade aggregate used is from recycled or secondary sources coming from within 30km of site
	Wst 03 (a and b). Operational waste	1	n/a
	Wst 04. Speculative finishes	1	n/a
	Wst 05. Adaptation to climate change	1	Tenuous link only, but the thermal mass of hard covering products could contribute to reducing the risk of overheating in buildings. With permeable outdoor paving only, a possible credit here could be the reduction of flood risk onsite.
	Wst 06. Functional adaptability	1	Could perhaps link to how easy it would be to remove the tiles/slabs/blocks/counter-tops and in a non-destructive manner.
Land use and ecology	Le 01. Site selection	3	n/a
	Le 02. Ecological value of site and protection of ecological features	2	n/a
	Le 03. Minimising impact on existing site ecology	n/a	n/a
	Le 04. Enhancing site ecology	3	n/a
	Le 05 Long term impact on biodiversity	2	n/a
Pollution	Pol 01. Impact of refrigerants	4	n/a
	Pol 02. NOx emissions	2	Not relevant in general as it is now, but perhaps a future recognition of photocatalytically active hard paving surfaces could be recognised here?
	Pol 03. Surface water run-off	5	Permeable paving with design infiltration rates could play a part in this credit, but is only part of a larger design. Some initial credit could arguably be given to the filtration capacity to remove polluting solids from stormwater.
	Pol 04. Reduction of night time light pollution	1	n/a although there is perhaps an argument for darker outdoor paving being recognised here (even if this could also be negative in terms of the heat island effect).

	Pol 05. Reduction of noise pollution	1	n/a
Innovation	Inn 01. Innovation	10	For demonstrating exemplary performance in any of the following criteria (1 credit each): Man 03, Man 05, **Hea 02**, Ene 01, Wat 01, **Mat 01, Mat 03, Wst 01, Wst 02 and Wst 05**. Most of these potential innovation credits (in bold above) are directly or indirectly relevant to hard covering products.

Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)

The Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) rating system requires fulfilment of 50 different criteria from six quality sections: environmental quality, economic quality, sociocultural and functional quality, technical quality, process quality, and site quality.

It can be tailored to meet country specific requirements while allowing for international benchmarking with worldwide certified buildings.

TÜV SÜD SCoRE

TÜV SÜD Sustainable Certification of Real Estate (SCoRE) system is a cost-efficient tool for assessing and enhancing the future viability of existing buildings.

This sustainability certification is developed on the basis of technical and environmental due diligence. It is uniquely suitable for analysing your property in depth and can detect factors that other systems might miss, such as contamination.

Green Squared (U.S.)

Green Squared[7] is the service mark for a tile and related installation material product certification program developed by the Tile Council of North America (TCNA) as part of its ongoing initiative to support the efforts of producers, purchasers and policy makers to improve the environmental and social sustainability of products and services, based on either established and/or advanced scientific principles, practices, materials and standards. It is a companion to the ANSI A138.1 American National Standard Specifications for Sustainable Ceramic Tiles, Glass Tiles and Tile Installation Materials.

Green Squared® certification conforms to ISO 14024 Type 1 environmental labelling and declaration requirements. Products which are Green Squared Certified® may contribute points or facilitate conformance to leading green building codes, standards, rating systems, and purchasing programs, including: LEED, Green Globes, NAHB National Green Building Standard, International Green Construction Code, ASHRAE 189.1, GSA P100, and EPA Recommendations to Federal Purchasers.

Products eligible for Green Squared certification include ceramic tiles, glass tiles, and tile installation materials. For the purposes of Green Squared certification, "ceramic tiles" includes mosaic, quarry, pressed floor, glazed wall, porcelain, and specialty tiles. "Glass tiles" includes cast glass, fused glass, and low-temperature coated glass tiles. "Tile installation materials" includes mortar adhesives, mastic adhesives, reactive resin

[7] https://greensquaredcertified.com/

adhesives, grouts, tile backer units, crack isolation membranes, waterproofing membranes, water containment membranes, and sound reduction membranes.

It is divided into five sections that include mandatory requirements and elective options. Conformance to Green Squared is met though achieving the mandatory requirements and a specified number of elective credit units (CUs). These elective requirements are specified by product type. The standard covers the categories

Table 4. Summary Green Squared Criteria[8]

Environmental product characteristics	**A.3.1 Recycled or reclaimed content**. Each product type (ceramic tile, glass tile, powdered installation goods, panel installation goods, etc.) has its own Recycled/Reclaimed content percentage criteria. As a prerequisite for conformance with ANSI A138.1, the criteria for Level 1 Recycled/Reclaimed Content shall be met. Additionally, an elective CU may be rewarded if the Level 2 criteria are met, and a second elective CU may be rewarded if the Level 3 criteria are met. **A.3.2 Indigenous raw materials.** An elective CU may be rewarded if the Level 1 criteria are met for indigenous raw materials. Additionally, a second elective CU may be rewarded if the Level 2 criteria are met, and a third elective CU if the Level 3 criteria are met **A.3.3 Packaging**. The criteria of at least one of the packaging elective options should be met: (1) minimal, (2) recyclable, (3) on-site reusable, (4) biodegradable, (5) with recycled content. **A.3.4 Product durability/conformance with industry standards**. Mandatory requirement. The product of interest is in conformance with its relevant industry standard. (A standard for each product type is referenced in ANSI A138.1). Lab reports reviewed are not required to originate from an ISO 17025 accredited laboratory. **A.3.5 Product emission criteria.** Mandatory requirement. If a tile manufacturer provides written documentation that the tile of interest has no post-fire adhesive, wax, or organic coating, no other testing or documentation is required. For tiles with post-fire coatings and for tile installation products, the manufacturer shall provide test reports or certification documentation verifying that the product of interest is within the emission limits. **A.3.6 Cleaning maintenance.** **A.3.7 Additional environmental characteristics.** (elective CUs): high solar reflectance index; high light reflectance value, sound abatement characteristics **A.3.8 Participation in Life Cycle Evaluation Initiatives.** (elective CUs): ISO 14040/14044 Life Cycle Assessment LCA, ISO 14025 Environmental Product Declaration EPC, Contribution to LCA software modules and general Life cycle Inventory (LCI) Database
Environmental product manufacturing and raw	***B.4.1 Pollution Prevention to Reduce Particulates*****.** All facilitates controlling particulate emissions from process equipment which are associated with the manufacture of the product of interest have pollution control equipment such that all PM emissions are less than or equal to 0.05 grams per dry standard

8 http://greensquaredcertified.com/wp-content/uploads/2017/10/Green-Squared-Certification-Program-Criteria.pdf

material extraction	cubic meter (g/dscm) for all dust collection systems. An elective CU may be rewarded to a product of interest if all PM emissions are less than or equal to 0.032 g/dscm for 50% (by unit) of its dust collection systems. A second elective CU may be rewarded if all PM emissions are less than or equal to 0.01 g/dscm for 25% (by unit) of its dust collection systems. A third elective CU may be rewarded if all PM emissions are less than or equal to 0.005 g/dscm for 10% (by unit) of its dust collection systems. **B.4.2 Combustion and Fuel Usage** (Fuel restrictions; only allowed fuel types are used: natural gas, LP gas (butane and propane), landfill generated methane, or bio-based fuel; Landfill generated methane; Bio-based fuel; Low NOx Burners— an elective CU may be rewarded to a product of interest if Low NOx burners are installed on at least 50% (by unit) of natural gas or LP gas (butane and propane) production related combustion units; Acid gas controls—an elective CU may be rewarded if acid gas controls are used on all kilns associated with the manufacture the product of interest). **B.4.3 Raw Materials Sourcing** **B.4.4 Outsourced Manufacturing and Packaging Services** **B.4.5 Restricted Leachability of Lead and Cadmium** **B.4.6 Environmental Management Plan**. **B.4.7 Conservation/Reduction of Utility Usage** (Lighting, heating, electrical conservation strategy and production water conservation mechanisms should be proved by external audits (mandatory requirements). Other , such as, Minimal wastewater discharge, ASHRAE audit, Cogeneration or combined heat and power systems , heat recovery systems may reward elective CU. **B.4.8 Renewable Energy Usage**. **B.4.9 Manufacturer Waste *Diversion/Minimization***: Waste minimization plan; Reuse of manufacturing waste or scrap for other products or projects; Offer for donation in lieu of disposal, Incoming shipping material recycling or reuse.
End of product life management	**C.5.1 Clean fill eligibility** e.g. an elective CU may be rewarded if the product of interest is solid and inert **C.5.2 Post-life collection plan availability**
Progressive corporate governance	**D.6.1 Social Responsibility Strategy.** **D.6.2 Labour Law Compliance.** **D.6.3 Forced Labour Prohibitions.** **D.6.4 Child Labour Prohibitions.** **D.6.5 Environmental Regulation Compliance.** **D.6.6 Health and Safety Regulation Compliance.** **D.6.7 Voluntary Safety Program Participation** (e.g. OSHA or equivalent). **D.6.8 ANSI A138.1 Conformance Assurance Program.** **D.6.9 Federal Trade Commission (FTC) Compliant Green Marketing Claims.** **D.6.10 Manufacturer Community Involvement.**

	D6.11 Manufacturer Public Disclosure (elective CU) **D.6.12 Manufacturer Annual Sustainability Reports.** (elective CU) **D.6.13 LEED or Green Globes Certification for Facilities** (elective CU).
Innovation	**E.7.1 Exceptional Conformance 1.**An elective CU may be rewarded if the manufacturer exceeds a quantitative criterion by at least one and a half times the most stringent threshold established. **E.7.3 Innovative Attribute or Process.** An elective CU may be rewarded if the product of interest possesses an ecological attribute not addressed by ANSI A138.1, is manufactured in a facility with ecological processes not addressed by ANSI A138.1, or belongs to an organization with an innovative corporate governance strategy not addressed by ANSI A138.1. **E.7.4 Greenhouse Gas Awareness.** An elective CU may be rewarded if a carbon footprint and effective greenhouse gas reduction strategy can be provided for the product of interest or its manufacturing organization.

Greenguard Certification (U.S.)

GREENGUARD Certification, part of UL Environment, certifies products and materials for low chemical emissions and provides a resource for choosing healthier products and materials for indoor environments. The Program has established test methods and emission limits for several product groups including **Building Materials.** The Certification is recognized and accepted by sustainable building programs and in building codes worldwide. Two tiers of certification are available:

The GREENGUARD Certification Program gives assurance that products designed for use in indoor spaces meet strict chemical emissions limits.

GREENGUARD Gold Certification offers stricter certification criteria, considers safety factors to account for sensitive individuals (such as children and the elderly), and ensures that a product is acceptable for use in environments such as schools and healthcare facilities.

The certification is used for natural and ceramic tiles but also by countertop manufactures.

1.4 Review of information in EPDs

Environmental Product Declarations (EPDs) form the basis for the data for assessing buildings on an ecological level. This is currently laid down in the new European Standards project "Sustainability of buildings". The Environmental Product Declarations are based on ISO standards and are therefore internationally aligned. They are suitable as proof of environmental claims in the public procurement arena. EPDs offer the relevant basic data on environmental properties of a product for sales and marketing purposes.

Most buildings are assigned to the building in one "system". A Type-III declaration for building products which also helps to assess the entire building, thus lent itself to being created. Resource consumption and environmental emissions are recorded throughout the entire manufacturing process. The resulting contribution to the greenhouse effect, or eutrophication or acidification of water can be quantified and assessed using Lifecycle Assessment methodology. Lifecycle Assessments also provide a systematic and standardised basis for data in order to create an ecological assessment of a building in the "modular construction system" from declarations on individual building products. In a lifecycle analysis, the entire life of the building, the building phase with possible conversions as well as demolition and disposal are taken into consideration and the contribution of the building products to energy efficiency or to other aspects of sustainable management of a building are represented.

The declaration includes statements on the use of energy and resources and to what extent a product contributes to the greenhouse effect, acidification, eutrophication, destruction of the ozone layer and smog formation. In addition, details are given about the technical properties, which are required for assessing the performance of the building products in the building, like durability, heat and sound insulation or the influence on the quality of the indoor air.

As a summary, the guiding principles of the Type III EPD following ISO 14025 (2006) are listed below:

- **Relationship to ISO 14020 (2000)** – the principles set out in ISO 14020 (2000) shall be applied when developing an EPD.
- **Voluntariness** – EPD programmes shall be voluntary in nature.
- **Based on life cycle approach**- EPD shall include all environmental aspects from their life cycle. He quantified environmental product information in a Type III environmental declaration shall be based on the results of an LCA in accordance with the ISO 14020 (2006) series of standards.
- **Information modules** – the LCA –based data (inputs and outputs) used to compile the environmental profile in EPD configuration shall be referred to as information modules and shall represent the whole or a portion of the life cycle of the evaluated material.
- **Openness and consultation** – EPD programmes shall implement a formal and open consultation mechanism for the participation of interested parties.
- **Comparability** - EPD results must be comparable in order to allow users to choose products with the best environmental performance. To ensure comparability is achieved, the standard encourages the harmonisation of programmes and the development of mutual recognition agreements.
- **Verification** – In order to ensure the content of EPD is appropriate and verifiable, the programme administrator shall specify the procedures for reviewing the PCR, the EPD, the LCA and LCI data and the results from EPD.
- **Flexibility** – EPD shall be flexible, since the contents of EPD can be amended as necessary and as required by the company/organisation after due external review and verification.
- **Transparency** – EPD programmes must be able to demonstrate transparency throughout all stages of their development and operation, thus implying that information shall be made available to interested parties.

International EPD system EPDs

The International EPD system follows the United Nations Central Product Classifications (UN CPCs). Each EPD must state which CPC code the product falls under. The most relevant codes and hierarchy for hard coverings are illustrated below.

Section 1: Ores and minerals; electricity, gas and water

Division 15: Stone, sand and clay

Group 151: Monumental or building stone

Sub-class 1511 - Slate

Sub-class 1512 - Marble and other calcareous monumental or building stone

Sub-class 1513 - Granite, sandstone and other monumental or building stone

Group 152: Gypsum; anhydrite; limestone flux; limestone and other calcareous stone, of a kind used for the manufacture of lime or cement

Sub-class 1520 - Gypsum; anhydrite; limestone flux; limestone and other calcareous stone, of a kind used for the manufacture of lime or cement

Group 153: Sands, pebbles, gravel, broken or crushed stone, natural bitumen and asphalt

Sub-class 1512 - Marble and other calcareous monumental or building stone

Sub-class 1531 - Natural sands

Sub-class 1532 - Pebbles, gravel, broken or crushed stone, macadam; granules, chippings and powder of stone

Sub-class 1533 - Bitumen and asphalt, natural; asphaltites and asphaltic rock

Group 154: Clays

Sub-class 1540 - Clays

Section 3: Other transportable goods, except metal products, machinery and equipment

Division 37: Glass and glass products and other non-metallic products n.e.c.

Group 374: Cement, lime and plaster

Sub-class 3743 - Slate

Sub-class 3744 - Portland cement, aluminous cement, slag cement and similar hydraulic cements, except in the form of clinkers

Group 375: Articles of concrete, cement and plaster

Sub-class 3754- Tiles, flagstones, bricks and similar articles, of cement, concrete or artificial stone

Sub-class 3755- Prefabricated structural components for building or civil engineering, of cement, concrete or artificial stone

Sub-class 3756- Other articles of cement, concrete or artificial stone

Group 376: Monumental or building stone and articles thereof

Sub-class 3761 - Marble, travertine and alabaster, worked, and articles thereof (except setts, curbstones, flagstones, tiles, cubes and similar articles); artificially coloured granules, chippings and powder of marble, travertine and alabaster

Sub-class 3769- Other worked monumental or building stone and articles thereof; other artificially coloured granules, chippings and powder of natural stone; articles of agglomerated slate

Of the 445 EPDs listed on the Environdec website to date (March 2018) under "construction products" (CPC 32193)".

1.5 Relevant European Legislation and Policies

This section details overarching EU legislation that is generally relevant to hard floor coverings, which is important when setting the framework in which standards and labels have been developed. Contracting Authorities should be also aware of and take into account any additional local, regional or national legislation pertinent to their situation with respect to a particular HFC product or service.

a) Directives of the European Parliament and the European Council:

Directive 2010/75/EU[9] on industrial emissions is the main EU instrument regulating pollutant emissions from industrial installations and has a strong influence on the European ceramic manufacturing industry and is anticipated to have a strong role to play with the revised EU Ecolabel criteria.

The IED was adopted on 24 November 2010. It is based on a Commission proposal recasting 7 previously existing directives, including in particular the IPPC Directive. The IED entered into force on 6 January 2011 and had to be transposed by Member States by 7 January 2013.

The IED is based on several pillars, in particular (1) an integrated approach, (2) use of best available techniques, (3) flexibility, (4) inspections and (5) public participation.

The IED aims to achieve a high level of protection of human health and the environment taken as a whole by reducing harmful industrial emissions across the EU, in particular through better application of Best Available Techniques (BAT). Around 50,000 installations undertaking the industrial activities listed in Annex I of the IED are required to operate in accordance with a permit (granted by the authorities in the Member States). This permit should contain conditions set in accordance with the principles and provisions of the IED. The integrated approach means that the permits must take into account the whole environmental performance of the plant, covering e.g. emissions to air, water and land, generation of waste, use of raw materials, energy efficiency, noise, prevention of accidents, and restoration of the site upon closure.

The permit conditions including emission limit values must be based on the Best Available Techniques (BAT). In order to define BAT and the BAT-associated environmental performance at EU level, the Commission organizes an exchange of information with experts from Member States, industry and environmental organizations. This process results in BAT Reference Documents (BREFs); the BAT conclusions contained are adopted by the Commission as Implementing Decisions. The IED requires that these BAT conclusions are the reference for setting permit conditions.

According to paragraph 3 of the Annex I (Categories of activities referred to in Article 10) of the IED Directive: Industrial plants for the production of:

> (3.1) production of cement, lime and magnesium oxide:
>
> (3.5) Manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain with a production capacity

[9] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:334:0017:0119:en:PDF

exceeding 75 tonnes per day and/or with a kiln capacity exceeding 4 m3 and with a setting density per kiln exceeding 300 kg/m3 paper and board with a production capacity exceeding 20 tonnes per day,are subject to the IED Directive rules and, in particular, they have to refer to the BREF, the Reference Document on Best Available Techniques (BAT), in order to reduce the environmental impacts associated to their productive processes.

In 2007, Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry the best available techniques (BAT) conclusions10, for ceramic manufacturing industry were established under IED Directive.

Directive 2008/98/EC[11] **on waste** This Directive lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use. The Directive sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling, recovery. It explains when waste ceases to be waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and by-products. The Directive lays down some basic waste management principles: it requires that waste be managed without endangering human health and harming the environment, and in particular without risk to water, air, soil, plants or animals, without causing a nuisance through noise or odors, and without adversely affecting the countryside or places of special interest. Waste legislation and policy of the EU Member States shall apply as a priority order the following waste management hierarchy:

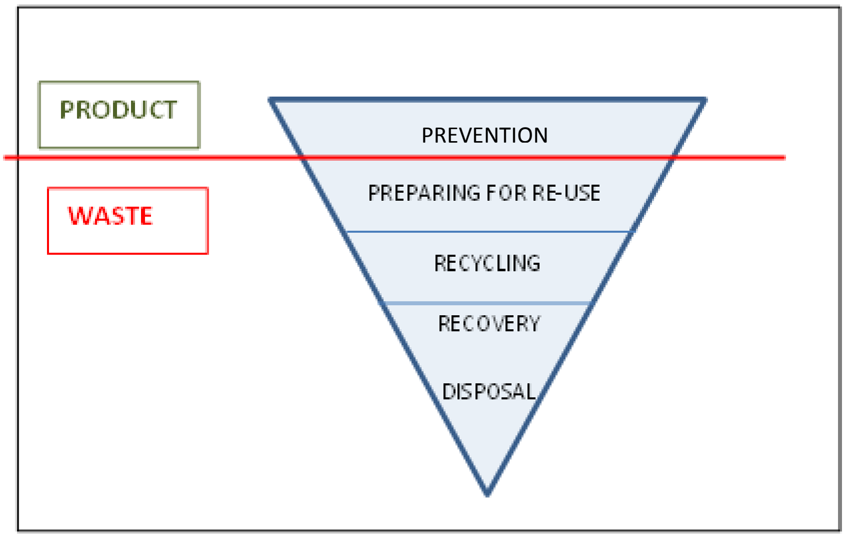

Figure 2. Waste management hierarchy

Directive 2002/49/EC[12] **concerning environmental noise.** The Directive applies to noise to which humans are exposed but does not apply to noise that is caused by the exposed person himself.

Directive 1999/31/EC [13] **on the landfill of waste (COM(2015) 594**[14] **Proposal for a Directive of the European Parliament and of the Council amending Directive**

[10] http://eippcb.jrc.ec.europa.eu/reference/BREF/cer_bref_0807.pdf
[11] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098
[12] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002L0049

1999/31/EC on the landfill of waste). It provides that the operators of existing landfill sites must have an approved conditioning plan which indicates how the requirements of the Directive are to be met within the required timeframe. These plans must help prevent the negative effects of landfill on surface water, groundwater, soil and air.

Directive 2000/60/EC[15] **(WFD) establishing a framework in the field of water policy.** The directive promotes the sustainable use of water, prevents deterioration of aquatic systems / wetlands, and reduces pollution of water and groundwater resources. This is of particular relevance in the extraction and manufacturing phases, where water use may be high and discharges to water bodies may result in pollution. Reducing water use in the life cycle of HFCs, in particular extraction and manufacture will contribute to the overall aims of the WFD. Re-use will reduce pressure on existing water sources, such as abstraction from surface waters.

N.B, A fitness check to evaluate this Directive, and the two other Directives directly linked to it (Directive 2006/118/EC on Groundwater and 2008/105/EC on Quality Standards) and the Floods Directive (2007/60/EC) has been launched end of 2017. The public consultation period end 4.03.2019.

Directive 2006/118/EC establishing a regime which sets groundwater quality standards and introducing measures to prevent or limit inputs of pollutants into groundwater and **Directive 2014/80/EU amending Annex II introducing technical adaptations** The directive establishes quality criteria that takes account local characteristics and allows for further improvements to be made based on monitoring data and new scientific knowledge. The directive thus represents a proportionate and scientifically sound response to the requirements of the Water Framework Directive (WFD) as it relates to assessments on chemical status of groundwater and the identification and reversal of significant and sustained upward trends in pollutant concentrations.

Directive 2009/28/EC[16] **the promotion of the use of energy from renewable sources** The Directive establishes an overall policy for the production and promotion of energy from renewable sources in the EU. It requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets. All EU countries must also ensure that at least 10% of their transport fuels come from renewable sources by 2020. The Directive specifies national renewable energy targets for each country, taking into account its starting point and overall potential for renewables.

Directive 2003/87/EC[13] **on emissions trading.** Energy-intensive industry sectors, such as the cement, and ceramic manufacturing industry fall within the scope of the Directives on emissions trading.

Directive 94/62/EC[17] **on packaging and packaging waste (and subsequent amendments)** seeks to reduce the impact of packaging and packaging waste on the environment by introducing recovery and recycling targets for packaging waste, and by

[13]http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31999L0031&from=EN
[14] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52015PC0594&from=EN
[15] http://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF
[16] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN
[17] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01994L0062-20150526&from=EN

encouraging minimisation and reuse of packaging. A scheme of symbols, currently voluntary, has been prepared through Commission Decision 97/129/EC[18]. These can be used by manufacturers on their packaging so that different materials can be identified to assist end-of-life recycling.

Directive 2005/31/EU[19]as regards a declaration of compliance and performance criteria of the analytical method for ceramic articles intended to come into contact with foodstuffs. The requires a written declaration by the producer or importer that the goods placed on the market comply with the lead and cadmium release limits

Directive 2009/147/EC[20] on the conservation of wild birds was adopted in November 2009. It is one of the EU's two directives in relation to wildlife and nature conservation, the other being the Habitats Directive. It aims to protect all European wild birds and the habitats of listed species, in particular through the designation if Special protection Areas (SPA). Of particular relevance to hard floor coverings, is the focus of the Directive on protection of habitat. The extraction of raw materials for hard floor coverings, such as quarrying has the potential to lead to habitat destruction if habitats are not considered and quarrying undertaken in a controlled manner. The Directive aims to establish and maintain a coherent network of suitable habitat for the relevant bird species. This takes the form of Special Protection Areas (SPAs) across Member States, which make up part of the Natura 2000 Network.

Directive 92/43/EEC[21] on the conservation of natural habitats and of wild fauna and flora provides further protection of habitat. It aims to promote the maintenance of biodiversity, taking account of economic, social, cultural and regional requirements. The Directive has had to evolve to reflect successive enlargements of the European Union, and successive amendment to the annexes have been made in 2003, 2006 and 2013.

Directive 2004/35/EC on the environmental liability has the objective of making operators of activities which cause environmental damage financially liable for that damage ('polluter pays' principle). Under the Regulations, obligations are imposed on operators whose activities have caused damage to protected species and natural habitats listed in the Birds and Habitats Directives to remedy this damage, and obligations are imposed on those whose activities have caused an imminent threat of damage to protected species and habitats listed in the Birds and Habitats Directives to take immediate steps to prevent damage.

b) Regulations of the European Parliament and the Council:

Regulation (EU) No 305/2011[22] laying down harmonised conditions for the marketing of construction products (CPR). It is designed to simplify and clarify the existing framework for the placing on the market of construction products. It ensures that reliable information is available to professionals, public authorities, and consumers, so they can compare the performance of products from different manufacturers in different countries. Article 2, paragraph 1 of the CPR defines a construction product as " any product or kit which is produced or placed on the market for incorporation in a

18 OJ L 050, 20.02.1997 P. 28 – 31
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31997D0129:EN:HTML

19 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32005L0031&from=EN
20 http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:020:0007:0025:en:PDF

21 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01992L0043-20130701&from=EN
22 http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011R0305&from=EN

permanent manner in construction works or parts thereof and the performance of which has an effect on the performance of the construction works with respect to the basic requirements for construction works". According to this regulation, construction products may be placed on the marked only if they are suitable for the intended use. That is to say if they have such characteristics that the works in which they are to be incorporated, assembled, applied or installed, can, if properly designed and built, satisfy the following essential requirements:

- Mechanical resistance and stability
- Safety in case of fire
- Hygiene, health and environment
- Safety and accessibility in use
- Protection against noise
- Energy economy and heat retention
- Sustainable use of natural resources.

Regulation (EC) No 1907/2006 23 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). It addresses chemicals, and their safe use, and aims to improve the protection of human health and the environment through a system of Registration, Evaluation, Authorisation and Restriction of Chemicals. Companies are required to demonstrate how substances can be used safely and risk management measures must be reported to users. The REACH Regulation also establishes procedures for collecting and assessing information on the properties and hazards of substances and requires that companies register their substances in a central database. As such, REACH encourages substitution of the most dangerous chemicals when suitable alternatives have been identified. As REACH applies to all chemical substances, in theory, it also covers the chemicals that are used in hard coverings products, e.g. glazed tiles.

Regulation (EC) No 1272/2008[24] on classification, labelling and packaging of substances and mixtures (CLP). The Regulation aims to ensure a high level of protection of human health and the environment, as well as the free movement of chemical substances, mixtures and certain specific articles, whilst enhancing competitiveness and innovation. In line with the GHS standard, CLP allows for the identification of hazardous chemicals and the communication of these hazards to users through labelling. It also provides the basis for safety data sheets (SDS) regulated under the REACH Regulation, and sets requirements for the packaging of hazardous chemicals.

1.6 Feedback from stakeholder consultation on the product group definition

Contact with relevant stakeholders, such as competent bodies, manufacturers and retailers are essential to evaluate the valid criteria and potential amendments. Direct interviews and a survey were performed to understand how Ecolabel is perceived by hard coverings manufacturers and why some organizations, for green procurements, prefer to adopt alternative communication tools.

[23] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006R1907-20140410&from=EN
[24] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:353:0001:1355:en:PDF

An initial scoping questionnaire to be filled out online was sent out not only to all parties who expressed their interest in the revision at the very beginning of the process but also to current license holders and potentially interested parties, such as European and national associations, research institutions and manufactures The questionnaire includes some higher level strategic questions about the product group in general, the scope and, for those who are interested, some specific questions about the suitability of the existing criteria.

A total of 20 stakeholders answered the initial scoping questionnaire. The most representative share of respondents were manufacturers of hard covering products (11 respondents, i.e. 55% of all responses). Others respondents were: consultant or research organisations (3 respondents, 15%), manufactures or trade associations (4 respondents, 20%), government or similar (2 respondents, 10%). Regarding the respondent's relationship with the current EU Ecolabel.

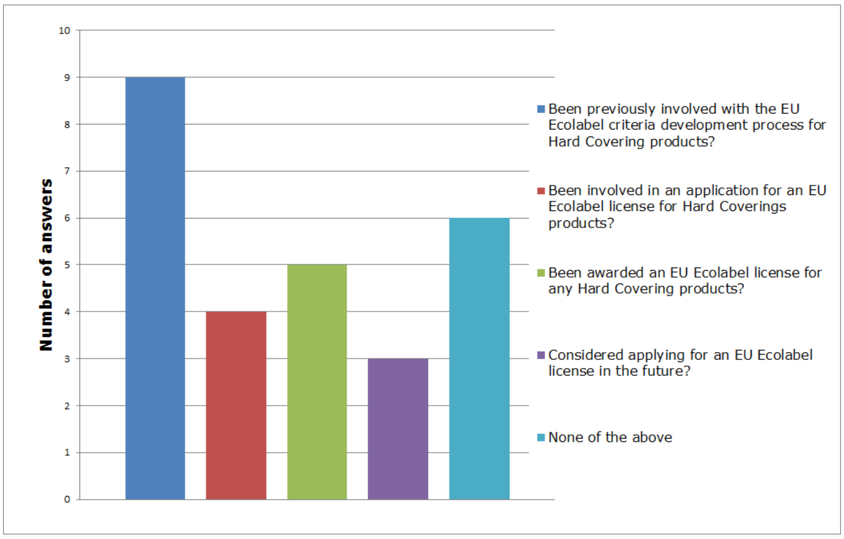

Figure 3. Involvement of the stakeholders with the EU Ecolabel

A total of 70% of respondents had some previous experience with the EU Ecolabel criteria for Hard Coverings – either during the criteria development process (45%), application for an EU Ecolabel (20%), obtaining an EU Ecolabel (25%) or simply by considering applying for the EU Ecolabel (15%).

Interestingly, a total of 55% (11 of 20) respondents had been involved in product assessments relating to greenhouse gas emission footprints (9 of those 11 being as part of EPDs). When only considering those respondents that could potentially apply for the EU Ecolabel (i.e. industry), the figure rose to 73% having previously worked with EPDs or carbon footprints.

Main findings from initial scoping questionnaire

A number of broad questions (e.g. factors that could help EU Ecolabel uptake and approaches to energy consumption control) were asked which virtually any stakeholder could offer an opinion on. The main findings are summarised below:

1) Recognition by Green Building Assessment schemes

Currently both BREEAM and LEED recognise and award credits for the use of a minimum number of construction products with EPDs. All of the sub-products covered by EU

Ecolabel for Hard Coverings can be considered as construction products. Given the success of these schemes, it is logical to ask if the recognition of EU Ecolabel products would be considered of added-value to manufacturers.

Due to the relative importance of the public sector to the Hard Coverings market (e.g. in infrastructure, public buildings and exterior paving almost everywhere) it was also worth asking what would be the potential importance of developing EU Green Public Procurement criteria for Hard Coverings to support uptake of the EU Ecolabel.

For these two considerations, the following feedback was received:

- 80% of respondents felt that recognition of the EU Ecolabel in Green Building Assessment schemes such as BREEAM and LEED would be important (15% were unsure and 5% said no).
- 65% of respondents felt that public procurement was important or very important for the Hard Coverings product group (30% were unsure and 5% said it was unimportant).

From this feedback, it is clear that efforts should be made to liaise with representatives of Green Building Assessment schemes to try and reach an agreement over how they could potentially recognise the environmental benefits associated with EU Ecolabel Hard Covering products by awarding points to such products under their schemes.

Although no development of Green Public Procurement criteria for Hard Coverings is foreseen in the Commission's workplan, the responses to this questionnaire suggest that it would be worthwhile to develop EU GPP criteria for Hard Coverings that support the EU Ecolabel criteria – at least once those Ecolabel criteria have been revised.

2) EU Ecolabel approach towards energy efficiency

Energy consumption is one of the major environmental issues related with Hard Coverings. There are different ways to reduce the environmental impacts associated with energy consumption: (i) improve the efficiency of the process, (ii) increase the percentage of renewable energy sources required or (iii) set a limit based on CO2 equivalent emissions. Each option has its benefits and drawbacks.

Energy efficiency is something that the applicant can directly control in most cases and which is in their own interests due to the fact that energy is generally expensive in Europe. However, this latter point is also the main drawback because it can be argued that industry already wants to be as energy efficient as possible, but only within the windows of acceptable returns on investment in more efficient equipment.

Requirements on renewable energy have a direct benefit on the environmental impact of the producer and their products but simply requiring renewable energy alone could mean that an energy efficient installation using fossil fuel could be unable to apply for the EU Ecolabel while an inefficient installation using biomass could.

A requirement of the greenhouse gas emissions of the product are of direct interest to consumers and fits in well with the growing trend of EPDs for construction products. Such a requirement rewards both increases in energy efficiency and increases in renewable energy sources used and so gives flexibility to producers in how exactly to improve.

For these o considerations, the following feedback was received:

- 70% of respondents agreed or strongly agreed that the EU Ecolabel for Hard Coverings should focus on energy efficiency.

- Only 40% agreed or strongly agreed that the EU Ecolabel for Hard Coverings should set direct requirements on renewable energy use (40% disagreed or strongly disagreed).
- Only 35% agreed or strongly agreed that the EU Ecolabel for Hard Coverings should set direct requirements on CO2 footprints (40% disagreed or strongly disagreed).

From the responses received, a clear preference for direct requirements on energy efficiency was expressed. Considerably less support was expressed for minimum requirements on renewable energy or on CO2 emissions. This was surprising given that 11 of the respondents had previously been involved in EPDs, where one of the key indicators is global warming potential.

3) General impressions about EU Ecolabel criteria for hard coverings

The current criteria have been structured in such a way as to reflect the life cycle impacts of all the sub-products in parallel. Not all of the criteria are relevant to each sub-product, so it can be quite difficult to read from the perspective of a potential applicant who is only interested in one sub-product. Consequently, it was considered relevant to as for the general impressions that stakeholders have of the current criteria.

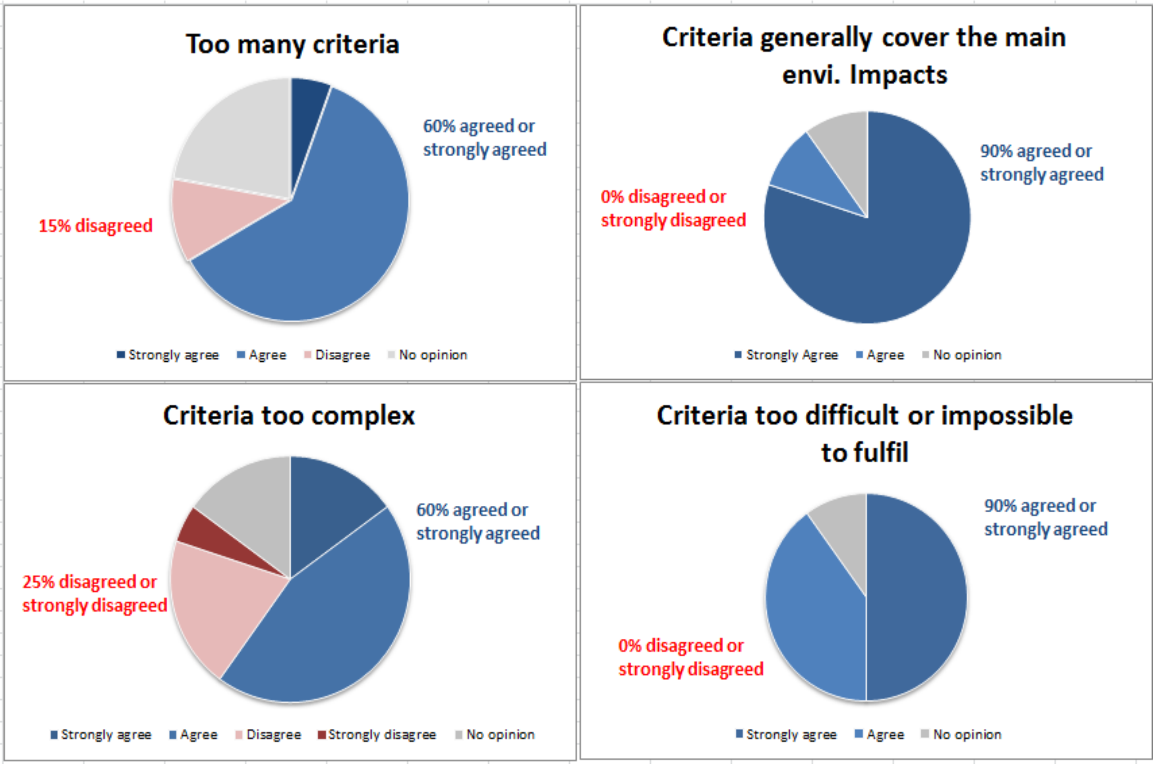

Figure 4. General overview about the current criteria.

Most of the respondents (60%) considered that there were too many criteria and that they were too complex. A major concern is that 90% of the respondents considered that the current criteria are too difficult or impossible to fulfil (see Figure 4). However, at the same time, 90% of respondents also though the existing EU Ecolabel criteria covered the main environmental impacts of hard covering products.

Despite the fact that the existing criteria are considered to cover the main environmental impacts of hard covering products, a clear need to simplify the criteria has been expressed. One particular concern was that only factors that the applicant can directly control should be set in criteria.

It is uncertain to what extent such complexity has impeded the uptake of the EU Ecolabel for Hard Coverings. However, considering that most of the respondents concerned about the complexity had already been involved in the EU Ecolabel before, it can be assumed that those who were not involved will only find it even more complex.

Regarding the scope and definition, it became clear that the main interest of almost all respondents was in ceramic tiles rather than terrazzo tiles, natural stone or agglomerated stone None of the respondents appeared to represent producers of concrete paving units or clay tiles.Itis noticible that almost all respondents (19 out of 20) to this first scoping questionnaire were based in the main production centres for ceramic tiles, natural stone and agglomerated stone (i.e. Italy and Spain).

Nonetheless, some interesting comments were made about the scope of the product group. It was proposed to explicitly include the following in the scope:

- Resins, plastic and metal.
- Large format ceramic tiles
- Porphyry
- Kitchen and bathroom countertops

The last 3 of the suggestions can certainly be considered in the scope although further discussion would be needed to clarify exactly what is proposed in the first suggestion in the list above.

Main findings from direct interviews

Additional information has been obtained from other sources, including direct interviews with national and international associations, for example, ASTA (the world-wide association of Agglomerated Stones Producers), Internazionale Marmi e Macchine Carrara (organization which provides research and consultancy to the stone industry at international scale), Confindustria Ceramica (the Italian national association of ceramic producers, one of the biggest in Europe), and ANDIL (Italian association of clay tiles/bricks manufacturers) and also with some of the most important manufacturing groups in the international ceramic tiles market – Concorde Group and Panaria Ceramica Group.

The main conclusion is that Environmental Product Declaration (EPD) seems to be preferred respect to Ecolabel, for a series of reasons described below.

First, it is important to remark we are talking about the building & construction sector where most of the efforts are true B2B more than B2C; this is probably enough to frame the current situation: when thinking about LEED (https://new.usgbc.org/leed) or BREEAM (https://www.breeam.com/) for instance, EPDs are officially recognized as a path to acquiring points toward certification. In this framework, end-users are mainly represented by professionals, such as architects, designers and consultants, who are encouraged to look for products with EPDs because they're viewed as an easier way to gather LEED point.

Even if Ecolabel is probably accepted as one of the best (B2C) communication tools, in this case neither LEED nor BREEAM include the possibility to reward Ecolabelled products.

This is probably why some ecolabelled certified companies, such as Panaria Group, Ceramica Magica S.p.a and NovaBell, have adopted also other environmental communication tools (mainly EPDs) which satisfy criteria for obtaining LEED credits.

Also in a green public procurement (GPP) situation, even if the EU Ecolabel is still used to support purchasing criteria, new paradigms coming from the Circular Economy approach[25] are giving priority to other tools such as EPDs where specific issues such as recycled content can be clearly stated.

Transparency is therefore another hot spot: EPDs and material ingredient reporting tools, provide architects, designers and public authorities more information on the contents in products and the manufacturing process than EU Ecolabel does. EPDs address how products are made and their material ingredients, including any recycling content declarations or bio-based materials, useful parameters to gain credibility (and credits) for the above-mentioned schemes.

All companies and private organizations met so far have remarked the importance for the EU Ecolabel to be recognised by certification schemes operating in the building sector as a way to get additional credits; a focus on Material & Resources (MR) as well as on Indoor Environmental Quality (IEQ) issues was recommended by same Companies for the next phase of the HC EU Ecolabel criteria revision.

Finally, the results of the interviews and surveys have been summarised in a SWOT analysis, which may serve as the basis for future considerations.

Table 1. SWOT Analysis of EU Ecolabel for HC products

STRENGTH	Well known and requested in some key markets (e.g. northern Europe) Still considered a strategic lever to improve market positioning If combined with efficient promotion, can lead to increase sales Credible: verified by independent consultants Used in GPP to support purchasing criteria
WEAKNESS	Low flexibility. Not recognized by green building standard such as LEED and BREAM (as opposed to EPD system). Expensive marketing actions to reach out a relevant number of consumers Includes less information about the product's performances respect to EPD Complex bureaucracy and differences among CBs High certification and management costs
OPPORTUNITIES	Environmental certifications are increasingly requested to companies in HC sector

25 European Union (2017) – Public procurement for a circular economy, Good practice and guidance, http://ec.europa.eu/environment/gpp/pdf/CP_European_Commission_Brochure_webversion_small.pdf

	Increasing consumers' willingness to purchase eco-friendly products
TREATHS	Decrease of EU Ecolabelled organizations may lead to a general skepticism Ecolabel is being replaced with other environmental communication tools in the construction sector Professionals oriented towards other certification systems which give different information GPP is oriented towards a Circular Economy approach and gives priority to other tools (EPDs) where specific issues can be clearly stated

1.7 Ecolabel licences and products

As of June 2018, the total number of HC licensees is 15. Of these, 12 are held by ceramic tiles manufacturers, while the remaining three are held by natural stone manufacturers. Other product group categories have no licenses. The majority of the license holders are concentrated in Italy for ceramic manufactures (8 out of 12) and Spain (3 out of 3). A list depicting the current license holders is given in Table 5.

Table 5. Ecolabelled hard covering products manufacturers

Ecolabel License Holders	Country	Product Category	N. of products
Granitos de Atios S.A	Spain	Natural stone	
Granitos de Louro SA	Spain	Natural stone	
Minera de Rocas S.L.U	Spain	Natural stone	
Ceramica Magica S.P.A	Italy	Ceramic	55
Ceramica Sant'Agostino	Italy	Ceramic	1708
Cooperativa Ceramica d'Imola	Italy	Ceramic	22
Florim Ceramiche S.P.A	Italy	Ceramic	312
Gardenia Orchidea S.P.A	Italy	Ceramic	3
La Fabbrica S.P.A	Italy	Ceramic	3
Novabell S.p.A ceramiche italiane	Italy	Ceramic	15
Panaria Group	Italy	Ceramic	159
Porcelanosa S.A	Spain	Ceramic	13
Sinyih Ceramic LTD	Czech Republic	Ceramic	2
Thai Ceramic	UK	Ceramic	14

EU Ecolabel hard coverings products are highly concentrated in terms of manufacturers' geographical distribution and certified product groups. Except for two cases, all the manufacturers currently holding the Ecolabel licenses came from Italy or Spain. Moreover, only natural stone and ceramic tiles products have been, so far, awarded with EU Ecolabel.

This situation is strictly related to the structure of the EU hard coverings market. Ceramic tiles industry, which represents by far the most important hard coverings sub-sector, has recently started a path towards a more sustainable and environmental-friendly way of operating. Spanish and Italian companies are the brightest stars of the European ceramic tiles sector and most of them adopt different environmental communication and certification schemes, such as Ecolabel, with the aim of differentiate their products in a high competitive market.

The same consideration is applicable to the natural stone sector, which - although not comparable to ceramic tiles one for production volume and value - still see the prominence of Italian and Spanish industries.

The rest of the hard coverings sectors seem not to be very interested in the EU Ecolabel. This may be due to the different market area served, e.g. extra EU markets, where the EU Ecolabel is not well recognized.

Considering the entire hard coverings sector, which can be assumed to be composed by more than one thousands of SME, percentage of ecolabelled manufacturers is extremely low (15 companies, around 1,5%). Moreover, EU Ecolabel hard coverings market seems to suffer for a period of stasis, with low certification requests and some important and traditionally certified companies – such as Concorde Group- not renewing their Ecolabel Licenses and/or preferring other environmental communication tools.

This situation should be reconducted to the specific features of the building & construction sector, where relationships are typically B2B and most sustainability efforts/initiatives hang around green building schemes (such as LEED and BREAM), which do not recognize Ecolabel as a scoring factor. A more market-oriented approach and the recognition of Ecolabel as a scoring factor, in addiction to stronger and more effective communication and marketing efforts from the Commission side, could be the key point for re-launching EU Ecolabel in hard coverings sectors.

2 OVERVIEW FOR NATURAL STONES

2.1 Terminology and classification

As defined by CEN/TC 246/N.237 prEN 12440 and 12670, natural stones are pieces of naturally occurring rock and include marble, granite, and other natural stones. The terminology "other natural stones" includes stones made out of marble and granite, such as sandstone, quartzite, slate, tuff, schist; generally, these stones are not quarried by blocks and do not acquire a mirror polish.

All natural stones, thanks to their mechanical, durable, and aesthetical properties, can perform both decorative and structural architectural functions in the building and construction sectors. Natural Stones are also named Dimension Stones (DS) in commercial terms[26].

Natural stones are primarily classified according to the genetic classification of the crustal rock they derive from. Three main rock classes are distinguished:

1. Igneous rocks: Igneous stones are exposed to extreme heat. Depending on where the cooling occurs they are classified into (a) *volcanic, also known as extrusive stones, where th*e outcropping magma has reached the surface and it undergoes rapid cooling, which hinders minerals crystallization and smaller crystal are formed and (b) *plutonic,* also known as intrusive stones: They are formed by slow cooling and consequent solidification of magmas inside the terrestrial crust. They are also called crystalline rocks because the slow solidification process allows complete mineral matter crystallization.The most popular igneous stones used in building are granite and basalt. Both contain large quantities of quartz and silica, but it is the heavy metals such as iron and magnesium that give the stones their dark colour.

- **Granite** is a hard 'intrusive' stone, extremely durable, strong and coarse grained with large crystals, which give it a flecked look. It mainly contains the minerals potassium, feldspar and quartz with small amounts of mica. Most of the continent is made of granite.

  Granite is one of the hardest, most popular building materials used in the world and is commonly used indoors for kitchen benchtops, bathroom vanities, floors and furniture. Outdoors it is used in large structures such as bridges, monuments, retaining walls and steps and in large public floor areas due to its solid character and ability to withstand deterioration. Granite is usually used as a slab rather than a tile, so its weight must be considered when choosing an application.

  Polished granite is hard wearing, easily maintained, heat, chip, bacteria, fire and scratch resistant and is not affected by acidic liquids such as juice, coffee, tea and wine when treated with a good quality penetrating sealer. Granite has an ageless beauty, is longer wearing than manmade stones and will retain its colour and finish longer than other stones.

  Colours are usually shades of black, grey, brown, red, pink and yellow, which are determined by the minerals trapped when the stone is forming.

- **Basalt** also known as bluestone is 'extrusive', hard stone, fine-grained with small crystals. Most of the ocean floor is made of basalt. Basalt was traditionally used for cobbled roads and laneways due to its durability and because water drained away from the surface efficiently allowing it to dry quickly. It was also popular due

[26] Cosi, M. (2015). The dimension stone sector: new perspectives on the global market and on the reporting of international mining standards. European Geologist, pp. 24-30. Retrieved from https://eurogeologists.eu/wp-content/uploads/2017/08/a_efg_journal.pdf

to its texture, which made it a non-slip surface. It is now commonly used in outdoor areas for paving, stairs, exterior wall cladding, ponds, landscaping, pathways and indoors for countertops, walls and floors. Colours are usually blue/grey, green/grey, grey and black.

2. Sedimentary rocks: They originate as a result of the external geodynamic activity on the surface of the Earth's crust. On the surface, rocks become weathered, disintegrate or decompose. Later on, different types of rocks generate in different environments due to diverse crystallization, sedimentation and burial processes. These rocks can be further classified into two main groups depending on the genetic process involved in their genesis, namely, (a) d*etrital rocks*, which are generated by accumulation of more or less cohesive fragments of other rocks. Sandstones are the most appreciated as natural stone due to their cohesion and (b) c*hemical rocks*, which are formed by mineral precipitation. Carbonates are the most frequently occurring and also the most used subgroup, i.e. limestone, mainly composed by microscopic calcite crystals (calcium carbonate), although other minerals may also occur, but far less frequently: silica, clays, iron and manganese oxides, organic matter and other carbonates. Iron oxides confer interesting yellow, orange, red and black coloration. Meanwhile, organic matter confers black or grey colours. If dolomite (magnesium carbonate) content is high, the term dolomite rock is used. Depending on the content of either carbonate (calcium or magnesium carbonate) rocks will receive different names, such as dolomite rock, limestone or calcareous dolomite rock.

Examples of sedimentary stone commonly used in building include limestone, travertine and sandstone. Most sedimentary stones are rated around a 3 on the Mohs Scale of hardness.

- **Limestone** is a soft stone, primarily formed from calcium rich organisms like seashells and bones. It is commonly used as a building material as it is easy to manipulate and readily available. It has a smooth surface and can vary in hardness. It contains the mineral calcite however some limestone also contains magnesium, which makes it harder and allows it to take a polish like marble. This harder limestone is also more weather resistant. A type of limestone known as fossil stone contains visible fossils including seashells and plants however this is quite porous and cannot be polished.

  Limestone is used to produce benchtops, fireplaces, floors, vanities, ornamental pieces, interior and exterior wall cladding and paving. It is prone to absorbing oil, water and other liquids therefore it must be protected with a penetrating sealer. It can also scratch and is sensitive to acidic substances such as juice and wine. The softer varieties of limestone are not recommended for high stress areas. Colours are usually soft and include grey, light beige to tan, white, pastel pink, green and yellow.

- **Travertine** is a soft, porous type of stone made from the calcium in limestone and usually found near natural springs. The calcium is washed from the limestone bed by hot spring water. It floats to the surface where the water evaporates leaving a layer of crystals. As this process continues over time, many layers are produced. Carbon dioxide bubbles become trapped in the layers as the stone is being formed. Holes caused by these bubbles are typical in travertine.

  Travertine is not particularly hard wearing, but if the holes are filled with cement or resin during the manufacturing process, it can be honed or polished and used in high traffic areas. It is mainly used to produce interior and exterior wall cladding, exterior tiles, paving and curbing, furniture and vanities etc. Like other limestone, travertine is sensitive to acidic substances such as juice and wine and must be sealed with a penetrating sealer. Colours are usually cream, beige, brown, pink, red and gold.

- **Sandstone** is a soft stone, formed when sand containing a variety of minerals including quartz, pyrite, iron, silica, calcite and some organic matter are cemented together by pressure. Other minerals, which give sandstone its character and add colour include mica, hematite, feldspar, ilmenite and clay minerals. Sandstone was commonly used in the construction of buildings and bridges up to the 1800's, prior to the introduction of reinforced concrete.
- It is a strong and durable stone with a matt finish and has excellent slipresistance. It can have a fine or coarse texture and is particularly suited to outdoor pool areas. Sandstone is used mainly to produce interior and exterior flooring, paving and walls. It is porous and must be sealed with a penetrating sealer. Colours are usually cream, brown, red, grey and sometimes green, depending on the minerals covering and cementing the sand, for example sandstone that contains iron will be red to brown, whereas sandstone with a silica content will be more white.

3. Metamorphic rocks: This category includes rocks that have undergone major transformations in texture, structure and atomic organization due to intense pressure and/or high temperatures, as a result of the activity of the Earth's crust. Examples of metamorphic stone commonly used in building include marble, serpentine, slate and onyx. Most metamorphic stones are rated around a 3-4 on the Mohs Scale of hardness.

- **Marble** is a soft stone that is formed in the earth's crust through the metamorphic process. It is formed mainly from limestone reacting to the extreme heat underground but not directional pressure. It mainly contains the minerals calcite and dolomite; however impurities in the original limestone recrystallise to form other minerals that create a variety of colours in the marble. White marble contains more calcite, yellow marble contains limonite, reddish marble contains hematite and green marble contains serpentine. It also has a wide variety of vein like patterns, which add to its appeal. These veins are created when minerals in the stone liquefy due to the heat in the earth's crust, then flow through the stone and solidify as the earth cools.

  Marble is a popular stone commonly used for its strength and beauty and its ability to achieve a 'mirror like' finish when polished. It has been used for centuries as a building material and also to create sculptures, as it is soft but strong. It is a versatile material also used for floors, furniture, vanities, bathroom tiles and ornaments. Although it is fairly resistant to erosion and fire, acidic liquids will etch the surface and grit will scratch it. It is not an ideal surface to use as a kitchen benchtop where spills and scratching are common. Its longevity will be determined by its treatment and maintenance. Sealing with a penetrating sealer is recommended, and will protect the surface from staining. Regular cleaning with recommended products will prolong the glossy look and feel of the marble. Colours are usually white, red, black, green, yellow and various shades of these colours.
- **Serpentine** (Green Marble) is a soft, silky feeling stone, formed in the earth's crust during low-grade metamorphic conditions. It is classed as a non-foliated metamorphic rock as it is not layered like slate. The pattern in the marble is said to resemble a serpent's skin, hence its name. Its green colour is mainly due to the magnesium content.

  Serpentine is often used for furniture and ornaments, as it is soft and ideal for carving. It is not a stone that weathers well and is therefore suited to indoor applications. Unlike other marble and limestone, serpentine is not affected by acidic liquids and therefore can be used for kitchen benchtops. Thin slabs of serpentine may be used for wall panelling, and stair treads. Although it will take a polish it does not have a highly reflective finish. Colours are usually yellowy green, olive, dark green, brown, grey and black. It usually has a white vein, a soft, waxy feel and an opaque to translucent look.

- **Slate** is a fine-grained, foliated stone formed under the ocean when layers of sedimentary rock, clay, shale or quartz are compressed under low-grade heat and pressure. Due to its layering, slate can be easily split, slabs can thus be obtained, their usual thickness being 2-8mm. It can range from very soft to hard depending on its origin. Soft slate is found in the USA and hard slate in the UK.

  Slate is popular for both indoor and outdoor use because of its strength and rustic appearance. Once installed slate is a particularly durable surface, resistant to wear, especially in areas where there is a large amount of foot traffic. It is heat, fire and weather resistant, non-porous, so spills are not absorbed and highly resistant to acidic liquids. It is slip resistant due to its surface texture and retains warmth. There are some softer slates however that can break, chip and scratch so the environment must be considered when choosing a slate. A good quality penetrating sealer will provide added protection and strength. Slate can also be coated with a wet look sealer to protect it and enhance its appearance. Colours are usually shades of black, grey, green, brown, yellow, purple, pink and sometimes copper.

- **Onyx** is a soft, fine-grained stone made from calcium layered under extreme heat and pressure. The layering occurs in limestone caves when water drips over limestone and redeposits forming stalactites and stalagmites. The name onyx has Greek origins and means claw or fingernail which has a similar translucent appearance to onyx stone. It is mainly found in the USA, Germany, Brazil, Mexico, India, and Africa. Onyx is known for its opalescence or translucence, spectacular patterns and vibrant colours. It must be professionally sealed with a penetrating sealer otherwise stains can be difficult to remove. Onyx etches with acidic liquids and must be maintained with care. It can be used to make tiles, tables, hand basins, vases, bowls and ornaments that can be backlit, as the light will shine through the stone. Onyx products are usually highly polished to bring out the beautiful patterns and colours in the stone. Colours range from earthy reds, browns and greys to a variety of pastel greens, creams, gold, amber and white.

Natural stones can be also classified based on the mineralogy characteristics in calcareous and siliceous stones:

- **Calcareous stone** is made mainly of calcium carbonate, a chemical compound commonly found in natural stone, shells, and pearls. It’s sensitive to acidic substances and usually requires different cleaning methods than siliceous stone. Examples include marble, travertine, limestone, and onyx.
- **Siliceous stone** is made of silicates like quartz, feldspar, mica, etc. It is usually resistant to most acids found in the kitchen or bath. However, they can contain trace levels of minerals that are acid sensitive. It tends to be very durable and relatively easy to clean. Types of siliceous stone include granite, slate, sandstone, quartzite, bluestone, and soapstone.

Table 6 shows a summary of the geological natural stone classification

Table 6. Geological classification chart

	Sedimentary	**Metamorphic**	**Igneous**
Calcareous	Limestone Travertine Onyx	Marble Serpentine	
Siliceous	Sandstone	Slate Quartzite Soapstone	Granite

Furthermore, another classification may be given based on the mechanical treatments applied to the stone fair face, which can be for aesthetical purposes as well as for providing slabs, or tiles, with specific end-use functions and characteristics. For instance, the rock face may be polished, grounded, bush-hammered, etc. (see detailed explanation in the finishing operations chapter).

2.2 Relevant standards

STANDARD	Main aspects
General –Natural stone	
EN 12670.	**Natural stone – Terminology** Defines the recommended terminology covering scientific, and technical terms, test methods, products, and the classification of Natural Stones
EN 12440:	**Natural stone – Denomination criteria** Specifies the criteria for the designation of natural stone from raw material to finished products. Natural stones will receive a description which shall include the following parts: Name of the natural stone, petrological family according to EN 12670, typical colour and place of origin.
EN 12407.	**Petrographic examination** Specifies methods for making technical petrographic descriptions of natural stone, except for roofing slates, in order to highlight features influencing its chemical, physical and mechanical behaviour. Natural stones are characterized not only from the point of view of their mineral components and of their fabric and structure but also in terms of any features as: colour, presence of veins, of fossils, of discontinuities, etc. On the basis of the data generated from the macroscopic and microscopic examination relating to grainsize, fabric and mineralogical composition a petrographic definition shall be assigned to the stone sample, using EN 12670 and fixing at least the rock family.
Other relevant Natural Stone Test Methods	
EN 1925	Determination of water absorption coefficient by capillarity
EN 1926	Determination of uniaxial compressive strength
EN 1936	Determination of real density and apparent density, and of total and open porosity
EN 12370	Determination of resistance to salt crystallisation
EN 12371	Determination of frost resistance
EN 12372	Determination of flexural strength under concentrated load
EN 13161	Determination of flexural strength under constant moment
EN 13364	Determination of the breaking load at dowel hole
EN 13373	Determination of geometric characteristics on units
EN 13755	Determination of water absorption at atmospheric pressure
EN 13919	Determination of resistance to ageing by SO2 action in the presence of humidity
EN 14066	Determination of resistance to ageing by thermal shock
EN 14146	Determination of the dynamic modulus of elasticity

EN 14147 EN 14157 EN 14158 EN 14231 EN 16306 EN 1926	Determination of resistance to ageing by salt mist Determination of abrasion resistance Determination of rupture energy Visual alterations Determination of resistance of marble to thermal and moisture cycles Determination of uniaxial compressive strength
Radiation description	Radiation Protection 112(*)

*Values under 6 comply with established limits in RD 78/2001 about Sanitary Protection against ionized radiations

2.3 Market data

All data and information presented in the following pages have been drawn from the report "XXVIII World Marble and Stones Report 2017"[27], that provides a broader, accurate and up-to-date international perspective of this sector. In addition, the information collected via direct interviews with business associations and relevant companies is included.

2.3.1 World production and consumption

World production of natural stones highlights a positive trend, mainly for the driving force of a few leading countries, especially from Asia. In 2016 production overtook the 145 million tons, of which 85 million tons belongs to processed products, revealing a high incidence of processing waste (Figure 5). Processing waste include also waste material destined for granules, powders and similar uses.

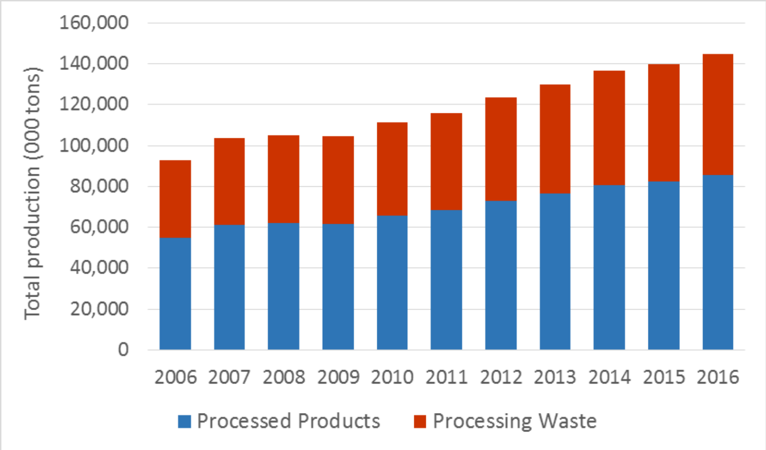

Figure 5. World natural stone production trend

The three-major world producers, China, India and Turkey count with more than 55% of world production (in weight). Europe covers 15% of the total production, mainly thanks to the contribution of Italy, Spain, and Portugal (Figure 6).

[27] Carlo Montani (2017), *XXVIII World Marble and Stones Report 2017,* Aldus Edizioni, Carrara (Italy).

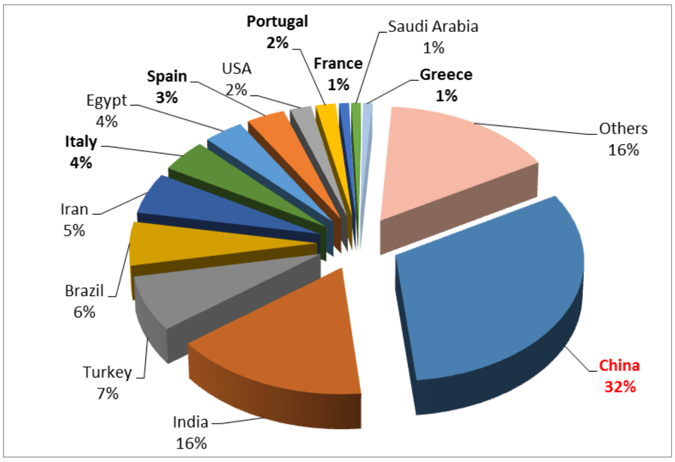

Figure 6. Main stone producers in 2016 (% respect total amount produced).

Based on its composition, 58% of the total production belongs to the calcareous stone type (i.e. Marble, Serpentine, Limestone, Travertine and Onyx), 39% of the total production is covered by siliceous stones (i.e. Granite, Bluestone/Basalt, Slate, Quartzite, Soapstone and Sandstone) and the remaining 3 % is covered by other composition, or mixed ones.

World consumption of natural stones shows a constant positive trend. In the last fifteen years, global stone consumption almost doubled, reaching more than 1500 million square meters in 2016 (Figure 7).

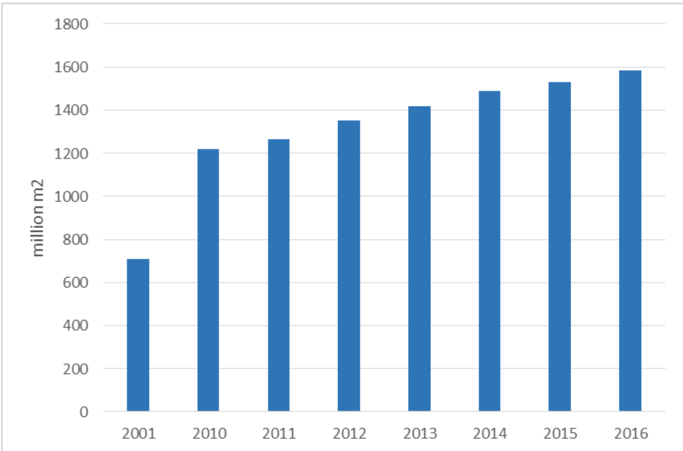

Figure 7. World stone consumption trend

Table 7 analyzes the stones consumption trends in some of the leading countries interested by natural stone trade. In 2016, the consumption of natural stone has grown considerably in Canada, China, India, South Korea, Spain and Turkey, while in all other, the changes have been less significant (below one hundred thousand tons of difference).

More than two-fifths of 2016 consumption came from the three leading countries, China, India, and United States, the first two being the only ones who have passed the hundred million tons. It is important to highlight the remarkable progress of South Korea, whose consumption rose sensibly earning a position at the expense of Brazil and Italy (Table 7).

Table 7. Consumption trends in leading countries, values in thousands of tonnes

	1994	2001	2009	2010	2011	2012	2013	2014	2015	2016
AUSTRALIA	104	131	325	367	453	429	460	473	503	520
AUSTRIA	296	389	442	441	399	388	409	490	478	434
BELGIUM	411	567	871	1.090	1.184	1.048	998	961	830	835
BRAZIL	779	668	2.274	2.313	2.688	2.767	3294	3230	3007	3082
CANADA	171	104	595	618	867	963	925	1024	1413	1573
CHINA	2.238	3.964	11.601	14.533	16.537	19.354	22180	21704	21754	23351
FINLAND	113	184	208	189	141	151	163	157	175	179
FRANCE	1.103	1.415	1.410	1.586	1.601	1.728	1788	1583	1699	1597
GERMANY	1.837	2.328	1.670	1.503	2.008	1.700	1750	2065	1805	1800
GREECE	833	775	744	642	422	268	273	215	214	234
INDIA	983	1.997	4.459	4.712	5.106	5.656	5708	6051	7060	7712
ITALY	2.700	3.231	3.205	3.232	3.084	2.676	2425	2397	2244	2211
JAPAN	2.054	1.862	1.352	1.149	1.095	1.148	1120	1055	878	807
NORWAY	90	169	234	244	300	252	246	316	401	405
POLAND	72	262	584	683	821	729	563	585	583	581
PORTUGAL	314	507	632	601	532	434	366	376	414	401
RUSSIA	338	400	447	701	696	858	927	877	694	758
SINGAPORE	132	125	315	286	280	221	334	331	319	156
SOUTH AFRICA	62	294	275	322	276	338	302	296	272	262
SOUTH KOREA	767	1.371	2.585	2.679	2.838	2.401	2621	2311	2751	3384
SPAIN	1.479	2.437	2.135	2.113	1.764	1.348	1198	1279	1297	1393
TAIWAN	656	1.041	1.035	1.242	1.495	1.588	1284	1341	1214	980
TURKEY	221	578	1.821	1.611	1.551	1.592	1753	2026	1730	1914
USA	1.220	2.889	3.835	4.009	3.849	4.157	4715	5368	5549	5304

2.3.2 International trade

In 2016 the overall budget of international traded stones came to 53.5 million tons, with Asia controlling more than two-thirds of the world exports and almost half of imports.

With regard to the composition of the products being internationally traded, in 2016 the values are similar for calcareous (49% of the total volume) and siliceous (51 % of the total volume).

Figure 8 reports the market shares of the various countries' exports of natural stone. Around 70% of the market share, in terms of value, is detained by seven countries. China has the highest market share, accounting for almost one third of the world market value followed by Italy with 10.2 % of the world market share. It should be mentioned that Italy falls to the fourth place preceded by India in terms of world quantity market share.

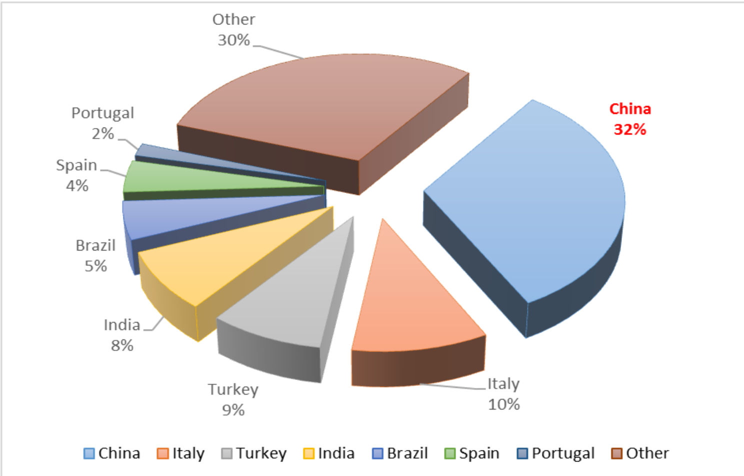

Figure 8. World Export value shares

The same countries accounting for 70% of the production volume share, namely China, India, Turkey, Italy, Brazil, Spain and Portugal (Figure 9), and have exported more than one million tons during 2016. In terms of imports (Figure 10), there are eight countries that have supplied ca. one million tons in 2016; China is leading the imports, followed by South Korea and the United States. In fourth position follows Germany, a traditional leader of European imports.

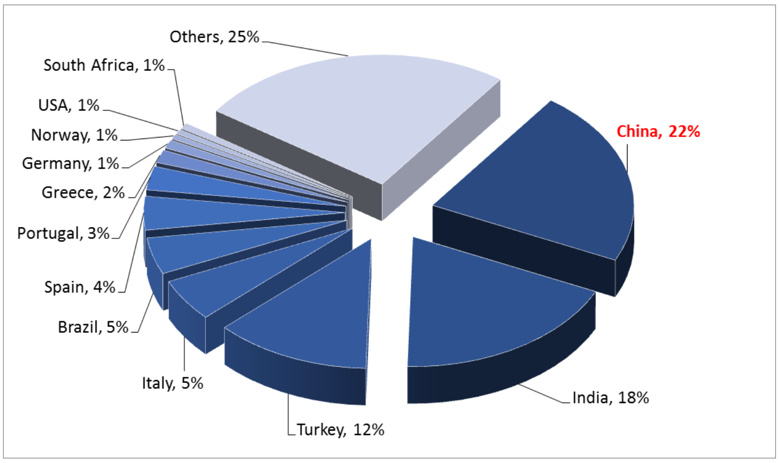

Figure 9. Main exporting and importing countries in 2016

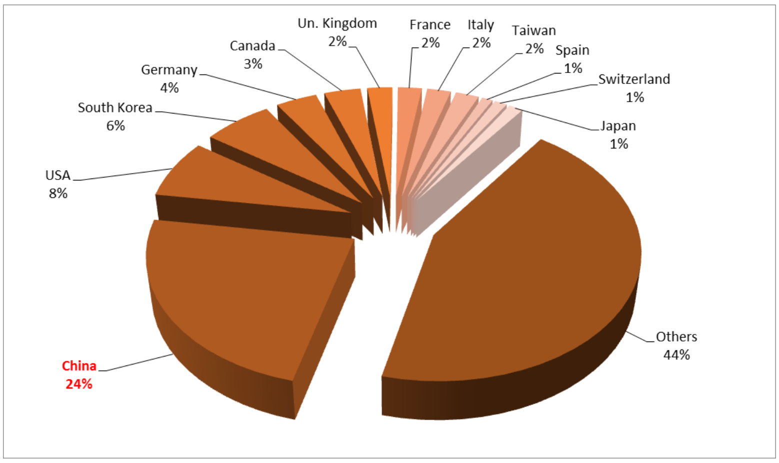

Figure 10. Main importing countries in 2016

2.3.3 European production

In the last years the EU natural stone production has undergone a decreasing trend (Figure 11). In 2016, EU production started to rise again, reaching the 22 million tons produced, ca. 15% of the total world production.

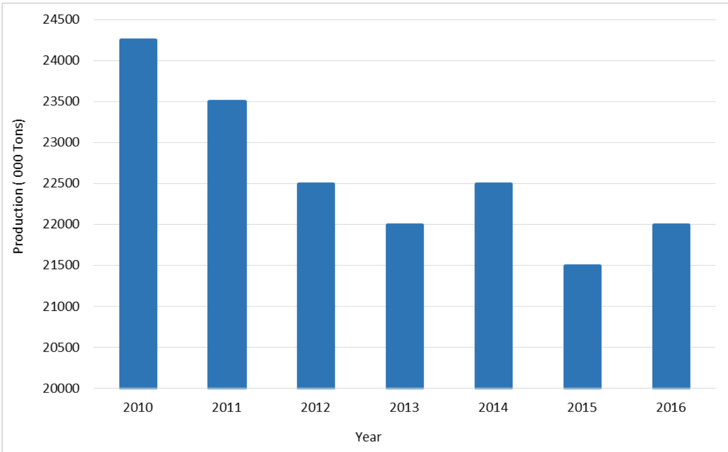

Figure 11. EU stone production (in volume) trend from 2010 to 2016.

The distribution of manufactures within Europe is represented in Figure 12. Italy, Spain and Portugal account for more than two thirds of the European stone production (63%), with Italy leading the group with 30% of the total volume.

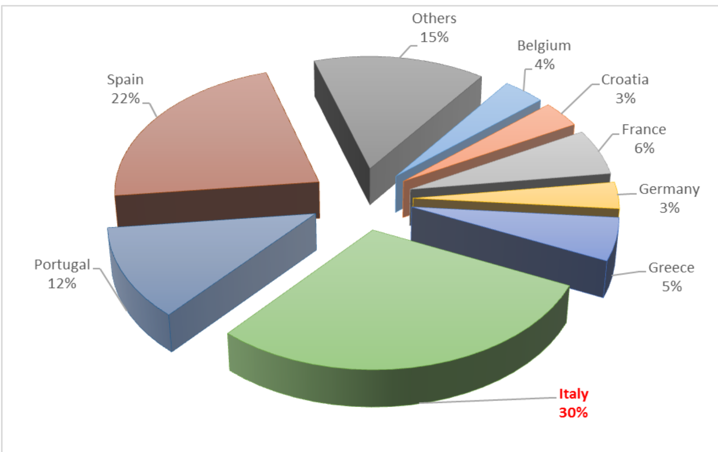

Figure 12. Main EU manufactures (% volume) in 2016

Figure 13 shows the trend of European stone production by mass from 2010 to 2016, with a focus on the three main European producers.

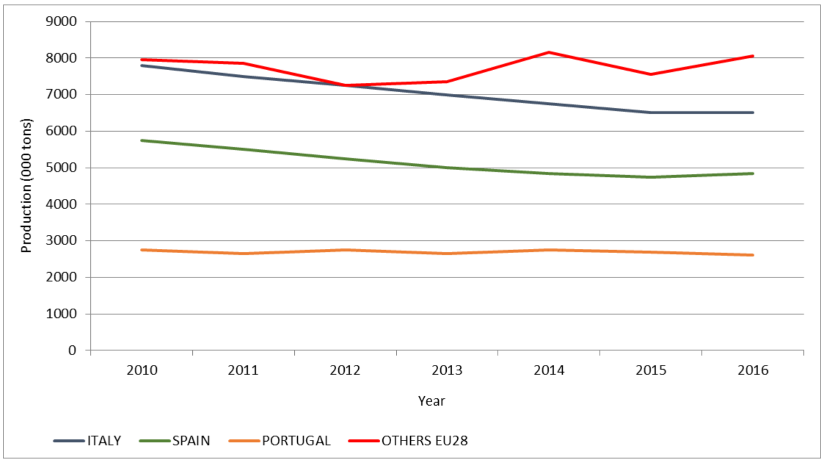

Figure 13. Main European stone producers trend (by mass**).**

2.3.4 European exports and imports

Within the European Union, in 2016 total exports of natural stone products reached 10.1 million tons, which represents a reduction of of 7.8 % compared to total exports in 2015. AS in previous years, Italy, Spain and Portugal are leading the market, representing almost 65% of the total European exports. The other European countries, except from Greece and Germany, have a complementary role in export (Figure 14).

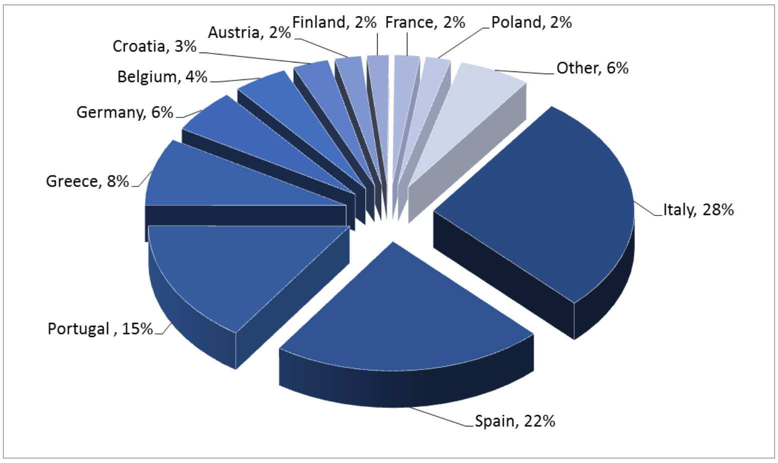

Figure 14. Main EU exporting countries, by mass (2016)

In 2016, European imports of natural stone products reached 10.2 million tons. As for exports, a geographical concentration can be observed, with 53% of total imports coming from only four countries (Germany, United Kingdom, Italy and France) where the domestic production is insufficient to meet their market demand (Figure 15).

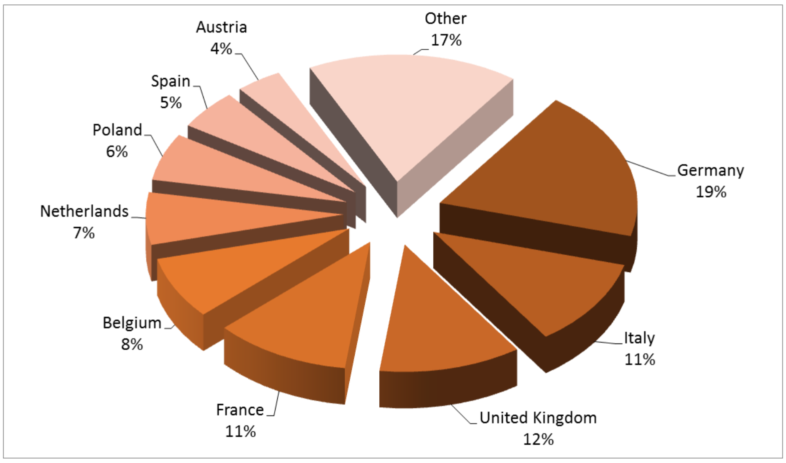

Figure 15. Main EU importing countries, by mass (2016)

2.4 Review of production technology and any innovations

Several innovations and technology improvements have been registered in the natural stone product group sector. The steady growth in market demand triggered the change towards more efficient production technologies and a consistent reduction of raw material waste. Some technological changes were also forced to meet more recent and strict environmental legislation. Figure 16 shows the areas (green circles) where major changes occurred, which will be further discussed.

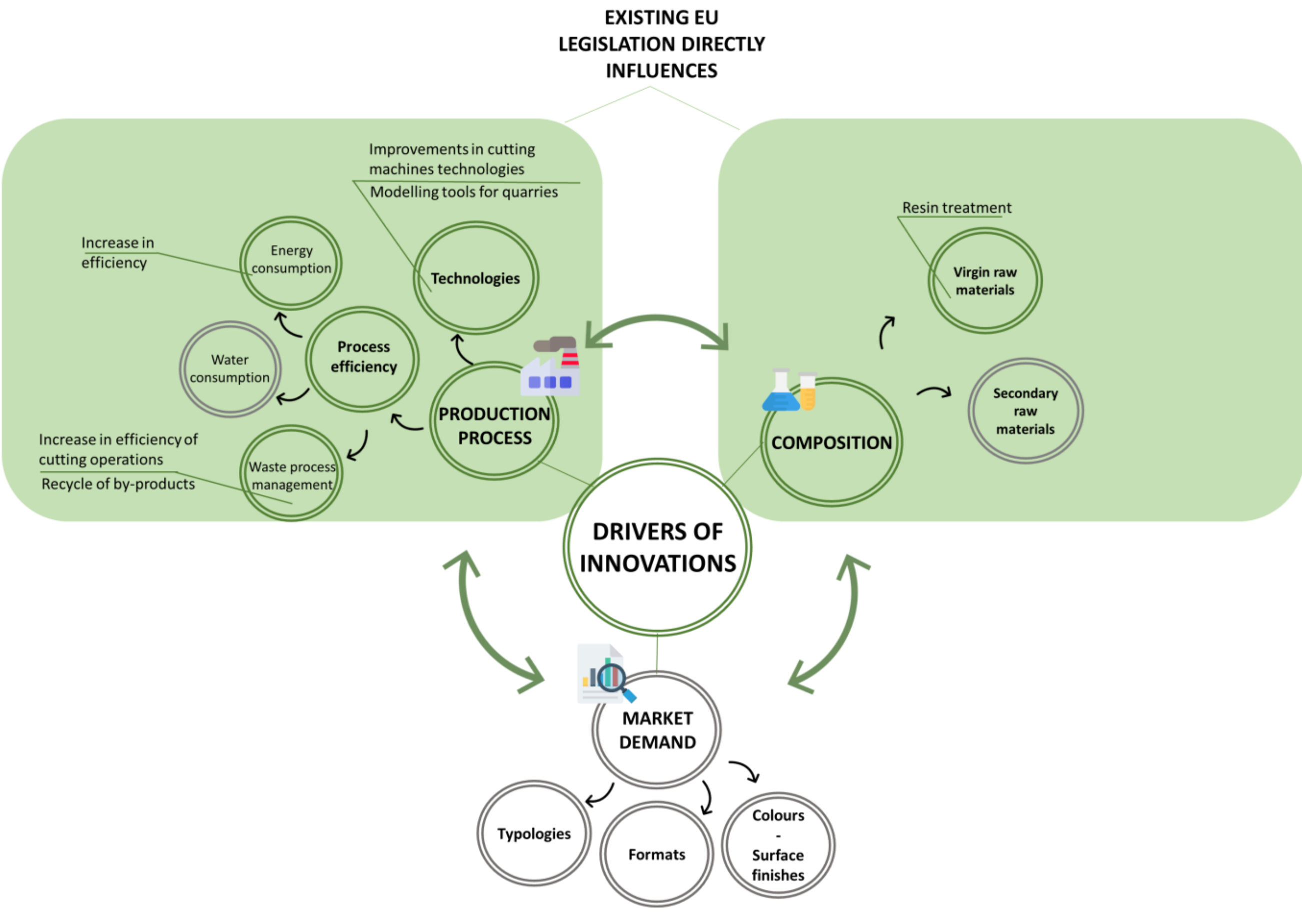

Figure 16. Main improvements and innovations for natural stones.

2.4.1 Manufacturing process

The manufacturing process, as showed in Figure 17, consists in three main stages: (1) the quarrying (extraction) operations, (2) the processing operations, subdivided into cutting and finishing operations, and (3) packaging and storage operations.

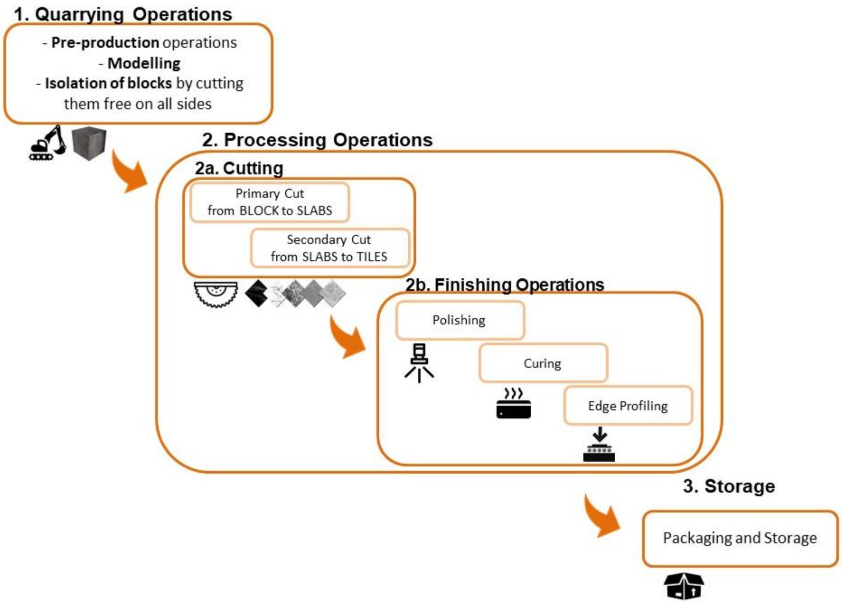

Figure 17. Main stages of the natural stones manufacturing process.

Quarrying operations

Extraction (more commonly referred to as quarrying) consists of removing blocks or pieces of stone from an identified and unearthed geologic deposit. Differences in the particular quarrying techniques used often stems from variations in the physical properties of the deposit itself—such as density, fracturing/bedding planes, and depth—financial considerations, and the site owner's preference. Nevertheless, the process is relatively simple: locate or create (minimal) breaks in the stone, remove the stone using heavy machinery, secure the stone on a vehicle for transport, and move the material to storage.

The first step in quarrying is to gain access to the natural stone deposit. This is achieved by removing the layer of earth, vegetation, and rock unsuitable for product—collectively referred to as overburden—with heavy equipment that is sometimes coupled with small explosive charges. The overburden is then transferred to onsite storage for potential use in later reclamation of the site. This stage usually requires the highest amounts of energy and water, and produces the largest amount of raw material waste, considering the current range of excavation yield varying between 25 to 45%[28]. The percentage of waste is very variable from quarry to quarry but also within the same quarry. This is due to the fact that stone is a natural material and, as a consequence, its properties are not homogeneous; moreover some quarrying techniques can cause damages to stone benches and in other cases natural discontinuities can cause bench ruptures.

[28] Internazionale marmi e macchine Carrara S.p.A. (2017). Stone Sector 2017 Trade and Innovation. International Trade and Innovation in the dimension stone sector.

While in the past, quarrying of dimension stone was carried out by traditional methods, it is evolving from a technical point of view to develop remote non-invasive techniques, requiring inputs from geology and mining engineering, ranging through blasting technology, non-explosive rock breaking, rock mechanics, quarry design (3D models[29]), geostatistics and reserves evaluation.

There is no one universally applicable quarrying method, and the engineering involved in planning and operating a dimension stone quarry is well versed in a variety of cutting and splitting techniques, as well as has a thorough understanding of both the geology and the physical properties of the material he is extracting in order to design an optimum mining method for that quarry. Typical quarrying methods include:

<u>Drilling and splitting</u>, generally utilized for granites. This technique is the most traditional and consists in drilling holes on top of the rock, which are then used as guide to insert the detonation cord, or other explosives, to split the blocks from the rock face. This is the least efficient and precise extraction method since the explosion provokes large amount of waste material as well as unfinished blocks of various sizes and shapes, which will have to undergo through further cutting and finishing processes.

<u>Hydraulic drilling</u>: particular hydraulic driller for rotation and advancing. This characteristic allows obtaining top performances not obtainable with traditional systems: exceptional drilling speed, low air consumption, light weigh, small dimensions, and deviation error free. It can drill in every position (horizontal or vertical).

<u>Chain-sawing,</u> generally utilized in limestone quarries, with well-organised bench structures. Chainsaw machines are used for vertical and horizontal cuts, to produce large blocks of natural stones that are low to medium abrasive, and with a soft to medium strength, in both underground and surface mining operations[31]. A chain saw's cutting performance is dependent both on geological and geotechnical features of the quarry, design of the machine, and operational conditions. Generally, these machines produce an efficient working environment, since they create less waste material and dust, eliminate friction problems, do not need drill holes to guide the cut, and produce directly saleable blocks. However, they cannot be used to cut neither very hard and abrasive stones nor heavily fractured deposits[30].

<u>Diamond wire cutting (DWC)</u>, generally utilized for marbles and in some granite quarries. The diamond wire cutting machinery is easy to handle and cost effective, however it is also potentially hazardous due to possible breakages of the wire[31]. This method requires drilling holes to guide the wire for each cutting cycle, in which the bank of marble is cut from the rock face, as well as a continuous water flow for cooling the wire. The cooling water is also useful in abating the fine dust that is generated during the rock sawing and that it settles at the base of the cutting area.

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[29] D. González-Aguilera et al 3D Modelling and accuracy assessment of granite quarry using unmanned aerial vehicle. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume I-3, 2012 XXII ISPRS Congress, 25 August – 01 September 2012, Melbourne, Australia

[30] Copur, H., Balci, C., Tumac, D., & Bilgin, N. (2011). Field and laboratory studies on natural stones leading to empirical performance prediction of chain saw machines. International Journal Of Rock Mechanics And Mining Sciences, 48(2), 269-282. http://dx.doi.org/10.1016/j.ijrmms.2010.11.011

[31] Hekimoglu, O. (2014). Studies on increasing the performance of chain saw machines for mechanical excavation of marbles and natural stones. International Journal of Rock Mechanics and Mining Sciences, 72, pp.230-241.

Combination of chainsaw and diamond wire saw[30]*:* it may be used to implement the efficiency and versatility of chainsaw machines with the hardness of diamonds and therefore successfully quarrying harder natural stones such as marble.

Air and hydro bags[32]: generally utilized to enable the splitting of blocks from the rock face. They consist of dilating hydraulic cushion that can expand, under the pressure of air or water, and exert a thrusting force respectively up to 200 and 1000 tons per cushion. Considering their thickness when empty, they can easily fit into the space of a wire saw cut. They can be reused until any breakages are verified.

Detonating cord: currently utilized rarely and mainly in particular circumstances, for instance for blasting large portions of barren rock.

Once the block has been isolated and removed from the rock face, it can be further subdivided to reduce the size and produce smaller blocks. The constraints for the maximum block width are given by safety factors in handling and transportation of the blocks as well as the dimensions of machineries used to cut the block to produce slabs (primary cut). Afterwards, the slabs or blocks of natural stone are transported to the processing site[33].

Processing operations

Processing operations include much more variation than extraction, depending both by rock characteristics and the final product specifications. The basic processing sequence includes (a) cutting (primary and secondary cut) and (b) finishing operations (polishing, curing, edge profiling).

(a) Cutting

The blocks obtained at the quarry blocks are sent to factories for the manufacturing of the finished products that are used in building sites. The block is delivered at the factory and cut into thin layers called slabs or boards. These are typically 2-4 cm thick, but any thickness is possible. When the block is large enough, the cutting is usually done on machines called "weavers". When the blocks are smaller, the cutting is performed with rock cuttings. The boards of finished products are further divided into smaller pieces, usually on request. The most common examples are plates for cladding, paving tiles, pavers, kitchen worktops, washbasins etc.

Diamond blades are normally used although, for special formats, other systems such as water jet cutting can be also used. A short description of different types is given below.

Monowire and monoblade machines, whose wire and blade can respectively be made of diamond, used to give rectangular shape to irregular block as well as for the production of slabs of varying thickness. Their use significantly improves the productivity of the cutting process as it helps achieving a better cutting efficiency and reducing the material waste. The monowire has a higher feed rate while the monoblade has a narrower cut and a longer lifetime but a lower productivity level[30].

Multiblade gang-saw, used for cutting blocks into slabs of limited thickness.

[32] Korman, T., Kujundžić, T. and Kuhinek, D. (2015). Simulation of the chain saw cutting process with a linear cutting machine. International Journal of Rock Mechanics and Mining Sciences, 78, pp.283-289.

[33] Gazi, A., Skevis, G., & Founti, M. (2012). Energy efficiency and environmental assessment of a typical marble quarry and processing plant. Journal of Cleaner Production, 32, 10-21. http://dx.doi.org/10.1016/j.jclepro.2012.03.007.

Block and bridge cutters, which can be mono or multi blade and of many dimensions according to the type of production and final products, generally used to produce tiles or cut-to-size products.

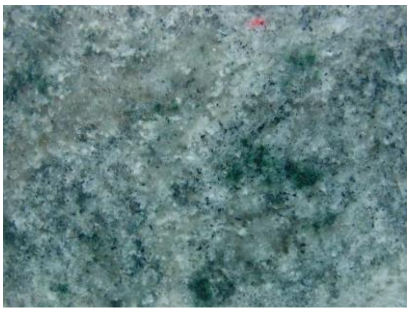
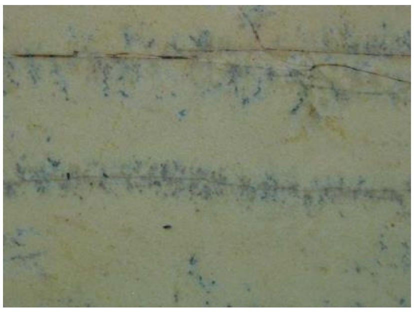
Water jet cutting, which uses a highly pressurized water flow containing abrasive materials passing through a small-diameter nozzle.

(b) Finishing

The surface finish of the stone determines its roughness or texture and also its tonality. The smoother the surface finish, the more the tonality of the stone darkens. This is specially the case with polished rocks.

The most common surface finishes are:

- ***Polished***: this treatment is applied with fine grain grinds and subsequent polishing with alumina powder, iron oxalate or other similar products which continuously appear on the market. This surface is very smooth and not porous.
- ***Grinded***: this surface finishing is achieved using carborundum grinding of grain size 60.
- ***Honed***: this surface finish is achieved with carborundum grinding of grain size greater than 120. Provides a flat to low sheen gloss. This surface is very smooth, but often very porous. This texture is common in high traffic buildings. Honed floors should always be protected with penetrating sealer because it has wide-open pores. Honed stone colours are not as vibrant as polished stone.
- ***"Bush-hammered"***: this finish is obtained through the continuous beating of a hammer, or buss hammer, with square pyramidal elements on its face side, which provide a rough finishing.
- ***Flamed***: this kind of finish is obtained with a thermal lance at a temperature of 1.200°C, which causes the release of small particles. This provides a very rough surface finish. This surface is very porous and must be treated with an impregnator.
- ***"Apiconado":*** this surface finishing is obtained "chipping" the piece by hand with a suitable chipping hammer.
- ***Sliced***: this is rough finishing which can be achieved by parting the piece with a press with two blades which breaks the material and creates a rough surface.

	
Polished granite	Honed dolomitic marble

 Bush-hammered limestone	 Flamed basalt
 Apiconada" sandstone	 Sliced limestone

***Figure 18**. Most common surface finishing (source Natural Stone in Aragon [34])*

Regarding colour, natural stone is probably the building material with the widest colour range, which, together with its natural or man-made textures, provides endless design possibilities for designers. This variability is related to rock formation mechanisms.

Indeed, the large numbers of completely random variables involved in rock formation processes, which are controlled solely by the physical and chemical laws of nature, provide us with a large range of varieties. However, such diversity does not occur at every quarry and may only apply to a single one, even at the same operation level. Nevertheless, it should be noted that changes in tonality, texture and overall appearance are to be expected in natural stone. This may give natural stone its competitive advantage over other monotonously uniform.

Common equipment used in the finishing process:

- Polishing machines, used to adjust the product thickness to a prescribed tolerance and to give light reflecting properties to the stone surface.
- Possible modules for resin application, combined with curing treatment machines, which use either ultraviolet or infrared radiation for curing.
- Bush-hammering tools, ribbing and polishing heads, used for the texturization of the surface, to acquire specific visual effects as well as to make them suitable for anti-slipping applications,
- Edge profiling machines, is used to give the desired inclination to the upper edges of each product.

Most of the equipment in the processing plant utilizes a large amount of water. The waste water contains considerable quantities of dust and stone residues and therefore a waste

[34] http://www.aragon.es/estaticos/GobiernoAragon/Departamentos/IndustriaInnovacion/Areas/Mineria/Natural%20Stone%20in%20Aragon.pdf

water treatment facility is required in order to reuse water. The configuration of the latter may vary from plant to plant, but it accustomed to obtain a water recycling efficiency of 70 to 90%[35].

Treatments for improvements

Finished products are usually subjected to different improvement treatments in order to increase the durability of the product. The most common improvement treatments are the following:

- Board unseen side reinforcement with nylon mesh and resins.
- Filling of holes and hollows of the face side with special fillers.
- Priming with fluid resins in order to seal open pores of the stone.

Packaging and Storage

The processed and finished natural stone's tile, slab or block are stored in designated warehouses or directly distributed to consumers after packaging, which generally consists of wooden boxes and plastic film for further protection of the products.

2.4.2 Innovations and improvements

The steady growth in demand has triggered a general trend towards the adoption of a more efficient and professional approach to natural stone production. Production technologies have developed during the past three decades although these developments have been incremental rather than revolutionary. The main innovations and developments are described and discussed in the following paragraphs.

Increase yield of excavation - Resin treatments

Treatments with epoxy resins, both during quarrying and processing operations, have become widely common. They are used both to increase the yield of excavation (up to 80%), to reinforce the blocks' mechanical properties and reduce breakages during processing, as well as to improve safety, performances and mechanical homogeneity of the final product[36]. These treatments are mostly implemented with marble rocks.

In a recently patented process, the application of epoxy resins is performed by injecting the resin between the stone block (usually marble) and a layer of an air-proof material secured to the quarry bank. The function of the latter is, through specific portable pumps, to make the quarry bank vacuum-sealed.

Reduction energy consumption - Chain saw performances

Chain saw machines are used for cutting low abrasive soft to medium strength natural stones, such as, travertine and marble, in both, underground and surface quarries. They can perform both vertical and horizontal cuts and usually are used together with diamond wire cutting machines. Using chain saws for dimensional stone production increases the overall performance of the quarries by providing for higher quality product, reducing

[35] Careddu, N., & Siotto, G. (2011). Promoting ecological sustainable planning for natural stone quarrying. The case of the Orosei Marble Producing Area in Eastern Sardinia. Resources Policy, 36(4), 304-314. http://dx.doi.org/10.1016/j.resourpol.2011.07.002

[36] López-Buendía, A., Guillem, C., Cuevas, J., Mateos, F. and Montoto, M. (2013). Natural stone reinforcement of discontinuities with resin for industrial processing. Engineering Geology, 166, pp.39-51.

production losses to enter a new face and time losses for horizontal borehole drilling and wire placement.

Chain saw performance depends on geological conditions of the quarry, chain saw mechanical features/specifications, and operational parameters. Geological parameters include rock mass properties such as joint set number and frequency, dip and direction of the deposit, and intact rock properties such as uniaxial compressive strength, tensile strength, elastic properties, texture and petrographic properties. Mechanical parameters include torque-power-thrust capacities, jib (boom) length, lacing design of the cutting tools and cutting tool properties. Operational parameters include jib cutting angle, chain rotation speed, and water feeding when cutting, cutting vertical or horizontal, jib cutting angle, quality of labour, material availability, etc. In this context, analysis of chain saw performance is an important subject.

Research is ongoing to optimise operational parameters[32] and the wear of the cutting tools. For example, increasing the depth of cut[32], the energy spent decreases in relation to the amount of material cut, thus improving the chain saw performances. The development of high-performance components, such as nanometric deposits used as a metal substrate in the cutting tools[28] which have self-lubricating properties, resulting in up to 50% reduction of the friction coefficient, and an extended lifespan.

Improving the operational parameters leads to a reduction of energy consumption with a consequent productivity increase; while reducing the tools' wear leads to an energy and cost decrease for production industries.

Waste reduction - Diamond wire cutting

Diamond wire cutting produces less waste compared to traditional blades, which can amount to significant savings when working with expensive materials, and unlike slurry saws that use bare wire paired with an abrasive cutting fluid which can be challenging to dispose of, DWC uses plain water (or oil), and some materials can even be cut dry.

The main technological improvements are related to the wire speed and the rotation angle.

- The wire speed range, commonly varying between 30–38 m/s[37], is with current technologies increased to 40 up to 45 m/s.
- The rotation angle. Diamond wire saws are capable of cutting in all directions, including perpendicular cutting, horizontal cutting and slope cutting.

Improving wire speed and rotation angle lead to a reduction of energy consumption with a consequent productivity increase.

Waste reduction - Modelling methods for cutting optimization

The importance of assessing quarries' properties before extraction activities begin, such as changes in material, fractures, discontinuity and rock homogeneity, has been emphasised by several scientific studies as well as by sector's associations and companies themselves, whose main scope is the evaluation of the productivity of the natural stone reserve. New advanced 3D modelling tools allow such explorations. A

[37] Cardu, Marilena & Giraudi, Alessandro & Murthy, V. (2011). Evaluation of dimension stone cutting by diamond wire saw in two marble quarries. Diamond Tooling Journal.

recent study from Yarahmadi et al. (2018)[38] gives an exhaustive perspective on all studies concerning methods for in-situ block geometry identification applicable to the natural stone industry.

- 3D modelling tools allow to extract stones with the required properties, and to reduce stone waste upon cutting. Several 3D modelling methods have been developed being the most relevant:
- Ground-Penetrating Radar (GPR)[33], which allows for a semi-quantitative evaluation of quality and homogeneity of massive rocks, potentially leading to primary waste reduction.
- Geometric characterization of in-situ blocks, which consists in the identification of shape and volume of blocks with the aim of optimize the extraction defining the most productive cutting pattern.
- Algorithms for rock cutting optimizations[39].

<u>Waste reduction /Increase of productivity – Consolidation of stone</u>

In general, environmental benefits of the consolidation of natural stone are:

- Increased effectiveness of the natural stone production chain by increasing the cohesion of fractured blocks and slabs by means of environmentally friendly consolidating agents based on water based resins.
- Reduction of the emission of pollutants (VOC) to atmosphere by substituting organic consolidating agents by water based resins.
- Increased durability of natural stone. Reduction in maintenance works after placing.

Use of water borne resin for consolidation instead of the widely use of volatile organic resins. The aim has been the development of consolidation technologies based in water borne epoxy dispersions or construction stones, which do not imply the use of toxic and irritating compounds. The epoxy resins are the consolidants providing the best performance and the most commonly used for ornamental stones. However, labour and environmental health problems caused by the use of the current epoxy resin coatings can be reduced. New formulations based on waterborne epoxy dispersions able to substitute the current solvent based epoxy resins were tested for natural stone consolidation, considering the parameters affecting the epoxy/amine/additive formulations, which determine its consolidation capacity. Solvent based adhesives have currently great importance and wide number of applications. However, because of economic, environmental and health reasons, these adhesives are suffering a hard social pressure.

The growing interest of the water based emulsions industries is due to the non flammability, non toxicity and the European environmental regulations (Directive 99/13/CE), which are more and more exigent respect to the VOC emissions. Water based adhesives are in most cases efficient alternatives respect to the solvent based adhesives.

Main breakthrough is the substitution of the epoxy resins commonly used (thermosetting polymers) for the natural stone consolidation. These resins contain toxic and irritant components (between 50-70% of toxic components). Epoxy resins based on water based

[38] Yarahmadi, R., Bagherpour, R., Taherian, S. and Sousa, L. (2018). Discontinuity modelling and rock block geometry identification to optimize production in dimension stone quarries. Engineering Geology, 232, pp.22-33.

[39] Fernández-de Arriba, M., Díaz-Fernández, M., González-Nicieza, C., Álvarez-Fernández, M., & Álvarez-Vigil, A. (2013). A computational algorithm for rock cutting optimisation from primary blocks. Retrieved 15 January 2018, from

emulsions are the alternative. The technological impact is very high due to the wide number of applications of the epoxy based consolidants: in-situ cultural heritage and building restoration, reinforcement of dimensional natural stone, etc.

Dust reduction – Respirable Crystalline silica

Respirable crystalline silica is one of the substances with the highest respiratory health risk to stone manufacture workers, together with asbestos. Crystalline silica is a natural component of the earth's crust and is a basic component of sand, quartz, and granite rock (Table 8).

Table 8. Crystalline Silica concentration in common materials

Sandstone, gritstone, quartzite, flint	More than 70%
Concrete, mortar	25% -70 %
Slate	Up to 40 %
Granite	Up to 30%
Basalt, dolerite	Up to 5%

Source: - http://www.hse.gov.uk/pubns/guidance/cnseries.htm

Respirable crystalline silica is created when cutting, sawing, grinding, drilling, and crushing stone (also applicable to rock, concrete, brick, block, and mortar), abrasive blasting with sand; manufacturing stone countertops resulting in worker exposures to respirable crystalline silica dust. Workers who inhale these very small crystalline silica particles are at increased risk of developing serious silica-related diseases, including: silicosis, an incurable lung disease that can lead to disability and death; lung cancer; chronic obstructive pulmonary disease; and kidney disease.

A Binding Occupational Exposure Limit Value of 0.1 mg/m^3 for Respirable Crystalline Silica Dust is set in the Directive (EU) 2017/239840 of 12 December 2017 amending Directive 2004/37/EC on the Protection of Workers from the risks related to exposure to Carcinogens or Mutagens at work. Several countries have adopted stringent occupational health and safety rules in a bid to reduce or eliminate workers' exposure to granite dust. For example Spain a lower rate a lower rate of 0.05 mg/m^3 has been adopted[41].

As occupational health regulations are becoming increasingly severe and demanding with respect to respirable crystalline silica dust particle exposure among workers the conventional methods for reducing exposure to dust based on water to supress dust or equip grinders and saws with ventilation devices that capture and route dust to an industrial type vacuum have been improved. In this context is worth to mention innovative solutions like the design of special polycarbonate and steel structures to confine the cutting installations[42]. A reduction of 30% of the dust produced has been measured.

[40] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017L2398&from=EN
[41] http://www.insht.es/InshtWeb/Contenidos/Documentacion/LEP%20_VALORES%20LIMITE/Valores%20limite/Limites2018/Limites2018.pdf (page 103)
[42] http://www.fctgranito.es/blog.php?b=157. Grupo Levantina and Cluster del Granito

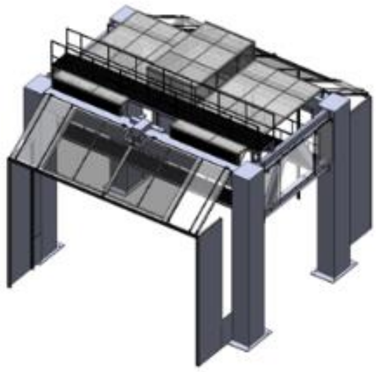


Figure 19. View of polycarbonate–steel structure (source Fundación Centro Tecnológico)

Material waste management

As it has been described above there are two main sources of material waste production: quarrying (>50%) and processing of manufacturing (30-40%) the final product.

Figure 20 depicted the whole production cycle indicating the different operational activities where wastes are produced. The main types of "wastes" are.

- Quarrying waste types:
  - Defective block
  - Large irregular blocks
  - Small irregular blocks
  - Small particles and fine size sand and slurry
- Processing waste types:
  - Large to medium size broken pieces called scrap
  - Medium to small size pieces like splints, flakes, chips
  - Fine size particles mainly in the form of slurry.

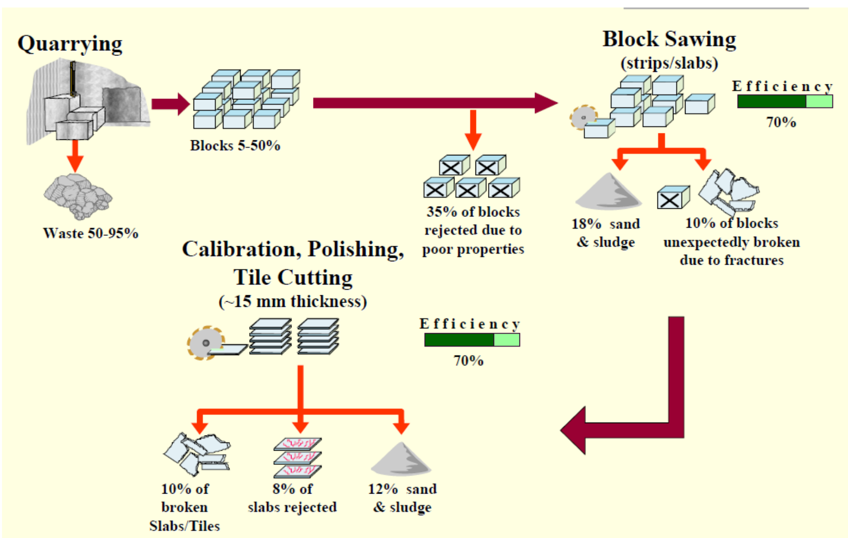


Figure 20. Natural Stone production chain (source G. Papantonououlos)[43]

[43] G. Papantonopoulos et al . 3rd International Conference on Sustainable Development Indicators in the Minerals Industry

The waste management is achieved through both the modification of process to adopt cleaner technologies and the reuse/recycling of "waste" materials". In Table **9** are summarised different options and tand best preactices that can be applied for optimisation of waste management.

Table 9. Options for material waste management (*)

	Operation	**Techniques/Methods**
PREVENTION / WASTE REDUCTION	Quarrying	Using of clean technologies like diamond tools, ramps and access roads, Adopting exploitation methods like underground quarrying
	Manufacturing	Reinforcement of mechanically unsound blocks Thinner cutting disks Recycle of slurries with decantation and pressing
WASTE RECYCLING/RECOVERY	Quarrying	Using third choice blocks as low price elements for external uses Using large shapeless blocks for armourstone and aggregates Using small shapeless blocks as aggregates Using small *to fine size particles for* construction admixtures, plasters and mortars
	Manufacturing	Using scraps for low-cost rustic floorings and coverings, generally for outdoor applications Scraps, splints can be crushed for aggregate production Splints, chips can be used for aggregate Using splints as land-fillers for agricultural purposes Using calcareous sludge to: neutralize acidic industry by-products or contaminated agricultural land de-sulphurise the fumes produced by high-power thermoelectric plants as additive in hydraulic mixtures, plasters. produce paper fillers, polymeric fillers (PVC), water paints, artificial stones. Using granite sludge produced by disk saws or by the polishing process in: ceramic industry moulding of plastics (PVC) when the inert material does not need to be calcareous.
DISPOSA L	Final	Common disposal sites for quarry clusters Careful selection of disposal site Backfilling if possible Special treatment of sludge

(*) three waste management levels according to the Directive 2008/98/EC

New applications

Natural stones, like any other construction material, are not unaffected by the development of new products, which mainly result from technological advances both in cutting processes and adhesives. In this regard, it is worth mentioning: the tiles or panels involving a stone slice of about 4-5mm in thickness to which a cheaper material has been adhered with suitable adhesives, thereby providing the material with enough rigidity. The materials used on the stone may be ceramic or made of fibre cement, or they may be lightweight honeycombed aluminium structures or a nylon mesh with a thick enough layer of resin.

The main advantage is a more efficient use of the mineral resources since these products require a smaller volume of stone material per square metre of covered area. Some products, especially those with honeycombed structures, allow to manufacture large but very light panels, which significantly improves installation process.

Other rather novel products in the market are the so-called aged stone units. These are pieces that have been subjected to physical erosion treatments with abrasives, such as steel shot projection, or chemical erosion, which provides them with a rough, altered look similar to that of those materials that have been degraded by use and or by the passing of time.

2.5 Life Cycle Assessment: natural stone (marble and granite)

The main environmental impacts associated with the production of natural stone-based products are broadly split between impacts at the quarry (where blocks are produced) and impacts at the processing plant (where blocks are processed into tile or slab products). Impacts such as noise and vibration are not well captured by LCA methodologies while the emission of dust may be highly localised and difficult to link to human toxicity effects if very few people are actually exposed to the dust.

Impacts due to water consumption are difficult to capture on the quarry in cases were rainwater is used. There is very little data available about the types of contaminants and their concentrations in wastewater effluents from natural stone processing plants.

More tangible impacts are those associated with the consumption of diesel and electricity to run site vehicles and processing equipment (and their associated emissions) and the impacts on land use.

Quarrying operations cause a great stress on the local environment and especially on the natural habitat. Quarrying carries the potential of destroying habitats and the species they support. Even if the habitats are not directly removed by excavation, they can be indirectly affected and damaged by environmental impacts – such as changes to ground water or surface water that causes some habitats to dry out or others to become flooded. Even noise pollution can have a significant impact on some species and affect their successful reproduction. Nevertheless, with careful planning and management, it is possible to minimise the effect on biodiversity and in fact, quarries can also provide a good opportunity to create new habitats or to restore existing ones. However, as mentioned earlier, LCA methodologies are not well suited to addressing impacts on less tangible aspects such as biodiversity.

The material efficiency of natural stone extraction will have a major effect on the results of any LCA study. Any by-products that can be sold could also influence results via the allocation of impacts. Extraction efficiencies from the quarry generally vary from 25 to 45%, the rest constitutes waste material. Of the successfully extracted material, another 25%[33] may be lost at the processing plant, both due to fractures in the slabs and to the cutting and finishing processes (see Figure 21). Material waste management, therefore, represents a crucial element to be improved and accounted for, especially considering that solid waste and dust from natural stones can be re-used (and its applications are growing) as a by-product in other building and construction materials (e.g. as aggregates in cement, in road construction, in terrazzo tiles, in agglomerated stones).

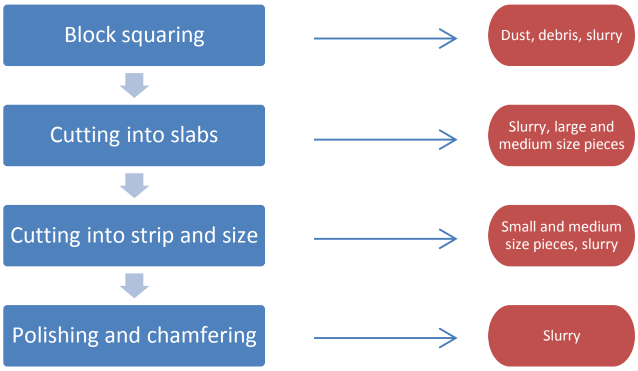


Figure 21. Generation of stone waste.

Screening of available academic literature and technical reports for relevant information relating to the life cycle impacts of natural stone products has been carried out to assess the environmental impacts' trends that are associated with natural stones products available in the European market, and to identify the hotspots across different life cycle stages. Table 10 summarises the main findings of the LCA studies and EPD studied.

Table 10. Summary of main LCA, EPD sources and findings.

Source	**Rock type**	**m²/ton**	**GWP (kg CO_2 eq/ton)**	**AP (kg SO_2 eq/ton)**	**EP (kg PO_4^{-3} eq/ton)**	**POCP (kg C_2H_4 eq/ton)**
Traverso et al., 2010[44]	Marble tiles	n.a.	116,6	0,44	0,03	0,02
Traverso et al., 2010	Marble slabs	n.a.	74,1	0,081	0,02	0,004
Palumbo, E., 2018[45]	Sandstone	n.a.	76,6	0,29	0,02	0,01
Palumbo, E., 2018	Sandstone	n.a.	52,4	0,08	0,02	0,004
Mendoza et al., 2014[46]	Granite	18,99	476	2,28	0,30	0,089
EPD Norge (2015), NEPD-316-192-EN	Quartzite schist	30,90	177	1,06	0,32	0,04
EPD IBU (2018), EPD-FRS-20170102-IBD1-EN	Limestone	25,64	122,8	0,48	0,07	0,03
EPD-EUR-2013253-CBG1-EN – EUROROC (2014)	*Igneous, Sedimentary and Metamorphic*	*9,11*	*255*	*0,73*	*0,068*	*0,042*

44 Traverso et al, Environmental performance of building materials: life cycle assessment of a typical Sicilian marble. Int J Life Cycle Assess (2010) 15:104–114

45 Palumbo, E. LCA Natural Stone. Strumenti e indicatori per la progettazione sostenibile di involucri litici secondo un approccio Life Cycle. Serie Ricerche, Dida Press (2018)

46 Mendoza et al.,Life cycle inventory analysis of granite production from cradle to gate. Int J Life Cycle Assess (2014) 19:153–165 DOI 10.1007/s11367-013-0637-6

In all cases the functional unit is the extraction and production of **1 ton of natural stone's product** with varying thickness and finishing. A reference density of 2.7 ton/m³. has been considered when data were expressed in m³.

In the analysis of the data the following considerations should be taken into account as they can have a large impact

- The mineral composition of the rock type and the characteristics of the quarry. Different ranges of energy and fuel consumption both for pre-production operations, rock extraction and cutting processes. In the table are presented five different rock types: granite, marble, quartzite schist, limestone and sandstone, which have different density and hardness properties.
- The type of final product. Thin tiles require more than one cut, possible reinforcement with polyester resins, and various curing and finishing operations. These steps are energy intensive, therefore additional cutting and finishing operations increase the energy consumption.
- The technologies used both in quarrying and processing operations. The type of technology and machinery determine the process efficiency and energy consumptions. For instance, the use of diamond wire cutting machines entails a much greater energy consumption compared to technologies as drilling and splitting.
- Location and data collection timeframe. The studies considered covered a large European geographical area (Norway, Italy and Greece), and data collection timeframe (2008 – 2017). This has an influence due not only to the different rock type and the quarry characteristics but also to the energy-mixes variety of the countries.

Process energy requirement

Processing operations account for the largest share of environmental impact influence. Energy consumption, generally greater in the processing operations compared to the quarrying operations, represents the main contribution to all the impact categories. Cutting and finishing operations are the main hotspots due to their energy-intensive nature.

Mendoza et al.[46] presented the relative contribution of each unit process to the most significant inputs and outputs of the granite production chain (Figure 22). In the quarrying phase (A1) the relevant inputs flows are the diesel consumption to operate the machineries and vehicles for on-site transportation, 95% of the total fuel requirement, and water consumption, 28% of the total water consumption. The relevant output flow is the production of extractive waste, up to 75%. The manufacturing phase (A3) represents the large majority of all the other energy and material flows and above all the electricity and water consumption, respectively 95% and 72%, to operate the machineries and dissipate heat. On top of these flows are added the ancillary materials consumption, among which steel is the most significant and its use is mainly due to the wearing out of cutting tools, and granite sawdust, generated principally in the sawing process.

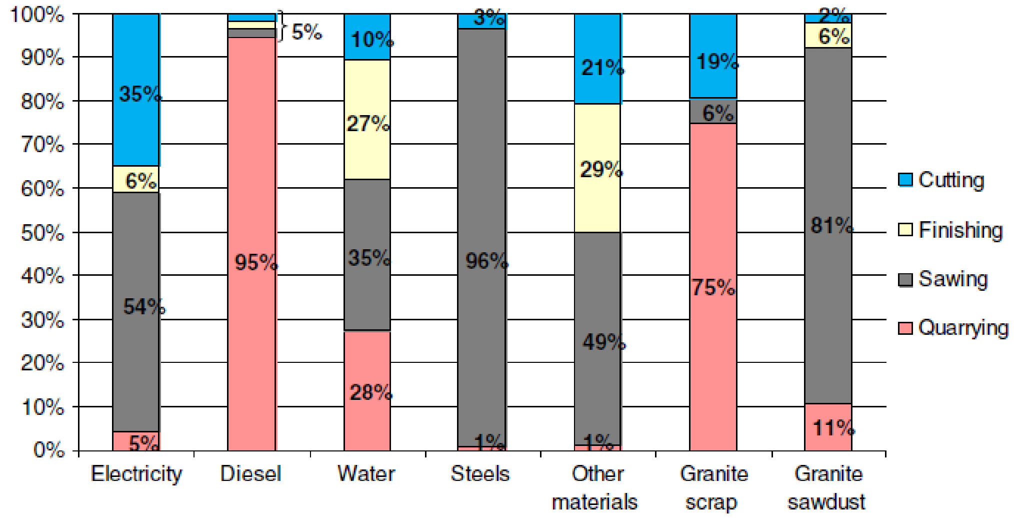


Figure 22. Relative contribution of the life cycle stages to the most significant material and energy input and output flows[47], from Mendoza et al. (2014).

Figure 23 presents the main environmental indicators for extraction and transportation to the processing plant (A1 and A2) and processing (A3). As it is shown in Figure 23 the so called A3 stage account for 35 to 90% of the total impacts for each impact category. These data refer to the extraction and production of 1 ton of sandstone[45]. Nonetheless, these results are similar to other natural stones types , such as granite[46] and sandstone and gneiss[48] (Figure 24).

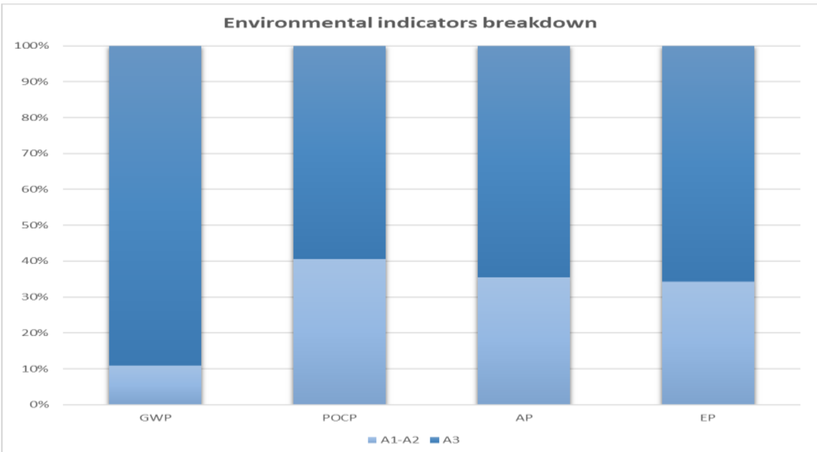


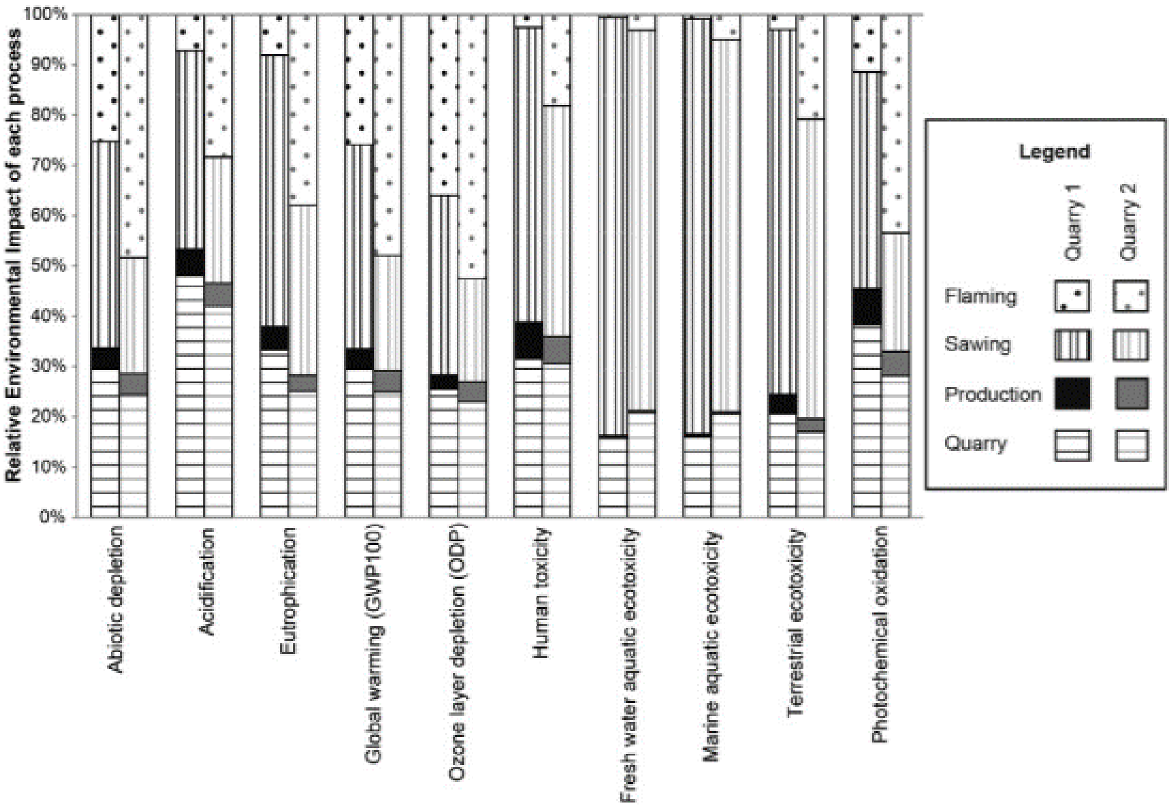
Figure 23. Environmental indicators breakdown referred to sandstone extracted from centre of Italy to produce tiles and slabs respectively of 2-3 and 5 cm.[45]

Ioannidou et al.[48] show for two different quarries that quarrying operations have a lower environmental impact than cutting and finishing operations (Figure 24). The results for both sites were similar for extraction and production processes regardless of the technologies applied, however for energy demanding processes, as sawing and flaming stages, the use of different technologies and energy-mixes entails a significant influence on the overall environmental impacts. For products that do not require a second cutting

[47] Quarrying includes all the extractive operations, Sawing is referred to the primary cuts (from blocks to slabs and panels), Finishing process includes: polishing, sandblasting, flaming and bush hammering; and Cutting to secondary cuts (from slabs to tiles of specific dimensions);.

[48] Ioannidou, D., Zerbi, S., Habert, G. When more is better a Comparative LCA of wall systems with stone. Building and Environment 82 (2014) 628-639. DOI 10.1016/j.buildenv.2014.10.004

of finishing process, as this is the case for slabs, the overall environmental profile decreases significantly, and the impacts' distribution is more balanced between the extraction and processing stages.



(*) Quarry includes: all the extractive operations (diamond wire, diamond wire and blasting); in "Sawing" are included all the operations related to the sawing and cutting from blocks to tiles of desired dimensions; in "Flaming" are specifically considered all the process flows related to flaming (propane, oxygen and acetylene); in "Production" are instead grouped all the general process flows related to the workshop and not directly included in any other process.

(**) Tile size: 40*40*4 cm

Figure 24. Single process contribution to LCA impact categories of the production of tiles (Ioannidou et al.)[48]

The energy consumption, higher in the processing stage and specifically in the cutting and finishing operations, has been identified as an environmental hot spot.

Influence of thickness of the final product

In order to consider all factors influencing energy consumption and other environmental aspects, features as final product thickness and the rock type should also be taken into account.

Palumbo et al. show that the nature of the stone detemine the amount of energy required for the extraction and processing steps and therefore on their environmental profile. However, the impacts decrease as the thickness tile increases, pointing out the significance of the characteristics of the final product in determining its environmental profile (see Figure 25).

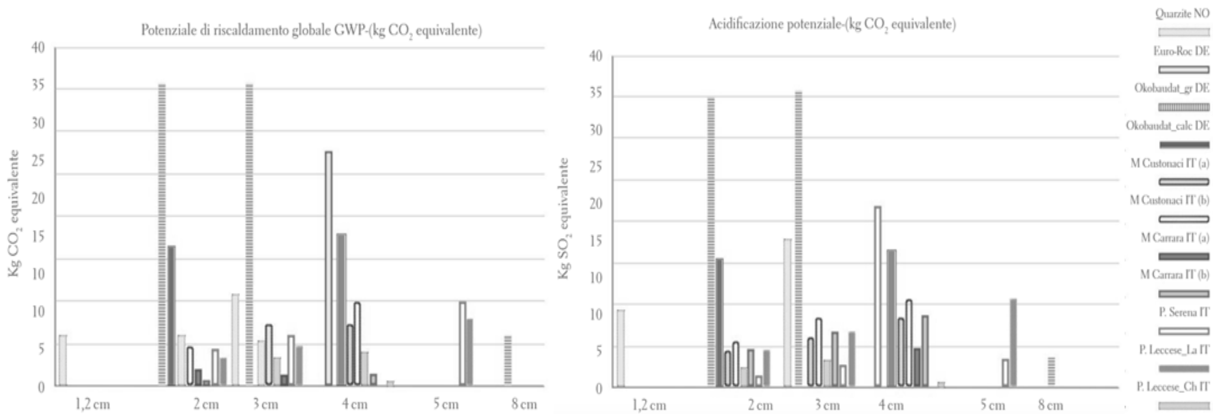


Figure 25. Impacts according to thickness and rock type (from Palumbo, 2018)

Ioanninodou et al. (2014) also investigated the influence of the thickness tile.Their findings (Figure 26) show that an increase in tile thickness results in a decrease in the environmental impact of the product (smaller amount removed during sawing, less treatment involved). If the functional unit is chosen to be 1 m^2, then the environmental impact increases with an increase of thickness. This is logical, since the volume extracted that corresponds to a specific surface increases, even though values for sawing and flaming corresponding to this surface area remain almost constant.

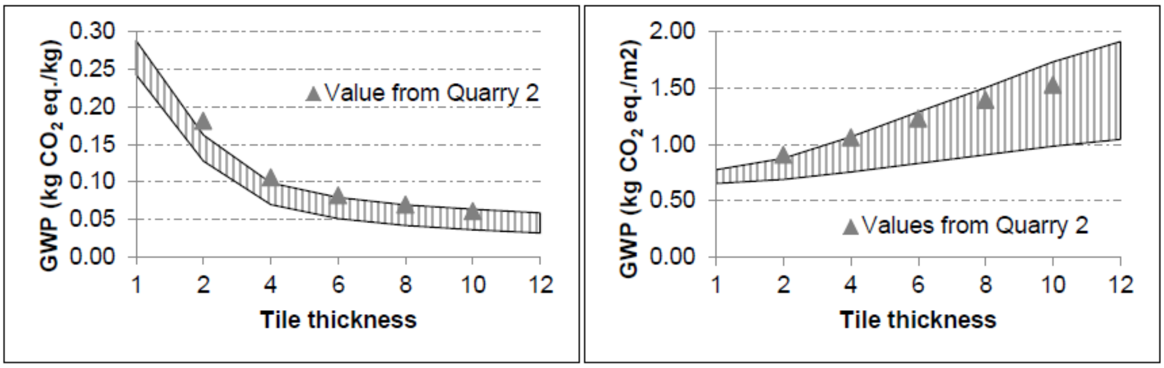


Figure 26. Uncertainty range for Global Warming Potential (GWP100) Impact of the production of a 40*40cm tile.[48]

The geometry of the pieces to be produced is a decisive factor for other inputs and outputs of the production chain, for example sawdust generation. The total production of sawdust during sawing is inversely proportional to the thicknesses of the final product to be manufactured, whereas the opposite scenario occurs in the cutting process[48]. This relationship is an important aspect to be considered as it may also affect the energy, water and material demands during granite sawing and cutting.

Waste management

Raw material waste is considered as one of the major environmental concern commonly associated with natural stone products, however in the available literature, EPDs and LCA studies, no quantifiable value of the environmental impact is reported. Similarly, the current Ecolabel criteria consists in the provision of documentation in accordance with the Directive 2006/21/EC. However, considering the great amount of natural resource wasted both in quarries (up to 75% of the extracted material) and in the production plant (up to 25%), and simultaneously taking into account the multitude of possible re-uses for such discarded material (e.g. as aggregates in cement, in road construction, in terrazzo tiles, in agglomerated stones, or for the environmental rehabilitation of quarries), the addition of a measurable requirement, for the amount of raw material waste that actually undergoes to a recovery and re-use process, could be further taken into account.

2.6 Natural stone used as Countertop

Many varieties of natural stone are used successfully for countertop surfaces. However, different types of stone have specific properties that offer advantages or disadvantages in various applications. The following is a brief overview of the common varieties of stone used as countertops.

- **Granites** are undoubtedly the most popular stone type used in countertop applications today. This group of stones includes many stone materials that are not true granites by geological definition. However, because their properties are so similar, they are name all together as 'granite'. These stones are known geologically as gabbro, anorthosite, gneiss, diabase, and diorite, etc. Whatever the name, these stones are some of the hardest of the common countertop stones, offering high levels of resistance to abrasion and scratching. The primary minerals in granite are resistant to almost all chemicals commonly found in a home; however, there may be trace minerals present in some granites and granite-like stones that are vulnerable to some acids.
- **Marbles, serpentines, and onyxes** are traditionally prized for their aesthetic appeal, accentuated by distinct veining and often bold colours. They are relatively softer than granite, although some serpentines are as dense as some granite types. Marbles can be scratched by kitchen utensils so it is best to use cutting boards and other protective measures.
- Marbles can also be etched by chemical attack. These stones are calcium carbonate- based and are damaged by exposure to acidic solutions such as lemon juice, tomatoes, vinegar, etc. The use of inappropriate cleaning agents may also trigger acidic attack. Acidic solutions can permanently etch the surface of the material. The application of a sealer will reduce, but not eliminate, the vulnerability to acidic attack. For these reasons, marble is not recommended for use in kitchens.
- **Slates** have high resistance to chemicals and have been traditionally used as chemistry laboratory tops. However, slates are softer than granite and therefore vulnerable to scratching and abrasion. Slate has a natural cleft (not a smooth surface). Some suppliers provide slate slabs that are not honed. Be specific about the kind of finish you desire. The same precautions mentioned for marbles with regard to damage should be applied to slates.
- **Limestones and travertine** are calcium based similar to marble. Therefore, they have the same weaknesses as marbles when used as countertops. Abrasion damage is a concern, particularly if the stone is polished. Many varieties of these stone types will absorb water to some degree and must be sealed to help protect them.
- **Stone tiles** can be used as a countertop surface material. The finished surface will carry the same precautions as the particular stone type from which it is made. The joint filler, whether grout, plastic sealant, epoxy or resin, may have specific requirements for protection and maintenance.

Countertop surfaces are made also from agglomerated stone, also called engineered stone. For further information please refer to chapter 5.

2.6.1 Countertop fabrication process

Inspecting the slab

In this first step, the fabricator will inspect your chosen slab(s). Stone, being a natural product often contains characteristics indigenous to that particular material. Some of these characteristics include dry seams, black spots, polyester resin fill, pits, and natural directional veining, feldspar or mica conglomerates (knots). Often times, these marks make the stone unique and beautiful. On occasion, a customer may find certain characteristics unacceptable and the stone fabricator will work to avoid those during templating and fabrication process.

Prior to templating, a final inspection is made of the stone, identifying any unacceptable areas, or areas that are more severe than the normal characteristics described above. The fabricator will mark those areas and work to avoid those during templating, while balancing the effort to minimize waste and therefore cost.

Template Layout

Once the slab is inspected, it is then laid out and the previously created templates are arranged on the stone to ensure the best appearance of vein texture and colour. The templates are also arranged to ensure appropriate flow for the various countertops in your layout. As an example with an L shaped countertop, or a countertop and an island that is parallel or perpendicular, you want to ensure the overall flow of the countertop pattern will work in your finished project. This natural beauty occurs more often in natural stone than in quartz, making this process especially important with granite or marble.

Cutting

The stone is then cut using either a water jet or a bridge saw. The bridge saw cuts with a diamond segmented blade, and cuts at a feed rate of approximately 2m/min. The water jet cuts with high pressure water with garnet particulate suspended in the water at a feed rate of 1 foot per minute. The benefit of the water jet is that it can cut circles, radius', or any intricate pattern, where the bridge saw cuts only straight lines.

Recently, a more specialized tool has come to the marketplace. A saw jet, which has a saw head and a water jet built into it. You program the saw jet with the parts you need cut, it then determines where to use the water jet and where to use the saw, giving you the best productivity of both worlds.

Once the pieces are cut from the large slab, those pieces are forwarded to a Computer Numerically Controlled (CNC) machine and with the help of a vacuum lifting system, the granite countertop pieces are then fabricated.

Fabricating

The first step is cutting the stone to approximately 1/16 of an inch of its final size. Then, the CNC machine is programmed to know the size of the stone or stones on the table. Multiple pieces of stone can be handled together. The CNC machine is then programmed to know where the stones are located and what to do to each of those pieces.

Once the holes are cut in the granite the edge is shaped by the CNC machine before the countertop is taken to final polish. There are a variety of stone edges to choose from, but the versatile CNC machine can produce any edge you select.

Strengthening

When the templates are cut out, a few stones have thin rails of granite, for instance behind or in front of a sink or cooktop. By nature, those thinner pieces are not as strong as a larger surface area of stone. In the early 2000's Great Lakes Granite and Marble conducted a study to find the best method for increasing the flexural strength of stone, specifically to reinforce this thin area. They tested various methods, working with the Marble Institute of America, and found the threaded rod technique described below to be the most effective.

In this step, rod slots (grooves in the granite) are cut and threaded rods are inserted into these grooves and encapsulated in high strength epoxy. This step increases the flexural strength of the countertop in that area by 400%.

Polishing

When the granite arrives from the quarry, the face of slab is already polished but the edge needs to be polished. Regardless of the edge, it will go through a 7 step polishing process. The industry use diamond polishing pads of increasing grit from 50 to 3,000 to polish the edge. The CNC machine first starts with a diamond polishing pad of 50, then 100, 200, 400, 800, 1500, ending at 3,000. The CNC shapes and polishes at the same time, leaving the edge shaped and polished.

Seam Phantom

During this step, the edges of the stone ground to remove the microchipping and achieve the best and tightest seam possible. It is an innovative system to produce near perfect seams in all types of stone and quartz. The system utilizes a diamond cup wheel followed by up to three diamond abrasives and a precise depth adjustment to eliminate chips and produce a clean sharp edge. The rigid design and glide guide straight edge keep each half of the seam straight and true. When assembled a nearly invisible seam is produced (see Figure 27).

Figure 27. Almost invisible seam (source nsi soutions).

Sealing

Granite is naturally 90% impervious to moisture migration. By applying one coat of sealer, we take that rate up to 95-97%. Both the edges and face of the stone are sealed during this step.

Quality Control & Hand Finishing

The final step in the process is inspection of the stones. The stone fabricator will ensure the edges are uniform around all sides of the stone(s). Then they will be reviewed from multiple angles to make sure the light is bouncing of the edges uniformly, and the colour of the top of the stone and the edges match perfectly.

Reinforcement techniques

As products of nature, stones have varying strength and behavioural properties. Stones of lesser soundness or stones that have had substantial areas removed from the slab (e.g., sink cutouts) benefit from reinforcement by a variety of techniques.

- **Fiberglass Mesh**. A common reinforcement for stone slabs of limited soundness is to apply a fiberglass mesh to the back surface of the slab. The adhesive used in this application is commonly an epoxy or polyester resin.
- **Liner Blocks**. Although not frequently used in stone countertop construction, a liner block of stone material can be adhered to the underside of the stone slabs (when no subtop is used) to reinforce seams or other vulnerable areas. The liner block need not be of the same type of stone material as the countertop.
- ***Splines*.** Seams, particularly those between narrow stone pieces, are often put together using a steel or stainless steel key. Commonly, a large washer is used as the spline key. The metal is fully encapsulated with polyester or epoxy resin and fitted to closely cut slots in the stone, similar to the "biscuit" joint reinforcements used in woodworking.
- **Rodding.** Rodding is beneficial to narrow strips of stone material, such as those in front or behind sink or cook top cutouts. This technique requires a shallow kerf (a narrow cut or groove) in the underside of the stone slab. The kerf is then closely fitted with a metal or fiberglass rod, which is then fully embedded in epoxy or polyester resin. The rod has greater resistance to bending than the stone and helps prevent the stone from bowing. A strip of fiberglass mesh backing is often applied over the rodded region for additional reinforcement.

2.6.2 Main improvements in countertops fabrication

The sequence of manufacturing steps has not changed but the type of machinery used. Three basic types of machines are involved in the fabrication process: saws, polishers, and routers.

- **Saws** perform several functions during fabrication. A block saw, or gang saw, cuts the massive stone blocks into slabs. These days, diamond wire saws make short work of this task. A metal wire is studded with industrial-grade or synthetic diamonds, and this wire quickly cuts through stone as hard as granite. A bridge saw is then used to cut the stone slab into the proper shape for its application. These saws typically use circular metal blades studded with diamonds, and water is sprayed onto the blade to cool it during the cutting process. Modern technology has produced a new type of saw utilizing water jets combined with an abrasive material, which cuts edges and holes quickly and smoothly, and many fabricators are upgrading to these machines.
- **Polishers** grind down the naturally rough surface of the stone to a polished surface. Hard stones like marble and granite can be polished all the way to a mirror finish. The polisher consists of rotating pads which are surfaced with an abrasive substance. The finer and smaller the abrasive grits are, the higher the polish. Most modern polishers can produce a variety of finishes, from the smooth, soft look of a honed finish to a slick, shiny mirror finish…even decorative finishes like flamed, tumbled, or hammered.

- **Routers** create edge profiles on a slab, and cut designs on larger pieces like fireplace mantles and hearths. There are dozens of standard edges for countertops and tables, from simple to highly decorative. Routers have a spinning blade covered with diamonds which is water-cooled. It travels along the edge of the slab to shape it.

With the introduction of **Computer Numeric Control (CNC) technology**, however, that time has been decreased. CNC utilizes digital technology to precisely control all three types of fabrication machines: saws, polishers, and routers. CNC has cut production time down to a single afternoon for a countertop, even with a very complex edge. CNC also makes the shaping of intricately-designed pieces fast and simple.

CNC has doubled (or more) the productivity. It has contributed significantly to the reduction in the cost of natural stone countertops, tables, sinks, tiles, and fireplaces, and will continue to bring these costs down. At the same time, it has dramatically increased the quality of the finished product.

3 OVERVIEW FOR CERAMIC TILES

3.1 Terminology and classification

Ceramic tiles are thin slabs from clays and/or other inorganic raw materials, such as feldspar and quartz as defined by CEN/TC 67. They are usually shaped by extruding or pressing at room temperature followed by drying and firing at temperatures sufficient to develop the required properties. Tiles formed by other processes are not covered by this EU standard. Tiles can be glazed or unglazed, are non-combustible and generally unaffected by light.

As shown in Table 11 ceramic tiles are classified according to according to two parameters[49]: by their method of manufacture (also referred to 'shaping') that is, by extrusion (expressed as group "A" tiles) or dry-pressing (expressed as group "B" tiles), and by their water absorption level (E, expressed as a percentage by mass). The test method used to determine water absorption level is the boiling method according to EN ISO 10545-3.

Furthermore, extruded tiles can be classified as "precision" or "natural". The classification is dependent upon the different technical characteristics.

Traditional terms used for extruded tiles are "split tiles" and "quarry tiles". They commonly indicate double extruded and single extruded tiles, respectively. The term "quarry tiles" only refers to extruded tiles with a water absorption coefficient of a mass fraction not exceeding 6 %.

Tiles can be glazed (GL) or unglazed (UGL). A tile with an engobed surface is regarded as an unglazed tile.

Table 11. Classification of ceramic tiles with respect to water absorption and shaping[49].

Shaping	**Water absorption (E_b)**			
	Group I **$E_b \leq 3\%$**	**Group II_a** **$3\% < E_b \leq 6\%$**	**Group II_b** **$6\% < E_b \leq 3\%$**	**Group III** **$E_b > 10\%$**
Method A **Extruded**	Group AI_a **$E_b \leq 0{,}5\%$** Group AI_b **$0{,}5\% < E_b \leq 3\%$**	Group AII_{a-1} Group AII_{a-2-}	Group AII_{b-1} Group AII_{b-2}	Group AIII
Method B **Dry -pressed**	Group BI_a **$E_b \leq 0{,}5\%$** Group BI_b **$0{,}5\% < E_b \leq 3\%$**	Group BII_a	Group BII_b	Group BIII
Groups AIIa and AIIb are divided into two parts (Parts 1 and 2) with different product specification. Part 1 covers most of the tiles in the group; Part 2 covers certain specific products, which are manufactured under different names (e.g. terre cuite in France and Belgium, cotto in Italy and baldosin catalán in Spain). Group BIII covers glazed ceramic tiles only. There is a low quantity of dry-pressed unglazed tiles produced with water absorption greater than 10 % that are not covered by this European Standard.				

[49] Ceramic tiles - Definition, classification, characteristics, assessment and verification of constancy of performance and marking.

Ceramic tiles in groups AIa and BIa can be designated as porcelain tiles, i.e. fully vitrified ceramic tile with water absorption of 0,5 % or less. These are the most commercially available ceramic tile, are characterized by a very compact structure, extremely low porosity and high performance. The average density is 2 300 kg/m^3 and, according to the characteristics, can be employed both outdoor and indoor.

Ceramic tiles consist of two main components, body and glaze. The main constituents of the body are clay, sand, and feldspar, but other components are also incorporated in the mixture, such as binder, pigments, fluidifying agents, and dispersants. Table 12 shows an example of a ceramic tile formulation.

Table 12. Example of a typical ceramic tile body and glaze composition.[50]

Body raw materials	Composition (wt%)
Feldspars	43.53
Clays	41.16
Sands	10.91
Unfired ceramics tile scrap	2.09
Kaolin	1.23
Fired ceramic tile scrap	0.53
Pigments	0.32
Deflocculants	0.23
Glaze and decorative raw materials	**Composition (%)**
Frit content	33
Feldspars	26.02
Quartz	21.04
Carbonates	19.73
Boron-introducing raw materials	7.35
Clays	6.54
Silicates	5.16
Zinc oxide	4.29
Zirconium	4.27
Kaolin	3.12
Alumina	2.48

Recent studies have proved the feasibility of introducing secondary raw materials inside the ceramic body composition. This aims to partially substitute the common raw materials employed in the formulations, clay, which, together with feldspars, represents one of the main player in the composition. A study by Andreola et al.[51] investigates the incorporation of packaging glass waste inside ceramic tile up to 60%.

Thickness

There are numerous ceramic tile types on the market. They range in size across the facial dimensions and thickness. The standard thickness varies between 5 and 16 mm (Table 13) to cater for different demands and intended uses. A lower limit of 5 mm is usually

[50] Ros-Dosdá, T., Celades, I., Monfort, E., Fullana-i-Palmer, P. Environmental profile of Spanish porcelain stoneware tiles. Int J Life Cycle Assess 2017.

[51] Andreola, F., Barbieri, L., Lancellotti, I., Leonelli, C., Manfredini, T. Recycling of industrial wastes in ceramic manufacturing: State of art and glass case studies. Ceramics International 42 (2016) 13333–13338.

adopted to provide adequate mechanical resistance, however due to the market demand the thickness has been reduced. The so-called thin tiles have a thickness between 3 to 5mm. Their weight is two times lighter than a standard tile (average value of 19.9 kg/square meters).

Table 13. Spanish ceramic tile manufacturing industries.[50]

Parameter	Designation	Values
Thickness	Low (L)	**5** mm (11 kg/m^2 weight unfired)
	Average (A)	**10.4** mm (24.5 kg/m^2 weight unfired)
	High (H)	**16** mm (34 kg/m^2 weight unfired)

3.2 Relevant technical standards

STANDARD	DEFINITION
EN 14411:2016	**Ceramic tiles - Definition, classification, characteristics, assessment and verification of constancy of performance and marking** It defines terms and specifies characteristics for ceramic tiles, including mosaics (i.e. any piece that can fit into a square area of 49 square meters) produced by extrusion or dry-pressing techniques, used for internal and/or external floorings (including stairs) and/or walls. It is not applicable to decorative accessories or trim, such as edges, corners, skirting, capping, coves, beads, steps, curved tiles and other accessory pieces.
STANDARD	**WATER ABSORPTION (test used for classification)**
EN 121	Extruded ceramic tiles with low water absorption (E~3%).Group AI.
EN 186	Extruded ceramic tiles with water absorption (3% <E<6%). Group AII_a.
EN 187	Extruded ceramic tiles with water absorption (6% <E~ 10%). Group AII_b.
EN 188	Extruded ceramic tiles with water absorption (E> 10%). Group AII.
EN 176	Dust-pressed ceramic tiles with low water absorption (E~3%). Group BI.
EN 177	Dust-pressed ceramic tiles with water absorption (3%<E~6%). Group BII_a.
EN 178	Dust-pressed ceramic tiles with water absorption (6%<E~10%). Group BII_b
EN 159	Dust- pressed ceramic tiles with water absorption (E> 10%). Group Bll.
STANDARD	**TESTING METHODS**

EN-10545:2015	**Part 1** - Sampling and basis for acceptance **Part 2** - Determination of dimensions and surface quality **Part 3** - Determination of water absorption, apparent porosity, apparent relative density and bulk density **Part 4** - Determination of modulus of rupture and breaking strength **Part 5** - Determination of impact resistance by measurement of coefficient of restitution **Part 6** - Determination of resistance to deep abrasion. Unglazed tiles **Part 7** - Determination of surface abrasion resistance of glazed tiles **Part 8** - Determination of linear thermal expansion **Part 9** - Determination of resistance to thermal shock **Part 10** Determination of moisture expansion **Part 11** - Determination of crazing resistance. Glazed tiles **Part 12** - Determination of frost resistance **Part 13** - Determination of chemical resistance **Part 14** - Determination to stains resistance **Part 15** - Extraction of lead and cadmium from glazed tiles **Part 16** - Determination of small colour differences **Part-17 -** Determination of coefficient of friction

3.3 Market data

The overall ceramic tiles market can be divided into three broad categories on the basis of the product type, namely, floor tiles, wall tiles and other types of ceramic tiles. The market is dominated by floor tiles which in 2015 accounted for more than half of the total global production volumes, followed by wall tiles[52]. Residential application represents the largest destination sector for ceramic tiles, accounting for around half of the total global consumption volume. Residential applications are followed by commercial applications. In both sectors, it is interesting to highlight the continuous trend towards different tiles formats with different shapes, sizes and thicknesses. In particular, , there is a growing demand for "large-format" tiles with sizes up to 1,500 mm X 3,000 mm or similar and very low thickness (3-5 mm)[53]. These thin slides can be used as laminated surface covers for furniture, like the outer layer or countertops, or as wall and floor finishes. Thanks to their extreme thinness, these products have a wide range of application and can be used in facades or to tile over existing tile surfaces, without adding significantly to the overall thickness of the floor finish.

[52] Ceramic tiles market by Product, by Application Analysis and segment forecasts to 2020. Grand Vie Research, 2015

[53] M. Bechthold, A. Kane, N. King (2015). Ceramic Material Systems in architecture and interior Design.

The recovery of the construction industry, particularly in developing nations and a increasing demand for products with better aesthetics, sustainability and structural reliability without a significant increase in price is expected to create opportunity in ceramic tiles market.

Most of data and information regarding global ceramic tiles market have been drawn from the article *"World production and consumption of ceramic tiles*[54]*"* published on Ceramic World Review in 2017, which offers an accurate overview of the international market. Data regarding the European market have been also provided by *Confindustria Ceramica*, the Italian Business Association of Ceramic Manufacturers. Other sources used in the document have been reported as footnotes.

3.3.1 World production and consumption

World ceramic tile production and consumption has shown a continuous increase since 2012, reaching 13,056 million square meters in 2016. In 2016, it is notable a growth of 5.7% and 5% in production and consumption, respectively (Figure 28).

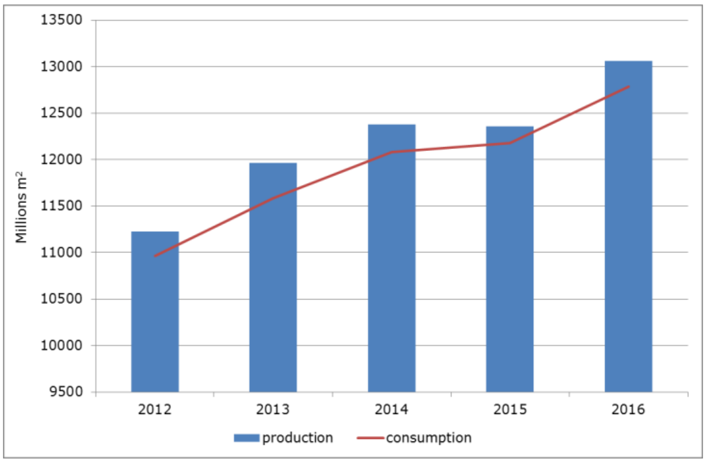


Figure 28. World ceramic tiles production and consumption by year.

This increase is mainly due to Asia's performance (driven mainly by China[55], India, Vietnam and Iran) which accounts for 71.5% of global production in 2016. European Union, which produced another 14% of world production (Figure 29).

[54] Baraldi L. "World production and consumption of ceramic tiles", CWR 153/2017

[55] China is the world's larger producer, consumer and exporter of ceramic tiles. In 2016, domestic consumption was estimated at 5,475 million square meters, equal to 42.8% of world consumption.

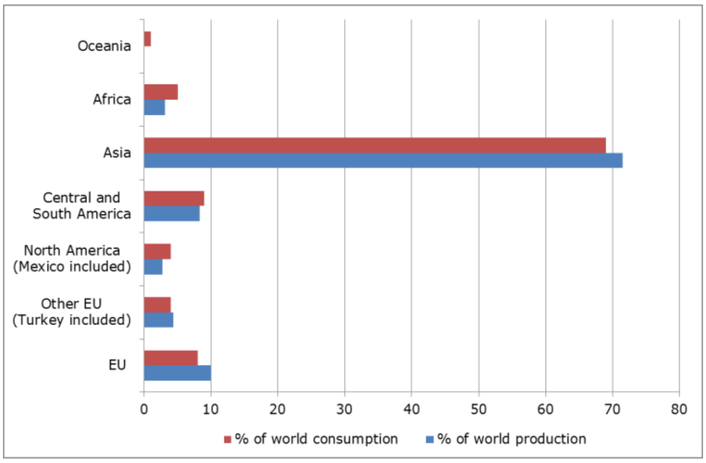


Figure 29. World production and consumption by region (reference date 2016).

At the same time, in 2016, world tile consumption increased by 5%. Specifically, Asian demand reached 8,818 million square meters, equivalent to 69% of global consumption. Consumption in the European Union also rose by 5.9%, thanks to growth in demand in most countries[54]. Demand in non-EU European markets fell slightly (-0.9%) due to the downturn in Russia, partly offset by the recovery in Turkey. In Central and South America, consumption dropped by around a hundred million square meters to 1,180 million square meters (-7.7%), a downturn that was entirely attributable to the slump in Brazil. North America's demand showed a very positive trend, rising from 507 to 547 million square meters in 2016, driven by almost identical increases in Mexico and the USA in both percentage and absolute value terms.

3.3.2 International trade

In 2016, world exports reached 2,794 million square meters, maintaining a fairly limited growth trend for the third year running compared to the previous period. The increase was almost entirely attributable to exports from the European Union, which rose from 856 to 903 million square meters, equivalent to one third of total world exports.

In 2016, more than 60% of world exports come from three countries, China, Spain and Italy respectively, while the top ten countries made up 85.5% (Figure 30). Amongst the largest exporter countries, Italy and Spain maintain the highest share of exports as a percentage of production (both 80%), compared to the 66.7% of the United Arabian Emirates, the 37% of Iran, the 32% of Poland, the 15.8% of China and shares of between 12% and 24% of India, Brazil, Turkey and Mexico. But the real sign of Italy's leadership position is its average selling price of 13.8 €/square meters compared to the 6.5 €/ square meters of Spain and between 2.6 €/ square meters and 5.8 €/ square meters of the other countries.

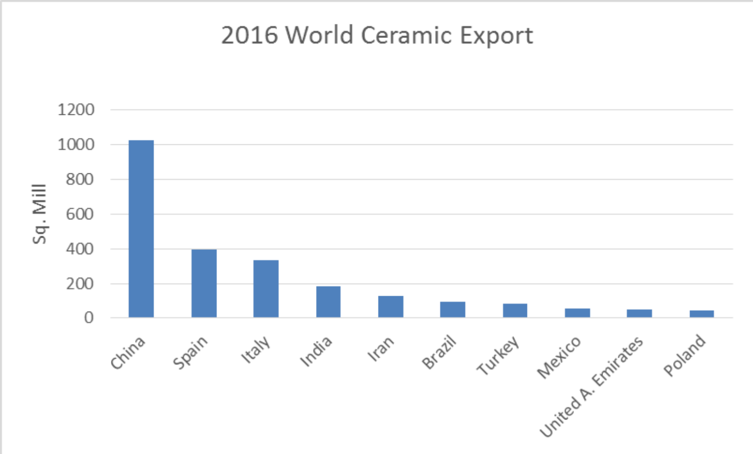


Figure 30. Main ceramic exporting countries.(2016).

As shown in Figure 31, in 2016 the top 10 importing countries purchased a total of 1,015 million square meters of ceramic tiles, equivalent to 36.3% of total world import/export flows. With the sole exception of Indonesia, in all the other top-10 countries imports account for more than 60% of domestic demand, with peaks of 98% in Iraq and between 87% and 92% in France, Germany and Israel.

In 2016, the USA became the world's biggest importer country, with a volume purchased of 194 million square meters (+8.4% respects to 2015) in response to the 8% growth in local demand from 254 to 274 million square meters.

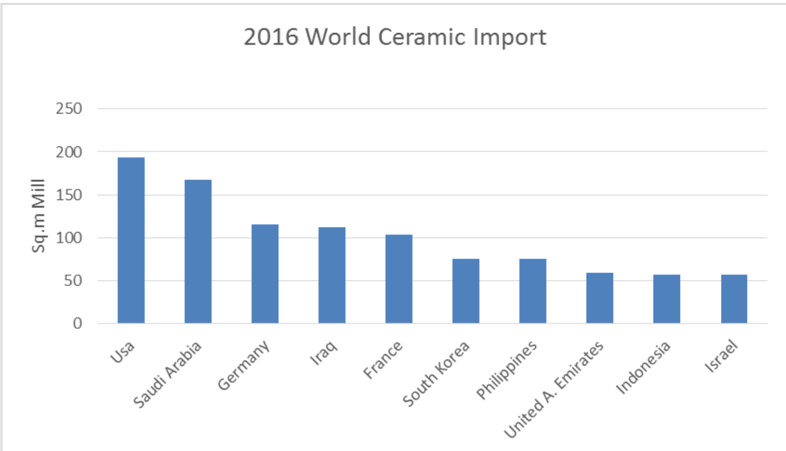


Figure 31. Main ceramic importing countries.

Looking at the trend in import/export flows over the years, it is interesting to note that ceramic tiles tend to be produced close to the place of consumption. Indeed, although world exports stand at 21.4% of production and 21.9% of global consumption, almost two-thirds of this volume consists of exports shipped within the same geographical region as that of production. For example, 79% of South America's exports remain in South America, 77% of North America's exports remain within US, Canada and Mexico, and 64% of Asian exports are shipped to other Asian countries. The EU is a partial exception in that as almost 50% of its exports is sold in non- EU countries.

3.3.3 European production [56]

In 2016 ,there were a total of 500 ceramic tile manufacturers in Europe. These companies (80% being Small to Medium-sized Enterprise, SME) employed a direct workforce of more 60,000 people and mainly developed in 25 European countries organized in industrial district. They play an important role as they are able to serve market providing the desired levels of quality, uniqueness and creativity. The wide availability of raw materials and the concentration of highly qualified workers contribute substantially to the European peculiar production structure.

Ceramic tiles production in Europe is mainly concentrated in Spain (37%), Italy (31%) and Poland (11%), followed by Germany (4%) and Portugal (3%), while the remaining states cover a marginal role in production. Production within the EU is geographically concentrated in the industrial district of Castellón (Valencia region) in eastern Spain and Sassuolo (Emilia Romagna region) of northern Italy. The latter is also the leading country with regard to the supply of technology and machinery for tile manufacturers.

As shown in Figure 32, both European production and consumption encountered a sharp decline between 2007 and 2009, mostly due to the financial crisis. From 2009 production volumes started to rise again. In 2016, the European ceramic tile industry produced 1.3 million square meters (20% lower than values achieved in 2006) with a total value of 10 billion euros. Regarding consumption volumes continued a declining trend until 2013. Nowadays, although annual consumption of ceramic tile is restarted to grow, it is still lower than the pre-crisis level (961 million square meters in 2016 against 1.334 million square meters in 2006).

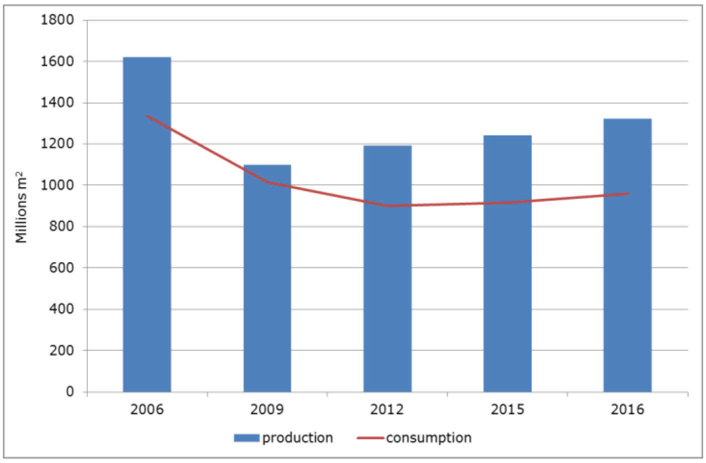


Figure 32. *EU production and consumption trends.*

3.3.4 European export and imports for ceramic tiles

Despite fluctuations, EU's trade balance looks positive (Figure 33). Exports volume collapsed between 2007 and 2009, consistently with the financial crisis that hit most of European production sectors, reaching the lowest peak in 2009 (293 million square meters). From 2010 onwards, exports started to rise again, reaching 451 million square meters in 2016, i.e. an increase of 18% respect to 2006[56]. In 2016 the European Union remained the area with the highest export share at 69.2% of the production contributing substantially to the growth of the global trend.

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[56] Data provided by Confindustria Ceramica.

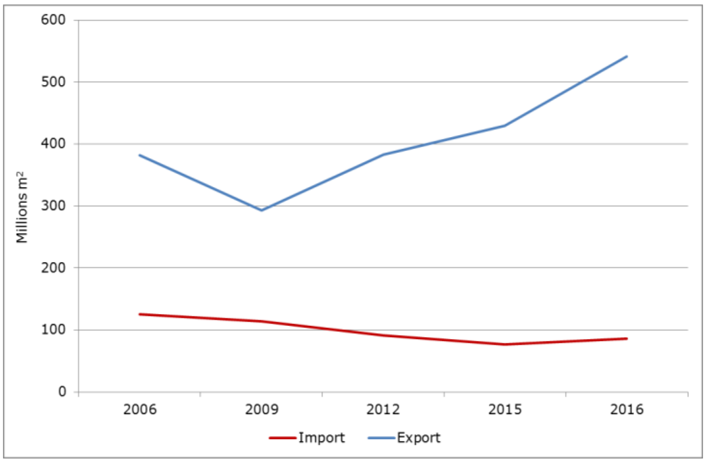

Figure 33. EU import and export trends.

The two main exporters in Europe remain Spain and Italy.

In 2016, Spain strengthened its position as the world's second largest exporter after China. It increased its production with output volumes reaching 492 million square meters (+11.8%), confirming the country's position at 4th in the rankings of world producers. This was due to the further recovery in domestic sales, which according to Ascer (the Spanish Association of ceramic tiles) exceeded 125 million square meters. The top foreign markets in terms of value were France, USA, the UK and Saudi Arabia. Italy.

Italy saw a further recovery in production, up from 394.8 to 416 million square meters. Domestic sales recovered after an 8-year downturn, rising to 83 million square meters (+3.2%) and a value of 829 million euros. As the world's third largest exporter increased its exports both in volume (from 316.6 to 331.7 million square meters, +4.8%) and even more significantly in value (from 4,318 to 4,588 million euros, +6.3%), thanks to an average price that has risen to 13.8 €/square meters. The sector's total turnover exceeded 5.4 billion euros (+5.9%), of which 85% was generated by exports

Regarding imports, a slightly decreasing trend has been observed in the last ten years (Figure 33). Contrary to the export values which are higher than that pre- financial crisis, no significant signs of recovery are observed for the import values. The import values remains below pre-financial crisis, even after a slight recovery reported for 2016 (+11% respect to 2015)[56].

Anti-dumping duties and measures probably represent the most important barrier to entry in the European ceramic tiles market. The ceramic manufacturing sector in EU benefits from a regulation[57] establishing duties on imports of Chinese ceramic tiles, aiming at restoring conditions of correct competition on the European market. The impact of the regulation in the EU import market is presented in

Figure 34, it is notable the reduction of 77% of ceramic imports from China since 2011.

[57] Commission Regulation (EU) No 258/2011 of 16 March 2011 imposing a provisional anti-dumping duty on imports of ceramic tiles originating in the People's Republic of China

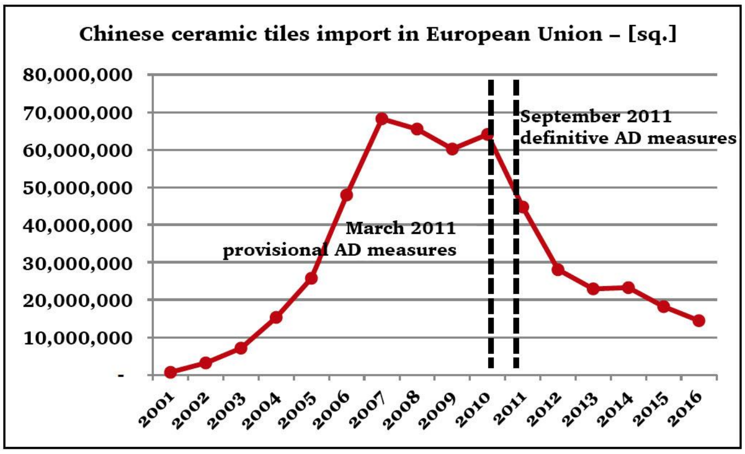

Figure 34. Chinese ceramic tiles import in EU (source Eurostat).

The European Ceramic Tile Manufacturers' Federation on behalf of producers representing more than 25 % of the total Union production of ceramic tiles requested the review of the expiry date. An anti-dumping investigation showed that the prices of Chinese exports of ceramic tiles to the Union were below the normal value. Furthermore, the production capacity and production were still increasing in China. Their export volume was rather stable and there are no indications that the Chinese domestic consumption would be able to absorb the enormous quantities produced and in stocks. On that basis, the Commission considered it is likely that significant volumes of Chinese ceramic tiles would be exported to the Union at dumped prices in case the measures were allowed to lapse. Therefore, in November 2017 the regulation was renewed[58], confirming the duty rates already in force (ranging between 30 % and 70% of the product value) and the five-year duration of the measures, bringing the new deadline to November 2022.

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3.4 Review of production technology and innovations

Ceramic tiles manufacturing process has highly evolved over the past years. Requirement of high quality materials with excellent efficiency levels have led to development of new firing and pressing technologies. Manufacturers have been trying to develop technologies for simple, flexible, and low cost production of the product. Environmental pollution and waste disposal has always been a major concern for ceramic tile manufacturers. They are now focusing on reduction of CO_2 emissions and water consumption through improved processing options during product manufacturing.

Other innovation have been mainly driven by market demand, which is looking for new formats, i.e. tiles of greater dimensions and different surface finishes, which are now obtained via digital glazing. New typologies have also been introduced, such as fiberglass reinforced tiles and photocatalytic tiles.

Figure 35 shows the areas (red circles) where major changes occurred, and which will be discussed more in detail in the following paragraphs.

[58] Commission Implementing Regulation (EU) 2017/2179 of 22 November 2017 imposing a definitive anti-dumping duty on imports of ceramic tiles originating in the People's Republic of China following an expiry review pursuant to Article 11(2) of Regulation (EU) 2016/1036 of the European Parliament and of the Council

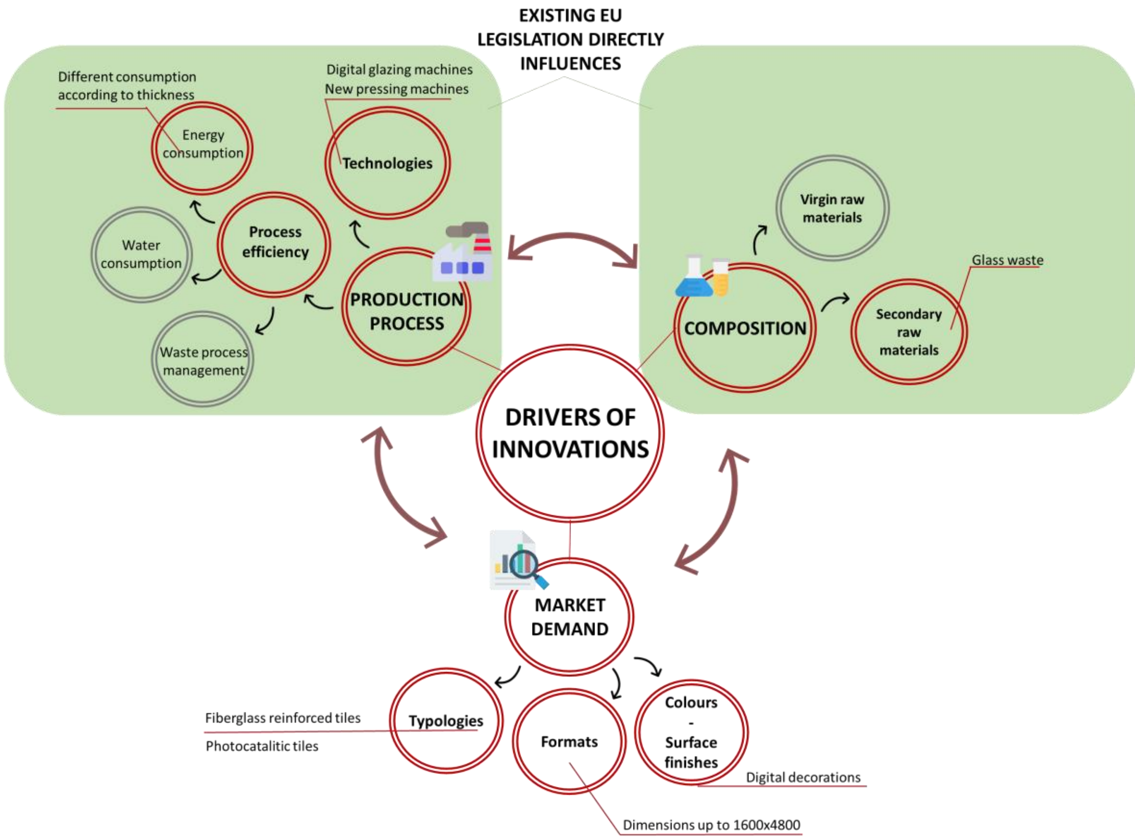


Figure 35. Main improvements and innovations for ceramic tiles.

3.4.1 Manufacturing process

After extraction of the raw materials, ceramic tile manufacturing process consists of several steps described in this paragraph. Figure 36 provides an overview of the manufacturing process. Particular attention is devoted to the innovative steps introduced.

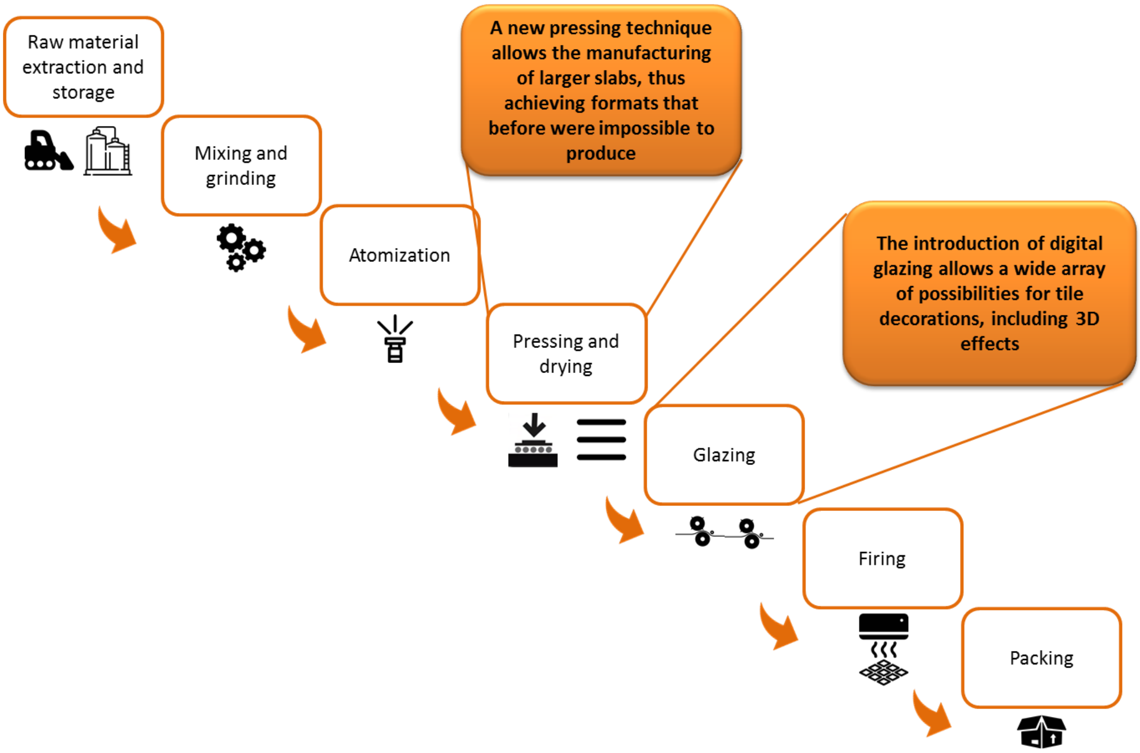


Figure 36. Overview of the ceramic tile manufacturing process.

Mixing and grinding

The extracted raw materials, including recycled waste coming from internal and external ceramic tile production, are mixed together with binders and fluidifying agents to achieve the appropriate composition and ground in mills. During the grinding stage, usually a wet process, the water content is around 25-30% and the slurry is atomized via spray driers. This process produces a dry powder with spherical granules, called green body, ready for the pressing step.

Pressing and drying

The mixture undergoes uniaxial semi-dry pressing. In the previous years, the mixture was poured and pressed inside moulds. With the introduction of recent techniques, the powder, instead of being poured inside molds with predefined size, is laid on a belt, where undergoes the pressing phase. This new method allows the manufacturing of larger slabs, obtaining formats that before were very difficult to produce. This mechanism leads to two main advantages:

- During the pressing phase, the slab undergoes low tension since it is not constrained;
- Slabs up to 1600x4800 are formed, thus expanding the range of possible applications.

Then, the ceramic body undergoes a drying process to reduce the water content, which might lead to fracture during the firing stage.

Cutting

The cutting step produces slab with the desired format; new techniques directly size the tile via computer-controlled saws, starting from the body laid upon the belt. All the different formats are obtained from one large slab.

Glazing

Once the tile is dried and cut in the desired shape, the product is glazed and decorated. A protective glaze is prepared and is applied via spraying or watering.

Firing

The firing phase occurs at different temperatures according to the type of tile, but usually is around 1000-1300 °C. This process is meant to achieve the required properties, in terms of abrasion, durability, water and chemical resistance and involves the highest fuel consumption, which is usually natural gas. The firing process can be:

- **Single firing**: when the tile and glaze are fired together in one step;
- **Double firing**: the firing stage occurs in two steps. First, the tile body is fired; then, once the glaze is sprayed, the tile undergoes a second firing step.

Nowadays, the single-firing technique is the most common process in ceramic tile industry since it provides great resistance to breakage and abrasion and lower energy consumption. For example, stoneware tiles, which are the highest selling product type in the ceramic tile sector, undergo single firing. Better bonding between the surface layer and the substrate makes single-fired tile suitable for outdoor use.

Firing time (and therefore energy consumption) is highly dependen on tile thickness. In general, we can consider three standard tile thickness:

- **Low thickness** (between 3-8 mm): these tiles have a firing cycle from 20 to 40 minutes. Despite the short firing cycle, this product has higher fuel consumption per kg of material due to lighter material going through the kiln, but lower fuel consumption per square meters since the cooking process is fast and more tile surface is cooked;
- **Intermediate thickness** (between 8-14 mm): these tiles have a firing time which lasts around 40-50 minutes and intermediate fuel consumption. Data provided by industries showed that 12 mm thick tiles have 18% and 15% natural gas consumption lower than 6 mm and 4.8 mm thick, respectively;
- **High thickness** (more than 14 mm): firing times are above 80 minutes and fuel consumption increases again since heat and subsequent cooling need to reach also the tile core in order to obtain a homogeneous temperature over the whole slab and avoid the presence of internal residual stresses.

Packaging

The manufactured tile is then usually packed in cardboard boxes and piled on wooden pallets. A plastic film is usually added to better protect the final product.

3.4.2 Innovations and improvements

Market demand has ben the main driven force for technological advancements and product changes. For example, by demanding thinner tiles which can be easily installed in renovation works without altering the previous existing floor, or new tiles with a air purification effect by depositing a layer of titania on the tile surface. Major improvements have been also in the filed of glazing technology and use of recycled materials. These technological improvements are described in the following paragraphs.

Ultra-thin glass fibre reinforced ceramic tile

In a study by Pini et al. (2014)[59], a 3.5 mm thick ceramic tile is achieved via reinforcement with fibreglass. The fibreglass gives greater sturdiness, lightness and elasticity thus improving both structural and chemical properties. A comparison with standar ceramic tile of 6 mm thick is shown in Table 14.

Table 14. Comparison of traditional and fiberglass reinforced ceramic tiles[59]

Physical and chemical properties	Large, thin ceramic tile with fibreglass backing	Traditional ceramic tile
Size	1000mm x 3000 mm	600mm x 600 mm
Thickness (mm)	3.5	9
Weight (kg/square meters)	8.2	19
Water absorption (%)	Average value 0.1	Average value 0.2
Resistance to deep abrasion (mm^3)	≤175	≤130
Resistance to thermal shock	Resistant	Resistant
Chemical resistance	No visible effect	No visible effect
Shock resistance	Average value 0.8	Average value 0.75

The manufacturing of fiberglass reinforced tile is similar to the standard process but before cutting the fibreback is pasted. Pasting is executed by an automated process, where a fibreglass backing is applied to the back of the entire tile. The pasting line includes the first unloading where the tile is conveyed by the metal platform to the conveyor belt, then covered by a protective film on the tile's "fair-faced" surface. Slabs are then passed into a horizontal electric heater (operating in a range of 37–40 °C) to stabilise the temperature of the material to be processed. The tile is then sprayed with a two-component adhesive in a booth with a pressurising system, and the adhesive residues that are collected are transported away using a paper carpet. Adhesive is batched, thanks to a fully automated system that ensures a homogeneous mix of both components. Fibreglass is then applied to the slabs, and possible offsets are automatically removed. Then, a tooled anthropomorphous robot carries out the squeegeeing to prevent irregular air spots on the surface. Then, the first catalysation step between the bonding agent and slab is performed in a vertical drier (60–80 °C). The tile rests for 15 min, then the protective film is removed, and the slab is loaded automatically onto the tray.The two-component adhesive, paper and protective film waste are collected and disposed of as hazardous waste through incineration. The dust generated from the pasting process is caught by an air filter and disposed of as municipal solid waste.

Introduction of secondary raw materials: glass waste in ceramic manufacturing

[59] Pini, M., Ferrari, A. M., Gamberini R., Neri P., Rimini B. Cycle assessment of a large, thin ceramic tile with advantageous technological properties. Int J Life Cycle Assess (2014) 19:1567–1580

The incorporation of packaging glass waste inside ceramic tile aims at partially substituting the common raw materials employed in the formulations, such as clay and feldspars. Formulations containing up to 60% of glass packaging waste have been tested.[60] The remaining composition is filled with other components like binders and plastifying agents.

Glass scrap employed in the formulations mainly comes from glass packaging waste and end of life fluorescent lamp glass; these two varieties slightly differ from each other for chemical composition.

This solution leads to several advantages:

- Due to the high content of secondary raw material and water content lower than traditional ceramic tile manufacturing, common mechanical mixers are enough to achieve proper mixing;
- The body can be worked with several methods, including pressing, lamination, and by hand. In this way, it is possible to obtain both thin (less than 5 mm) and thick slabs.
- The consolidation step reaches temperatures around 1000 °C slightly below the typical temperature adopted for ceramic tiles treatments.
- Beside the previously mentioned technological advantages, introduction of secondary raw materials affords environmental benefits, such as reduced raw materials extraction volume, reduced energy demand for raw materials processing, lower emissions, and landfill space saving.

The technology has been already extended to industrial scale. The developed technology, already patented is known as Relux technology consists in the production of innovative tiles with reduced environmental impact by implementing an environmentally ethical management system and allows recycling one end-of-life (EOL) fluorescent lamp for 1 m^2 of glazed tile. Since 2007, when began the production, up to the end of 2014, 1,760,000 m^2 of this commercial ecological product has been produced. The substitution of EOL lamp glass does not affect the final engobe particle size distribution and not cause changes on the related parameters (already industrially optimized) such as: fluency during application, porosity, drying time, etc. The lamps, commonly called neon lamps, prior to incorporation in the glaze, are properly treated to separate glass from other chemical elements.

Digital glazing

In recent years, digital decoration has been introduced in the ceramic tile industry and this new technique is taking over the previous glazing methods. This technique perfectly embraces the latest innovations in this sector, such as the production of larger slabs, since digital decoration is adjustable to any type of format. In the ceramic tile manufacturing process, the decoration phase follows the pressing step and comes before the firing stage, which, besides affording the tile body with the desired mechanical properties, fixes the glaze upon the body.

The traditional process posed several disadvantages, which have been overcome thanks to the introduction of digital decoration:

[60] Lázaro, C., Trilles, V. R., Gómez, F., Allepuz, S., Fraga, D., Carda J. B. Incorporating ceramic manufacturing waste and recycled glass into the integral ceramic process. Qualicer '12.

- Traditional printing is a contact decoration technique. In digital inkjet, the distance between the substrate and the printhead is generally 3-5 mm; since printing takes place while the tile is still fragile, the pressure of the roller on the tile body can easily fracture it, thus wasting both and the glaze. This disadvantage also generates the necessity of high volume of raw material stock, thus requiring greater storage room.
- Conventional decoration requires a lengthy preparation to set-up and properly prepare the printing roller that cannot satisfy customers demand (short time deliveries with highly customized designs).
- Traditional printing cannot print on textured 3D tiles, but exclusively on flat tiles. Moreover, screen printing edges cannot be reached by the printing roller, thus leaving a white, unprinted border; since digital decoration does not require contact with the tile, ink can also reach cavities and other impervious recesses.
- Digital glazing allows to precisely drop ink on previously well-defined and determined areas of the tile. Such high level of precision is achievable thanks to software and computer-controlled nozzles. Besides, digital printing allows high production rates, i.e. high square meters/hr, thanks to nozzles that span the entire width of the ceramic slab.

In summary, digital has led to several improvements, such as:

- Lower raw material consumption for glazing;
- Lower water requirement for the decoration technique;
- Lower waste production;
- Almost no sludge from water depuration;
- Safer work environment for vapours and odours reduction and dry floors;
- Lower energy consumption;
- 3D decorations and possibility to reproduce natural stones, pictures, and specific drawings;
- Prints can be easily tuned according to customer desire, thanks to modern digital glazing machines which have a wide array of customizable features:
- Number of inks;
- Print direction and speed;
- Print resolution;
- Drop size and greyscale levels.
- Shorter times to adjust drawing and colours.

<u>Ceramic tiles with photocatalytic properties</u>

Another innovation within the ceramic tile industry regards the incorporation of photocatalytic properties in the material. This breakthrough was achieved by introducing a coating of titanium dioxide (TiO_2) on the tile surface. If proper adhesion of this layer upon the substrate is obtained, TiO_2 acts as catalyst, triggering chemical reactions on the tile surface. TiO_2, in the form of anatase, behaves as a photocatalyst when UV irradiated and in the presence of moisture. With hydroxyl radicals and superoxide ions, TiO_2 can decompose organic compounds. Titanium dioxide is also able to increase hydrophilicity or wettability of the surface. The incorporation of TiO_2 aims at increasing indoor air quality through four main actions:

- **Antimicrobial action**: TiO_2 can kill a wide variety of microorganisms, including bacteria, viruses, fungi, and algae, thanks to the free radicals generated upon UV irradiation. The free radicals attack the microorganisms destroying the cell wall and, thanks to the increased hydrophilicity, the remaining biological debris is easily washed away;

- **Deodorizing**: TiO_2 decompose volatile organic compounds (VOCs) destroying the molecular bonds;
- **Air purification**: beside VOCs breakdown, TiO_2 can decompose nitrogen oxides NOx, one of the main contributors to acid rain together with sulphur oxides, into nitrates, soluble in water and harmless;
- **Hydrophilicity**: TiO_2 increases hydrophilicity of the surface, lowering the contact angle of water molecules.

Despite the advantages, there are some drawbacks;

- The efficiency of the photocatalytic action is highly influenced by the homogeneity of the TiO_2 layer on the substrate; the presence of gaps might alter the performance, lowering the previously described beneficial effects;
- Low humidity and dirt might stop TiO_2 from catalysing the reactions.

It must be noted that this effect does not decrease with use, because TiO_2, being a catalyst, accelerates the chemical reactions, without taking part or being consumed.

There are already available patented technologies which produce tiles with titania on the surface, such as BIONICTILE®, HYDROTECT®, and Active Clean Air & Antibacterial Ceramic™.

3.5 Life Cycle Assessment: ceramic tiles

A LCA has been carried out for a ceramic tile with a tickness glaze of 10 mm and a total weight of 23 Kg per/m^2 with SimaPro (Ecoinvent 2.2). The functional unit is 1 m^2 of surface covered, as per sub-PCR "Bricks, Blocks, Tiles, Flagstone Of Clay And Siliceous Earths (Construction Product)".

Figure 37 shows the life cycle stages considered for ceramic tiles. The terminology for modules A1-A2-A3 derives from the standard EN 15804. These modules represent the production stages of a construction product according to the standard EN 15804 for EPD issue. A1 is the raw material supply stage, A2 is the transportation of materials to the plant gate and A3 is the manufacturing stage.

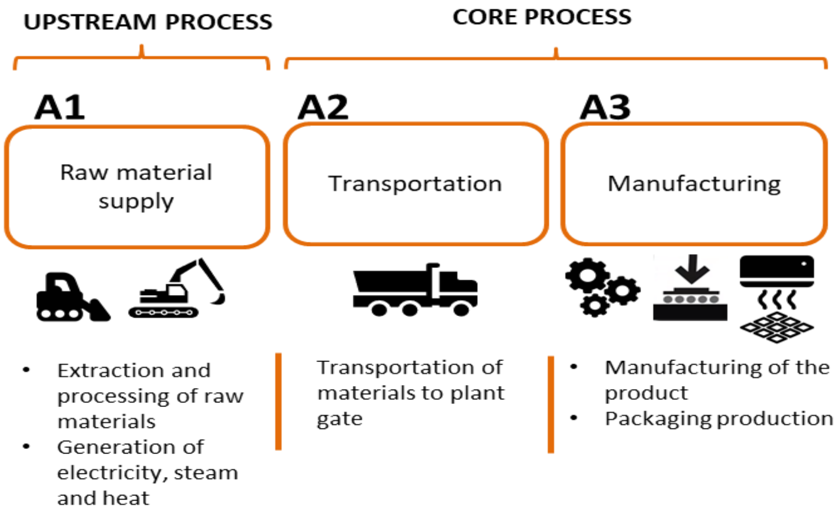


Figure 37. Life cycle stages of the product as per standard on construction products EN 15804.

The results reported per m^2 of surface covered are presented in Table 15 and in Figure 38 where the contribution of each manufacturing stages is indicated to help to identify the hot-spots across different life cycle stages.

Table 15. LCA results for potential environmental impact indicators for a 10 mm thick tile (per m^2 of surface covered).

Indicator	Unit	A1	A2	A3	Total
GWP	kg CO_2 eq/m^2	6	1	7	14
AP	g SO_2 eq/m^2	23	11	3	37
EP	g PO_4^{3-} eq/m^2	3	1	1	5
POCP	g C_2H_4 eq/m^2	1	0.4	0.2	2
ODP	g CFC-11 eq/m^2	<0.1	<0.1	<0.1	<0.1
ADP - Elements	g Sb eq/m^2	0.3	<0.1	<0.1	0.3
ADP - Fossil	MJ/m^2	210	11	5	226

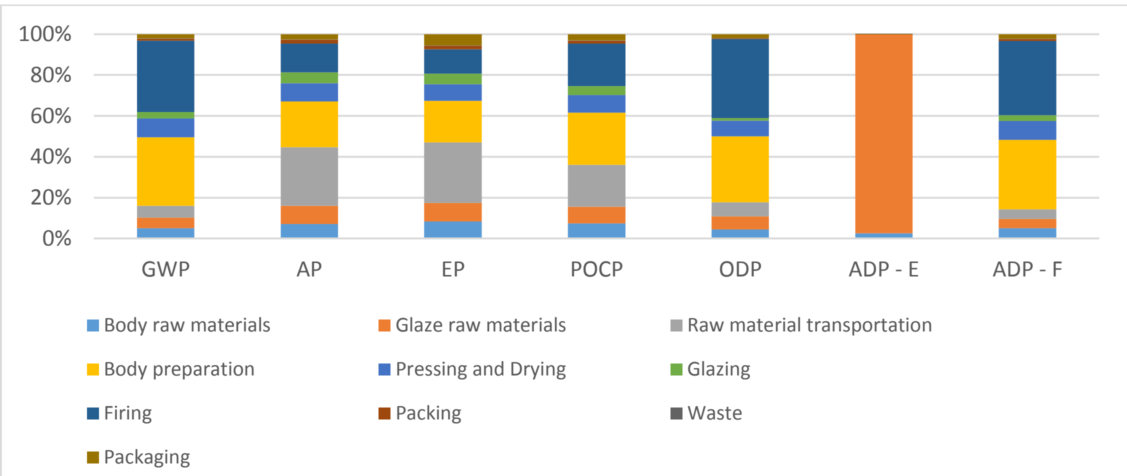


Figure 38. LCA indicators breakdown for 10mm tiles

Figure 38 shows that the tile manufacturing process accounted for more than 80% in the GWP impact category due to the consumption of energy, especially related to the firing stage. Emissions arising from the firing stage, electricity consumption and transportation to the plant also influence AP, EP and POCP indicators. SO_2 and NO_x can also affect AP both due to raw material decomposition[61] and to fuel combustion[59], especially if fuel other than natural gas are employed in the processes. The indicator ADP-elements is, instead, mainly influenced by raw material supply chain (A1), due to the materials contained in the glaze.

Influence of thickness

An additional study has been carried out to determine the impact of thickness . The results are summarised in Table 16. The life cycle inventory data are listed in Annex II.

Table 16. LCA results for potential environmental impact indicators versus thickness.

Total A1-A3					
		Thickness			
Indicator	**Unit**	**3mm**	**5mm**	**15 mm**	**20 mm**
GWP	kg CO_2 eq/m^2	9	13	19	25
AP	g SO_2 eq/m^2	20	31	53	68
EP	g PO_4^{3-} eq/m^2	3	4	6	8
POCP	g C_2H_4 eq/m^2	1	2	3	3
ODP	g CFC-11 eq/m^2	<0.1	<0.1	<0.1	<0.1
ADP - Elements	g Sb eq/m^2	0.1	0.2	0.4	0.4
ADP - Fossil	MJ/m^2	152	220	320	408

Pini et al.[59] show that not only the thickness has an impact but also and other characteristics such as reinforcement, on the environmental impacts. For example, for thinner tiles (3 mm thick) with fiberglass back reinforced, environmental may increase. GWP indicator goes up to 16 kg CO_2 eq due to additional material and process steps required.

[61] Ros-Dosdá, T., Celades, I., Monfort, E., Fullana-i-Palmer, P. Environmental profile of Spanish porcelain stoneware tiles. Int J Life Cycle Assess 2017.

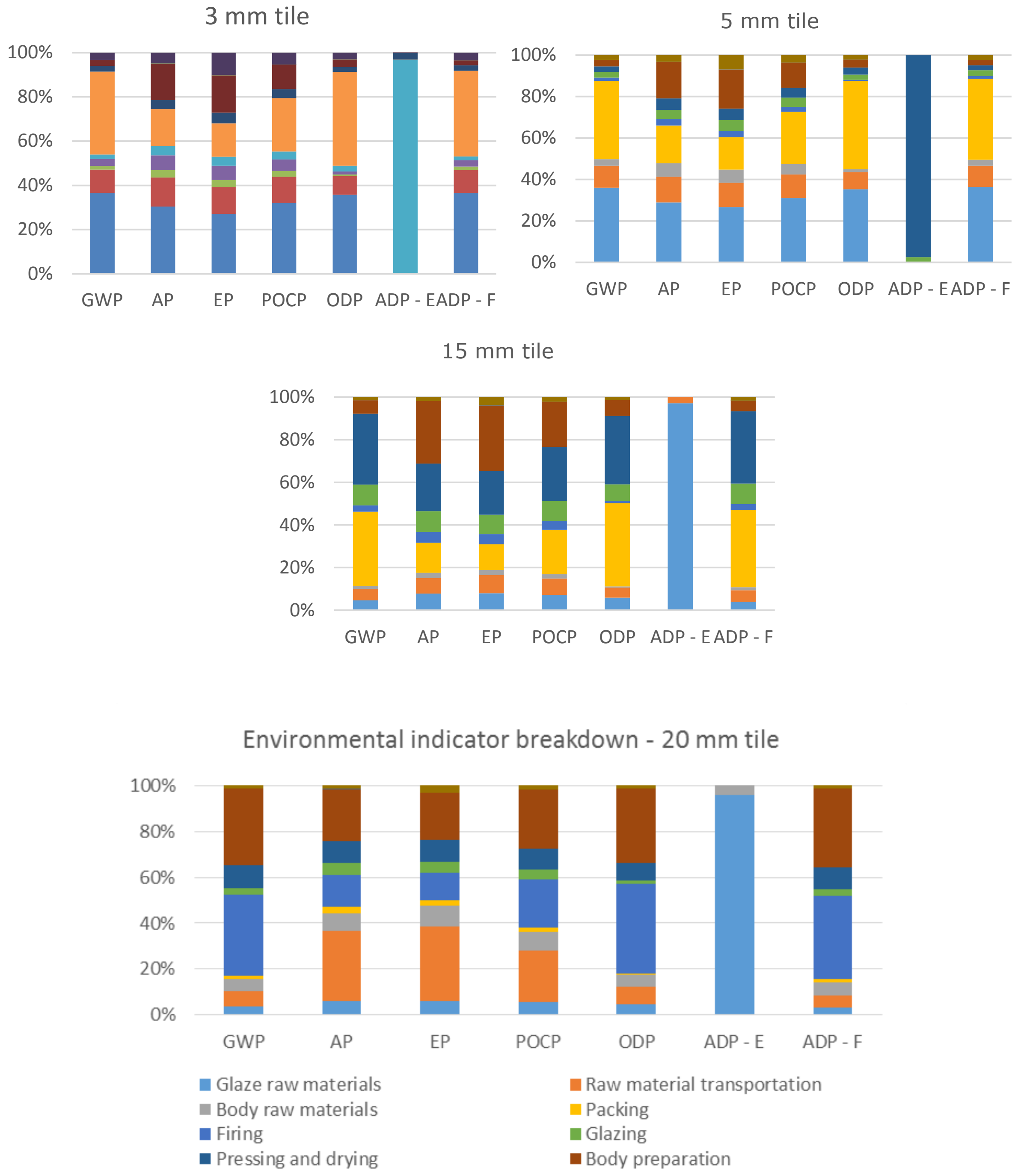


Figure 39. Environmental indicators as a function of thickness

Recycled/Secondary raw materials

New formulations include secondary raw materials to reduce demand of virgin materials. Secondary raw materials contributing to recycled content are pre- and post-consumer waste, which are incorporated in the ceramic body or glaze formulation. Scrap produced during tile manufacturing and reintroduced in the process within the same company does not account for recycled content since it is considered internally recovered material (ISO 14021). Ceramics with a high content of recycled material, up to 88%, are already presented in several EPDs (

Table 17).

Table 17. Secondary raw material content in publicly available EPDs**.**

EPD	Product	Program Operator	Secondary raw material content
Revigrés	Porcelain tile	IBU	23%-88%
Graniti Fiandre	Gres Porcelain sheets	Environdec	6%-7%

The incorporation of recycled material does not necessarily afford an automatic reduction of environmental impacts, since reduced extraction activities might be counterbalanced by impacts associated to sorting, reprocessing and transportation of waste. Regardless of the latest, using waste in the ceramic tile formulation brings a relevant decrease in resource consumption since leads to reduced mining activities, and thus to a reduced impact on the ecosystems. This positive trend is visible in the indicators ADP-elements.

Figure 40 considers ADP variation with the inclusion of recycled material.

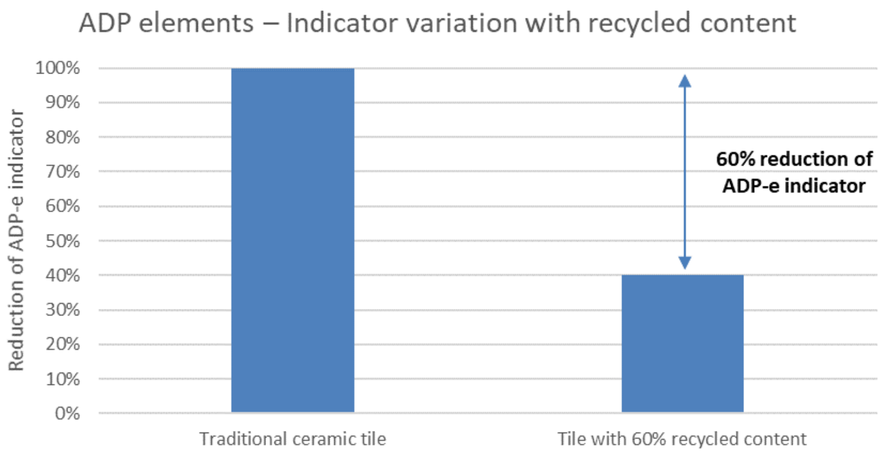


Figure 40. ADP indicator variation with recycled content.

These aspects could be eventually debated if the inclusion of recycled content among Ecolabel criteria is taken into account.

Energy requirement

IperCER project[62] shows the breakdown of thermal energy and electricity for the ceramic manufacturing process, subdividing the total consumption among body preparation, drying, and firing. Based on this information, it was possible to estimate energy consumption for the manufacturing stage. The contribute of each phase to the indicator GWP is presented below in

Figure 41.

[62] NIER Ingegneria. Efficienza energetica e industria ceramica: sviluppo delle prestazioni energetiche (2017) IperCER Project.

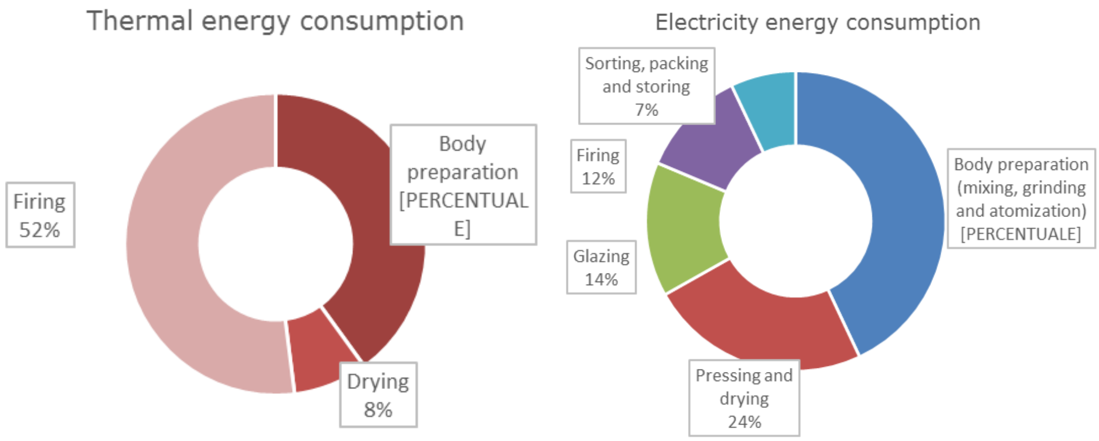


Figure 41. Contribution to GWP deriving from thermal and electricity energy consumption during the entire ceramic tile manufacturing process[62].

Firing stage represents the main contribute to GWP for thermal energy consumption, while body preparation stage is the electricity main contribution.

Industries provided primary data on fuel consumption in relation to tile thickness. Figure 42 shows fuel trend for firing stage, both per m^2 and kg. These data are representative for tiles composed of virgin raw materials. Tiles with recycled material in the formulation might show slightly different energy requirement.[63]

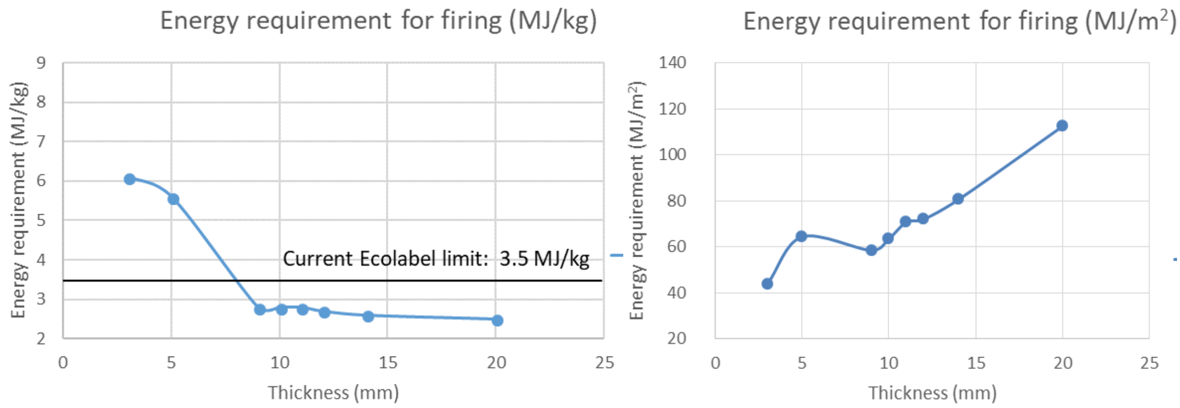


Figure 42. Energy requirement for firing expressd in MJ/kg (top) and MJ/m^2

[63] : WINCER – Waste synergy in the production of INnovative CERamic tiles (2015-2017).

Mezquita et al.[64] show that despite recent innovations in kiln designs, only 5% to 20% of the input energy goes into the chemical reactions occurring during the firing process. The remaining part is wasted through the chimney, cooling stacks, finished product, and losses through walls and vault of the kiln, as showed in Figure 43.

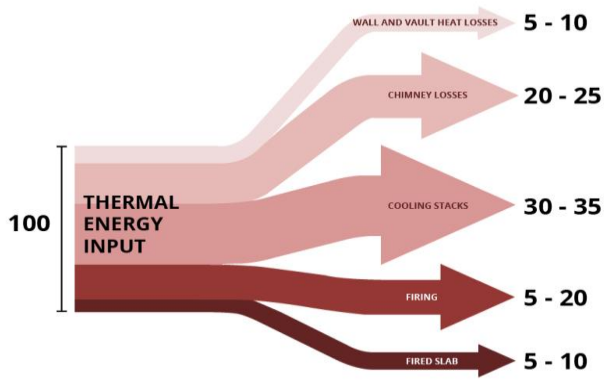


Figure 43. Kiln energy balance. Image from Ipercer report, data from Mezquita et al[64]

<u>Influence of fuel used for firing stage</u>

Fuel employed in the firing stage can have a considerable influence on on-site emissions. Natural gas is the most commonly employed fuel; however, in some cases, other fuels can be used. BREF on ceramic industry reports the average fuel mix for wall and floor tiles is natural gas 98% and fuel oil 2%.

A sensitivity analysis has been carried out to show how GWP and AP indicators vary considering a fuel mix ranging from 90% natural gas-10% fuel oil to 100% natural gas. Variation of the indicators GWP and AP are shown in Figure 44. The data have been calculated for 10 mm thick tiles, which require 64 MJ/m^2 for the firing stage. 10% decrease in fuel oil leads to a dratically drop (more than 80%) in the AP indicator, while GWP is less affected (less than 5% reduction). This is due to SO_2 emissions attributed to the fuel oil, which are instead in low concentration in natural gas, and have great influence on the AP indicator.

[64] Mezquita, A., Boix, J., Monfort Gimeno, E., Mallol Gasch, G. Energy saving in ceramic tile kilns: Cooling gas heat recovery. Applied Thermal Engineering 65-1 (2014), 102–110.

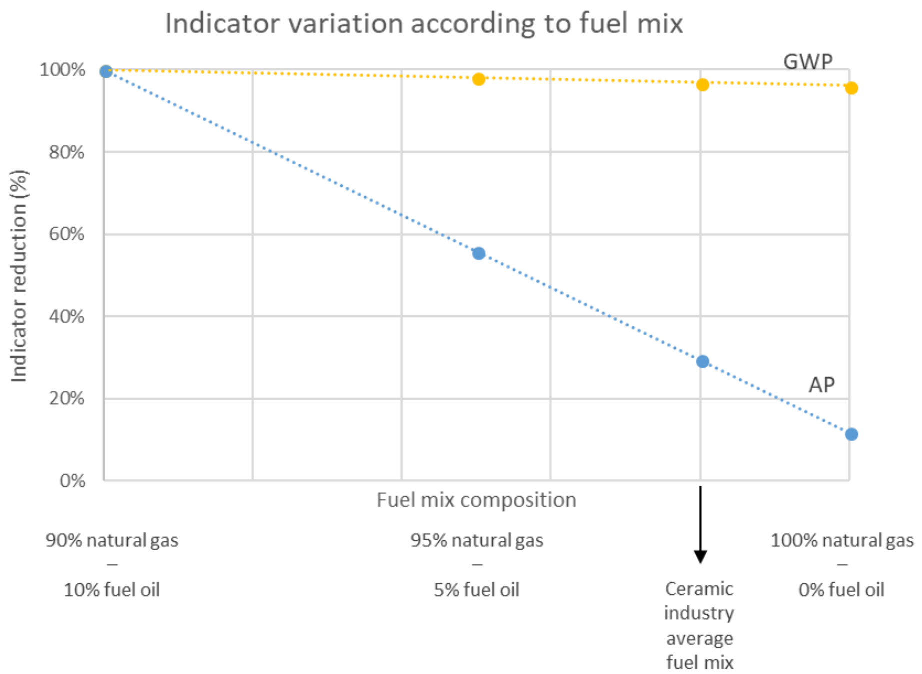


Figure 44. Percentage reduction of Global Warming Potential (GWP) and Acidification Potential (AP) upon variation of fuel mix composition. 100%. This graph refers to the firing stage only.

Water consumption and water recycling ratio

As far as water consumption is concerned, data collected from papers and EPDs are reported in compared with current Ecolabel

Table 18 and compared with current Ecolabel

Table 18. Water consumption of the ceramic tile manufacturing process.

Source: *	Water consumption (l/kg of product)	Current Ecolabel limit (l/kg product)
LCA studies (A3)**	0.9-1.1	1
EPDs (A1-A3)**	1.5 -2	

* sources reported data per functional unit (m^2); in order to obtain data per kg of product, values were normalized on the specific tile weight (kg/m^2) where available.
** data from EPDs refer to modules A1-A3, i.e. from raw material supply chain to the manufacturing stage, while existing criteria are referred to A3 only. Thus, water consumption in EPDs might be slightly overestimated but this aspect might require further analysis towards Ecolabel criteria revision.

Emissions to air

Currently, Ecolabel cover emissions attributed to pressing, glazing and spray drying (cold emissions) and, separately, those attributed to the firing stage of ceramic tiles. Data associated to the Best Available Techniques (BAT) reported in the BREF document have been used as a benchmark for existing Ecolabel thresholds. It is important to highlight that although the BATs indicate the best results reachable with the application of some specific techniques and technologies for the ceramic sector, the current BREF document is dated 2007, and, in some cases, emission ranges might have been surpassed by latest available technologies.

Data for emissions to air associated to the firing stage of the ceramic tile are reported in Table 19 also expressed in mg/m^2. [65].

Table 19. Emission ranges for the firing stage of ceramic tile as reported in the BREF of ceramic manufacturing industry

Pollutant	BAT value		Limit according to Directive 2010/75/EU (mg/m^2)	Ecolabel threshold (mg/m^2)
	Min (mg/m^2)	Max (mg/m^2)		
Dust	57	1 140	285	200
HF	57	570	-	200
NO_x	285	8 550	5 700	2 500
SO_2	57	17 100	1995*	1500 - 5 000

*emission limit refers to combustion plants using gaseous fuels; if considering plants using liquid or solid fuel, limit can vary.

The wide ranges for some of the polluting substances, such as NO_x and SO_2, can be attributed to the combustion process and are mainly related to the fuel employed. If solid or liquid fuels are used in the process, these emissions can increase, while gaseous fuels are usually low in S content.

[65] : for the conversion of firing stage emissions from mg/m^3 to mg/m^2 of finished product, a specific flowrate of 3 Nm^3/kg (source: Table 3.28 of BAT) and an average weight of the tile of 19 kg/m^2 were used. To provide the best available values on air emissions, the lower limit of the specific flow rate has been used for conversion.

4 OVERVIEW FOR CLAY TILES

4.1 Terminology and classification

Clay tiles are units that satisfy certain shape and dimensional requirements, used for the surface course of pavements and manufactured predominantly from clay or other materials, with or without additions as defined by CEN/TC 178. The specific weight of such tiles shall not exceed 40 kg/m².

Clay materials are mainly made of the following components:

- **Clay/Loam**: material with slightly variable composition composed of aluminium oxide Al_2O_3, silicon oxide SiO_2, iron oxide Fe_2O_3; this variation in components produces different colours in the manufactured product. For a generic composition of clay, refer to Table 20.
- **Sand and firing waste**: these materials are added to adjust natural fluctuations in raw clay;
- **Manganese oxide and iron oxide**: these oxides are added to achieve certain colours.

Recent studies have proved the feasibility of introducing secondary raw materials inside the clay body composition. This aims to partially substitute the common raw materials employed in the formulations.

Table 20. Example of chemical composition of clay. (Source: Dondi et al.[69])

Chemical composition	Weight (%)
SiO_2	43.8
TiO_2	0.6
ZrO_2	<0.1
Al_2O_3	12.8
Fe_2O_3	4.5
MgO	2.8
CaO	15.2
SrO	<0.1
BaO	<0.1
PbO	<0.1
Na_2O	0.8
K_2O	2.0
L.O.I	16.5

LOI represents the "loss on ignition" (weight loss due to organic compounds volatilization, decomposition of carbonates and water evaporation) during the firing stage

Currently, a wide array of clay products is available on the market. Such elements can be grouped in two broad families, cotto tiles and paving bricks[66]: Beside these two main groups, there are also other products with very specific use, mainly employed to fill delicate spots.

[66] Antonio Lauria, "Le pavimentazioni in laterizio. Mattoni, sestini e pianelle di cotto", edizioni Laterservice srl, Roma 2008.

a) Cotto tiles

Tiles for flooring purposes used both indoor and outdoor. The most common types available on the market are depicted in Figure 45. Each of these tiles can be produced with different dimensions of width, length and thickness. Two special formats are also included in this category:

- Tozzetto: tile with a square shape;
- Lath: long tile with rectangular section, often with 1:4 ratio between width and length.

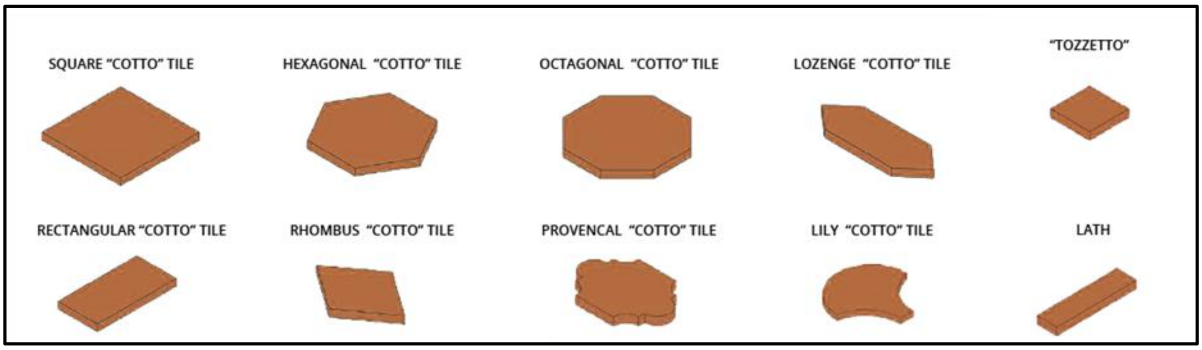


Figure 45. Types and relative shapes of commercially available cotto tiles. (Source Lauria[66])

b) Paving bricks

Paving bricks or clay pavers are for flooring purposes and usually have a rectangular wear side. These bricks can be laid both with flexible and rigid method and are usually used outdoor. This category includes two main components Figure 46.

- Sestino: ratio between wear side surfaces is 1 to 4, with a square section for the base element;
- Paving brick: ratio between wear side surfaces is 1 to 2;

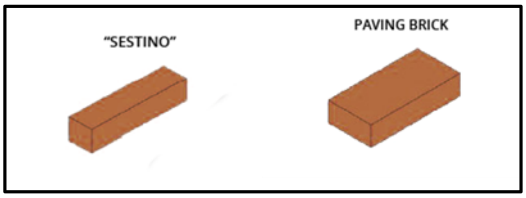


Figure 46. Type of bricks for flooring purposes. (Source Lauria[66])

c) Other - Finishing elements and extras

In order to provide adequate strength in critical points, some particular elements can be incorporated in pavements. These additional elements can be grouped in in three main categories:

- Skirting board elements;
- Staircase elements;
- Elements for the outdoor/street furniture.

A huge variety of products for the three categories with different sizes for all the dimensions (length, thickness and width) is produced, thus resulting in highly customized pieces related to the surface they are destined to. The following images (*Figure 48*) show the main features of these additional elements, commonly employed in both outdoor and indoor environments.

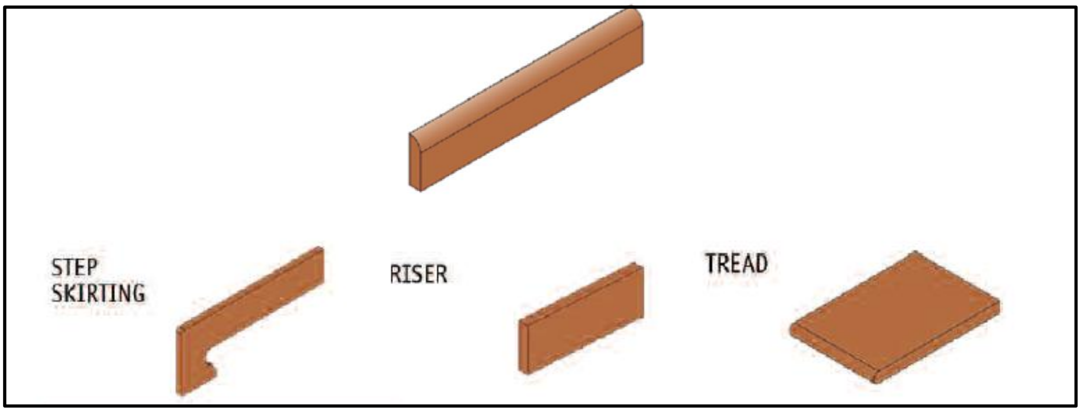


Figure 47. Skirting and staircase elements. (Source Lauria[66]).

Exclusively for exterior applications, several products with different shapes are produced. Figure 48 provides some of the possible outdoor elements. A brief description of each product is reported below each individual image.

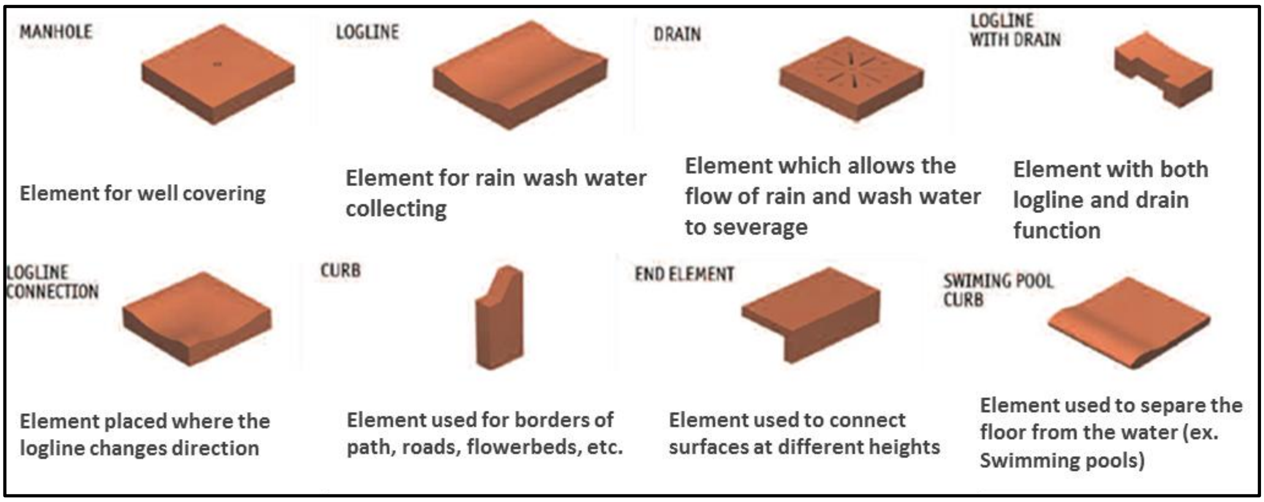


Figure 48. Elements for exterior applications. . (Source Lauria[66]).

4.2 Relevant technical standards

Clay products are regulated by two standards:

EN 1344: Clay pavers - Requirements and test methods. Clay products must comply with specific requirements regarding technical characteristics, provided by EN 1344 standard. This European standard defines the requirements of pavers and accessories manufactured from clay and applies to rectangular and other shaped units intended as construction products in pavements, both for internal and external use, subjected to pedestrian and vehicular traffic. Such products are described in the next sections. The EN 1344 also reports the characteristics and classes of performance and corresponding test methods. However, this standard explicitly excludes tiles, which are addressed by the EN 14411.

EN 14411: Ceramic tiles - Definitions, classification, characteristics, evaluation of conformity and marking. This European Standard defines the characteristics of ceramic tiles produced by extrusion and dry-pressing techniques, used for internal and/or external floorings (including stairs) and walls.

4.3 Market for clay tiles

Clay tiles are clay fired products used for floor covering. The CEN definition, as well as the one provided by the Decision 2002/272/EC, refers to clay tiles as units which satisfy certain shape and dimensional requirements, used for the surface course of pavements and manufactured predominantly from clay or other materials, with or without any additions

No public data regarding international clay tiles market has been found. Several relevant companies and sector business/manufacturer associations have been unsuccessfully contacted. The Eurostat database provide data but referring to the whole clay bricks and tiles sector (thus comprising building bricks, roof tiles, paving bricks and chimney and other clay constructional products such as cowls, flue-blocks and chimney liners. Another source of data, yet focusing on the entire sector, was the "*Final Report For A Study On Composition And Drivers Of Energy Prices And Costs In Energy Intensive Industries: The Case Of The Ceramics Industry - Bricks And Roof Tiles*" published by the Centre for European Policy Studies in 2014[67].

In any case, to provide a realistic overview of the European clay tiles sub-sector alone, it was decided to merge Eurostat dataset with national data provided by ANDIL, the Italian association of clay manufacturers, regarding the importance of the clay tiles respect to the whole sector. The relevance of the clay tiles sub-sector calculated for Italy (1% of the total, see Figure 49), was then adopted to discuss the Eurostat data. For this reason, data described in the following pages referring to production value, turnover and import/export values have been obtained by extracting from the total sector value (Eurostat data), the percentage corresponding to clay flooring tiles only (1%).

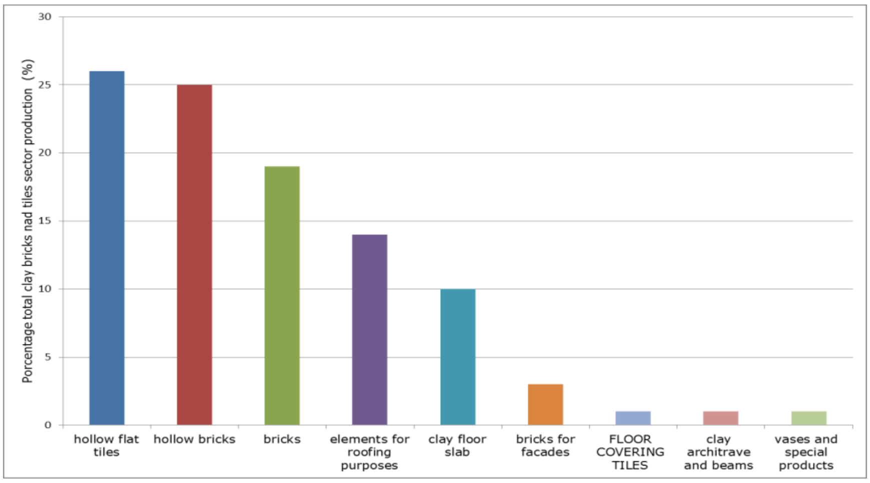


Figure 49. Breakdown of Italian clay bricks and tiles sector in 2016.

[67] Eggenhofer C., Schrefler L., Genoese F., Wieczorkiewicz J., Colantoni L., Stoefs W., Timini J. Final Report For A Study On Composition And Drivers Of Energy Prices And Costs In Energy Intensive Industries: The Case Of The Ceramics Industry - Bricks And Roof Tiles. Centre for European Policy Studies, 2014.

4.3.1 European production and consumption

The entire European bricks and roof tiles sector is composed by more than 1800 industries (reference 2016 data). While other ceramic sub-sectors are dominated by SMEs, the bricks and roof tiles industry is composed almost equally by a number of regionally settled SMEs and larger producers [67]. Figure 50 illustrates the distribution of the production of bricks and roof tiles among EU member states, which is highly concentrated in a few Member States. Thus, the production of Italy, Spain, Poland and Germany account for more than 50% of total EU production (2015 data).

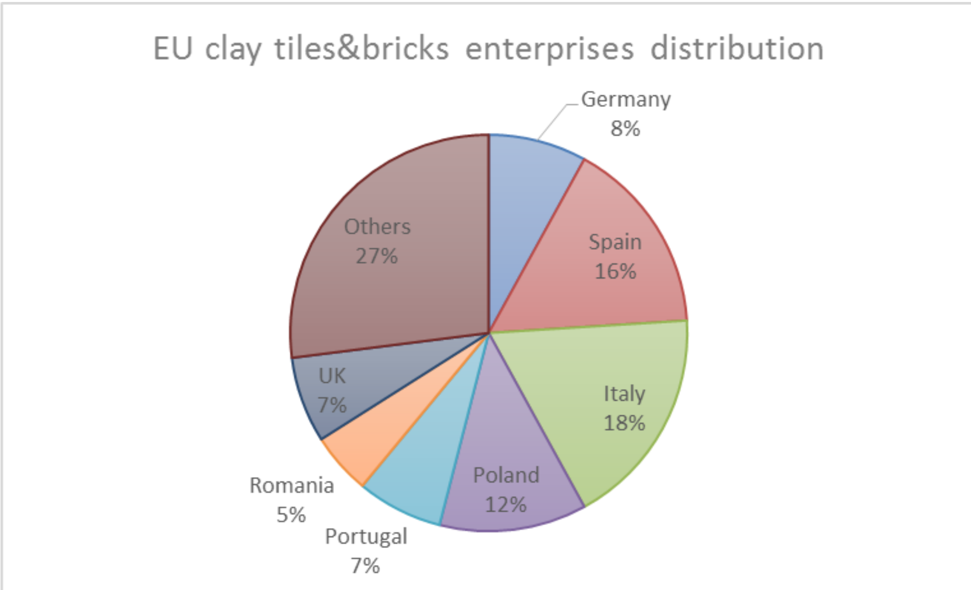


Figure 50. Geographical distribution of European clay tiles and bricks manufacturers.

The production volume index (Figure 51) shows a substantially decrease between 2007 and 2014, with a sharp peak between 2007 and 2009. From 2013 the trend has stabilized, but has not recovered the values pre-crisis, the current production volume is almost half of the production in 2007

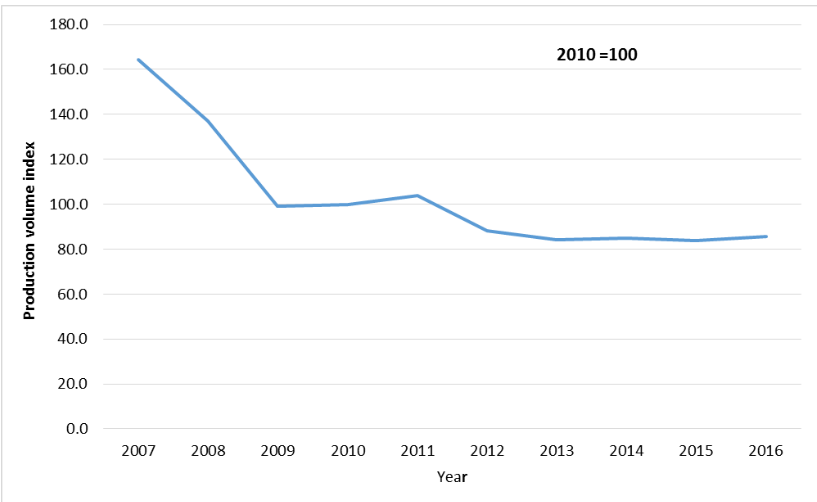


Figure 51. Production volume index of clay tiles sector.

4.3.2 European imports and exports for clay tiles

Bricks and roof tiles are characterized by high transportation costs[67], this factor has historically discouraged a strong global or European market for these products. For example, the British Competition Commission reports that 80% of clay bricks and tiles produced in the UK are sold not farther than 200 km away from their production sites.

Figure 52 shows the trend of export and import of clay flooring bricks, expressed in terms of value. Both exports and import values decreased noticeably between 2008 and 2009. From that date, exports rose again reaching the highest peak in 2014, while imports continued the negative trend until 2012, although in the last years the trend has changed.

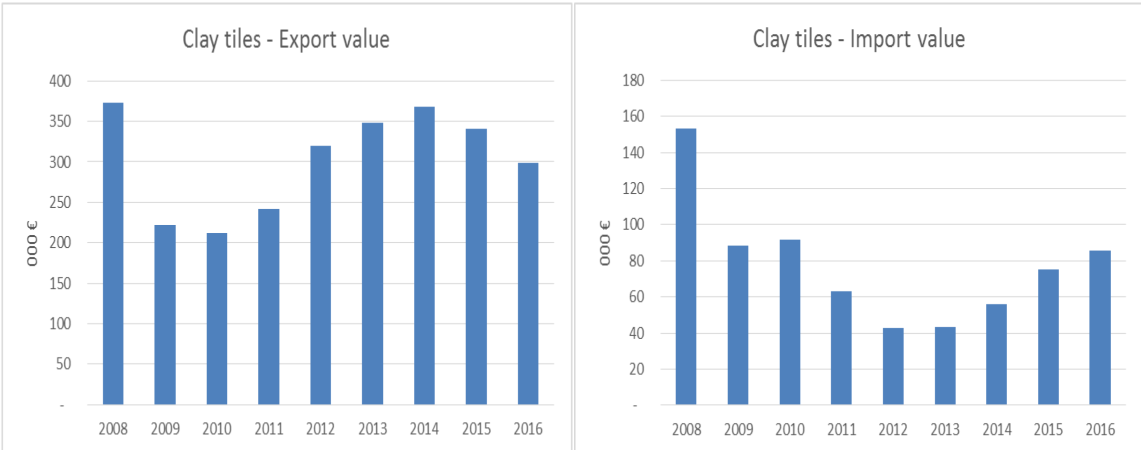


Figure 52. European clay tiles sector export and import expressed in terms of value.

4.4 Review of production technology and innovations

Unlike ceramic tiles, typologies and formats of clay tiles have mainly remained similar to the previous years, but constant improvements in manufacturing processes, compelled by the need to reduce energy consumption, have slightly increased overall process efficiency, while leaving untouched existing technologies. Besides, as far as the composition is concerned, formulations are being altered by introducing secondary raw materials, thus reducing demand for virgin resources. The following scheme (Figure 53) shows the areas (red circles) where the main changes have been registered.

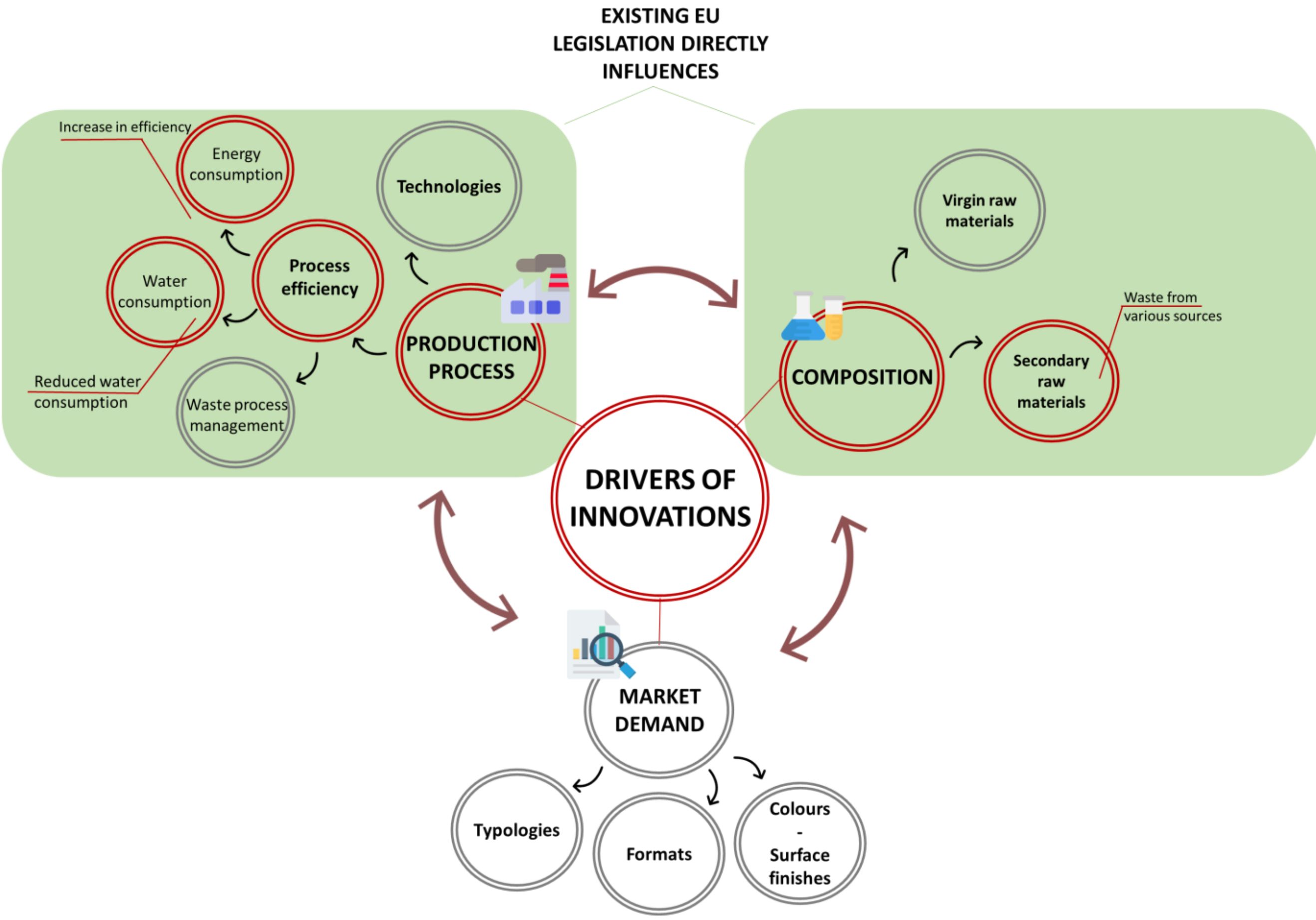


Figure 53. Main improvements and changes for clay tiles.

4.4.1 Manufacturing process

The manufacturing process has not registered substantial changes in the last decade. However, manufacturing plants are now more efficient thanks to technological advancements and the overall product quality is slightly superior. Clay industry has advanced mainly thanks to:

- a more complete knowledge of raw materials and their properties;
- better control of firing and improved kiln designs;
- widespread mechanization.

Manufacturing requires firing products at around 1000 °C, thus making clay production an energy-intensive process. The following images and data are related to brick manufacturing since this typology of clay product has the highest share in the market, while clay pavers have a very low share (~1%), as already highlighted by the market analysis. However, it is reasonable to assume a similar trend for paving products.

Figure 54 shows the main steps of the manufacturing process, which are furtherly described below.

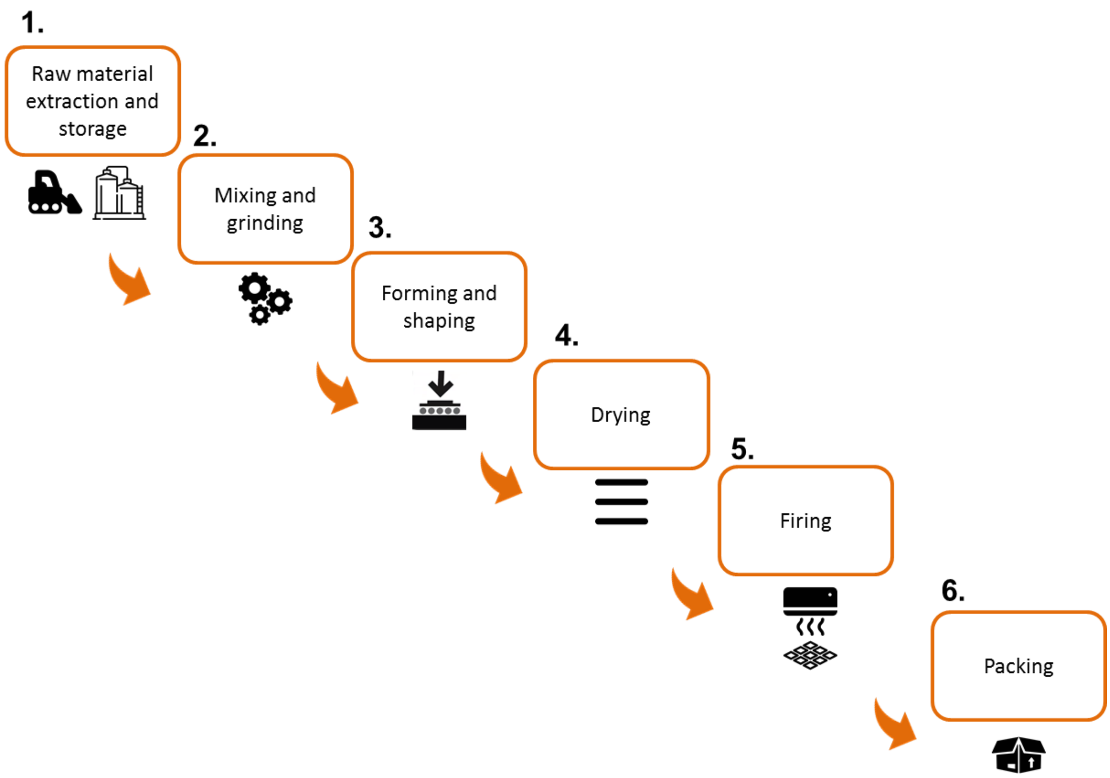


Figure 54. Main steps of clay product manufacturing.

Raw material extraction and preparation

Raw materials, such as clays and shales, are extracted in open pits. Materials can be transported from the quarry to the production site in two main ways:

- via conveyer: this route is preferred when short distances are involved. Besides, this method leads to less emissions related to raw material transportation;
- via truck or rails: when longer distances between quarry and manufacturing site exist, transportation with truck or trains is commonly employed.

Most of clay product factories are located close to the quarries where raw materials are extracted, thus making the use of conveyers ideal.

Mixing and grinding

After extraction, the clay raw material is laid out in order to obtain a homogeneous mixture. The clay is crushed and ground. Several types of grinding mills are used for this stage, such as dry pan grinders, roller mills, and hammer mills. Then, it is blended with additives to achieve the desired physical properties, such as strength, water absorption (porosity) and frost resistance. Materials such as sawdust or residue from the paper industry can be added to increase the porosity of the final product. Other additives can be added to modify the colour of the final product (see *Table 21*).

Table 21. Example of possible colours obtainable by variating the type of clay.

Colour	Type of clay/mineral
Red brick	Clay with iron oxides
Cream-like brick	Clay with reduced iron oxide

Yellow brick	Mixture of clay and calcium carbonate

The moisture content is controlled before processing; the initial moisture content usually varies from 3% to 15%, depending on the quarrying site. At this stage it may be necessary to add water to obtain the right consistency for forming.

Forming and shaping

Bricks are formed and shaped with three techniques:

- **Extrusion (stiff mud process):** water in the range of 10 to 15% is mixed with clay to produce plasticity. Afterwards, the mix is loaded in a vacuum chamber, where air is removed. The material is then extruded through a die. Oil or other lubricants reduce friction during extrusion. As a last step, bricks are cut via an automatic machine which slices the clay column.
- **Moulding (soft mud process):** higher content of water is added, 20 to 30%. The clay with the desired chemical composition is formed into bricks or tiles inside moulds, by pressing the mix into a sanded mould box. Sand main function is to prevent clay from sticking. A similar lubricating effect can be achieved with water instead of sand.
- **Dry-Press Process:** This process is particularly suited to clays of very low plasticity. Clay is mixed with a low amount of water (up to 10%), then pressed into an initial brick shape, and re-pressed into the final shape and size.

Although not spread at industrial level, it is worth mentioning the hand moulding technique. Handmade clay products still maintain their place in the modern market due to their individual character and the ability to match a wide variety of sizes and shapes, but they are segregated to very specific destinations, such as historic buildings.

Approximately 78% of current production is extruded and 22% is through the soft mud process. Handmade production makes up a very small amount of the output.

Bricks can be made in many different sizes but the market is dominated by units that are 65mm high, 215mm long and 103mm wide. Some plants also make bricks that are 73mm high, to be compatible with older properties and used for extensions and refurbishment.

For some products, surface can undergo a surface treatment, involving manganese dioxide, iron oxide, and iron chromite, in order to add colour to the product.

Drying

The moisture in the extruded or pressed green bricks is removed in a dryer (normally down to levels of one per cent or below) to make sure that they can be safely handled and fired. The bricks shrink during the drying process, so it needs to be carried out carefully to make sure that they don’t crack. Drying is very heat intensive as a large amount of water needs to be evaporated. Most dryers rely on recovered heat from the kiln to provide the bulk of their heat requirements. The most important parameters are temperature, humidity and air movement. A typical drying cycle starts with low temperature (around 30 °C) and high humidity and ends with high temperature (up to 120 °C) and low humidity. Fans control air movement and evenly distribute the air around the product in order to have a homogeneous brick drying process. Once the chamber dryer is filled with pallets of wet bricks until full capacity is reached, the drying cycle begins and lasts between 24 and 48 hours. In the most modern and efficient plants, dryers typically use waste heat from the cooling zone of the kiln. However, some plants heat dryers with gas or other fuels. Dryers may be in-line or totally separate from the kiln (see next paragraph).

Firing

Dried bricks are fired in kilns at temperatures between 900°C and 1100°C. The intense heat changes the chemical make-up of the clays, and partly melts them to give the desired strength and appearance.

There are three main types of kiln:

- **Tunnel kilns** in which stacks of bricks are transported continuously through the kiln. These are the most common kilns used, and are responsible for most brick production in the UK.
- **Intermittent kilns** in which bricks are placed in a single compartment, fired and removed on a batch basis. These are used for small throughput operations.
- **Continuous chamber kilns** in which a number of intermittent kilns are built into a single structure which are heated in sequence to give continuous production and to recover some of the waste heat. These were once relatively common but are no longer widely used as they are expensive to build and difficult to load and unload.

The firing process can be divided in 3 main phases, whose temperature profile is shown in Figure 55:

- **Heating**: heating of clay removes moisture, carbonaceous material, and leads to chemical and colour changes in the final product. The high temperature step is called vitrification and consists of clay particles melting and bonding, giving strength and resistance to the structure. This phase usually starts around 900 °C but, if oxides are included in the formulation, this temperature decreases. This explains the wide variation observed in firing temperatures.
- **Soaking**: during this stage, the temperature is maintained constant to allow homogeneous vitrification throughout the whole clay product.
- **Cooling**: upon cooling, the liquid solidifies to glass, thus bonding together the whole product. It is important to properly adjust the temperature, avoiding excessively quick cooling because it could lead to thermal stresses inside the brick and consequent cracking. Bricks leaving the cooling zone are close to ambient temperature.

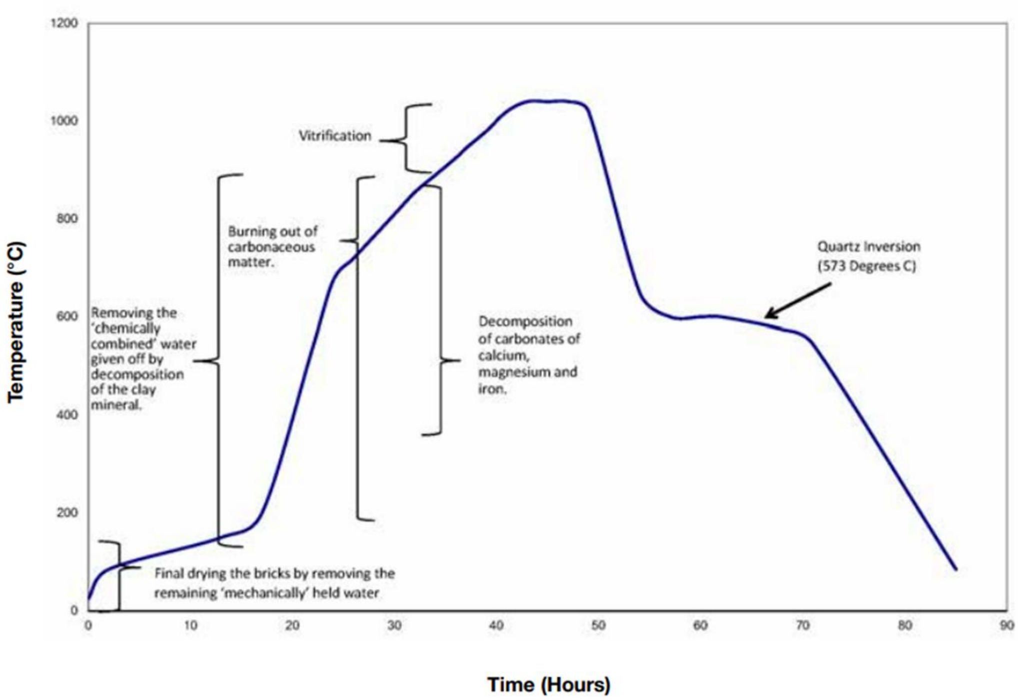


Figure 55. Time vs temperature curve. The important changes in clay structure are shown in the curve. *(Source:The UK clay manufacturing process report, March 2017)*

In some cases, at the end of the firing stage, excess fuel is fed to the kiln in a reduced atmosphere to provide different textures to brick surface. This process is called flashing and typically follows the firing zone. Afterwards, bricks are rapidly cooled.

The color of brick is determined by the raw materials and the firing method. Additives blended into the clay mixture can create color completely through the brick body. Sand coatings, ceramic slurries and other additives can be applied to the face of the brick to create different surface colors. Changing the firing temperature will also produce different shades of colour from the same raw materials. Flashing is one method of firing brick which burns some of the brick darker. These flashed brick add color range and highlights to many styles of brick.

Inspection and packing

After firing, the bricks are unloaded and inspected for appearance in a process known as "dehacking", before being packed and dispatched.

Pack sizes and types depend on the brick factory, but generally range between 300-500 bricks per pack, reaching up to 1.5 tonnes of weight. They are usually palletized and shrink-wrapped.

4.4.2 Innovation and improvements

The primary process improvements are:

- improved design of dryers and kilns
- computer control of drying and firing regimes
- Heat recovery systems from kilns (mainly hot air from cooling zones of kilns ducted to dryers)

- product modifications or innovations

The implementation of renewable energy is in constant progress:

- production or use of green electricity
- gas produced from landfill can be used in nearby clay brick and roof tile production plants or elsewhere, thereby reducing the reliance on non-renewable energy sources.

Renewable resources are also present in many ceramic production processes where biogenic additives, such as sawdust can be added to the raw clay. The utilization of such renewable additives reduces product weights and increases their insulating performance.

Use of secondary raw materials

No radical changes in the composition of clay products have been registered in the last decade. However, some attempts to introduce secondary raw materials in the formulations are worth to be mentioned. Some of the works found in literature focused on using the following waste in substitution of virgin resources:

- Sugarcane bagasse ash.[68]
- End-of-life TV sets and PC monitors.[69]
- Glass waste from structural glass wall. [70]

Despite the great difference in composition and origin of the waste, all these materials have been incorporated into the formulations with minor inconveniences. However, it is necessary to highlight that, while incorporation of resources coming from other processes can be advantageous, because it leads to reduction of extraction activities and virgin resources consumption, the supply chain of materials from alternative sources can increase environmental impacts since plants are usually located near the quarries, which is generally far from the alternative material sources.

Internally incurred production waste, such as broken or defective products, can be reprocessed and recycled in the production. External recycling materials are used as additives for certain product groups and generally processed together with the raw material mix during preparation. Recycling materials from biogenic sources (sawdust, paper fibres, sunflower hulls, etc.) can be also used as pore-forming agents in clay blocks.

Energy efficiency

Since clay industry is an energy-demanding process, efforts have been made towards reduction of fuel requirement and more efficient processes, mainly aimed at reusing and recycling waste heat from the kiln.

Most of the energy used in is thermal energy (natural and liquefied gas or oil), which is required to heat the tunnel kilns. The heat released during the cooling process is recovered and recycled into the drying process. Electrical energy plays a minor role in production. Manufacturers are exploring the possibilities of substituting alternative fuels

[68] Faria, K.C.P., Gurgel, R.F., Holanda, J.N.F. Recycling of sugarcane bagasse ash waste in the production of clay bricks. Journal of Environmental Management 101 (2012) 7-12.
[69] Dondi, M., Guarini, G., Raimondo, M., Zanelli, C. Recycling PC and TV waste glass in clay bricks and roof tiles. Waste Management 29 (2009) 1945–1951.
[70] Loryuenyong, V., Panyachai, T., Kaewsimork, K., Siritai, C. Effects of recycled glass substitution on the physical and mechanical properties of clay bricks. Waste Management 29 (2009) 2717–2721.

for fossil energy sources. Other fuels can be used, such as oil, coke, coal and LPG, but they are mainly a backup.

Water consumption

Water represents an important asset of brick manufacturing and it is harvested both from main and non-mains sources. Clay industry is trying to reduce water consumption by introducing proper water management and recycling systems; and by installing rainwater harvesting systems.

4.5 Life Cycle Assessment : clay tiles

No specific life cycle assessment has been conducted for clay tiles due to the fact that there is relatively little literature out there and the fact that the production process and raw materials used are very similar to those for ceramic tile products.

The most significant difference is that clay tiles are likely to have a lower LCA impact due to the lesser or non-use of glazes and the lower firing temperatures that are typically required.

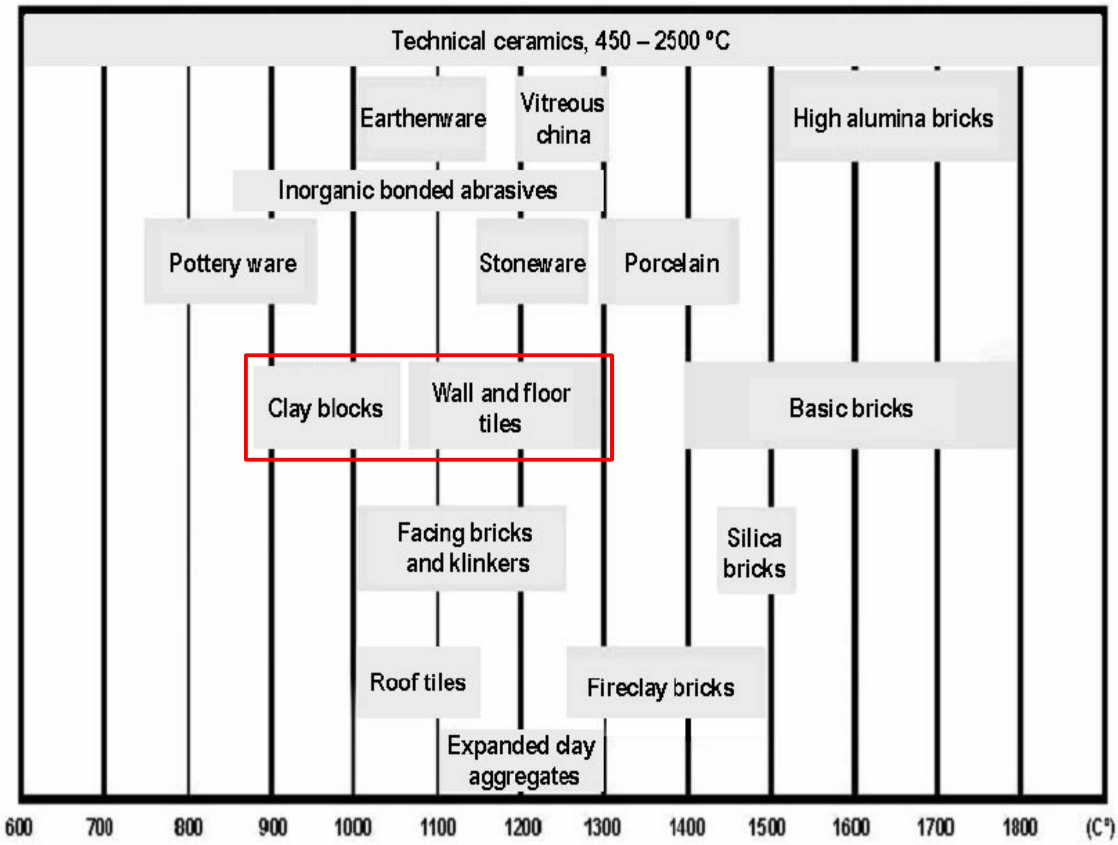


Figure 56. Ranges of maturation temperature for different products within the ceramic sector (Source: BREF, 2007)[71].

According to the data above, clay blocks require firing at temperatures that reach 900 to 1050°C whereas ceramic wall and floor tiles may require temperatures up to 1300°C.

[71] Reference Document on the Best Available Techniques in the ceramic manufacturing industry, August 2007.

5 OVERVIEW FOR AGGLOMERATED STONES

5.1 Terminology and classification

As defined by CEN/TC 229/N.246 EN 14618:2009, ‘agglomerated stones’, also known as engineered stones, are composite industrial products derived from a mixture of aggregates of various sizes, mainly consisting of natural stone’s gravel with binding additives. The gravel is commonly composed of natural stones granulate, such as marble, granite and quartz, coming directly from quarries or as by-products of natural stones processing operations as well as from recycling process. The binding additive is usually an artificial component such as unsaturated polyester resin, hydraulic cement, or a mixture of both. Additional materials can be added to the mixture (recycled glasses, mirrors, shells, and so on) to lend special effects and technical features to the finished products [72].

- The classification of the agglomerated stones is performed according to[73]:
- The type of binder: resins (unsaturated polyester or other types), cement, a mixture of cement and resin.
- The mineral nature of the main stony component: calcareous, siliceous, a mixture of the two.

Agglomerated stones are generally used to fulfil different functions: interiors and exteriors floor coverings and claddings, as well as slabs for benchtops[74].

5.2 Relevant technical standards

STANDARD	
General	
EN 14618 :2009	Agglomerated stone – Terminology and classification
Determination technical properties	
EN 15285 :2008	Agglomerated stone – Modular tiles for flooring and stairs (internal and external)
EN 15388 :2008	Agglomerated stone – Slabs and cut-to-size products for vanity and kitchen tops
	Agglomerated stone – Slabs and tiles for wall finishes (internal and external)
EN 15286	Water absorption and apparent density
	Flexural strength
EN 14617-1	Abrasion resistance
EN 14617-2	Frost and thraw resistance
EN 14617-4	Thermal shock resistance
EN 14617-5	Impact resistance
EN 14617-6	Slippliness
EN 14617-9	
EN 14231	

[72] Lam dos Santos, J., Rosa, L., & Amaral, P. (2011). Temperature effects on mechanical behaviour of engineered stones. Construction And Building Materials, 25(1), 171-174. http://dx.doi.org/10.1016/j.conbuildmat.2010.06.042

[73] www3.ipc.org.es. (2018). IPC - Classification and characteristics. [online] Available at: http://www3.ipc.org.es/guia_colocacion/info_tec_colocacion/los_materiales/piedra_art_resinas/clasificacion.html [Accessed 15 Feb. 2018].

[74] AstA World Wide. (2018). Engineered Stone Countertops Tiles Flooring Coverings. [online] Available at: https://www.astaworldwide.com/engineered-stones-uses/ [Accessed 15 Jan. 2018].

5.3 Market data

There is no public data available for agglomerated stone. The market data presented in this chapter have been provided by the Agglomerated Stone Manufactures Association (ASTA) from a confidential market research commissioned in 2014.

5.3.1 World production and consumption

Approximately 47 million square meters of engineered stone were produced in 2014 across four regions: Asia/Pacific, Europe, Africa and the Middle East and North America. Among these regions, Asia/Pacific was the largest producers, accounting for 46% of global manufacturing. Europe represented the second-largest region for production at 36%. Both Africa/Middle East and North America had shares of 9%, though the former produced slightly more engineered stone than the latter.

Similar to production, Asia/Pacific led the global consumption of engineered stones, representing nearly 60% of the world's total demand (44.5 million square meters). Europe and North America accounted for the second and third largest regions for demand, with shares of approximately 19% and 17%, respectively. The remaining 4% was constituted primarily by Africa and the Middle East's consumption, while Central and South America accounted for just 1% of global demand.

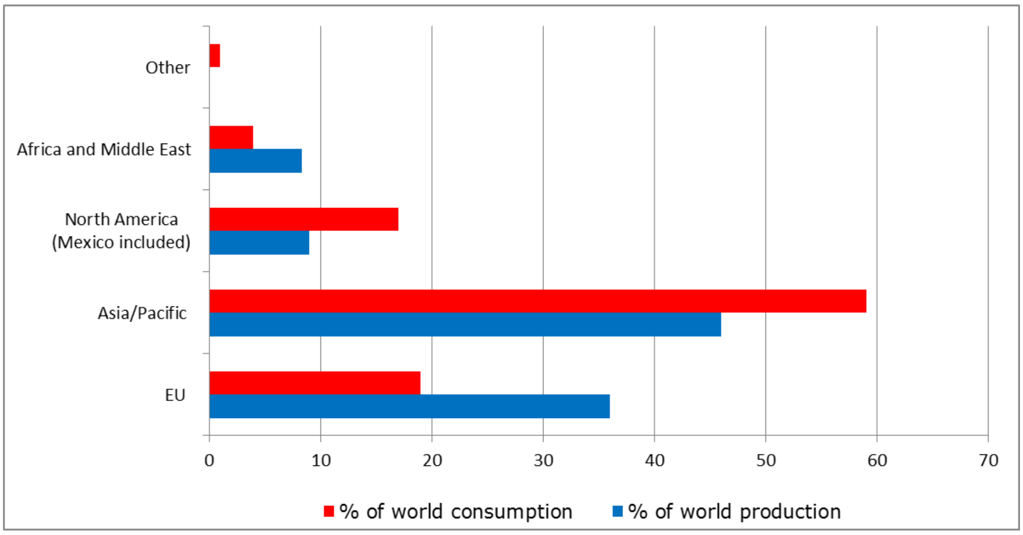


Figure 57. Agglomerated stone world production and consumption breakdown (in 2014).

It is expected that world production will continue to grow in the following two years, reaching 78.5 million square meters in 2019. Asia/Pacific, which has faced a strong growth in the last years, is expected to almost double by 2019, reaching 42 million square meters compared to 21.5 million square meters in 2014. North American production, completely supported by Breton machines, is facing a fast growth and is expected to reach 6.5 million in 2019. The European production, largely Breton-supported, is expected to increase its production by 7.5 million square meters from 2014 to 2019, as demand abroad continues to grow. Production levels in Africa and the Middle East are increasing too, although less sharply, and are supposed to achieve 5.3 million square meters2 in 2019.

Table 22. World agglomerated stone production (million square meters).

Item	2014	2019 (forecast)	Expected Growth %
North America	4.1	6.5	+58.8%
Europe	17.0	24.5	+44%
Africa & Middle East	4.3	5.3	+23.2%
Asia/Pacific	21.5	42.0	+95%
WORLD PRODUCTION	47.0	78.5	+67%

Agglomerated stones are mainly designated for furniture and construction applications. As shown in Figure 58, in 2014 furniture applications were the predominate end-use in every region. In total, furniture - which consists of countertops and vanities, accounted for 31.5 million square meters, representing approximately 70% of all demand. Construction end-uses comprised the remaining 30% of agglomerated stone demand in 2014. Only two regions saw construction applications represent 30% or more of demand: Asia/Pacific and Africa and the Middle East. Asia/Pacific had the largest market for construction and furniture applications in 2014, largely due to the size of the market overall.

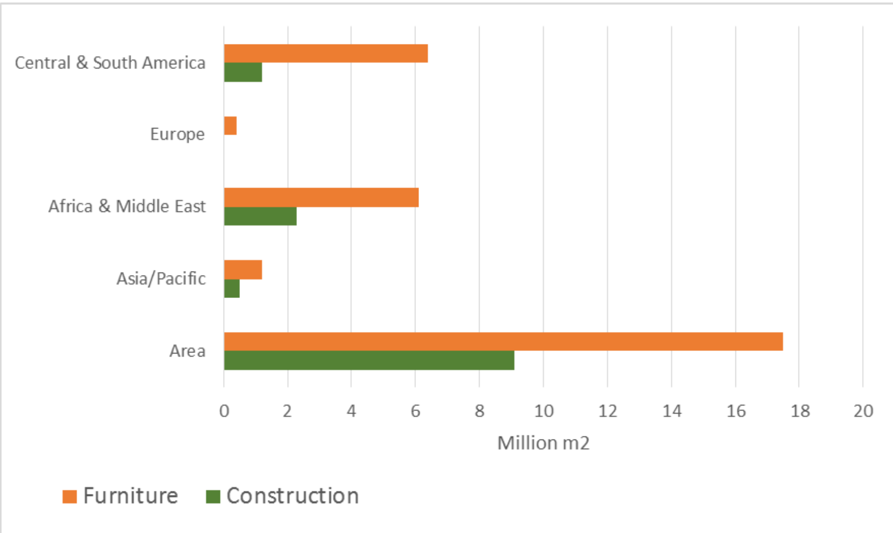


Figure 58. Agglomerated stone demand by application in 2014.

5.4 Review of production technology and innovations

In the agglomerated stones sector, only minor innovations and technological improvements have occurred. As shown in Figure 59 , the main improvements concern the production process, with a general increase in efficiency, and in the material composition, where, thanks to the diffusion of under-vacuum vibro-compression, higher percentages of natural stone aggregates can be used, reducing the requirement for binding agents, as well as the introduction of bio-resins.

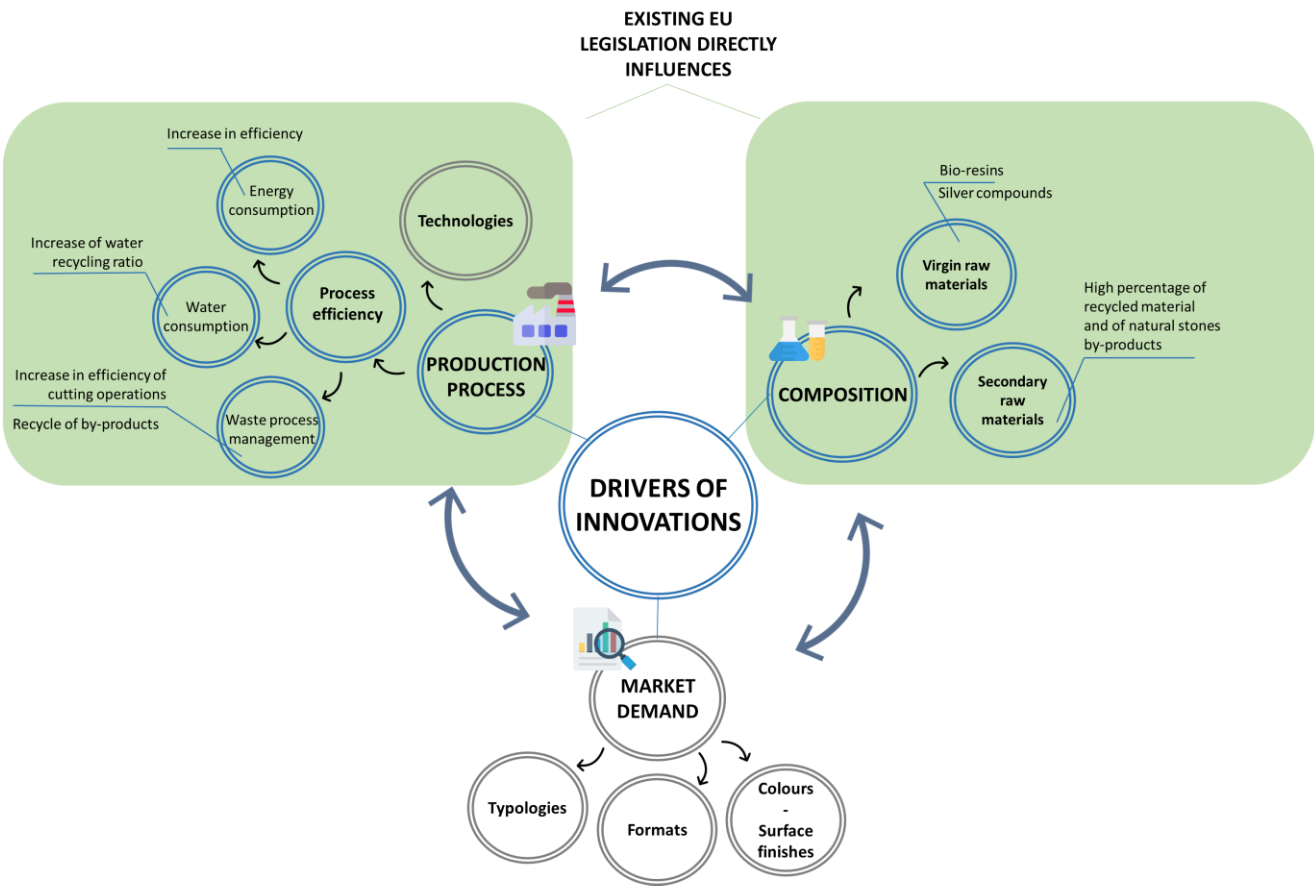


Figure 59. Main improvements and changes for agglomerated stones.

5.4.1 Manufacturing process

The manufacturing process of agglomerated stones can be divided into three main steps followed by the packaging and storage, as shown in Figure 60 and described in the following paragraphs.

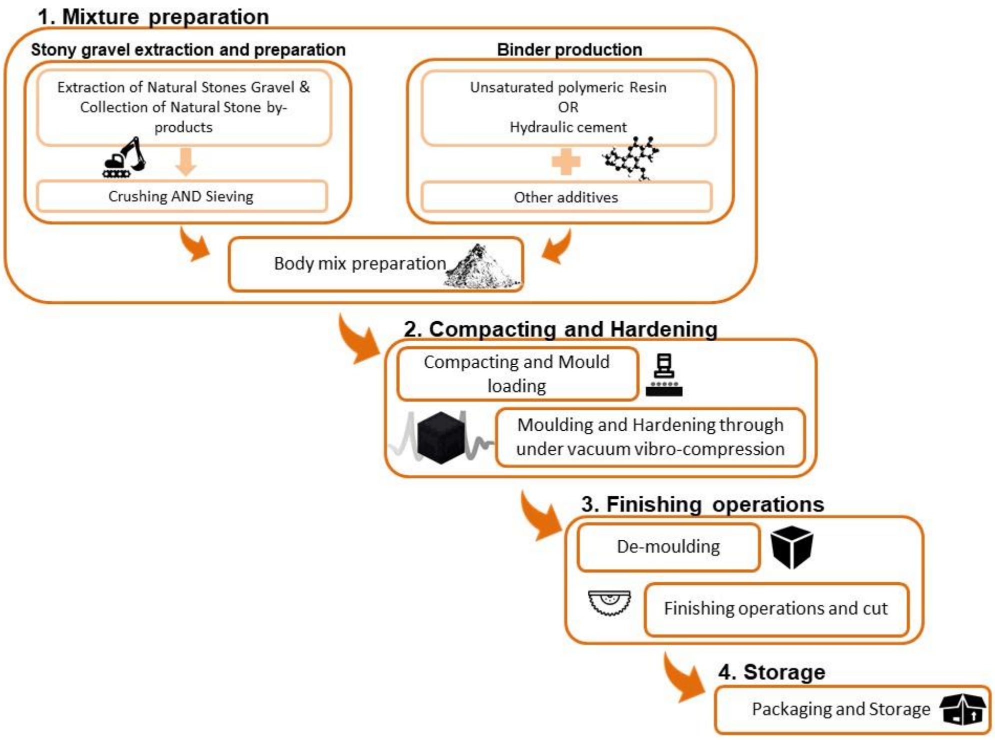


Figure 60. Main stages of the agglomerated stones manufacturing process.

Mixture preparation

The first step is the body mix preparation. The body mix is always composed by a large majority of natural stones' gravel with a binding agent and other additives.

The mineral type of the natural stones' gravel to be used in the mixture can be both siliceous or calcareous. The gravel is extracted from quarries in various sizes and shapes. Most of the gravel used to produce agglomerated stones is actually the by-product, otherwise discarded materials, resulting from natural stones quarrying operations. This mixture of gravel and boulders must undergo through crushing and sieving processes to obtain the desired dimensions, as well as to remove impurities and residues. To the natural stones' gravel are then added a binding agent, typically unsaturated polymeric resins or hydraulic cements, and other additives (glasses, dye pigments, mirrors, gems, etc.), which contribute in lending specific attributes and characteristics, both mechanical and aesthetical, to the final products.

According to the mineral type of the natural stone and to the binding agent chosen, different technologies can be applied, different percentages of natural stone materials can be used in the mixture, as well as different final products' dimensions can be produced. The different combinations are described in Table 23, whose data are based on the technology patented by the Italian company Breton S.P.A[75]., which is the dominant supplier of equipment for making agglomerated stone. It is important to highlight that to

[75] Breton method was developed by Italian equipment manufacturer Breton Spa (Castello di Godego, Italy) in the 1960s. The patented Bretonstone technology, properly referred to as a "compaction by vibrocompression vacuum process," uses elastomeric molds in which a crushed stone/resin mix is cast on a moving belt. Natural stone aggregate — usually specific types of minerals, such as quartz, or waste rock from quarries — is combined with a small amount of resin (between 5 and 10 percent for a filler loading of 90 to 95 percent), pigments and proprietary additives.

the use of polymeric resins as binding agents, instead of hydraulic cement, results in the weight percentage of natural stones' gravel in the mixture being significantly higher (from 76-78% with cement to 90-96% with resin)[76].

Furthermore, for an optimal body mixture preparation the water content needs to be lowered as much as possible before the addition of the resins, because of its incompatibility with water. Based on the granulation range of the natural stone gravel as well as on the desired finished product, the appropriate quantity of binder and other additives is calculated and finally added to the body mixture, which is now ready to be blended.

Table 23. Type of finished products, with their dimensional and material characteristics, according to the type of main mineral component and the type of binder chosen[77].

Finished products	**Dimension range (cm)**	**Thickness range (mm)**	**% natural stones by weight**	**Type of mineral**	**Type of binder**
Slabs	Up to 156 x 309	10 to 30	94%	Siliceous	Unsaturated polyester resins
		Can reach 6 to 8		Calcareous	
Blocks (further cut into slabs)	308 x 125 x 88	9 to 30	96%	Calcareous	Unsaturated polyester resins
Tiles (monolayer)	68 x 153	15 to 35	76%	Siliceous and calcareous	Hydraulic cement
Thin slabs (monolayer)	30 x30 , 40 x40	9.5 (only siliceous products) to 30			
	40 x 60, 60 x60				
Blocks (further cut into slabs)	308 x 125 x75	9 to 30	94%	Calcareous	Unsaturated polyester resins
		15 to 30	78%	Calcareous	Hydraulic cement
Slabs	140 x 309	9.5 to 30	78%	Siliceous and calcareous	Hydraulic cement

Compacting and hardening

When the body mixture has reached the desired composition, it can undergo the processes of compacting, moulding and hardening. Agglomerated stones blocks or slabs are moulded using specific elastomeric moulds through the patented technology of *under vacuum vibro-compression*[78].

[76] This is an aggregated data from different sources, whose references are included in the footnotes [30] ,[34]
[77] Breton (2018). La Pietra composita le tecnologie e gli impianti. [online] pp.10 -14, 19 - 28. Available at: https://www.breton.it/it/pietra-composita/bretonstone-lastre [Accessed 15 Jan. 2018].
[78] Several patents describing this technology and its evolution are available, the most recent, granted in 2015, is the US9085090B2.

The under vacuum vibro-compression creates the conditions for which the aggregates organizes themselves extremely close to each other, therefore minimizing the requirement for binding agents and increasing the mechanical features and quality of the resulting products. Furthermore, this means that macro-porosity is prevented in favour of micro-porosity in the final products, minimising the water absorption level: only 0.02% by weight[30] .

Finally, the agglomerated stones' slabs or blocks have to undergo to the curing process, usually in a room, or oven, at controlled temperature. The curing can be performed both at hot and cold conditions, the first is usually employed for slabs production. Slabs and blocks are let to cool down before proceeding with the production process.

Finishing operations

Once hardened and cooled down, the semi-finished agglomerated stones are removed from the mould before going to the standard cutting and finishing operations.

Slabs and blocks can be further cut to obtain the final products of desired shape and dimension, such as slabs and tiles of varying thickness, countertops or other similar elements. The finishing operations, available for the agglomerated stones coincide with those used in the Natural Stone sector; they commonly are: honing, polishing, sandblasting, gauging, skirting and possible secondary cuts.

Packaging and storage

Packaging generally consists of cardboard boxes, stacked in wooden pallets, and plastic film for further protection of the products.

5.4.2 Innovations and improvements

In the agglomerated stones sector, during the past decade, neither technological breakthrough nor major changes in the production technologies have occurred. However, progress and improvements in the already existing technologies for the compacting and hardening processes led to a decrease in energy consumptions.

The most recent innovative elements encountered are:

- the increase of natural stone aggregates in the body mixture thanks to technological improvements and research,
- the introduction of high-technology "bio-resins"[79],
- the incorporation of bacteriostatic properties through silver compounds.

The bio-resins are partially or completely made from renewable plant sources (for instance from no-food vegetable oil[80]), and they should, theoretically, contribute to increase the recyclability of the agglomerated stones' products. Furthermore, some of these bio-based resins include UV-protectors[34] in the mixture. The bacteriostatic properties are instead ensured incorporating, in the mixture, silver compounds whose controlled activation minimize the growth and proliferation of several types of bacteria[81].

[79] Compac. (2018). Environmental Commitment. Marble and quartz surfaces coverings for bathrooms, kitchens, floors and walls. [online] Available at: http://en.compac.es/quality/environmental-commitment/ [Accessed 30 Jan. 2018].

[80] Primary data from industry. The company name cannot be disclosed for confidentiality reasons.

[81] Silestone. Healthcare Applications. (n.d.). [online] p.7. Available at: https://mediaassets.cosentino.com/docs/file/661BFE4B-E50F-4C6A-

5.5 Life Cycle Assessment : agglomerated stone

Very little literature has been published regarding the LCA impact of agglomerated stone products and even less so on those which are floor or wall tiles. Only a few EPDs for engineered stone products (the term is considered as synonymous with agglomerated stone) have been published online and this particular example does not follow the EN 15804 framework because it is an American product. Nevertheless, it is possible to approximate which EN 15804 modules the American life cycle stages correspond to when reading their descriptions:

- **Material acquisition (and pre-processing):** This stage includes the extraction of materials from nature, processing required to create the raw materials used in surfaces production, and transportation of the materials to the construction stage. Any processing of secondary materials used in surfaces production is also included.
- **Construction:** During construction, raw materials for the countertop are processed into slab. The stage also includes production and inbound transport of packaging materials.
- **Installation:** The installation stage starts with the transportation of the slab to a warehouse, distributor, and/or fabricator. The fabricator, who is responsible for customizing the slab, is assumed to travel to the installation site to take initial measurements. These measurements are used to customize the slab back at the fabrication facility. Since Corian® Quartz is used for more than residential countertops, a 10% scrap rate is assumed. Lastly, the customized slab is transported to the installation site and installed with Corian® joint adhesive.
- **Use and maintenance:** Use includes product maintenance—typically cleaning with tap water and soap—over the 10-year timeframe. No sealing or additional maintenance is needed.
- **End-of-Life:** The end-of-life stage includes the disposal of the surface, as well as the disposal of packaging from installation. Corian® Quartz is assumed to be disposed entirely to landfill or incinerated.

The so called A1-A3 stages account for 45 to 65% of the total impacts for each impact category, which is a reasonable justification for setting EU Ecolabel requirements at the production stage. It is interesting to note how significant the LCA impacts are at the installation stage because the nature of the "engineered stone" material (uniform microstructure and relative ease of shaping/cutting) these product lend themselves well to cutting after the slab has been finished. These customisation procedures are assumed to result in 10% of the material being scraped at this stage. This scrap rate and the need for a specialised joint adhesive are no doubt the main reasons behind the significant influence of the installation stage on LCA impacts.

In Table 24 available industry data concerning technical features of agglomerated stones, such as percentages of natural stones' gravel and recycled materials in the mixture, energy consumption and air emissions, are presented in order to provide a benchmark on the state of the art of agglomerated stones' technologies, specifically looking into the features contributing to the environmental impacts. From this table, a few considerations can be done: firstly, the common practice to use, in the mixture, a fair amount of pre-consumer recycled materials, intended as derivates and by-products of natural stones

B3D998DFD3B822A9/SILESTONE%20APLICACIONES%20SANITARIAS%20ESP-ING.pdf [Accessed 19 Jan. 2018].

quarrying operations; secondly, the recurrence of high ratios of natural stones' gravel in the mixture to which correspond a general low use of artificial binding agents, both resins and cement. One last consideration can be done on the generally high percentage of waste water recycling, demonstrating the established presence of efficient water system managements in the sector.

Table 24. Industries data, primary from 2 companies and aggregated from 6 available sources, concerning technical features of agglomerated stones products, compared to the current Ecolabel criteria[82].

	Primary data (2 companies)		**Aggregate available industry data**	**Current Ecolabel criteria and limits**
Recycled materials (w/w %) (Pre-consumer, e.g. waste from quarries, and post-consumer, e.g. glass)	≤ 20 %	n.a	Min: 7% Mean: 46% Max: 75% (100% if cement is the binder)	n.a.
Binding agent content (w/w%) (Elaboration obtained as the complementary from the amount of naturals tone gravel used in the mixture)	≥ 7%	n.a	Min: 4% Mean: 8.7% Max: 15.5%	Criteria 2.3 - No asbestos - Polyester resins content (in production) < 10% of the raw materials total weight
Energy consumption (MJ/kg)	1.1	0.7	≤ 1.1	Criteria 4.1 Process energy requirement (PR): 1.3
Waste water recycling ratio (%)	n.a.	n.a.	Up to 95% (recurring data)	Criteria 4.2 ≥ 90%

Agglomerated stone products can be expected to have a long service life when correctly specified and used. The main environmental impacts can be expected to be associated with the embodied energy and impacts of the binding resin and related curing chemicals. It would be interesting to compare the embodied energy of the binder with the specific process energy consumption of the production equipment in order to decide best how these two aspects should be weighted in EU Ecolabel criteria.

Other impacts that may not be so well captured by LCA analysis but which are nonetheless of importance are the potential VOC emissions from the product.

[82] The companies cannot be disclosed for confidentiality reasons.

6 OVERVIEW FOR CONCRETE PAVING UNITS AND PORTLAND CEMENT

6.1 Terminology and classification

Through this chapter the analysis of the Portland cement is carried out in parallel to the analysis of concrete paving units due to the fact that Portland cement is the key ingredient that imparts the cementitious gel that is responsible for holding the aggregates together in the concrete.

6.1.1 Concrete paving units

Concrete paving units are products for outer floor-coverings obtained by mixing sands, gravel, cement, inorganic pigments and additives, and vibro-compression as defined by CEN/TC 178. This group also includes concrete flags and concrete tiles.

The concrete paving units as defined by CEN/TC 178 are a very specific subset of precast concrete that today is centred on vibro-compression technology. These products are examples of what is known as dry-cast concrete due to the low water to cement ratios involved (0.30 to 0.36). Some of the main definitions for these products are provided below:

- Concrete paving block (as per EN 1338) means a precast concrete unit used as a surfacing material which, a) at a distance of 50mm from any edge, any cross-section does not show a horizontal dimension less than 50 mm and b) its overall length divided by its thickness is less than or equal to four.
- Concrete paving flag (as per EN 1339) means a precast concrete unit used as a surfacing material which, a) the overall length does not exceed 1 m and b) the overall length divided by its thickness is greater than four.
- Concrete kerb units (as per EN 1340) means a precast concrete unit, intended to separate surfaces of the same or different levels to provide a) containment or physical or visual delineation, b) drainage channels (individually or in combination with other kerbs) and/or c) separation between surfaces submitted to different kinds of traffic.

Concrete pavers were found to be an economical alternative to clay-based blocks during reconstruction efforts after World War II. The mass production of concrete paving units began in Germany in the 1960's when Fritz van Langsdorff launched the UNI product line of interlocking concrete pavers.

These interlocking concrete pavers are used in the construction of flexible pavements which are composed of the following layers: compacted soil subgrade (bottom); compacted aggregate base; sand bedding course and finally the concrete pavers (top). The grading and degree of compaction of the sub-layers will depend on the site geology and whether the pavement is intended to be permeable or not.

The pavers are laid with very specific gaps between them which are filled with sand. By applying pressure, the pavers become interlocked and are capable of transferring loads via the sand in the joints. The main benefit of this mechanism is the reduction of loads transmitted to the lower parts of the pavement structure.

Over 50 years and hundreds of patents later, interlocking concrete pavers are used worldwide. The purpose of this section is to briefly explain the vibro-compression process and its main variations as well as the different types of materials used in the concrete mixes.

On the market, there is a wide array of available concrete products, which mainly differ from each other for their shape. Thanks to this variety, pavements can be covered with many possible combinations. The most common paver unit has a 2:1 ratio between length and width, thus making it easy to install in several patterns (Figure 61).

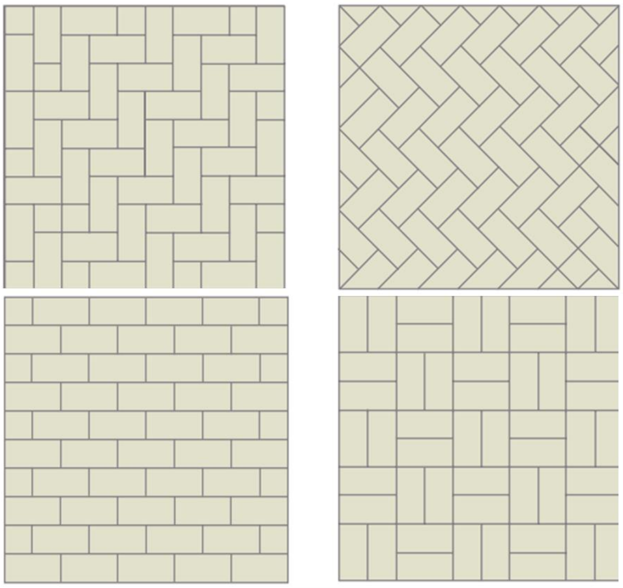


Figure 61. Some of the possible patterns obtainable with 2:1 concrete paving units. The names of the patterns from left to right: 90 degree herringbone, 45 degree herringbone, stretcher bond, and basket weave.

While the 90 and 45-degree Herringbone pattern (Figure 61) are suitable for any loading category, including heavily trafficked areas, the stretcher bond and the basket-weave patterns are destined to light traffic and pedestrians, respectively. Nowadays, several formats are available on the market, which gives birth to a wide array of laying possibilities. Some of the formats different from the 2:1 model are shown in Figure 62.

Figure 62. Concrete paving units can be produced in many different shapes. It must be noted that this image is not exhaustive since many more formats can be found on the market.

In descending order, the main materials used in concrete are: aggregates > cement > water > filler and any pigments. Pigments are based on different metal oxides and can impart a range of colours to the entire block or can be selectively used only in the facing layer of a two layer block.

6.1.2 Portland cement

The cement used is almost exclusively based on Portland cement, which is basically a combination of Portland cement clinker and a minor addition of gypsum (around 5%). There are a number of different classes of Portland cement depending on the degree to which the Portland cement clinker has been blended with supplementary cementitious materials such as coal fly ash, silica fume, ground granulated blast furnace slag, burnt shale, natural pozzolana and limestone powder.

Table 25. Different classes of Portland cement in Europe (adapted from EN 197-1).

Type	Code	From kiln			From other sources (supplementary cementitious materials)							Other
					Pozzolana		Fly ash					
		Clinker	Blast furnace slag	Silica fume	natural	natural calcined	siliceous	calcareous	Burnt shale	Limestone		
		K	S	D	P	Q	V	W	T	L	LL	
CEM I	CEMI I	95-100	-	-	-	-	-	-	-	-	-	0-5
CEM II	CEM II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	0-5
	CEM II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	0-5
	CEM II/A-D	90-94	-	6-10	-	-	-	-	-	-	-	0-5
	CEM II/A-P	80-94	-	-	6-20	-	-	-	-	-	-	0-5
	CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	0-5
	CEM II/A-Q	80-94	-	-	-	6-20	-	-	-	-	-	0-5
	CEM II/B-Q	65-79	-	-	-	21-35	-	-	-	-	-	0-5
	CEM II/A-V	80-94	-	-	-	-	6-20	-	-	-	-	0-5
	CEM II/B-V	65-79	-	-	-	-	21-35	-	-	-	-	0-5
	CEM II/A-W	80-94	-	-	-	-	-	6-20	-	-	-	0-5
	CEM II/B-W	65-79	-	-	-	-	-	21-35	-	-	-	0-5
	CEM II/A-T	80-94	-	-	-	-	-	-	6-20	-	-	0-5
	CEM II/B-T	65-79	-	-	-	-	-	-	21-35	-	-	0-5
	CEM II/A-L	80-94	-	-	-	-	-	-	-	6-20	-	0-5
	CEM II/B-L	65-79	-	-	-	-	-	-	-	21-35	-	0-5
	CEM II/A-LL	80-94	-	-	-	-	-	-	-	-	6-20	0-5
	CEM II/B-LL	65-79	-	-	-	-	-	-	-	-	21-35	0-5
	CEM II/A-M	80-88	< --12-20-- >									0-5
	CEM II/B-M	65-79	< --21-35-- >									0-5
CEM III	CEM III/A	35-64	36-65	-	-	-	-	-	-	-	-	0-5
	CEM III/B	20-34	66-80	-	-	-	-	-	-	-	-	0-5
	CEM III/C	5-19	81-95	-	-	-	-	-	-	-	-	0-5
CEM IV	CEM IV/A	65-89	-	< ------------------------11-35------------------------ >					-	-	-	0-5
	CEM IV/B	45-64	-	< ------------------------36-55------------------------ >					-	-	-	0-5
CEM V	CEM V/A	40-64	18-30	-	< ------------18-30------------ >			-	-	-	-	0-5
	CEM V/B	20-38	31-49	-	< -----------31-49------------- >			-	-	-	-	0-5

Table 25 shows that there are 27 different types of Portland cement that are defined for the EU market in EN 197-1. The 27 cement types can be aggregated into 5 distinct groups:

- **CEM I: Portland cement.** Basically Portland cement clinker plus a maximum of 5% gypsum or hemihydrate.
- **CEM II: Portland-composite cement.** The broadest group which covers any combination of Portland cement with anywhere between 6% and 35% of the clinker being substituted for supplementary cementitious materials.
- **CEM III: Blast furnace cement.** Where the only supplementary cementitious material used is blast furnace slag and where the content is anywhere between 36% and 95%.
- **CEM IV: Pozzolanic cement.** Where one or more of several supplementary cementitious materials that are known to exhibit pozzolanic activity substitute Portland cement clinker at levels ranging from 11-55% (blast furnace slag is a known pozzolanic material but is not included since there are dedicated groups for that material (CEM III and CEM V). Freedom is given in terms of combining different supplementary cementitious materials in the same cement.
- **CEM V: Composite cement.** Clinker must be substituted by a certain amount of blast furnace slag (18% to 49%) and any combination of pozzolana (natural or calcined) and siliceous fly ash (18% to 49%).

When purchasing cement, the codes listed in Table 25 must be communicated to customers in delivery invoices and packaging and inform about the material composition of the cement. Other notation that can be included to inform customers about the performance of the cement relate to:

- Standard compressive strength development at 28 days (32,5, 42,5, or 52,5).
- Setting time and early compressive strength development at 2 or 7 days (L, N or R).
- Sulfate resistance (SR, SR0, SR3 or SR5).

These latter codes act as proof of conformity of the cement product and quality control of the manufacturing process with certain minimum physical performance of the cement.

6.2 Relevant technical standards

6.2.1 Concrete paving units

Relevant standards include those that apply to the final concrete product, those that apply to aggregates used and those that apply to the cement used.

Table 26. Summary of the most relevant EN standards for precast concrete blocks, flags and kerbs.

Standard	Main aspects
EN 13369	**Common rules for precast concrete products.** Scope: Unreinforced, reinforced and pre-stressed precast concrete products made of compact light-, normal- and heavyweight concrete according to EN 206-1 with no appreciable amount of entrapped air other than entrained air. Concrete containing fibres is also covered. It does not cover prefabricated reinforced components of lightweight aggregate

	concrete with open structure. General requirements are defined for concrete production in the factory (e.g. placing, compaction and curing). Strength classes are defined and reference to suitable standards and methods for testing properties such as shrinkage, dry density, water absorption and, in cases where the thermal performance of a building is being assessed, thermal conductivity and/or specific heat capacity of the concrete products
EN 1338	**Concrete paving blocks – Requirements and test methods** Scope: Unreinforced cement bound precast concrete paving blocks and complementary fittings for pedestrian use, vehicular use and roof coverings, e.g. footpaths, precincts, cycle tracks, car parks, roads, highways, industrial areas (including docks and harbours), aircraft pavements, bus stations, petrol filling stations. This standard does not deal with the tactility or visibility of blocks. Blocks with side features to provide wider joints for permeable pavements are included but permeable blocks with large holes or voids or with an interconnected pore structure to allow water to pass through the block are not included. The standard prohibits the use of asbestos or asbestos containing materials and dimensional tolerances are specified. A minimum freeze-thaw resistance with deicing salts (≤1.5kg/m^2 mass loss for any result and ≤1.0kg/m^2 on average) and tensile splitting strength (all results ≥2.9 MPa, ≥3.6 MPa on average) are defined. Classes are also defined in cases where water absorption (B if ≤6.5% absorption), abrasion resistance (H if ≤23.0mm or ≤20000mm^3/5000mm^2; I if ≤20.0mm or ≤18000mm^3/5000mm^2) or slip/skid resistance (Q if ≥35, R if ≥45 or S if ≥55) are measured.
EN 1339	**Concrete paving flags – Requirements and test methods** Scope: Unreinforced cement bound precast concrete paving flags and complementary fittings for use in trafficked paved areas and roof coverings. This standard does not deal with the tactility or visibility of flags nor with permeable flags. The standard prohibits the use of asbestos or asbestos containing materials and dimensional tolerances are specified. A minimum freeze-thaw resistance with deicing salts (≤1.5kg/m^2 mass loss for any result and ≤1.0kg/m^2 on average), average bending strength (≥2.9, ≥4.0 or ≥5.0MPa for S,T or U markings respectively) and average breaking load (≥3.0, ≥4.5, ≥7.0, ≥11.0, ≥14.0, ≥25.0 or ≥30.0kN for markings 3, 4, 7, 11, 14, 25 or 30 respectively) are defined. Classes are also defined in cases where water absorption (B if ≤6% absorption) or abrasion resistance (G if ≤26.0mm or ≤26000mm^3/5000mm^2; H if ≤23.0mm or ≤20000mm^3/5000mm^2 or I if ≤20mm or ≤18000mm^3/5000mm^2) are measured.
EN 1340	**Concrete kerb units – Requirements and test methods**

	Scope: unreinforced cement bound precast concrete kerb units, channels and complementary fittings that are for use in trafficked paved areas and roof coverings for physical separation, visual delineation, drainage or the containment of paved or other surfaced areas. This standard does not deal with the tactility or visibility of kerbs. The standard prohibits the use of asbestos or asbestos containing materials and dimensional tolerances are specified. A minimum freeze-thaw resistance with deicing salts (≤1.5kg/m^2 mass loss for any result and ≤1.0kg/m^2 on average), average bending strength (≥3.5, ≥5.0 or ≥6.0MPa for S,T or U markings respectively) are defined. Classes are also defined in cases where water absorption (B if ≤6% absorption) or abrasion resistance (H if ≤23.0mm or ≤20000mm^3/5000mm^2 or I if ≤20mm or ≤18000mm^3/5000mm^2) are measured.

The standards EN 1338, 1339 and EN 1340 are very similar with the main difference being the specific type of precast concrete product they refer to (i.e. blocks, flags or kerbs) and the relevant dimensions. The physical requirements are very similar although bending strength is something that is specific to the longer and thinner flag and kerb products only.

6.2.2 Portland cement and other concrete ingredients

Quality control for concrete also depends on the consistency and quality of the constituent materials that are used, especially cement. Consequently it is worthwhile to look at the most relevant standards for aggregates, cement and other constituents that may be used in concrete mixes.

Table 27. Summary of the most relevant standards for aggregates, cement and other constituents in precast concrete blocks, flags and kerbs

Standard	Main aspects
EN 12620	**Aggregates for concrete** Sets out a series of geometrical (EN 933), physical (EN 1097), chemical (EN 1744) and durability (EN 1367) requirements and specifications for aggregates to be used in concrete. This standard can apply to natural, manufactured or recycled aggregates.
EN 196	**Methods of testing cement (various parts)** Closely linked to EN 197-1 and defines procedures for measuring strength (part 1), setting time(part 3), pozzolanicity (part 5), fineness (part 6), heat of hydration (parts 8 and 9), water soluble Cr(VI) (part 10) and other chemical analysis (part 2).
EN 197-1	**Cement - Part 1: Composition, specifications and conformity criteria for common cements** Sets out the compositional requirements and specifications for 27 common

	cements (see section 6.1.2.), 7 sulfate resistant cements and 5 low early strength cements. Minimum initial setting times (≥45 to ≥75 minutes), soundness (≤10mm), early strength (2 or 7 days) and standard strength (28 days) are defined. Some other requirements are further defined for specific cement classes.
EN 450	**Fly ash for concrete - Part 1: Definition, specifications and conformity criteria** Sets out requirements for coal fly ash to be used in concrete. It places limits on the extent that coal can be co-combusted with other materials. Limits on chemical composition, such as loss-on-ignition, chloride, sulphate, alkalis, phosphate and free lime are also set as well as a minimum reactive silica content. Tests and limits are also defined for the effect of the fly ash on strength development, setting time and mixing water demand.
EN 934-2	**Admixtures for concrete, mortar and grout - Part 2: Concrete admixtures - Definitions, requirements, conformity, marking and labelling** Defines and sets minimum requirements for different admixtures used in the production of concrete. Although the standard is aimed at normal consistence concrete, the same admixtures can be equally relevant for vibro-compressed precast concrete, which will tend to contain less water.

6.3 Market data

The PRODCOM database for sold production, exports and imports (NACE Rev. 2) was cross-checked for relevant product group codes and associated statistics. The following PRC code was considered to be of highest relevance:

23.61.11.50: Tiles, flagstones and similar articles of cement, concrete or artificial stone (excluding building blocks and bricks).

An idea of how significant concrete tiles and flagstones are in the wider context of the precast concrete market can be gathered by considering PRODCOM data for the sold production volumes of other precast concrete products such as:

- 23.61.11.30: Building blocks and bricks of cement, concrete or artificial stone
- 23.61.12.00: Prefabricated structural components for building or civil engineering, of cement, concrete or artificial stone
- 23.61.20.00: Prefabricated buildings of concrete
- 23.69.19.30: Pipes of cement, concrete or artificial stone
- 23.69.19.80: Articles of cement, concrete or artificial stone for non-constructional purposes (including vases, flower pots, architectural or garden ornaments, statues and ornamental goods.

The most relevant PRC codes that relate to raw materials and ingredients used in concrete production were considered to be as follows:

- 23.51.11.00: Cement clinker
- 23.51.12.10: Portland cement
- 23.51.12.90: Other hydraulic cements
- 08.12.12.10: Gravel and pebbles of a kind used for concrete aggregates, for road metalling or for railway or other ballast; shingle and flint
- 08.12.12.30: Crushed stone of a kind used for concrete aggregates, for road metalling or for railway or other ballast (excluding gravel, pebbles, shingle and flint.
- 20.59.57.50: Prepared additives for cements, mortars or concretes

It was considered that a comparison of overall cement clinker production (PRC code 23.51.11.00) and overall Portland cement production (PRC code 23.51.12.10) should give a reasonable idea of what general level cement clinker is being substituted by supplementary cementitious materials (see Table 25). However, it became clear that clinker production only accounted for around 10% of the cement production. Such a low % of clinker content clearly implies that most of the clinker production is not actually sold but used internally to make cement and thus not reported in PRODCOM.

6.3.1 Concrete paving units

Trends in sold production quantity and sold production value of concrete tiles and flagstones at the European level is summarised below.

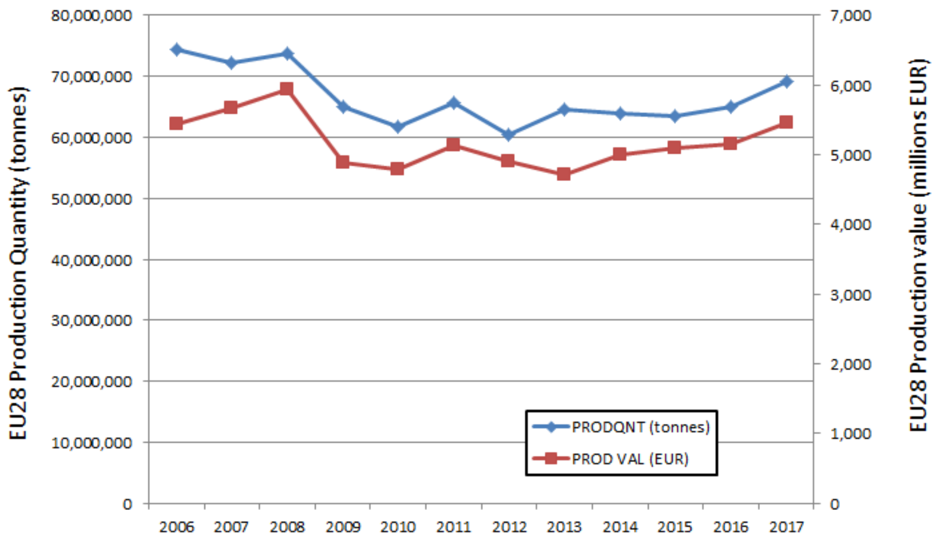


Figure 63. EU production volume and value for concrete tiles and flagstones (Source: PRODCOM)

The data reveal a 15-20% drop in both the volume and value of sales between 2008 and 2010 due to the global economic crisis. The sector shows gradual signs of recovery during the years 2015, 2016 and 2017 but values have not yet returned to pre-crisis levels. A breakdown of the 2017 data for Member States is provided below.

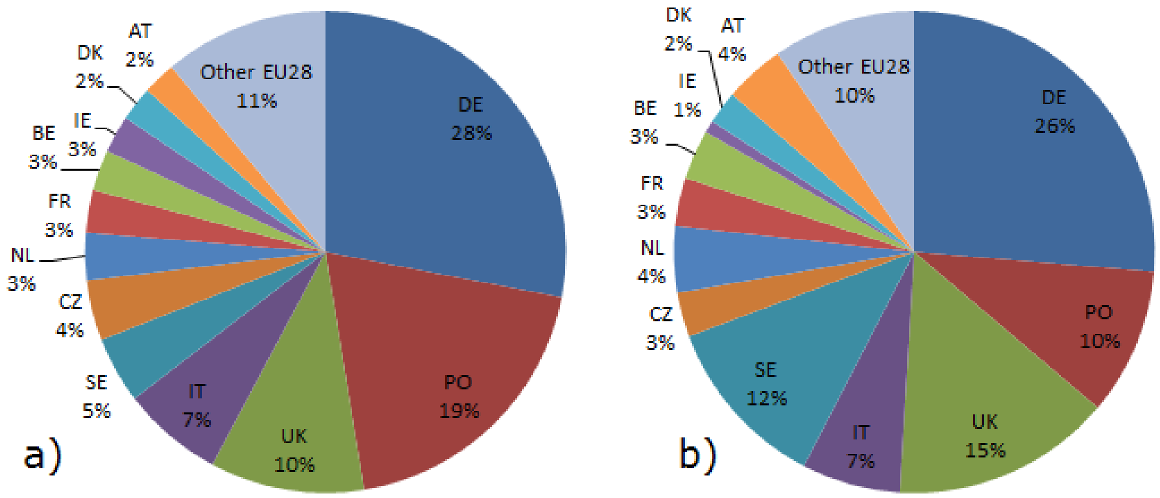


Figure 64. Breakdown of EU concrete tile and flag production in 2017 by a) volume (total 69.2 million tonnes) and b) value (total 5460 million EUR) (Source: PRODCOM)

The 2017 production data generally reveal that Germany, Poland, the UK, Italy and Sweden are the top five Member States in terms of production volume and value, with Germany as a clear leader in the sector. When comparing the production volume and production value shares, it is interesting to note that some countries have significant differences. For example, Sweden has 5% of production volume but 12% of production value and Austria has 2% of production volume but 4% of production value. Conversely, Poland has 19% of production volume but only 10% of production value. An average unit value of production for each Member state was therefore calculated using the same data in Figure 65.

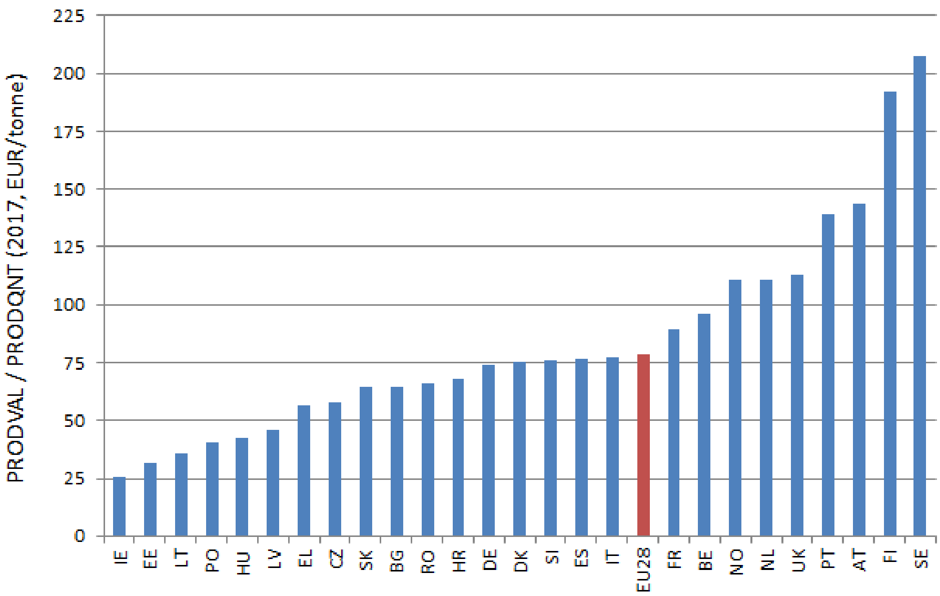


Figure 65. Average unit production value of concrete tiles and flags in 2017 (Source: adapted from PRODCOM)

The data presented in Figure 65 show a major variation in average unit production value (in EUR/tonne) at Member State levels. The cheapest Member States have unit production values up to 9 times lower than the highest unit production value and 3 times lower than the EU28 average unit production value. There are a number of factors that can affect unit price which include: regional availability and transport costs for raw materials, labour costs, cement quality and cost, aggregate quality and cost, taxes and electricity costs.

By far the highest unit production values are associated with Sweden and Finland. Together with Portugal and Austria, the unit production values in these countries stand clearly above other Member States. At the lower end of the spectrum, Ireland, Estonia, Lithuania, Poland, Hungary and Latvia are all more than 33% lower than the EU average.

Focussing on Italy only, discussions with ASSOBETON, the Italian Association of Concrete Manufacturers, revealed that total Italian production of concrete pavers was estimated to be around 12.5 million square meters in 2016, generating revenues of 60-70 million EUR. According to ASSOBETON, the Italian market is highly fragmented, with more than 90% of companies reporting annual revenues of less than 2 million EUR and none reporting revenues or more than 10 million EUR. The market is almost exclusively set at the regional level and many companies only operate in one or two specific regions. A similar pattern is expected in other EU Member States.

Precast concrete production context

The PRODCOM database has been accessed to compile data for PCR codes that are clearly related to sales of precast concrete production. The overall EU28 data is provided below.

Table 28. Comparison of different precast concrete sectors (Source: PRODQNT data from PRODCOM)

PCR code listed under the PRODCOM database	2015		2016		2017	
	Tonnes	% of Total	Tonnes	% of Total	Tonnes	% of Total
23611150 - Tiles, flagstones and similar articles of cement, concrete or artificial stone (excluding building blocks and bricks)	63,428,303	28.0	65,000,000	29.9	69,157,544	28.0
23611130 - Building blocks and bricks of cement, concrete or artificial stone	66,070,712	29.2	70,600,000	32.5	77,266,236	31.2
23611200 - Prefabricated structural components for building or civil engineering, of cement, concrete or artificial stone	80,000,000	35.3	60,000,000	27.6	81,000,000	32.7

23691930 - Pipes of cement, concrete or artificial stone	7,094,488	3.1	6,777,055	3.1	7,093,112	2.9
23691980 - Articles of cement, concrete or artificial stone for non-constructional purposes (including vases, flower pots, architectural or garden ornaments, statues and ornamental goods)	10,000,000	4.4	15,000,000	6.9	12,876,845	5.2
TOTAL	**226,593,502**	**100**	**217,377,055**	**100**	**247,393,737**	**100**

It is worth mentioning that PCR 23.61.20.00 was also considered in this exercise although only PRODVAL data of sales was available, not quantity of sales. When conducting the analysis, some discrepancies were noted in the EU28 values and the sum of values reported for individual Member States, the discrepancies could range from a few percent to >30%. In almost all cases the EU28 data was higher than the sum of individual Member State data. Since some Member State data can be unpublished due to confidentiality reasons, but that all aggregated data should normally appear under the EU28 total, it was decided to follow the EU28 data in all cases.

Ready mixed concrete was not included since this relates to concrete poured onsite, an activity which is beyond the scope of the precast concrete sector.

The data in Table 29 shows that tiles and flagstones represent a significant fraction (28-30%) of the EU precast concrete sector. The remainder of the sector is mainly split between prefabricated structural components (27-35%) and building blocks (29-33%). The same analysis was repeated for PRODVAL data and the results are summarised below.

Table 29. Comparison of different precast concrete sectors (Source: PRODVAL data from PRODCOM)

PCR code listed under the PRODCOM database	2015		2016		2017	
	Million EUR	**% of Total**	**Million EUR**	**% of Total**	**Million EUR**	**% of Total**
23611150 - Tiles, flagstones and similar articles of cement, concrete or artificial stone (excluding building blocks and bricks)	5100.4	18.4	5150.8	22.5	5459.9	19.4
23611130 - Building blocks and bricks of cement, concrete or	3563.5	12.8	3690.0	16.1	3920.0	13.9

artificial stone						
23611200 - Prefabricated structural components for building or civil engineering, of cement, concrete or artificial stone	15000.0	54.0	10000.0	43.8	14000.0	49.8
23612000 – Prefabricated buildings of concrete	1800.0	6.5	1500.0	6.6	1600.0	5.7
23691930 - Pipes of cement, concrete or artificial stone	722.4	2.6	712.9	3.1	744.9	2.6
23691980 - Articles of cement, concrete or artificial stone for non-constructional purposes (including vases, flower pots, architectural or garden ornaments, statues and ornamental goods)	1600.0	5.8	1800.0	7.9	2400.0	8.5
TOTAL	**27786.3**	**100**	**22853.7**	**100**	**28124.8**	**100**

When considering sold production in terms of value, concrete tiles and flagstones remain as an important market share (18 to 23%) but not to the same extent as when considered in terms of sold production volume (28-30% of sold tonnage). The main reason for the reduced share of value is related to the higher specific value (EUR/tonne) of prefabricated structural components.

6.3.2 Portland cement

Global level

Concrete is basically a matrix of mineral aggregates bound together by a cementitious gel that is created by the hydration of cement. Portland cement is by far the dominant type of cement used in all mainstream concrete materials and so market trends and data focus on the production of Portland cement.

Table 30. Global Portland cement production trends during the last 10 years (Source: CEMBUREAU, 2017 activity report)

	2008	2009	2010	2011	2012	2013	2014	2015	2016
China	1388.4	1644.0	1881.9	2063.2	2137.0	2420.0	2480.0	2350.0	2410.0
India	185.0	205.0	220.0	240.0	270.0	280.0	260.0	270.0	290.0
EU28 (% of global total)	250.8 (10.2%)	209.0 (8.0%)	192.1 (6.7%)	191.6 (6.1%)	172.6 (5.4%)	166.6 (4.7%)	166.8 (4.6%)	167.2 (4.8%)	169.1 (4.8%)
USA	86.3	63.9	65.2	68.6	74.9	77.4	83.2	83.4	85.9

Turkey	51.4	54.0	62.7	63.4	63.9	72.7	71.2	71.4	75.4
Indonesia	38.5	36.9	39.5	45.2	32.0	56.0	65.0	65.0	63.0
Saudi Arabia	37.4	37.8	42.5	48.0	50.0	57.0	55.0	55.0	61.0
Brazil	51.6	51.7	59.1	63.0	68.8	70.0	72.0	72.0	60.0
Russian Federation	53.5	44.3	50.4	56.1	53.0	72.0	68.4	69.0	56.0
Japan	67.6	59.6	56.6	56.4	51.3	57.4	53.8	55.0	56.0
South Korea	51.7	50.1	47.4	48.2	48.0	47.3	63.2	63.0	55.0
Mexico	37.1	35.1	34.5	35.4	35.4	34.6	35.0	39.8	40.8
Germany	33.6	30.4	29.9	33.5	32.4	31.5	32.1	31.1	32.7
Italy	43.0	36.3	34.4	33.1	26.2	23.1	21.4	20.8	19.3
France	21.2	18.1	18.0	19.4	18.0	17.5	16.4	15.6	15.9
South Africa	13.4	11.8	10.9	11.2	13.8	14.9	13.8	14.0	13.6
Canada	13.7	11.0	12.4	12.0	12.5	12.1	12.8	12.5	11.9
Argentina	9.7	9.4	10.4	11.6	10.7	11.9	11.8	12.2	10.9
UK	10.5	7.8	7.9	8.5	7.9	8.5	9.3	9.6	9.4
Australia	9.4	9.2	8.3	8.6	8.8	8.6	9.3	9.3	9.4
Global Total	**2453.8**	**2625.4**	**2884.1**	**3117.0**	**3187.2**	**3539.1**	**3600.5**	**3485.9**	**3545.3**
Year on year growth	**-**	**+7.0%**	**+9.9%**	**+8.1%**	**+2.3%**	**+11.0%**	**+1.7%**	**-3.2%**	**+1.7%**

The global production data shown in Table 30 reveal that the combined production of EU28 Member States places it as the third largest producer but currently more than 10 times smaller than Chinese production.

The CEMBUREAU data show that although the EU28 production began to decline abruptly in 2008 due to the economic crisis global production continued to grow until 2014. Since 2013-2014, production at both the EU28 and global levels appears to have stabilised. However, EU28 production remains around one third below the pre-crisis levels.

European level

The CEMBUREAU data indicate that the main EU producers of Portland cement are Germany, France, Italy and the UK. A more detailed analysis of Member State production data was carried out using 2017 PRODCOM data (PRC code 23.51.12.10: Portland cement).

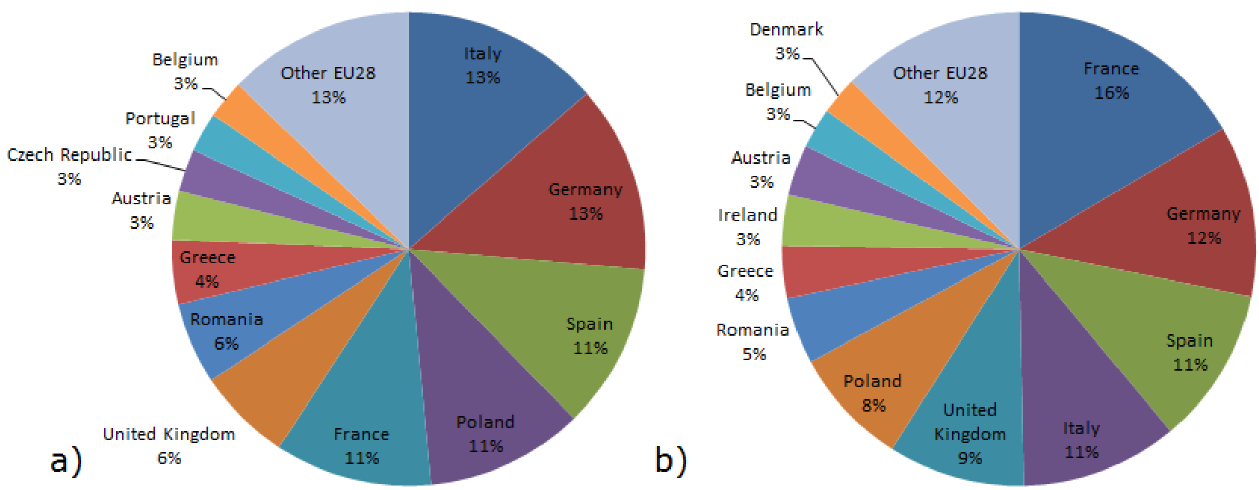


Figure 66. Breakdown of EU Portland cement production in 2017 by a) volume (total 145.3 million tonnes) and b) value (total 10393 million EUR) (Source: PRODCOM)

The most dominant Member State in terms of Portland cement sold product volume in 2017 was Italy (13%) but in terms of sold product value it was France (16%). In general, the top 6 Member States were France, Germany, Spain, Italy, the UK and Poland. However, as observed earlier with precast concrete tiles and flags, some discrepancies were noted between the % share of product volume and % share of product value for certain Member States. This lead to a further analysis of PRODCOM data to generate indicative unit values per Portland cement product volume for each Member State.

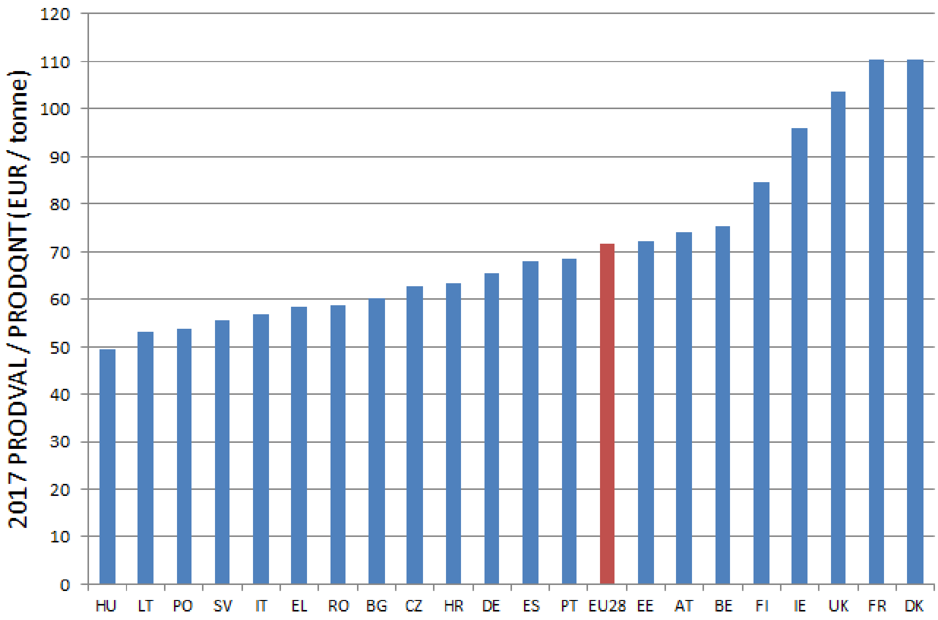


Figure 67. Average unit production value of Portland cement in 2017 (Source: adapted from PRODCOM)

The data in Figure 67 reveal that the unit value of sold Portland cement at Member State level can vary by more than a factor of 2. The range of variation is much lower than that observed for concrete tiles and flags in Figure 65 (where a factor of 9 variation was noted).

The highest sold cement value: volume ratios were associated with Denmark and France. Together with the UK, these 3 Member States were the only ones to exceed the 100 EUR/tonne threshold. Ireland was the next highest, which is surprising because Ireland was also associated with the cheapest concrete tile and flag value: volume ratio. The EU28 average ratio was around 71 EUR/tonne and the three cheapest Member States were all from the Eastern European side (Poland, Latvia and Hungary) where lower labour costs may be a factor.

Recycled aggregates

If any requirements should be set relating to recycled aggregate content, it is worthwhile paying attention to the trends in recycled aggregate production in comparison to virgin aggregate in different EU Member States[83].

[83] Tam V.W.Y., Soomro M. and Evangelista A.C.J., 2018. A review of recycled aggregate in concrete applications (2000-2017). Construction and Building Materials, 172, p.272-292.

Table 31. Estimates of recycled and virgin aggregate production in some European countries

	Type of aggregate	2010	2011	2012	2013	2014	2015
Belgium	Recycled	15	15	15	15	15	15
	Virgin	67	73	67	67	66	66
Denmark	Recycled	1	6	2	2	2	2
	Virgin	48	45	43	37	39	43
Finland	Recycled	1	0	1	1	1	2
	Virgin	84	89	89	84	80	76
France	Recycled	17	19	20	25	20	20
	Virgin	348	360	340	351	334	303
Germany	Recycled	60	65	68	66	68	68
	Virgin	475	533	496	480	496	477
Ireland	Recycled	0	0	0	0	0	0
	Virgin	50	32	29	25	26	28
Italy	Recycled	0	0	0	5	5	4
	Virgin	300	240	195	150	147	151
Netherlands	Recycled	20	18	17	16	25	18
	Virgin	56	55	66	48	48	62
Norway	Recycled	0	0	0	2	2	2
	Virgin	67	77	79	80	80	82
Portugal	Recycled	0	0	0	0	0	0
	Virgin	67	56	43	29	29	31
Spain	Recycled	0	0	0	1	1	1
	Virgin	208	173	113	92	91	95
Sweden	Recycled	1	1	0	0	0	0
	Virgin	80	80	79	76	79	88
Switzerland	Recycled	5	5	5	5	5	5
	Virgin	46	46	45	51	47	44
United Kingdom	Recycled	49	50	44	46	51	52
	Virgin	177	175	158	170	186	196
Total	Recycled	169	179	172	184	195	189
	Virgin	2073	2034	1842	1740	1748	1742
	% recycled	**8.2**	**8.8**	**9.3**	**10.6**	**11.2**	**10.8**

Although the data presented above can be considered as estimates only and are not specific to any one sector, it is clear that the significance of recycled aggregates in the broader aggregate market is generally low (10%) and that there is a significant variation in performance between different European countries (from 0% to 30%). The best performing countries were generally the Netherlands, the UK and Belgium.

These frontrunner countries have taken specific legislative measure to promote recycled aggregates. For example, in the Netherlands, the Environmental Management Act, The Environmental Protection Act, the Decree on landfills and landfill bans (including a landfill tax) and the promotion of voluntary extended producer responsibility schemes for concrete have all encouraged the market for recycled aggregates to develop. In the UK, in addition to taxes on waste sent to landfill and a tax for virgin aggregates, the environment agency for England and Wales has developed a quality protocol[84] for recycled aggregates in order to boost confidence in the use of recycled aggregates and promote good practice.

6.4 Review of production technology and innovations

The industrial processes used to produce concrete paving blocks, concrete paving units and concrete kerb units is described in this section. Due to its importance on the overall environmental impact of concrete products, the production process for Portland cement is also described afterwards.

6.4.1 Concrete paving units

6.4.1.1 Manufacturing process

The production of dry-cast concrete uses what is known as the "vibro-compression" process and is a type of pre-cast concrete production. The main distinction for dry-cast concrete is the lower water to cement ratio used (0.30-0.36 instead of ≥0.40). At these lower water to cement ratios the mixture has zero slump and so must be compacted under vibration in order to produce a block of sufficient stiffness for demoulding. This technique produces a stiff mass ready for demoulding in a matter of minutes. This means that demoulding is carried out only minutes after mixing and that the same mould can be used much more frequently than in other pre-cast techniques, resulting in important economic benefits for mass-produced products and is the main reason why dry-cast concrete is the technology of choice for these types of products.

The lower water content in dry-cast concrete means that, compared to wet-cast concrete paving units, the dry-cast concrete products:

- take longer to set in the curing room,
- will achieve a higher strength once cured properly and
- tend to have a rougher surface (good for slip resistance).

Dry-cast concrete pavers may be completely homogenous or dual-layered. The dual layered versions will use cheaper and lower quality materials in the non-facing layer which afford the possibility to save on pigments and potentially use secondary materials without any risks about affecting the aesthetics of the facing layer.

Figure 68. Examples of homogenous (left) and dual-layered (right) concrete pavers (Source: pavingexpert.com)

The overall dry-cast concrete procedure for both types of product (single or homogenous and dual-layer) is illustrated below and described thereafter.

[84] WRAP / EA, 2013. Quality Protocol. Aggregates from inert waste. End of waste criteria for the production of aggregates from inert waste.

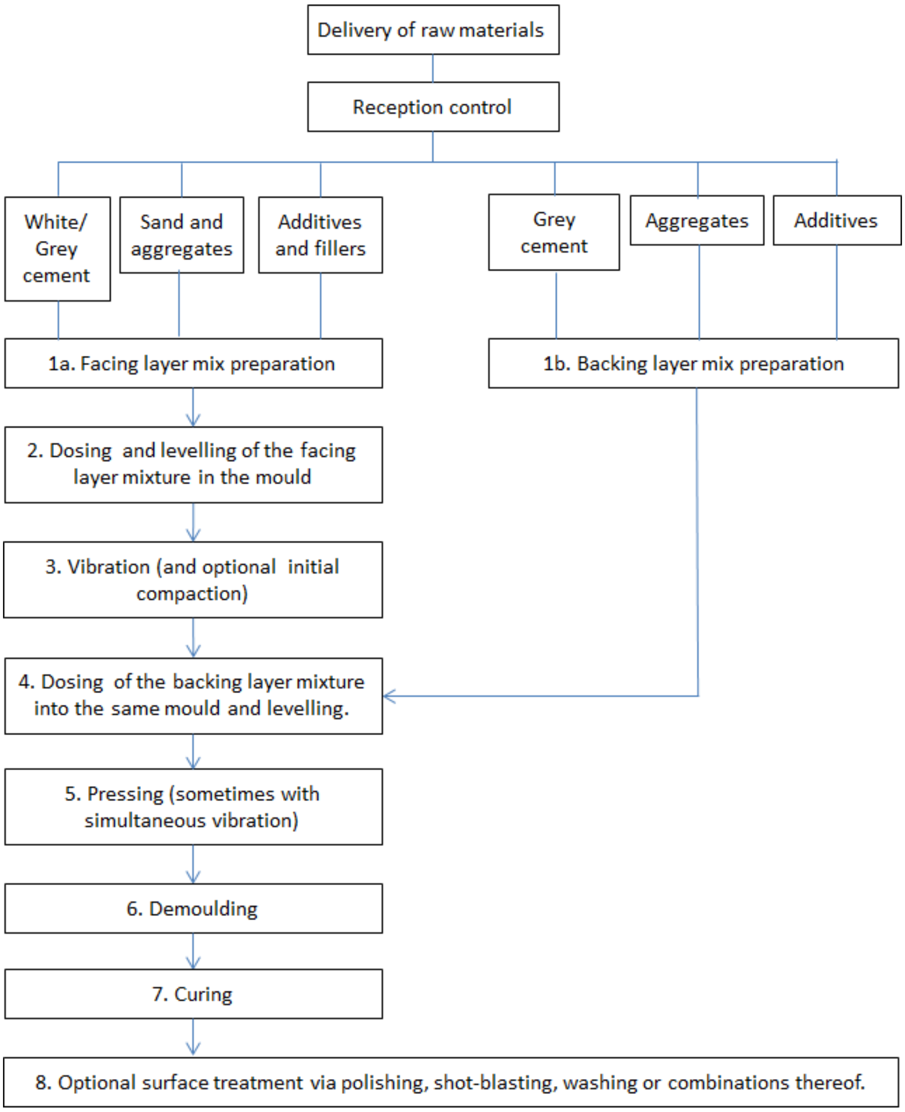


Figure 69. Dry-cast concrete production process for a two layered concrete paver (Adapted from tecnopavimento.org).

Concrete pavers can also be produced as single layer products, in which case steps 1a and 1b would be combined together and step 4 would be removed from the process diagram shown above. All of the equipment used in these process steps will run on electricity that is typically supplied from the grid rather than onsite CHP units.

Delivery and storage of raw materials

Quality control of ingredients is of fundamental importance as deviations in ingredient quality may affect the appearance of the finished product. Care must be taken with the exposure of hygroscopic raw materials to atmospheric humidity, especially with cements where the absorbance of moisture actually causes premature cement hydration on grain surfaces to a minor degree.

The granulometry of aggregates has a fundamental effect on the mix ratios required for the process and on the appearance and properties of the final product. The concrete paver producer may directly specify the granulometry when purchasing aggregates or apply some in-house crushing and sieving processes when necessary.

In all cases, the recommendations of the raw material supplier should be followed with regards to storage conditions and the maximum storage times before the material should be used.

Mix preparation and dosing of raw materials to the mixer

In cases where dual-layered pavers are produced, there are two separate dosing and mixing processes going on in parallel – one for the facing layer and one for the backing layer.

The facing layer will contain white or grey cement (depending on the final colour required), filler, sand, high specification aggregates (siliceous or calcareous) and special additives. The backing layer will generally never use the more expensive white cement and will tend to use lower specification aggregates (siliceous or calcareous) and be a much drying, lower slump mixture than the facing layer. For the cement used in the bed layer, there are a wider range of compositions available which may include waste materials or industrial by-products as partial substitutes for the cement

In both processes, the raw materials are combined together in very specific doses to achieve mixes that are fit for the processing equipment to be used and that will result in satisfactory finished products based on the manufacturer's experience.

The dosing equipment is semi or fully automated in order to ensure greater mix precision and more consistent batches. One possible exception to the automated dosing process may be with pigments dosed for the facing layer, which may sometimes be weighed out manually and to the nearest 0.1g.

The quantity of water added is carefully controlled to ensure that the manufacturing process will operate correctly. Just enough water should be added to the facing layer mix to ensure that the mix spreads out evenly across the mould during vibration.

The containers with the facing layer mix and the bed layer mix tend to operate in a semi-continuous manner. Ingredients are periodically dosed into the container from above and the homogenous concrete mixture is dispensed from the bottom of the container into a mould in regular steps. The exact mixing time required will be based on the experience of the manufacturer but must be sufficient to ensure homogeneity of the mix (especially regarding the uniform distribution of pigments in the facing layer mix).

Dosing of the mix(es) to the mould and vibro-pressing

The aim of the dosing equipment is to also dispense a consistent same volume of mix into the mould. The facing layer mix is dosed first and the mould is normally vibrated to ensure the complete distribution of the material across the entire mould, at a uniform thickness and with any entrained air bubbles being removed. The pressing action ensures that the aggregates are closely packed. Both the vibration and pressing actions ensure that a low water to cement ratio can be used which in turn, ensures that a stronger and less porous concrete will form.

In cases where low-relief surface features are to be introduced, it is necessary to place a fitting at the bottom of the mould that would impart the desired surface features to the facing layer before the facing layer mix is added.

A semi-dry mortar that will become the backing layer is then introduced into the mould from above in a slight excess quantity. It may be "pre-pressed" at this point prior to any excess mortar being swept away as the bed layer is mechanically levelled to match the top of the mould. It is worth noting that the water content of the backing layer has to be carefully controlled and the backing layer mix must be sufficiently drier than the facing layer to ensure a sufficient absorption of water from the facing layer during pressing that will cause the two layers to adhere to each other quickly during pressing.

The two layers are then pressed together in the mould using a hydraulic press. The press itself may contain a customised stamp that imprints the manufacturers name, brand and or batch ID onto the face of the backing layer. The time and pressure of the pressing stage will be chosen based on the experience of the manufacturer and must be sufficient to ensure the sufficient adherence of the two layers so that the piece will remain perfectly intact during the demoulding process, which will happen just a few seconds after pressing.

Demoulding and curing

Demoulding can be carried out automatically or manually. The demoulded tiles or slabs are stored on porous and stackable trays prior to their transfer to the curing chamber.

The curing process is necessary to allow the cement in the pressed tiles and slabs to hydrate and set under standard conditions of temperature and relative humidity. It is precisely the hydration of the cement that imparts the mechanical strength of the tile.

There are different options available for curing:

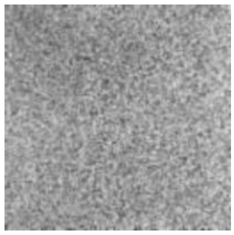
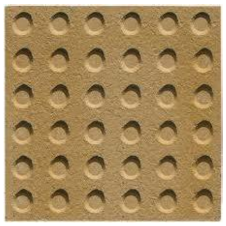
- **Normal:** typically the temperature is controlled at near ambient temperature (typically 20-30°C) and a minimum relative humidity is maintained (typically >90%) which results in the tiles/slabs being ready for further handling/treatment in 2-3 days.
- **Accelerated:** whilst still ensuring sufficient relative humidity, a moderately elevated temperature is applied in the curing chamber (around 40°C) which accelerates the hydration reactions of the cement to the extent that they are ready for further handling/treatment within 1-2 days instead of 2-3 days.

It is also worth noting that the Portland cement hydration reactions are not completed after 1-3 days but will actually continue in a gradual manner at least until 28 days, further increasing the mechanical strength of the tile and refining its porosity as the calcium-silicate-hydrate gel continues to grow and be generated from unreacted or partially reacted cement grains.

Optional surface treatment and incorporation of other surface features

A number of surface features may be applied to concrete pavers, either via surface treatment of the demoulded specimen of via adaptations to the mould. The main techniques used are summarised in the table below.

Table 32. Description of main surface treatments for concrete pavers (Adapted from tecnopavimento.org)

Description of technique	**Example**
Polishing: the upper face is polished in the factory using industrial polishers with any of a wide range of different grit pads (generally starting with a 24 grade and gradually polished finer and finer, up to as high as 800 grade), depending on client demands, to provide a smooth and glossy surface. This is the most common surface treatment for concrete pavers used in indoor environments.	
Shot-blasting: the upper face of the facing layer is blasted with steel shot to provide a rough textured and non-slip surface. Careful control of the shot-blasting process ensures that the tile surface still remains acceptably flat. Any surface defects in sub-standard tiles will be exposed by this treatment and later rejected.	
Washing: the upper face has been deliberately washed to selectively remove a fine layer (often <1mm) of the cement paste, thus exposing the aggregates to a much greater degree, as with a terrazzo tile but with an uneven surface texture. Washing can be carried out either immediately after pressing, via the use of a carefully controlled water spray, or after curing. In the latter case, it is necessary to apply a thin layer of cement setting retarder to the top of the facing layer so that even after curing, this top layer can still be easily and selectively washed away.	
Texturing: is not strictly a later surface treatment because it is directly imparted by the mould itself and thus requires no secondary treatment of the upper face. Very specific and reproducible textures can be imparted. The most common textures that are those that imitate natural stone or that imitate shot-blasted tiles.	
Low relief: like texturing, low-relief tiles have features that are directly imparted by the mould. The range of surface patterns and designs that are possible is only limited by the creativity of the client and the cost associated with creating custom reliefs to fit to the moulds. Low-relief tiles may also be polished for a higher aesthetic value. Particularly with polished tiles, care should be taken with these types of tiles that the necessary minimum slip resistance of the upper face is met in all directions.	 
Tactile: are a specific type of low-relief tile whose elevated surface markings are designed to provide support to disabled users, providing information about certain pathways to blind people who can feel the regular raised surfaces with their canes (for example to inform about the beginning of a pedestrian crossing).	

Ultimately, the choice of any surface treatment will depend on the specifications of the client and on certain technical standards (e.g. slip resistance for polished pavers and dimensional specifications for tactile tiles).

Depending on the production process and the required precision for tile dimensions, the evenness of the backing layer face of the paver may be refined (levelled).

Packaging and labelling

The final stage of the production process is a final visual check of the tiles prior to their packing into cardboard boxes, sealing with cable tiles and then stored on pallets with or without plastic film wrap. This stage of the process may be manual, semi-automatic or fully automatic. Each box and/or pallet should be labelled with information about the relevant product class.

Concrete block pavers and flags are normally stacked onto pallets in loads of 1 tonne of material secured with steel banding and plastic wrap. Kerbs and other borders are typically packed into groups of 10 to 25 units, also being secured with steel banding and plastic wrap.

6.4.1.2 Concrete paving units: innovations and improvements

The dry-cast concrete production process is a relatively low-tech industry which is based on semi-automated controls for dosing and mixing plus fully automated controls for placement in moulds, pressing, vibration and demoulding. The paving unit sector is not directly involved in cement binder production and so it was decided to present innovation in new cements in the later section specifically about cement production.

Although research is still at an early stage, in the last few years several flagship projects have been publicised[85] which use asphalt or paved surfaces with photovoltaic surfaces to generate electricity. The photovoltaic surfaces may be retrofitted to paved surfaces[86] or constructed as actual blocks and are not produced together with the underlying paving material. The platio solar paving product[87] does actually include some underlying paving support but this is made of recycled plastic, not concrete or other materials covered within the scope of "hard coverings". In all cases, special translucent coating layers are needed that are able to repel dirt, withstand mechanical loads and other aggressive environmental factors. Once installed, it would be necessary to connect the blocks together for wiring and different electrical components to control the power distribution.

Better established innovations, which are more closely related to the competencies of concrete paving unit manufacturers, can be summarised as follows:

- **Block and flag forms:** there exists an impressive variety of three dimensional block forms which is reflected by the hundreds of relevant patents that have been filed for this purpose. The main motivation behind the different forms may be for aesthetic purposes, to optimise load transfer behaviour, to facilitate more consistent joint gaps between laid blocks, to impart a controlled extent of permeability in the laid blocks (either via joints and/or via the block itself), to facilitate easier demoulding at the dry-cast concrete plant or for other reasons.
- **Dual-layer blocks:** the adaptation of the production process to accept doses into the mould first from the facing layer mix and secondly from the backing layer mix

[85] See: http://www.solarroadways.com/ and https://en.solaroad.nl/
[86] See: http://www.wattwaybycolas.com/en/
[87] See: https://www.platio.cc/en/

have obvious economic benefits because lower specification materials can be used in the backing layer. From an environmental perspective, dual-layered blocks can offer savings in pigment consumption for coloured surfaces and allow for greater design flexibility with regards to the incorporation of recycled aggregates and other secondary materials in the backing layer. The incorporation of recycled materials and secondary materials is discussed below.

- **Chemicals:** the use of speciality chemicals to improve a number of process conditions is well-established although some of these chemicals evolve to less hazardous variations, for example, the potential substitution of demoulding agents based on mineral oils for lower volatility chemicals, resulting in lower VOC emissions onsite.
- **Lower environmental impact cements:** There are well established blended Portland cements where the clinker content has been substituted to one extent or another (ranges of 6% to 95% are addressed by EN 197-1). There are also novel cements based on lower kiln operating temperatures or avoiding the use of cement kilns altogether (i.e. geopolymers or alkali-activated cements). These innovations will be discussed in more detail in the Portland cement part.
- **Permeable blocks:** this is one of the more widely discussed innovations and is discussed in more detail below. Permeable paving can refer to blocks that are permeable themselves or to impermeable blocks that are designed and laid out in such a way that freely draining voids are created in the paving pattern.
- **Material efficient blocks**: this term would apply to blocks which are laid with higher void contents between blocks (i.e. permeable designs) or to standard size blocks that incorporate significant contents of recycled aggregates and filler.
- **Photocatalytic blocks:** the use of paving blocks with an active photocatalytic substance (generally TiO2) embedded in the surface layer that is capable of oxidising air pollutants in the presence of UV radiation. This innovation is discussed in more detail below.

<u>Permeable paving blocks</u>

Paved surfaces are beneficial in the sense that they provide flat and solid surfaces that are designed to drain well and which facilitate the continued optimum movement of pedestrians and vehicles. The classical design of paving systems is to be impermeable to water and to be sloped in order to quickly divert rainwater to drainage systems. As urbanisation has increased in developed and developing countries, so too has the extent of impermeable paving. During a storm event in a particular river catchment, water that hits an impermeable area is rapidly conveyed via the drainage system to the river whereas storm water hitting a greenfield site infiltrates into the ground and only once the ground is saturated, it would flow across the vegetated surface towards the river or be trapped in natural depressions in the surface topography. The result is that, for a given storm event, there is a higher and more concentrated peak flow in watercourses fed by impermeable areas compared to those fed by greenfield areas.

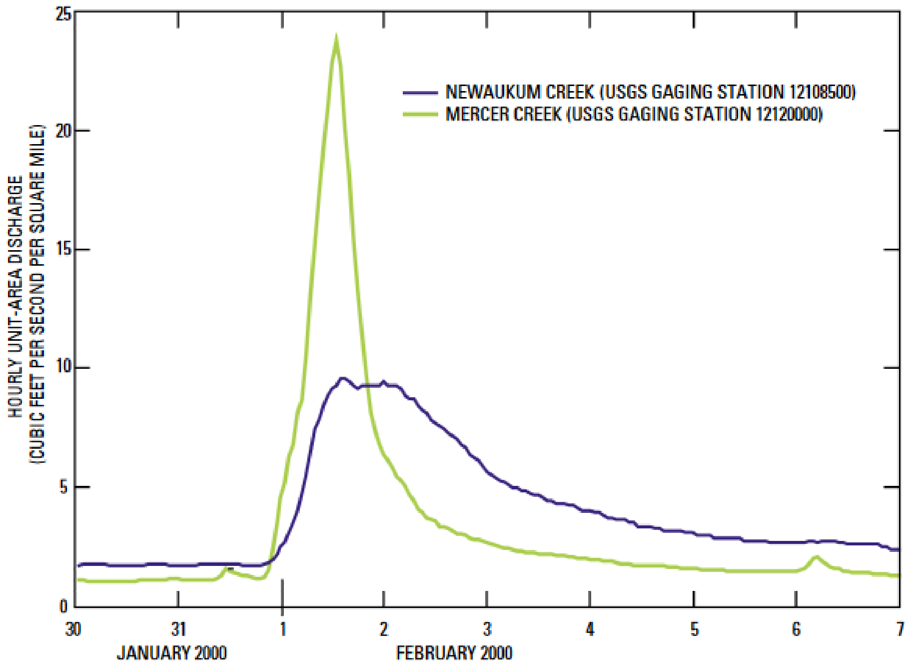


Figure 70. Specific runoff rates in an urban stream (green) and a rural stream (purple) that are located in the same area[88].

Even though the rainfall event on the 1st February was essentially the same for both stream catchments, the urban stream shows a much higher (x2.5) peak runoff rate. Furthermore, almost all of the storm runoff has passed to the stream within one day whereas this process takes more than 5 days in the rural stream. The two runoff behaviours indicate that watercourses in urban areas are much more susceptible to the phenomenon of flash flooding simply due to the increase in speed with which stormwater reaches the watercourse.

Impermeable pavements play an important role in the rapid conveyance of stormwater to watercourses. To design and construct paved areas that deliver more gradual runoff in a similar (or better) manner when compared to a greenfield site, permeable paving is one of a number of options possible, all of which fall under the concept of sustainable (urban) drainage systems (SUDS for short)[89].

Apart from elevated risks of flash flooding, impermeable paving reduces the possibility of recharging of groundwater aquifers. Permeable pavements can be designed for full, partial or zero infiltration, depending on what is most appropriate for the local area, by adjusting the broader paving system design and underlying base layers that are installed. Focusing purely on the top paving layer, there are two broad types of permeable paving:

- impermeable blocks with larger joints that are to be filled with high void content aggregate.
- concrete blocks that are permeable on the surface of the block itself (i.e. pervious concrete).

With the first option, in order to ensure the permeability of the filled joints, it is necessary to fill joints with aggregates with a very low fines content, to ensure that voids between coarse aggregates are not filled by small aggregates.

[88] From: Konrad CP., 2003. USGS Fact Sheet FS-076-03. Effects of urban development on floods.
[89] See: http://www.bgs.ac.uk/research/engineeringGeology/urbanGeoscience/suds/what.html

With the second option, for pervious concrete, it is also important to restrict the fines content in aggregates as well as the cement content. Ranges of mix compositions (aggregate, cement and water) that have been used in academic research have been summarised by Chandrappa and Biligiri, 2016[90]. With correct compositional control, pervious concrete with an interconnected void content of 15-35% can be produced (Kia et al., 2017[91]).

In the considerable academic literature that exists on the subject of pervious concrete the main advantages and disadvantages are:

- Advantages: major reduction in site runoff rates during storms (50-100%); reduced need for stormwater infrastructure and the capture of pollutants (particulates, heavy metals and oils).
- Disadvantages: Poorer durability in high load environments, susceptibility to freeze-thaw damage and susceptibility to clogging.

Research has shown that the technical properties of pervious concrete can be significantly improved via the addition of silica fume or latex polymers but that other process parameters need to be adjusted accordingly[92]. As with impermeable block, the potential to incorporate recycled aggregates into pervious blocks exists and has been investigated. Recycled concrete aggregate fractions of up to 100% can be used to produce technically viable pervious concrete[93].

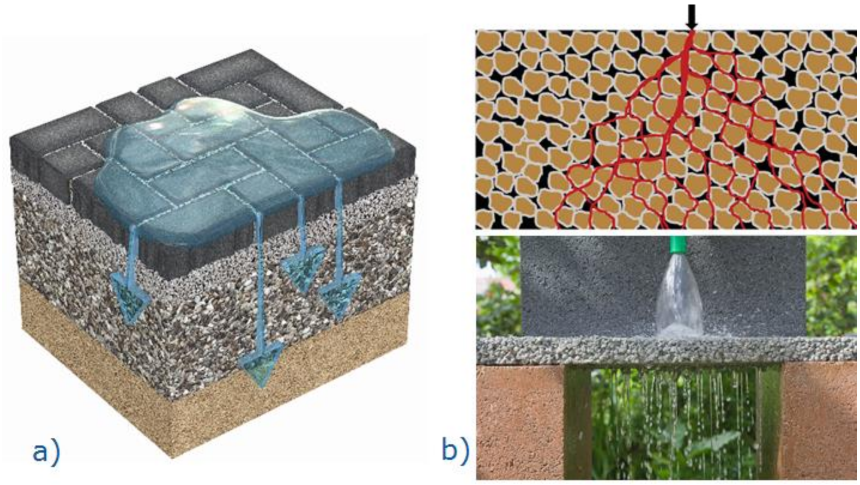


Figure 71. Drainage mechanisms in a) paving with permeable joints and b) pervious concrete blocks[94].

It is worth noting that permeable paving is recognised by a number of green building assessment schemes. Points can be awarded under credit 6 (Stormwater Management) of LEED for reducing the runoff rate by at least 25% (credit 6.1) and removing at least

[90] Chandrappa AK. and Biligiri KP., 2016. Pervious concrete as a sustainable pavement material – Research findings and future prospects: A state-of-the-art review. Construction and Building Materials, 111, p.262-274.

[91] Kia A., Wong HS. and Cheeseman CR., 2017. Clogging in permeable concrete: A review. Journal of Environmental Management, 193, p.221-233.

[92] Giustozzi f., 2016. Polymer-modified pervious concrete for durable and sustainable transportation infrastructures. Construction and Building Materials 111, p.502-512.

[93] Yap SP., Chen PZC., Goh Y., Ibrahim HA., Mo KH. and Yuen CW., 2018. Characterization of pervious concrete with blended natural aggregate and recycled concrete aggregates. Journal of Cleaner Production, 181, p.155-165.

[94] For image a) See: https://www.marshalls.co.uk/homeowners/view-driveline-priora-permeable-block-paving and for the top image in b), see: Kia et al., 2017.

80% of total suspended solids and 40% of total phosphorus (credit 6.2). The BREEAM scheme has a requirement related to surface runoff rates (Pol. 03), HQE rewards building plot designs with fewer impermeable areas (criterion 5.2.1) and that limit rainwater discharge into combined sewers (criterion 5.3.3).

If claims for permeable paving are to be recognised, it is important to consider exactly how the claims should be assessed and verified. Although results will also depend on the correct specification of joint filler and underlying base materials, one simple and reproducible test is to measure the infiltration rate of water (in mm/h) under standard conditions. It is unclear if there is a harmonised European standard for this type of test but one example used in the UK is BS DD 229:1996 (Method for determination of the relative hydraulic conductivity of permeable surfacings). With impermeable pavers that are interlocked with permeable joints and spacings, a simple specification would be to specify the permeable area as a fraction of the total area.

Material efficient pavers

The idea of material efficient pavers overlaps to some extent with permeable pavers, at least when considering impermeable block patterns with high percentages of void spaces.

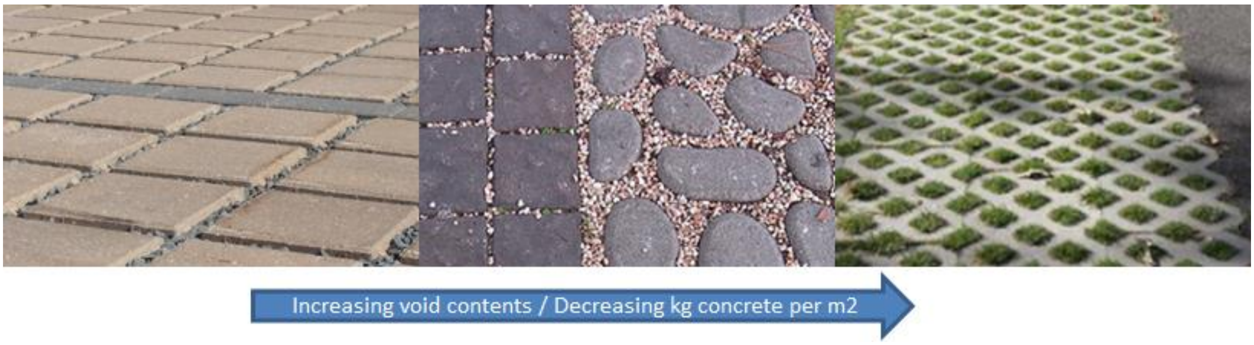


Figure 72. Examples of more "material efficient" concrete paving designs

The material efficient pavers with larger void spaces may not be suitable for heavily trafficked pavements and tend to be used in walkways or parking areas, where there may be combined with more traditional, impermeable asphalt or concrete-based pavements. Some paving designs will be deliberately designed to facilitate growth of grass while others do not. The growth of grass has the advantage of preventing loss of void fill material but will require greater maintenance if the traffic volume is not sufficient to keep the grass low. Weed growth in void spaces where vegetation is not intended will also result in greater maintenance.

Independent of whether a paver is part of a permeable design or not, the other major influence on material efficiency is the use of recycled aggregates. An important source of recycled aggregates is construction and demolition waste (CDW), which is one of the most voluminous waste streams generated in the EU and accounts for 25-30% of all EU waste[95]. The reduction of CDW is a political priority, as implied by Article 11.2 of the Waste Framework Directive, which states: "*Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 17 05 04 in the List of Wastes shall be prepared for re-use, recycled*

[95] See: http://ec.europa.eu/environment/waste/construction_demolition.htm

or undergo other material recovery". The term "other material recovery" may also include backfilling.

The heaviest fractions of CDW are concrete and brick, which have good potential as recycled aggregates in concrete paving blocks. Apart from glass, the other major components of CDW, namely gypsum, wood, metals, plastics and excavated soil are not suitable for use as recycled aggregates.

There is a lack of harmonised approach to the regulation of CDW in Member States, which in turn leads to a wide range in performance. It is generally understood that CDW does not travel far, since it the materials are generally bulky and of low value. Selective demolition of gypsum plasterboard is one sensible approach due to the higher added value of gypsum and the fact that the sulphate present in gypsum is undesirable in any waste that would be sent to landfill (possible anaerobic biodegradation to sulphide gases) or in recycled aggregates used in concrete (as it could adversely affect the Portland cement hydration chemistry).

A large volume of research has been published regarding the use of recycled aggregates in concrete products. Structural engineers are reluctant to use recycled aggregates in structural concrete due to concerns about consistency of properties, especially the fact that recycled aggregates tend to be weaker than natural ones and that they will show a higher, and variable water absorption. As Poon et al., (2002)[96] explain, the concerns about recycled aggregate in structural concrete do not extend to mechanically moulded concrete bricks and blocks. The authors demonstrated that up to 100% of the natural aggregate could be replaced by recycled aggregate of a suitable size distribution with only a minor decrease in compressive strength, a minor reduction in density, a minor increase in drying shrinkage and a notable increase in skid resistance. With both masonry unit bricks and paving blocks, a 50% replacement of natural aggregates by recycled aggregates improved all physical properties.

<u>Photocatalytic paving blocks</u>

Emissions of air pollutants is considered as arguably the most significant cause of premature death in the EU and contributes to major healthcare costs and lost productivity associated with respiratory diseases[97]. Air pollution is a major issue in many European cities due to emissions from vehicles that are powered by internal combustion engines. Apart from CO_2, the emissions of concern are mainly nitrogen oxides (NOx), hydrocarbons (VOCs) and carbon monoxide. The potential of NOx to interact with other air pollutants to form particulate matter, ozone and other oxidants led the WHO to set guideline values for NO_2 of 200μg/m^3 for 1 hour exposure and 40μg/m^3 for annual average exposure[98]. The EU Ambient Air Quality Directive[99] adopted the same limits as recommended by WHO with the additional detail that the one hour limit should not be exceeded for more than 18 hours in any one year. and that special measures must be taken if an alert limit is triggered (3 consecutive hours of NO2 concentrations exceeding 400μg/m^3).

[96] Poon C.S., Kou S.C. and Lam L., 2002. Use of recycled aggregates in molded concrete bricks and blocks. Construction and Building Materials, 16(5), p.281-289.
[97] EC, 2013. COM (2013) 918. A clean air programme for Europe.
[98] WHO, 2003. Health aspects of air pollution with particulate matter, ozone and nitrogen dioxide. Report on a WHO working group, Bonn, Germany.
[99] Directive 2008/50/EC on ambient air quality and cleaner air for Europe.

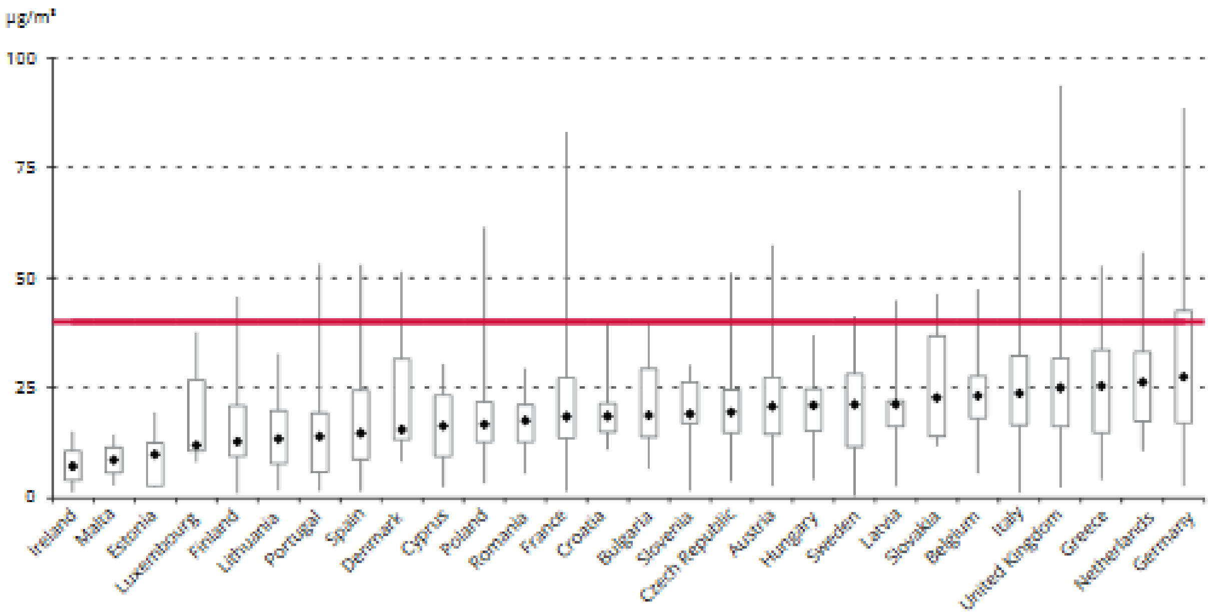


Figure 73. Annual average NO2 values at Member State level: lowest value = bottom of line; highest value = top of line; 25th and 75th percentiles = bottom and top of rectangles: overall mean = black point and red line is WHO guideline for annual average[100].

The EEA reported that 12% of all stations in the EU28 reported values that exceeded the 40µg/m3 annual average limit. Of those stations exceeding the limit, 94% were classified as "traffic stations", highlighting the fact vehicular emissions are a major source of NO2 pollution in Europe.

The EEA also compiled data at the national level as shown above in Figure 73, which show that Germany has the most severe problem with NO2 levels in ambient air but that around half of all Member States had some stations that were above the WHO recommended annual average limits for human health.

Policy efforts to reduce NO2 levels have correctly focussed on the source of the problem, i.e. vehicular emissions. However, even with improvements in emissions of individual vehicles, NO2 levels can increase due to increasing volumes of traffic and increasing traffic congestion in urban areas resulting in engines running longer for a journey of a fixed distance.

One interesting possibility to tackle NO2 pollution is the incorporation of photocatalytic surfaces onto road paving. Such surfaces contain TiO2 particles which, in combination with UV radiation from the sun and the presence of moisture, can generate free radicals that will breakdown common air pollutants such as NOx and VOCs.

[100] EEA, 2016. Air quality in Europe – 2016 Report. EEA Report No 28/2016, ISSN 1977-8449, ISBN 978-92-9213-824-0..

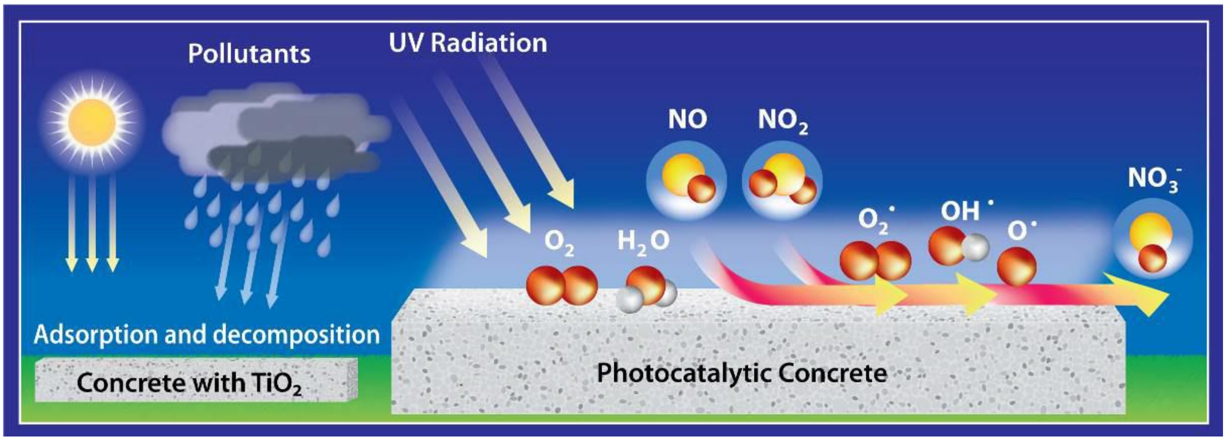


Figure 74. Schematic representation of the photocatalytic breakdown of NO and NO_2 to water soluble NO_3^-.[101]

The photocatalytic activity of treated surface can be tested under standard conditions according to ISO 22197-1:2016 where gas of a controlled NOx concentration is passed over a defined surface area subject to a controlled level of UV radiation at a controlled velocity and the NOx concentration of the outlet air measured.

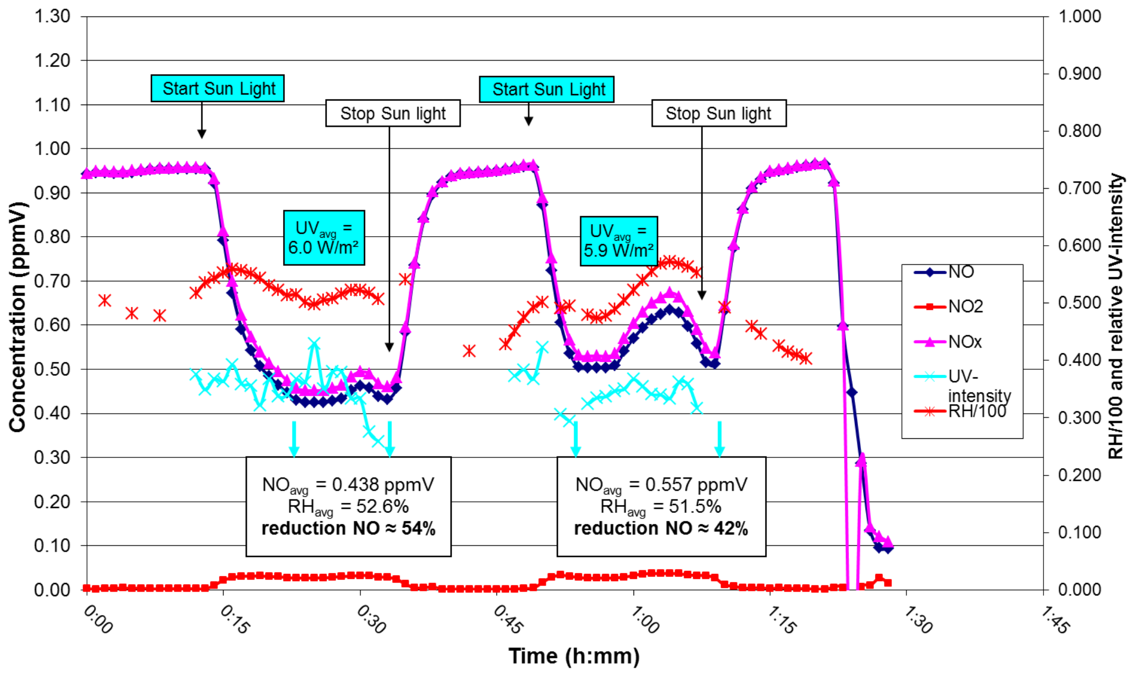


Figure 75. Real measured data of tested photocatalytic concrete pavers (Boonen and Beeldens, 2014).

In the example laboratory data provided above, average NOx reductions of 42% and 54% are achieved. Whether or not these results are translated into real life situations is much more difficult to predict because of the many complex variables that can influence performance (e.g. relative humidity, dust build-up, UV intensity, air velocity, traffic volume and active surface area to airflow ratios). Initial experience suggests that dual-

[101] Boonen E. and Beeldens A., 2014. Recent photocatalytic applications for air purification in Belgium. Coatings, 4, 553-573.

layered concrete, with a 50mm active top layer is much more durable in its photocatalytic function than any surfaces that are simply coated.

6.4.2 Portland cement: review of production technology

6.4.2.1 Manufacturing process - review of dry cast production technology

A description of the Portland cement manufacturing process is briefly summarised based on the information provided in the BAT Reference document for the production of cement, lime and magnesium oxide[102]. Although the core of Portland cement production process, the rotary kiln, remains essentially unchanged during the last 100 years, improvements have been made to capacity, degree of automation and thermal efficiency of the kilns. One of the main reasons for improvements in thermal efficiency was the introduction of preheater and precalciner units, which feed material must pass through prior to entering the kiln. The overall Portland cement manufacturing process and the five main variations of kiln set-up are illustrated in Figure 76 below

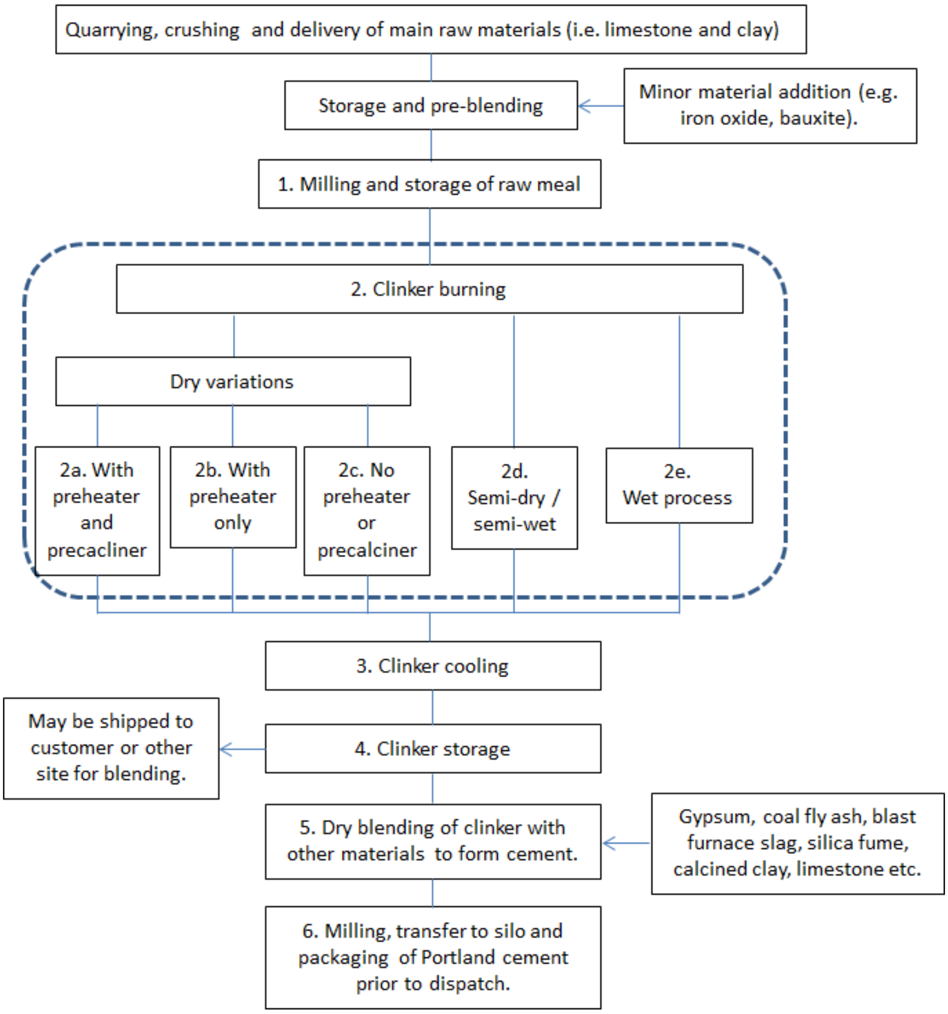


Figure 76. Overview of Portland cement manufacturing process

<u>Raw material extraction, storage and pre-blending</u>

[102] Schorcht et al., 2013. Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide. ISBN: 978-92-79-32944-9

The production of a CEM I type Portland cement will consist of around 80% limestone and most of the remaining material will be clay. Minor additions of bauxite, iron oxide and/or sand may be added to control the Ca:Si:Fe:Al ratios that are so important to ensure the correct formation of cementitious phases in the clinker. Consequently, the choice of cement plant location is heavily influenced by the availability of local limestone. Good quality control about raw material composition and careful dosing control when pre-blending are key to ensuring the correct Ca:Si:Fe:Al ratios are maintained.

Milling of raw meal and homogenisation

The grinding process will vary depending on whether or not white cement is to be produced instead of grey cement and also on the water content of the raw meal, which will be linked to the type of rotary kiln that will be used.

With white cements, it is important to keep the Fe content very low. Contact with steel parts can result in the transfer of Fe to the raw meal. Two ways to reduce the risk of transfer of additional Fe to the raw meal are (i) the use of grinding aids are used to minimise the grinding time needed or (ii) the use of special steels or ceramics for key parts of the mill and grinding media.

Raw meal that is sufficiently dry and is to be fed to dry and semi-dry kiln systems are normally milled using tube mills or vertical roller mills and the fineness of material leaving the mill is controlled by the type of separator used. With raw meal that is to be used in semi-wet or wet kiln systems are normally converted to slurry via the addition of water and subjected to closed circuit wet grinding techniques. Once material is sufficiently fine, it will pass through separator screens. To minimise increases in specific energy consumption, the water added to the slurry is keep to the bare minimum (32-40% w/w) and thinners may be added to maintain pumpability of the slurry at lower water contents. After milling (wet or dry), the milled material is stored in tanks or silos where it is homogenised.

Preheating and precalcining

These techniques are used by dry process kilns and, by optimising the contact of heat with raw materials, reducing the specific energy consumption of clinker production.

Preheating techniques involve the placement of stacked cyclone separators (typically 4-6 cyclones in series) which solids must pass through in a downwards direction prior to entering the rotary kiln while exhaust gases from the kiln pass in a counter-current flow, moving upwards through the cyclones. For a given production capacity, dry kiln processes with preheaters can be much shorter (length to diameter ratios can be 13:1 to 16:1 instead of 38:1 for a wet kiln).

The use of cyclones has the advantage of reincorporating a significant fraction of the kiln dust back into the raw meal but also increases the risk of build-up of scale deposits based on minor elements in the raw meal which are volatile (i.e. Na, K, Cl and S) at the temperatures in the burner zone but then liquefy and cycle back as they are blown up to the cooler parts of the kiln together with the combustion air. This cycling phenomenon can result in the formation of rings of calcium sulfates, potassium chlorides and alkali sulfates.

Precalciners can be used when preheaters are used and are placed in between the preheater and the entry to the rotary kiln. The term precalciner is coined because it offers the opportunity to operators to introduce any of a variety of fuels to raise the air and solids temperature to such point that limestone in the raw meal will be calcined to a significant degree (i.e. 75-99% decarbonation of CaCO3 to free lime (CaO) and CO2). In theory, the introduction of a precalciner means that a shorter kiln can be used for a given target production capacity. In reality, most kilns with precalciners seem to simply run with a higher production capacity instead of using a shorter kiln length (i.e. length to diameter ratio remains around 13:1 to 16:1).

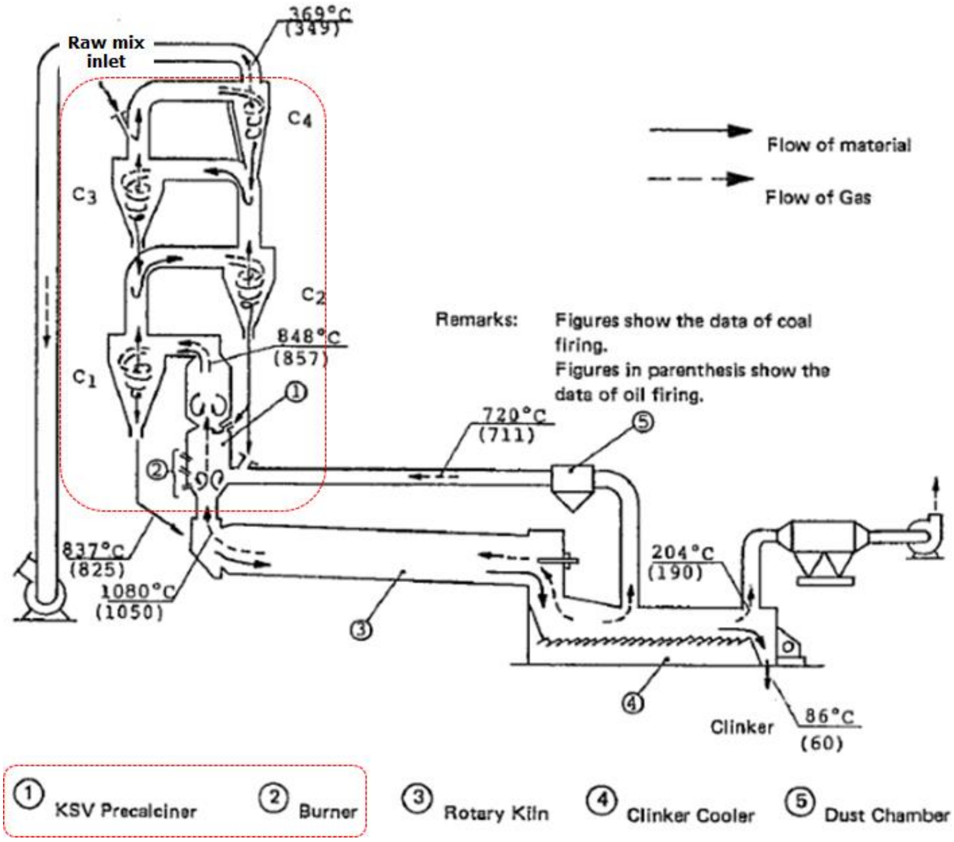


Figure 77. Flow diagram for Portland cement production with a 4 stage preheater and precalciner (highlighted)[103].

There are many minor variations of the precalciner and preheater setup but the principle is the same. The preheater can offer different inlets for fuels to be used (e.g. lump coal, powdered coal, oil or alternative fuels). The air temperature in the precalciner is carefully controlled around the 800-1000°C range to ensure that calcination can proceed efficiently but that sintering of particles will not yet occur, which could cause the precalciner to clog up.

Clinker production

The five main kiln types identified in Figure 76 are briefly described here. The wet process kilns are the oldest type of rotary kiln and are constructed of sufficient length to allow for the water from the slurry to evaporate as well as the necessary calcination and clinkering reactions to proceed (length to diameter ratios of 38:1). Some long dry kilns have also been produced but have higher specific energy consumption than other dry kiln process types.

The main distinction between the wet, semi-wet and semi-dry kiln processes are the degree of wetness of the raw meal fed to the kiln. While wet kilns receive wet slurry of

[103] Adapted from: http://www.cementequipment.org/home/suspension-preheaters-with-precalciner/

32-40% water content, semi-wet processes receive filter cakes (produced by pressing the slurry on filter plates to squeeze out a fraction of the water content) and semi-dry processes receive nodules made from dry meal on a noduliser disk.

With dry processes, precalcined (or just preheated) material enters the kiln at temperatures of around 1000°C. Fuels, such as coal, petroleum coke, gas, oil and alternative fuels, are fired directly into the kiln to ensure that the raw materials reach material temperatures of 1450°C. The kiln, which usually is a brick-lined metal tube 3-5 metres wide and 30-60 metres long, rotates about 3-5 times per minute, and the raw material moves through hotter areas of the kiln towards the flame. The heat causes chemical and physical reactions that partially melt the powder into spherical balls of clinker.

The clinker then reaches the end of the rotary kiln and enters the clinker cooler. A rapid cooling is important to lock the mineralogical characteristics of the phases present in clinker, especially alite, and generally results in a clinker that is easier to grind later on. Coolers generally act to transfer heat to incoming combustion air that will be fed to the precalciner or kiln burners and/or for preheating purposes (of kiln feed, for fuel drying, supplementary cementitious material drying or raw material drying). The cooling technology used can be broadly split into rotary coolers and grate coolers. With white cement, water cooling is typically employed in an oxygen-free atmosphere to prevent reactions that would reduce the whiteness of the cement.

Cement grinding and blending

Grinding to a certain fineness (normally expressed as blaine fineness in cm^2/g) has major effect on the properties of the cement, particularly on compressive strength development after reaction with water. Close control of the fineness can be achieved by using standard separators in closed milling systems. The most common technologies for cement grinding are tube mills, roller presses and vertical roller mills. Practical limits to grinding are set based on overheating of the cement powder (which could cause dehydration of any gypsum present) and for energy efficiency purposes.

To produce a CEM I type Portland cement (i.e. a "pure" Portland cement) the clinker is ground together with less than 5% w/w gypsum or anhydrite, which acts to delay the initial setting of the cement to an acceptable time period. To ensure no problems with leachability of Chromium VI from the cement (which may be imparted to the cement via contact with steel materials under aggressive grinding conditions or come from impurities in raw materials) reducing agents such as ferrous sulphate or tin sulphate may be added in small amounts to ensure less than 2ppm soluble chromium VI[104].

For other types of Portland cement (i.e. CEM II, III, IV and V) grinding with gypsum, anhydrite and reducing agents is carried out together with one or more supplementary cementitious materials (or mineral additions). If these mineral additions are not pre-dried, then care has to be taken with the choice of milling technology (vertical roller mill is best). The main mineral additions involved and the associated quantities have been previously mentioned in Table 25.

It is worth adding here that for white cements, special grinding aids can be used in quantities up t o1% w/w together with finely ground microfillers such as white marble, mica, talc, quartz glass, kaolin, metakoalin or small amounts TiO2.

[104] As per requirements set out in Directive 2003/53/EC.

6.4.2.2 Portland cement: innovations and improvements

A commonly reported figure is that Portland cement production is responsible for 5-8% of anthropogenic CO2 emissions (Sharp et al., 2010[105] and Barcelo et al., 2014[106]). The Portland cement industry is covered by the EU Emissions Trading Scheme[107], which results in an economic incentive to reduce CO2 emissions. Consequently, many of the technical improvements and innovations relating to the cement industry have focussed on reducing the specific carbon footprint of cement.

Carbon emissions with cement production are dominated by[108,109]:

- Direct emissions due to decarbonation of limestone (CaCO3 → CaO + CO2) in the kiln (around 60% of total emissions).
- Direct emissions due to the combustion of fuels (thermal energy consumption) to reach kiln gas temperatures of 1800-2000°C (around 30% of total emissions).
- Indirect emissions due to grid electricity consumption (around 10% of total emissions)[110].

Most electricity used is supplied by the grid and is thus beyond the direct control of the cement industry. As a general rule of thumb, a specific carbon footprint of 1 tonne CO2 / 1 tonne Portland cement has been used although this can typically range from 0.69 to 1.15 t CO2/t cement, with an average value being around 0.84 t CO2/t cement (Van den Heede and De Belie, 2012).

The most commonly researched methods to reduce the specific carbon footprint of Portland cement include; altering the phase composition of the clinker, improving the thermal efficiency of the kiln, using alternative fuels with lower carbon intensity and reducing the clinker factor of the cement. Each of these approaches is described in more detail below.

<u>Innovation 1: Lower Ca content Portland cement clinker</u>

The key to the cementitous behaviour of Portland cement is the formation of a Calcium-Silicate-Hydrate (CSH) gel upon reaction with water. The two main Calcium Silicate phases in Portland cement clinker are alite (an impure form of tricalcium silicate, C3S) and belite (an impure form of dicalcium silicate, C2S).

Alite phases are sufficiently reactive to form good early strengths but belite phases take longer. The extra calcium required for the alite formation comes from limestone, which decarbonises in the kiln to produce extra CO2 emissions. Furthermore, due to the endothermic nature of this reaction, the kiln temperature required to form sufficient quantities of alite is around 1450°C whereas, if only belite was required, the temperature could be reuced to 1200°C, saving fuel CO2 emissions as well as raw material CO2 emissions.

[105] Sharp J.H., Gartner E.M. and Macphee D.E., 2010. Novel cement systems (sustainability) Session 2 of the Fred Glasser Cement Science Symposium, Advances in Cement Research, 22(4), p.195-202.
[106] Barcelo L., Kline J., Walenta G. and Gartner E.M., 2014. Cement and carbon emissions, Materials and Structures, 47(6) DOI: 10.1617/s11527-013-0114-5
[107] See: https://ec.europa.eu/clima/policies/ets_en
[108] IEA, 2018. Technology Roadmap. Low-Carbon transition in the cement industry. International Energy Agency
[109] Bosoaga A., Masek O and Oakey J.E., 2009. CO2 capture technologies for cement industry. Energy Procedia, 1(1), p.133-140.
[110] Shokker AJ., 2010. The sustainable concrete guide, strategies and examples. US Green Building Council. ISBN: 978-0-87031-362-2.

To compensate for the reduced reactivity of belite at early ages, either more sulfate can be added to the raw meal, to produce reactive calcium aluminosulfate phases and/or minor elements can be added that will alter the mineralogy of belite, producing a more reactive form. In general, reactive belite clinkers could potentially result in the reduction of CO2 emissions by some 20-25%[111].

Innovation 2: Improving the thermal efficiency of the kiln for clinker production

The thermal efficiency of the kiln is responsible for around one third of Carbon emissions associated with Portland cement production and the efficiency is very much a function of the type of kiln technology used. As a general rule, drier processes are more efficient and the use of preheaters and precalciners each improve the efficiency further. The use of preheaters began in the 1930s and the use of precalciners began in the late 1970s.

Cement kilns are major capital investments with long amortization periods, although fuel consumption is also a significant operating cost. The trends in kiln technology deployment since 1990 are illustrated below, both at the European and global levels.

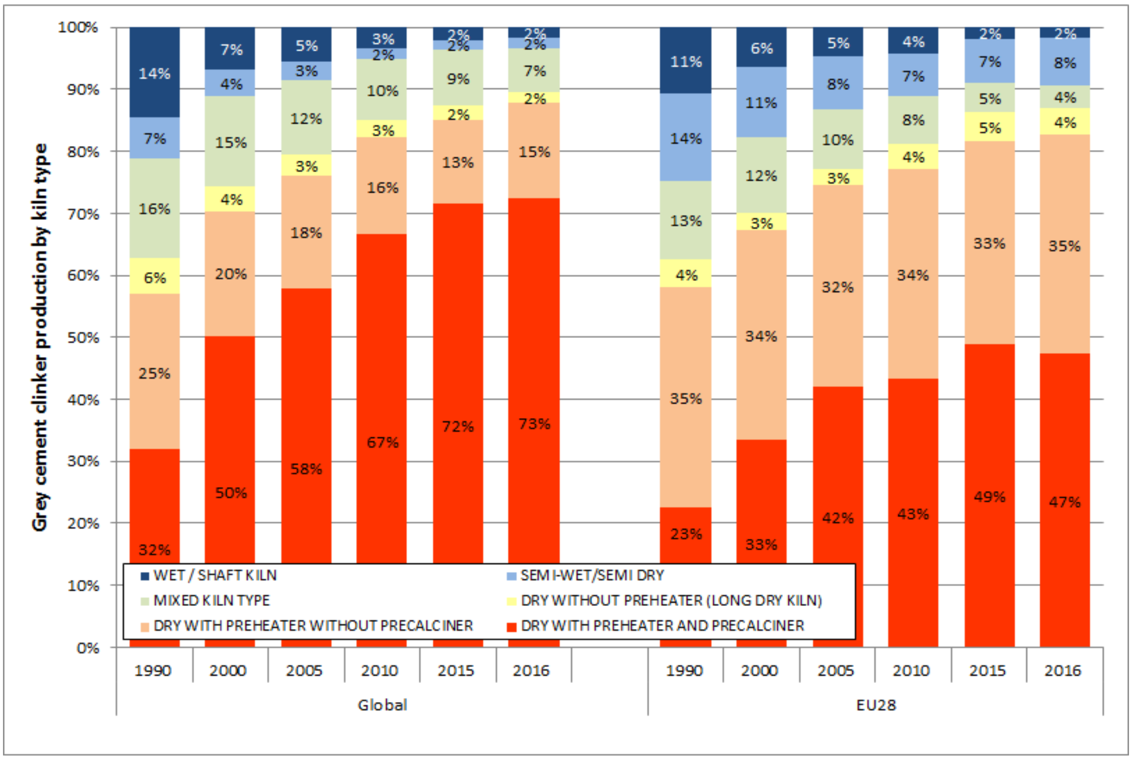


Figure 78. Trends in kiln technology used for grey cement clinker production (Source: GNR database)

Looking at the data reported by the GNR database it is clear that there is a trend away from wet kiln processes (in blue) and towards dry processes with preheaters and precalciners (red). It should be noted that while the data presented above covers 90% of EU28 cement production, it only covers around 20% of global cement production.

The GNR database also presents useful data about the specific thermal energy consumption as a function of kiln type and how this has evolved during the last 25 years.

[111] Gartner E., Quillin K., 2007. Low CO2 cements based on calcium sulfoaluminates. International Confernece on sustainability in the cement and concrete industry. Lillehammer, Norway 16-19 Sept.

Table 33. Specific thermal energy consumption as a function of kiln technology or cement type in the EU28

Product	Kiln type	Units	1990	2000	2005	2010	2015	2016
Grey cement clinker	Dry with preheater and precalciner	MJ/t	3614	3403	3387	3390	3385	3388
		% change since 1990	0%	-5.8%	-6.3%	-6.2%	-6.3%	-6.3%
	Dry with preheater	MJ/t	3856	3684	3636	3694	3690	3730
		% change since 1990	0%	-4.5%	-5.7%	-4.2%	-4.3%	-3.3%
	Dry without preheater	MJ/t	4584	4466	4288	4016	3881	3843
		% change since 1990	0%	-2.6%	-6.5%	-12.4%	-15.3%	-16.2%
	Semi-wet or semi-dry	MJ/t	4006	3780	3797	3827	4307	4108
		% change since 1990	0%	-5.6%	-5.2%	-4.5%	+7.5%	+2.5%
	Wet	MJ/t	6314	6003	6104	5982	5734	5906
		% change since 1990	0%	-4.9%	-3.3%	-5.3%	-9.2%	-6.5%
White cement	Averaged across all kiln types	MJ/t	6394	6256	5919	5495	5305	5244
		% change since 1990	0%	-2.2%	-7.4%	-14.1%	-17.0%	-18.0%

The specific thermal energy consumption data reveal a number of interesting facts, which can be summarised as follows:

The choice of kiln technology has a major effect on the specific thermal energy consumption for grey cement clinker production (ranging from 3400 to 5900 MJ/t, almost a factor of 2 difference). Considered together with the data in Figure 78 it is clear that the most energy intensive kiln types only represent a small fraction of the EU production capacity, with a weighted average grey cement clinker thermal energy consumption of around 3650 MJ/t).

That all kiln technologies have shown modest to moderate improvements in thermal energy efficiency of 2-18% during the last 25% but that further improvements are not anticipated, especially in the most efficient dry kilns with precalciners.

That white cement, which has different applications and market niches, generally has a higher specific thermal energy consumption (5250 MJ/t) and so should be considered separately from grey cement clinker (weighted average around 3650 MJ/t) when setting energy criteria for cement production.

Although the type of limestone raw material available (wet or dry) influences the optimum kiln technology, for new plants there is a definite trend towards dryer kilns with preheaters and precalciners due the inherent improvements in thermal efficiency. This trend is further encouraged due to the relatively high energy costs in Europe. However, the sharp decrease in European cement production caused by the global economic crisis (see Table 22) and the fact that production levels have not yet returned to pre-crisis levels (still around on third below 2008 production) has created an overcapacity in Europe. This development, coupled with the fact that the cement industry is highly capital intensive[112] and that cement is not so economic to transport long distances to

[112] Boyer M. and Ponssard J-P., 2013. Economic analysis of the European cement industry. <hal-00915646>

growing markets outside of Europe[113], means that investment in new kilns in Europe is not expected even in the medium term.

Based on the above data and comments, further improvements in cement kiln thermal efficiency are not expected beyond what is already possible with dry process kilns with preheaters and precalciners.

Innovation 3: Use of alternative and less carbon intensive fuels

Traditionally the main fuels used by the cement industry have been coal, petroleum coke, fuel oil and natural gas, which are all fossil based. Since thermal energy costs account for some 20-25% of cash costs[114], there is a potential economic incentive for the cement industry to accept alternative fuels, especially hazardous wastes that may actually represent a source of income, rather than just a reduced cost. Cement kilns offer certain physicochemical conditions that are particularly amenable to the processing of certain hazardous wastes. These conditions include[115]:

- High air temperatures of 1800-2000°C near the main burner.
- Relatively long residence time in air at ≥1000°C (5s compared to >2s required for waste incineration).
- Excess oxygen combustion conditions to ensure complete oxidation and combustion (may not apply to some white cement plants).
- Alkaline environment that will neutralise acidic gases.
- Incorporation of any residual inorganic ashes from fuels into the clinker, greatly reducing ash generation compared to when the same waste would be sent to conventional energy from waste plants and also reducing the demand for raw materials to make the cement clinker.

Table 34. Alternative fuel substitution rates in different countries compiled from different sources[116]

Country	**NL**	**BE**	**DE**	**PO**	**SE**	**ES**	**EU27**
Alternative fuel %	85	60.0	53.6	45.0	45.0	22.4	18.0

The data sources in the table above were published during or prior to 2013. More recently, CEMBUREAU (2017)[117], claim that alternative fuels now account for 43% of all fuels used by their members, that this figure could rise to 60% in the medium term and, if certain regulatory barriers are removed, could reach 95% in the longer term. This serves to highlight the recent and considerable advances in the uptake of alternative fuels by the European cement industry.

[113] See: http://lowcarboneconomy.cembureau.eu/index.php?page=transport-efficiency
[114] Madlool N.A., Saidur R., Hossain M.S. and Rahim N.A., 2011. A critical review on energy use and savings in the cement industries. Renewable and Sustainable Energy Reviews, 15, p.2042-2060.
[115] WBSCD, 2014. The Cement Industry: Creating solutions for safe, resource-efficient waste management. World Business Council for Sustainable Development.
[116] Rahman A., Rasul M.G., Khan M.M.K. and Sharma S., 2015. Recent development on the uses of alternative fuels in cement manufacturing process. Fuel, 145, p.84-99.
[117] CEMBUREAU, 2017. Activity Report.

The main alternative fuels that have been used by the cement industry are briefly presented below, some of the more commonly used fuels are then discussed in more detail and then finally how trends in the uptake of alternative fuels have affected the carbon intensity of the fuel mix in companies reporting to the GNR database will be demonstrated.

Table 35. Main types of alternative fuels used in cement production (Source: Karstensen, 2007[118])

Liquid waste fuels	Solid waste fuels	Gaseous waste
Sewage sludge	Industrial plastic	Landfill gas
Asphalt slurry	Plastic residues	Pyrolysis gas
Paint waste	Wood waste	
Petroleum coke	Rubber residues	
Waste oil	Refuse derived fuel plastic	
Petrochemical waste	Scrap paper	

Scrap tyres are one of the most popular and well known alternative fuels in the cement industry and there is already decades of experience with this material. The different waste management options for end-of-life tyres are shown below.

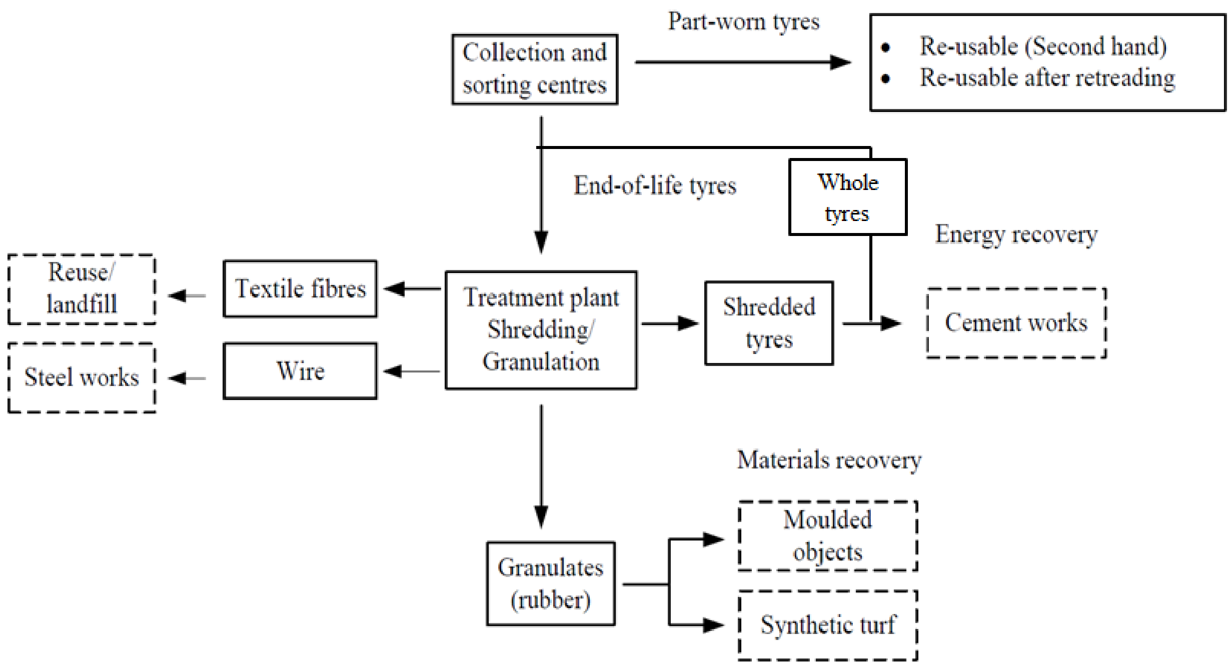


Figure 79. End-of-life options for scrap tyres (adapted from Aranda et al., 2012)[119]

Tyres can be fed whole or shredded. The shredded option allows the fuel to be dosed without any technical adaptations and for steel banding to be recovered for recycling (ca. 275kg per tonne of tyres processed), but requires electricity (ca. 308kWh/tonne tyres processed), process water (ca. 150L per tonne of tyres processed) for the process according to Aranda et al., 2012. Burning whole tyres results in an increasing Iron

[118] Karstensen K.H., 2008. Formation, release and control of dioxins in cement kilns. Chemosphere, 70(4), p.543-560.

[119] Aranda U.A., Ferreira G., Zabalza B.I. and Zambrana V.D., 2012. Study of the environmental performance of end-of-life tire recycling through a simplified mathematical approach. Thermal Science, 16(3), p.889-899.

content (i.e. not suitable for white cement production) in the clinker mix which needs to be accounted for and which can reduce the need for iron raw materials in grey cement production. The high carbon content, high calorific value (ca. 30-37 MJ/kg)[120,121], low moisture content and the possibility to charge gate fees for accepting the tyres make this waste material cost competitive with natural gas and coal. The impact of tyre burning on gaseous emissions from the kiln may result in modest increases in CO and hydrocarbon although other authors found no statistically significant increases in gaseous emissions of these substances or SO2 and NOx. The main concern with the use of tyres as an alternative fuel is the potential increase of Zn content of the clinker. Tyres can contain up to 4% ZnO by weight and the Zn presence in the kiln can increase the fluxing behaviour of clinker, rate of alite formation or nature of the tricalcium aluminate phases[122] in a manner that may be positive or negative depending on whether kiln operators are able to take advantage of these changes in clinker behaviour. Excessive Zinc content in the clinker can affect the formation and subsequent reactivity of tricalcium aluminate, which in turn will have an effect on the setting time and strength development of hydrated Portland cements[123]. Due to concerns with Zn content in clinker, it has generally been recommended to limit the use of tyres as alternative fuels to no more than 30% of total thermal energy requirements (Chatziaras et al., 2015).

Refuse derived fuel (RDF) is closely linked to the management of municipal solid waste (MSW) and so the potential for this alternative fuel in a given cement plant will depend on the MSW management strategies in surrounding regions. Prior to use as an alternative fuel, it is necessary to convert MSW (highly heterogeneous composition with calorific value of 8-11 MJ/kg) into RDF (less heterogeneous composition with a calorific value of 15-20 MJ/kg) (Rahman et al., 2015). This conversion process will involve pre-sorting, shredding and mechanical separation to remove recyclable, inert and wet fractions, which may account for 50-80% of the total mass of MSW (Chatziaras et al., 2015). The main concerns with RDF as an alternative fuel are variable water contents, the sulfur content and the chlorine content. Chlorine contents of >0.3% in RDF (or any alternative fuel) increase the risk of corrosion, heavy metal volatilization and dioxin formation – leading to the need to increase flue-gas bypass rates and thus reducing energy efficiency[124]. The RDF fuel may still need to be dried using waste heat from the cement factory in order to reach acceptable calorific value. To produce a more consistent RDF, the production of a syngas via gasification of RDF is also an option[125].

Meat and bone meal (MBM) became an interesting alternative fuel following the European ban on MBM use in cattle feed, which led to stockpiles of MBM in some regions which did not have appropriate incineration infrastructure in place[126]. The calorific value of MBM,

[120] Karell M.A. and Blumenthal M.H., 2001. Air regulatory impacts of the use of tire-derived fuel. Environ Prog, 20(2), p.80-86.
[121] Chatziaras N., Psomopoulos C.S. and Themelis N.J., 2016. Use of waste derived fuels in cement industry: a review. Management of Environmental Quality: An International Journal, 27(2), p.178-193.
[122] Bolio H. and Glasser F.P., 1998. Zinc oxide in cement clinkering: part 1. Systems CaO-ZnO-Al2O3 and CaO-ZnO-Fe2O3. Advances in Cement Research, 10(1), p.25-32.
[123] Kolovos K.G., Barafaka S., Kakali G. and Tsivilis S., 2005. CuO and ZnO addition in the cement raw mix: effect on clinkering process and cement hydration and properties. Ceramics – Silikaty, 49(3), p.205-212.
[124] Murray A. and Price L., 2008. Cement manufacture: Analysis of fuel characteristics and feasibility for use in the Chinese cement sector. Ernest Orlando Lawrence Berkeley National Laboratory, Report LBNL-525E.
[125] Galvagno S., Casciaro G., Casu S., Martino M., Mingazzini C., Russo A. and Portofino S., 2009. Steam gasification of tyre waste, poplar and refuse-derived fuel: a comparative analysis. Waste Management, 29(2), p.678-689.
[126] Deydier E., Guilet R., Sarda S. and Sharrock P. Physical and chemical characterisation of crude meat and bone meal combustion residue: waste or raw material?". Journal of Hazardous Materials, 121(1-3), p.141-148.

like that of RDF, is relatively modest, typically around 15-17 MJ/kg. Unlike other alternative fuels, the ash content, which can account for around 30% of the total MBM mass, is dominated by calcium phosphate minerals (Deydier et al., 2005). There are tight limits to P contents allowed in raw meal that is fed to a Portland cement kiln due to its ability to decompose alite into belite, reducing the reactivity of the cement and increasing the free lime content (which is also undesirable)[127,128].

Sewage sludge has been used as an alternative fuel in some cases where regional logistics and legislative changes have complicated or blocked altogether the traditional disposal routes of sewage sludge. Since 1986, restrictions on the application of sewage sludge to agricultural land were imposed for Member States under the Sludge Directive and amending legislation[129]. A number of individual Member States have also implemented stricter limits and restrictions for the spreading of sewage sludge to land[130]. Since 1999, the Urban Wastewater Treatment Directive[131] banned the disposal of sewage sludge at sea in 1999. Chatziaras et al., (2015) report that sewage sludge needs to be dried prior to its use in the cement industry, whether it is to be dosed as a fuel directly or gasified to produce a gas for combustion. The inorganic fraction of sewage sludge is dominated by Si, Al, Ca, Fe and P. The first four elements are key constituents of the main cement clinker phases and so can reduce the need for raw materials in the kiln feed. However, the P content can be problematic, for the same reasons as mentioned above for MBM, and effectively limit the use of sewage sludge in the fuel mix.

Table 36. Trends in average carbon intensity of fuel mixes used in the cement industry (Source: GNR, code 593AG)

	2000	**2005**	**2010**	**2015**	**2016**
AT	88	79	76	71	69
CZ	90	83	77	68	65
DE	91	81	80	71	70
ES	93	91	88	80	81
FR	83	79	83	76	76
IT	93	92	92	87	98
PO	97	94	86	74	71
UK	95	92	85	72	75
EU28	**91**	**88**	**85**	**77**	**77**
World	**90**	**88**	**88**	**86**	**86**

The data in table above reveal a general reduction in the carbon intensity of cement kiln fuel mixes in almost all countries and regions since 2000, with the only exception being Italy, where the data have changed suddenly between 2015 and 2016. Reductions in the

[127] Ifka, T. Palou MT. Bazelova Z., 2012. The influence of CaO and P2O5 of bone ash upon the reactivity and the burnability of cement raw mixtures. Ceramics – Silikaty 56(1) p.76-84.

[128] Noirfontaine M-N, Tusseau-Nenez S, Signes-Frehel M, Gasecki G., Girod-Labianca C., 2010. Effect of phosphorus on tricalcium silicate T1: from synthesis to structural characterization.

[129] Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. OJ L 181, 4.7.1986, p.6-12

[130] Donatello S. and Cheeseman C.R., 2013. Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. Waste Management 33, p.2328-2340.

[131] Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. OJ. L135, 30.5.1991, p.40-52.

carbon intensity of fuel mixes can be achieved by substituting coal for natural gas or for substituting fossil-based fuels for biomass-based fuels and/or waste materials.

It should be noted that the numbers reported above are for fuel mixes used in grey cement clinker production and the trends numbers for white cement production may be different.

Innovation 4: Reducing the clinker factor of the cement

Portland cement is basically a combination of Portland cement clinker and <5% calcium sulfate (gypsum or anhydrite). As alluded to in Table 25, technical standards are in place for cements where the clinker component has been partially replaced by one or more of a number of defined mineral additions at levels ranging from 6 to 95%. Each of the mineral additions have a lower environmental impact than the clinker and so can be considered to be a hugely important part of innovation in the sector towards lower impact cements. Some brief mention of the main mineral additions is provided below.

Blast furnace slag is a by-product of the steel production process and can be separated from molten iron in a blast furnace thanks to its lower density. The slag is formed by the reaction of calcium and/or magnesium from fluxing agents with aluminosilicate materials present in the iron ore, resulting in a chemical composition that is predominantly based on Ca, Si and Al – very similar to that of Portland cement clinker. Rapid cooling of the slag with large quantities of water produces a granulated slag material with sand-sized granules and reactive mineral phases that will participate in the formation of cementitious gel under the typical conditions of Portland cement hydration. This material can then be ground to produce ground granulated blast furnace slag, in order to improve its reactivity further to the point where it can replace up to 95% of the Portland cement clinker fraction in CEM III/C type cements. It is also worth noting that there are other ways to cool blast furnace slag that can result in more stable mineral phases that would make the slag suitable for a variety of applications as an aggregate[132].

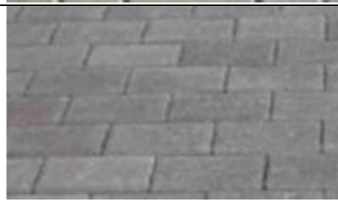
6.5 Life cycle assessment: concrete paving units

Most of the LCA research in the literature has focussed on the production of cement and one or two specific types of concrete product but only a small fraction of this research has looked at concrete paving products. An example of some relevant EPD data is provided below.

Table 37. Examples of different mix recipes for concrete products within the proposed scope (Source: HBF, 2018)[133]

Mix recipe	Image
1m^3 of 200mm Hollow Concrete Masonry Unit: 146kg water; 250kg Portland cement; 1000kg crushed coarse aggregate; 1150kg crushed fine aggregate; 250kg natural fine aggregate	

[132] See: http://www.nationalslag.org/blast-furnace-slag
[133] HBF, 2018. Hard Block Factory EPD Declaration Number EPD 082, issued June 22, 2018.

1m^3 of 200mm Solid Concrete Masonry Unit: 120kg water; 140kg Portland cement; 850kg crushed coarse aggregate; 1410kg crushed fine aggregate; 250kg natural fine aggregate	
1m^3 of 80mm grey rectangular concrete paver: 136kg water; 422kg Portland cement; 782kg crushed coarse aggregate; 843kg crushed fine aggregate; 0kg natural fine aggregate	
1m^3 of 50mm Grey roof tiles: 108kg water; 424kg Portland cement; 790kg crushed coarse aggregate; 841kg crushed fine aggregate; 0kg natural fine aggregate	

Despite the significant variations in cement content and aggregate types used, the impacts due to raw material extraction (A1) are consistently more important than impacts during concrete processing (A3).

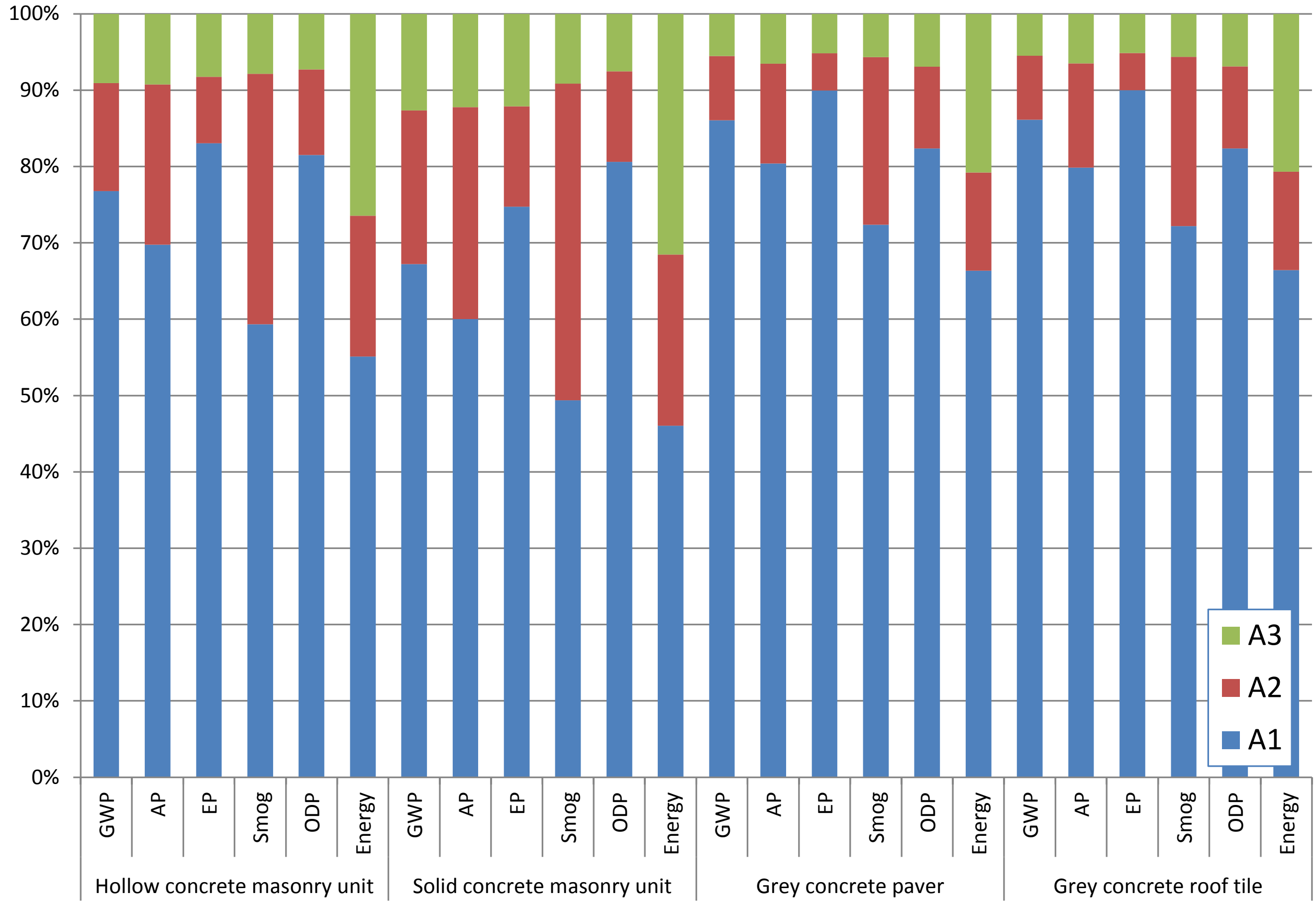


Figure 80. A1, A2 and A3 impacts for manufacture of 5 different concrete products.

Due to the dominance of A1 stages, it is justifiable that EU Ecolabel criteria should pay particular attention to the raw materials used. The relative influences of aggregates and cement on the overall impacts of concrete have been examined by many authors in the LCA literature. There is a broad consensus that impacts due to cement are far higher, despite the fact that aggregates are present in levels up to 10 times higher in the concrete mix recipe.

The relative importance of cement and aggregates on LCA impacts

Marceau et al., 2007[134] showed that for concrete masonry units, the average total embodied energy was 1.32GJ and the 69% of this energy was due to the cement, even though cement accounted for only 8.7% of the concrete mass. Conversely, in the same production process, aggregates accounted by just 3.8% of the energy footprint despite accounting for 75.3% of the concrete mass. In a similar manner, Flowers and Sanjayan (2007) reported that cement accounted for 74 to 81% of CO2 emissions and aggregates for 13 to 20% of emissions. The same authors also showed that the emissions associated with cement could be reduced by 13-15% when replacing 25% of the cement with coal fly ash, or be reduced by 40% when replacing 40% of the cement by blast furnace slag. However, no mass or economic allocation of impacts was made for coal fly ash or BFS to electricity production or steel production, respectively.

Higher performance concrete, for example higher strength or frost-resistance concrete will tend to have a higher cement content and a lower water content. Across all of the main types of concrete, the cement content may vary from 150 to 450 kg/m^3 concrete.

In terms of all LCA indicators, cement is far more important than aggregates, even when considering that aggregates can account for more than 10 times the fraction of concrete mass than cement does. However, it has also been argued that the normal abiotic depletion indicator is not suitable for considering the impacts of aggregate use because, when global resources are considered, the impact is negligible, but at a regional or local level, the impacts on abiotic depletion are far more significant. Due to the fact that aggregates are low value and high bulk materials, increasing the transportation distance by 30 miles (by truck) can double the cost of the aggregate[135]. Consequently, the benefits of using recycled aggregates is greatly increased if consequential impacts of reduced land use impact (via avoided landfill and reduced quarrying) (Blengini and Garbarino, 2011[136]) and reduced transport emissions (via the preservation of natural aggregate resources at the local or regional level). Another important aspect is that, especially in developed areas, recycled aggregates tend to be available in the local environments where construction activities are taking place and may even be reincorporated into the same project where demolition activity precedes new construction on the same site.

In cases where recycled aggregates are available, but require longer transport distances than natural aggregates, there is a trade-off in environmental impacts. Blengini and

134 Marceau ML, Nisbet MA, VanGeem MG, 2007. Life Cycle Inventory or Portland Cement Concrete. Portland Cement Association, Research and Development Information, Serial No. 3007.

135 Robinson Jr GR, Brown WM (2002). Sociocultural dimensions of supply and demand for natural aggregate; examples from the Mid-Atlantic region, United States. Open-File Report 2002-350, United States Geological Service.

136 Blengini GA, Garbarino E (2010) Resources and waste management in Turin (Italy): the role of recycled aggregates
in the sustainable supply mix. Journal of Cleaner Production 18:1021-1030.

Garbarino (2010) estimated that the use of recycled aggregates (when compared to natural aggregates) can remain environmentally beneficial up until the point when the transport distance for recycled aggregates becomes 2-3 times longer than for natural aggregates.

Effect of reducing the clinker factor on LCA impacts of cement

The substitution of Portland cement for supplementary cementitious materials has economic benefits and obvious environmental benefits, especially when considering industrial wastes and by-products. Following the principles of the Waste Framework Directive, as soon as a route away from disposal becomes established, a waste ceases to become a waste and starts to be considered as a by-product. From an LCA perspective, the environmental impacts associated with production should somehow be split (or allocated) between the main product and any co-products or by-products. The choice of the allocation procedure used (if any) can have a significant influence on the results of any LCA study.

Two important examples of the importance of allocation are with the use of blast furnace slag (BFS) and coal fly ash (FA) as SCMs. Chen et al., (2010)[137] and Van den Heede and De Belie (2012)[138] highlighted the difference between mass allocation and economic allocation for these materials. With BFS, 19.4% of all the impacts of steel production would be allocated to BFS if allocated on a mass basis whereas just 2.3% of the impacts would be allocated if considered on an economic basis, more than a factor of 8 difference. With FA, there is a factor of 12 difference with mass allocation bringing 12.4% of the impacts associated with coal-fired power generation whereas only 1.0% would be allocated is done on an economic basis. Even in the less severe economic allocation process, FA and BFS could show some higher specific impacts than pure cement, especially freshwater and marine ecotoxicity.

The greatest reduction of the clinker factor is to reduce it to zero. It is possible that mineral additions such as metakoalin, fly ash or blast furnace slag can completely replace Portland cement clinker (and the gypsum as well) so long as they are mixed with a highly alkaline solution (e.g. 8 M NaOH that may or may not contain dissolved sodium silicate as well) and that the cement/concrete is cured at moderately elevated temperatures. Such formulations avoid all the environmental impacts associated with Portland cement but bring new impacts associated with the need for NaOH and sodium silicate. The importance of any allocation method becomes even more important for fly ash or BFS based geopolymers, since they account for all the starting solid material instead of the typical 0-40% range that is most common in CEM type Portland cements.

Habert et al., (2011)[139] composed average geopolymer concrete formulations for fly ash-based (n=49), BFS-based (n=13) and MK-based (n=17) mixes from 16 different literature sources. The authors found that in general the life cycle impacts for the different concretes where (in order of highest impact first): MK-geopolymer > FA-geopolymer > BFS geopolymer > normal OPC concrete > blended OPC concrete. Even

[137] Chen C, Habert G, Bouzidi Y, Jullien A, Ventura (2010) LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. Resources, Conservation and Recycling 54:1231-1240.

[138] Van den Heede P, De Belie N., 2012. Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: Literature review and theoretical calculations. Cement and Concrete Composites, 34(4):431-442.

[139] Habert G, d'Espinose de Lacaillerie JB, Roussel N (2011) An environmental evaluation of geopolymer based concrete
production: reviewing current research trends. Journal of Cleaner Production 19:1229-1238.

with no allocation of impacts to FA or BFS, the LCA impacts were higher for the geopolymer concretes. The only reduced impact, which depended on there being no allocation, was a 15-20% reduction for FA-geopolymer concrete and a 40-45% reduction for BFS-geopolymer concrete. In both cases, the performance of blended Portland cement concrete (30% of cement replaced by FA or BFS) was actually better under the same allocation procedure.

The importance of the production plant

With the production of concrete masonry units (1m^3 or 131 masonry units) with elevated temperature curing, Marceau et al., (2007) showed that average energy used in a survey of 13 production plants was 0.297GJ/m^3, accounting for around 22% of the concrete energy footprint but less than 9% of the CO2 footprint. A breakdown of the plant energy was as follows: 25% diesel in light trucks onsite; 62% natural gas for steam generation and curing chamber and 13% electricity for plant equipment and installations.

The same authors reported a much higher average plant energy consumption of 0.82 GJ/m^3 of precast concrete production, following a survey of 15 plants. It was not possible to estimate how significant this was at the individual plant level since individual data were reported and compared to "representative precast mixes". Nonetheless, the authors provided a breakdown of plant energy consumption as follows: 44% for steam production for accelerated curing; 32% for fuel in light trucks and forklifts onsite and 17% for electricity for plant equipment and installations.

In both the masonry unit and precast concrete plants, it is clear that significant energy savings can be achieved by minimising the acceleration of curing by using only moderately elevated temperatures, using waste heat from other sources or using ambient temperature curing.

Aspects generally neglected in LCA studies on concrete

There are many aspects that have not been covered by LCA studies because they have been assumed to be insignificant and/or there is a lack of information available. The energy consumed for quarrying of raw materials is generally considered to account for only 2% of the embodied energy in concrete. The contribution of demoulding oils in precast concrete production, estimated to be on average 180ml/m^3 concrete (Gursel et al., 2014), is generally ignored. Flowers and Sanjayan (2007) considered that the total volume of admixtures (super-plasticisers, set accelerators and water reducers) typically added to concrete was less than 2L/m^3 concrete. Even assuming the highest impact admixture (53×10^{-6} $tCO_{2eq.}$/L) this would account for less than 0.1% of the total 0.25-0.32 tCO_2eq./m^3 concrete reported by the same authors. Conversely, Sjunnesson (2005)[140] concluded that superplasticisers could account for 0.4% of CO2eq. emissions and as much as 10.4% of photochemical ozone creation potential.

[140] Sjunnesson J (2005) Life Cycle Assessment of Concrete. MSc Thesis. Department of Technology and Society, Lund University.

7 OVERVIEW FOR TERRAZZO TILES

The modern version of terrazzo tiles is widely considered to have begun in 19th century Venice as a cheaper alternative to marble stone floor tiles. These Portland cement-based tiles experienced surges in popularity in the post-war reconstruction periods in Europe although their popularity waned as home owners became more affluent and began to choose from a wider range of alternative flooring materials and designs.

Today it is possible to produce terrazzo tiles based on epoxy binders instead of Portland cement. The epoxy tiles are lighter and offer an even wider range of colours than cement-based tiles. However, while cement-based tiles are suitable for indoor or outdoor use, epoxy-based tiles tend to be limited to interior applications.

Another distinction is that some interior floorings may be poured, cured, coated and polished in-situ. This type of installation can be coupled with some intricate design features that lead to spectacular interior floor spaces.

Figure 81. Example of terrazzo floor space at City of Phoenix Airport.

As can be seen from Figure 81, the in-situ pouring and custom designs require highly specialised companies to cut metal pieces according to the design, manually lay the different coloured mixes within each segment and then cure, coat and polish the floor.

Such activity is more fitting of a specialist service rather than a standard product. Consequently, the scope for terrazzo tiles in the EU Ecolabel is limited to factory produced tiles.

'Terrazzo tiles' as defined by CEN/TC 229 EN 13748:2004/2005[141], 'terrazzo tiles' are a composite industrial product derived from the compression of a conglomerate of stone aggregates of various sizes with water, dyes, additives usually found in cement mixtures, and cement as the binding agent. The stone aggregates are composed of natural stones granulate, such as marble, granite, quartz and quartzite coming directly from quarries or as by-products of natural stones processing operations as well as from recycling process.

The main ingredients used in cement-based terrazzo tiles are: aggregates (various specifications), white cement, grey cement, fine marble powder (<1.4mm) and pigments. The pigments are usually metal oxide compounds based on titanium (white colour), chromium/cobalt (green/blue) or iron (yellow, orange, red, brown and black).

Other minor additives may also be used such as plasticisers (to allow the water to cement ratio to be reduced without reducing the fluidity of the mix), waterproofing agents (to prevent the build-up of moisture in pores or on the surface) and fibres (to impart improved mechanical properties to the tile).

[141] The scope of the CEN/TC 229 technical committee is to establish European Standards concerning denomination criteria (14618) terminology covering scientific and technical terms, classification and test methods for agglomerated stones.

Cment-based terrazzo tiles may be single or dual-layered. The single-layered tiles are made completely of granulates or chipping of a suitable aggregate, embedded in grey and white cement and water. The dual-layered tiles are terrazzo tiles made up of the facing layer (with single-layered composition) and a second layer, known as bed layer, whose surface is not exposed during normal use and which may be partially removed.

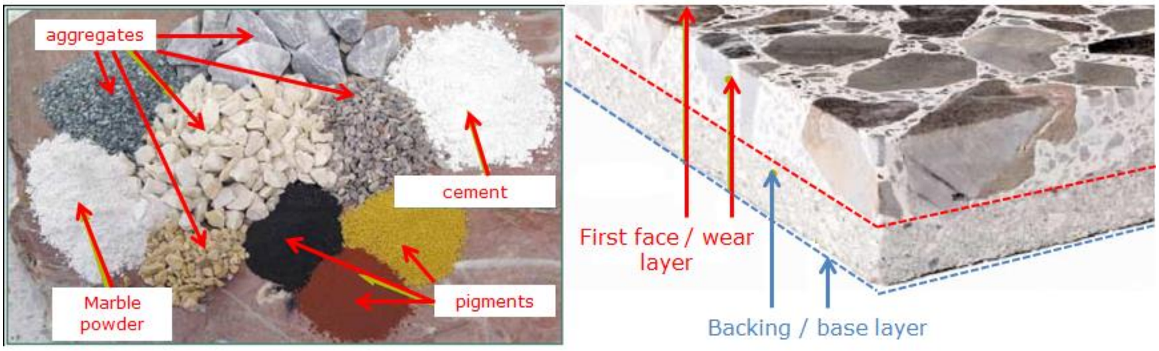


Figure 82. Cross-section of terrazzo tile. Image adapted from (Technopavimento).

This chapter will provide an overview of the different types of terrazzo tiles that are produced, market data, directly relevant technical standards, a comprehensive overview of the manufacturing process and an assessment of any relevant LCA literature.

7.1 Terminology and classification

Apart from the binder (epoxy or cement), the main distinctions between different terrazzo tile products are in the dimensions of the tile and the appearance, resistance and texture of the facing layer. These differences are deliberately introduced depending on the intended placement of the terrazzo tile (i.e. indoors or outdoors) and the use intensity of the floor environment (i.e. normal, intensive or industrial).

Dimensions

Cement-based terrazzo tiles can have thicknesses that range from 25 to 100mm, but normally in the range of 30 to 60mm. The surface face dimensions are limited in order to facilitate ease of handling and placement but can range from 15x15cm to 100x100cm. The larger and thicker tiles are especially suitable for intensive use environments but require special handling and laying procedures. The most common dimensions (all in cm) manufactured are:

- **Thickness 2.5-6.0** with lengths and widths of 15x15; 20x20 or 25x25
- **Thickness 3.0-6.0** with lengths and widths of 25x25, 30x30, 33x33, 40x40, 50x50, 33x50, 40x60, 60x60 or hexagonal formats.
- **Thickness 6.0-10.0** with lengths and widths of 60x60, 80x80, 80x40, 90x90 or 100x100.

It is also worth mentioning that pieces are available for skirting around the edges of interior floor areas that will normally consist solely of the facing layer in order to ensure that it is not too thick.

Epoxy-based terrazzo tiles can be much thinner due the properties of the resin binder, with thicknesses ranging from 6-10mm. This makes epoxy-based terrazzo much lighter on a per square meters basis and is an important cost factor since epoxy binders are more expensive than cement binders.

Surface treatment

There are a number of distinct surface treatments that are defined for terrazzo tiles. The choice of treatment is directly related to the intended end-use. Apart from appearance, surface treatment will directly influence the resistance of the tile to mechanical loads, resistance to aggressive conditions (spills, weather etc.) and the resistance to slipping.

- **Polished tiles:** have the upper face polished in the factory using industrial polishers with any of a wide range of different grit pads (generally starting with a 24 grade and gradually polished finer and finer, up to as high as 800 grade), depending on client demands, to provide a smooth and glossy surface.
- **Shot-blasted tiles**: have the upper face blasted with steel shot to provide a rough textured and non-slip surface. Careful control of the shot-blasting process ensures that the tile surface still remains acceptably flat.
- **Textured tiles:** have a very specific and reproducible surface texture that is directly imparted by the mould itself and thus requires no secondary treatment of the upper face. The most common textures that are provided are those that imitate natural stone or that imitate shot-blasted tiles (see Figure 83).
- **Low-relief tiles**: have distinct surface patterns and designs that are imparted by having ridges or grooves on the upper face (see Figure 83). The range of surface designs possible is huge, only limited by the creativity of the client and the cost associated with creating custom moulds. Low-relief tiles can be produced directly from the moulding process or also be polished, for a higher aesthetic value. In any case, care should be taken with these types of tiles that the necessary minimum slip resistance of the upper face is met in all directions.
- **Tactile tiles**: are a specific type of low-relief tile whose elevated surface markings are designed to provide support to disabled users, providing information about certain pathways to blind people who can feel the regular raised surfaces with their canes (for example to inform about the beginning of a pedestrian crossing).
- **Washed tiles:** are tiles where the upper face has been deliberately washed to selectively remove a fine layer (often <1mm) of the cement paste, thus exposing the aggregates to a much greater degree. Washing can be carried out either immediately after pressing, via the use of a carefully controlled water spray, or after curing. In the latter case, it is necessary to apply a thin layer of cement setting retarder to the top of the facing layer so that even after curing, this top layer can still be easily washed away.

Combinations of the above-mentioned surface treatments are also possible, for example shot-blasting followed by polishing. Speciality treatments are also possible where a particular design is laid over the surface of a cured tile and then shot-blasted together.

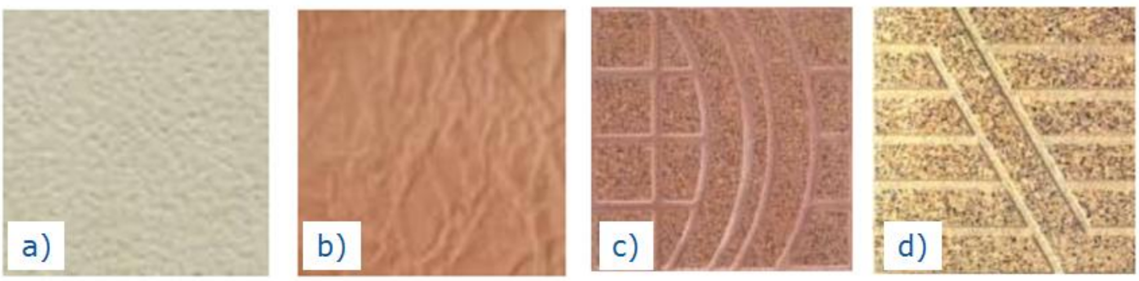


Figure 83. Examples of low relief tiles: a) imitating shot-blasted tiles, b) imitating natural stone, c) and d) imparting specific patterns.

Considering the different textures that can be imparted by the surface treatments above together with the different types of aggregates and the different pigments available, it is clear that there is an extremely broad range of surface appearances possible for terrazzo tiles.

Interior applications can apply to homes, shopping centres, hotels, schools, hospitals, bus/train stations, sport centres and industrial factories or warehouses. The use intensity of these interior environments has been split into the following three categories: normal, intensive and industrial.

Exterior applications can apply to private homes, public buildings, walkways, school playgrounds, sport centres and patios and pavements in a number of different situations.

7.2 Relevant technical standards

Although the most relevant standard for terrazzo tiles is EN 13748 (parts 1 and 2). In cases where cement is used as the binder, the standards mention in Table 27 will also be relevant.

Looking in more detail at EN 13748 (parts 1 and 2), there is a lot of flexibility in the choice of cements, aggregates and admixtures used in the production of terrazzo tiles. The most restrictive detail appears to be the requirement for any fly ashes used as supplementary cementitious materials (SCMs) or fillers to comply with EN 450.

EN 13748 specifies final product requirements and defines different classes and markings according to how the final product performs in a number of different physical tests.

Table 38. Final product requirements defined in EN 13748-1 and -2.

Requirement	Indoor use (EN 13748-1)		Outdoor use (EN 13748-2)			
	Average	Individual value	Class	Mark	Average	Individual value
Edge length	± 0.3%		-	-	± 0.3%	
Thickness tolerance	± 2mm if <40mm ± 3mm if <40mm		-	-	± 2mm if <40mm ± 3mm if <40mm	
Breaking strength (MPa)	≥5.0	≥4.0	1 2 3	ST TT UT	3.5 4.0 5.0	2.8 3.2 4.0
Breaking load (kN)	-	≥2.5 if tile <1100csquare meters ≥3.0 if tile >1100csquare meters	30 45 70 110 140 250 300	3T 4T 7T 11T 14T 25T 30T	3.0 4.5 7.0 11.0 14.0 25.0 30.0	2.4 3.6 5.6 8.8 11.2 20.0 24.0
Abrasion resistance	-	≤25mm (Wheel test) ≤30cm^3/50csquare meters (Bohme test)	1 2 3 4	F G H I	No measurement ≤26mm or ≤26cm^3/50csquare meters ≤23mm or ≤20cm^3/50csquare meters ≤20mm or ≤18cm^3/50csquare meters	
Weathering resistance	-	≤8% water absorption ≤0.4g water/csquare	1 2	A B	Water abs. n/a	Freeze thaw loss n/a

		meters absorbed via upper face	3	D	≤6% n/a	n/a ≤1.0kg/square meters (avg.)

It is also worth noting that the values set for interior use tiles for breaking load and abrasion resistance are typical of normal use applications. It is possible that higher values are specified for floors that are placed in areas subject to intensive public activity or industrial operations.

One of the most relevant final product properties that can vary as a function of the intended use is abrasion resistance. Some recommendations published by the Spanish concrete tile and slab association (Tecnopavimento) for minimum abrasion resistance results are summarised below.

Table 39. Abrasion resistance recommendations as a function of use

<table>
<tr><th colspan="5">Interior use</th></tr>
<tr><th>Environment</th><th>Use (class)</th><th colspan="2">Abrasion resistance</th><th>Facing layer texture</th></tr>
<tr><td rowspan="3">Homes and private buildings</td><td>Home (Normal)</td><td colspan="2">≤24mm</td><td>Polished</td></tr>
<tr><td>Common walkways in apartment blocks (Intensive)</td><td colspan="2">≤22mm</td><td>Polished</td></tr>
<tr><td>Garage floor (Industrial)</td><td colspan="2">≤21mm</td><td>Polished, unpolished / rough</td></tr>
<tr><td rowspan="5">Commercial buildings</td><td>Shops and restaurants (Intensive)</td><td colspan="2">≤22mm</td><td>Polished and impermeabilised</td></tr>
<tr><td>Corridors (Intensive)</td><td colspan="2">≤22mm</td><td>Polished</td></tr>
<tr><td>Garages (Industrial)</td><td colspan="2">≤21mm</td><td>Smooth / rough</td></tr>
<tr><td>Warehouses (Industrial)</td><td colspan="2">≤21mm</td><td>Polished / smooth</td></tr>
<tr><td>Food handling areas (Industrial)</td><td colspan="2">≤21mm</td><td>Polished and impermeabilised</td></tr>
<tr><td rowspan="4">Hospital</td><td>Patient rooms (Normal)</td><td colspan="2">≤24mm</td><td>Polished</td></tr>
<tr><td>Waiting rooms and corridors (intensive)</td><td colspan="2">≤22mm</td><td>Polished</td></tr>
<tr><td>Food handling areas (Industrial)</td><td colspan="2">≤21mm</td><td>Polished / smooth</td></tr>
<tr><td>Garages (Industrial)</td><td colspan="2">≤21mm</td><td>Smooth / rough</td></tr>
<tr><th colspan="5">Exterior use</th></tr>
<tr><th>Environment</th><th>Use</th><th>Breaking load*</th><th>Abrasion resistance</th><th>Facing layer texture</th></tr>
<tr><td rowspan="5">Homes and private buildings</td><td>Terraces and balconies</td><td>4(4)kN</td><td>≤22mm</td><td>Smooth / rough</td></tr>
<tr><td>Parks and gardens</td><td>4(7)kN</td><td>≤22mm</td><td>Smooth / rough</td></tr>
<tr><td>Swimming pool</td><td>4(4)kN</td><td>≤22mm</td><td>Rough</td></tr>
<tr><td>Garage ramp</td><td>4(7)kN</td><td>≤21mm</td><td>Rough</td></tr>
<tr><td>Garage</td><td>5(7)kN</td><td>≤21mm</td><td>Smooth / rough</td></tr>
<tr><td rowspan="4">Public spaces</td><td>Terraces and patios</td><td>4(4)kN</td><td>≤22mm</td><td>Smooth / rough</td></tr>
<tr><td>Gardens</td><td>7(11)kN</td><td>≤22mm</td><td>Smooth / rough</td></tr>
<tr><td>Swimming pools</td><td>7(11)kN</td><td>≤21mm</td><td>Rough</td></tr>
<tr><td>Pavements</td><td>7(7)kN</td><td>≤21mm</td><td>Smooth / rough</td></tr>
</table>

*values in brackets refer to cases when the tile/slab is more than 40cm long

In the use applications above, where the surface is recommended to be impermeabilised, this is a treatment that should be applied only once the tiles have been installed in-situ.

7.3 Market data

There is no obvious NACE code for terrazzo tiles and clarification is needed about what sector these products are classified under. As far as the authors are aware, the production of cement-based terrazzo tiles follows a dry-cast vibro-compression type process that is very similar to the method used to produce concrete paving units.

However, according to EN 14618 it seems that cement-based agglomerted stone products can also be produced and some producers of agglomerated stone may, depending on the nature of the aggregates used, decide to refer to their product as terrazzo tile.

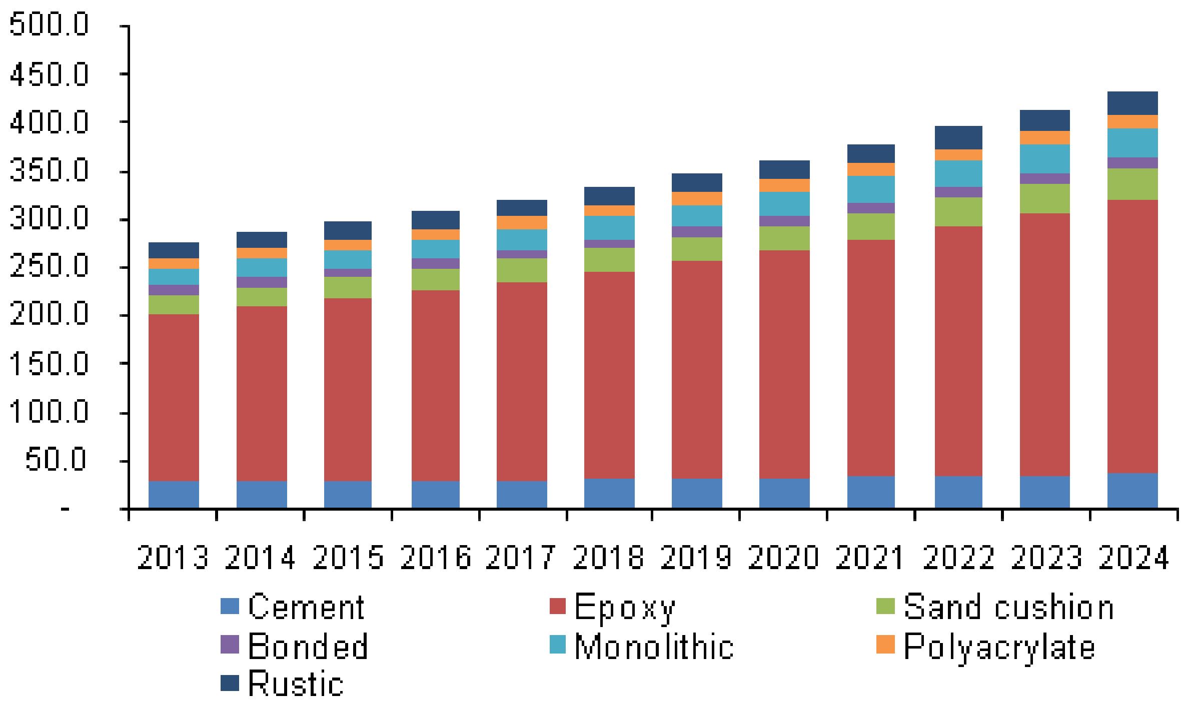


Figure 84. US terrazzo market volume (Million Square Feet) by product, (Grand View Research).

Market data from the US shows the relative importance of epoxy-based terrazzo when compared to other types. The cement-based terrazzo is worth less than 10% of market share and is expected to lose more share to epoxy-terrazzo in the coming years. However, the authors also understand that the "sand cushion", "bonded", "monolithic" and "rustic" type products are based on cement-bonded terrazzo but have distinct features in the sub-structure of the installation (not included in the scope of EU Ecolabel) or on surface texture (in the specific case of "rustic" products). Counting these other groups as cement-based terrazzo improves the market share for cement-based terrazzo but does not change the expected trend.

Specifications found on the National Terrazo and Mosaic Association website imply that epoxy terrazzo is suitable for indoor applications, especially in multi-storey buildings due to its light weight. Cement-based terrazzo products are better suited for outdoors and use environments where heavy loads may occur.

Value chain

The terrazzo value chain begins with raw material suppliers, then tile manufacturers (the potential EU Ecolabel applicant), wholesalers and installers before ending with the client. The value chain for customised in-situ poured terrazzo floors would be more complex as it would also involve client services, graphic designers, metalworkers for customised spacers and specialist staff onsite for the in-situ curing, coating and polishing.

The raw material supply chain is, in volume terms, dominated by granite, marble and quartz aggregates. Waste aggregates from natural stone production sites should naturally be more economical to purchase than bespoke graded aggregates direct from the quarry. Although it is good business for manufacturers of natural stone to convert their waste into saleable by-products, there may be some degree of price sensitivity in the sense that terrazzo flooring will be a direct competitor to natural stone in several markets. In the case of marble powder, the use of any off-colour material or powder that is contaminated with sawing residues may be restricted in terrazzo tiles due to the aesthetic concerns with the facing layer.

Alternative waste aggregates may also be procured from post-consumer glass cullet or construction and demolition waste although concerns with long term stability in supply and about the consistency of aggregate properties may limit the use of these types of aggregate.

The terrazzo tile manufacturer has complete control over the choice of raw materials although the energy consumption of the tile production process will be locked-in as a function of the equipment that has been purchased.

The installers of terrazzo tile may or may not be associated with the terrazzo tile producer although, due the importance of correct installation on customer satisfaction and the reputation of the tile producer, it is common that tile producers will have recommended installers and will provide clear instructions about the do's and don'ts of installation, choice of sealants and applicability of other chemicals and any in-situ surface treatments and maintenance.

Product range

The dominant market for terrazzo tiles is in flooring. However, there are a number of pre-cast options that are available for other complimentary uses such as steps and risers, skirting, wall panels, kitchen countertops and in bathrooms. However, care should be taken with sealing in non-floor applications to ensure that the ingress of water via exposed edges is prevented.

7.4 Review of production technology and any innovations

Figure 85 shows innovations and technology improvements registered in the terrazzo tiles product group (blue circles). A general increase in technology efficiency has been registered, in cement production and product composition.

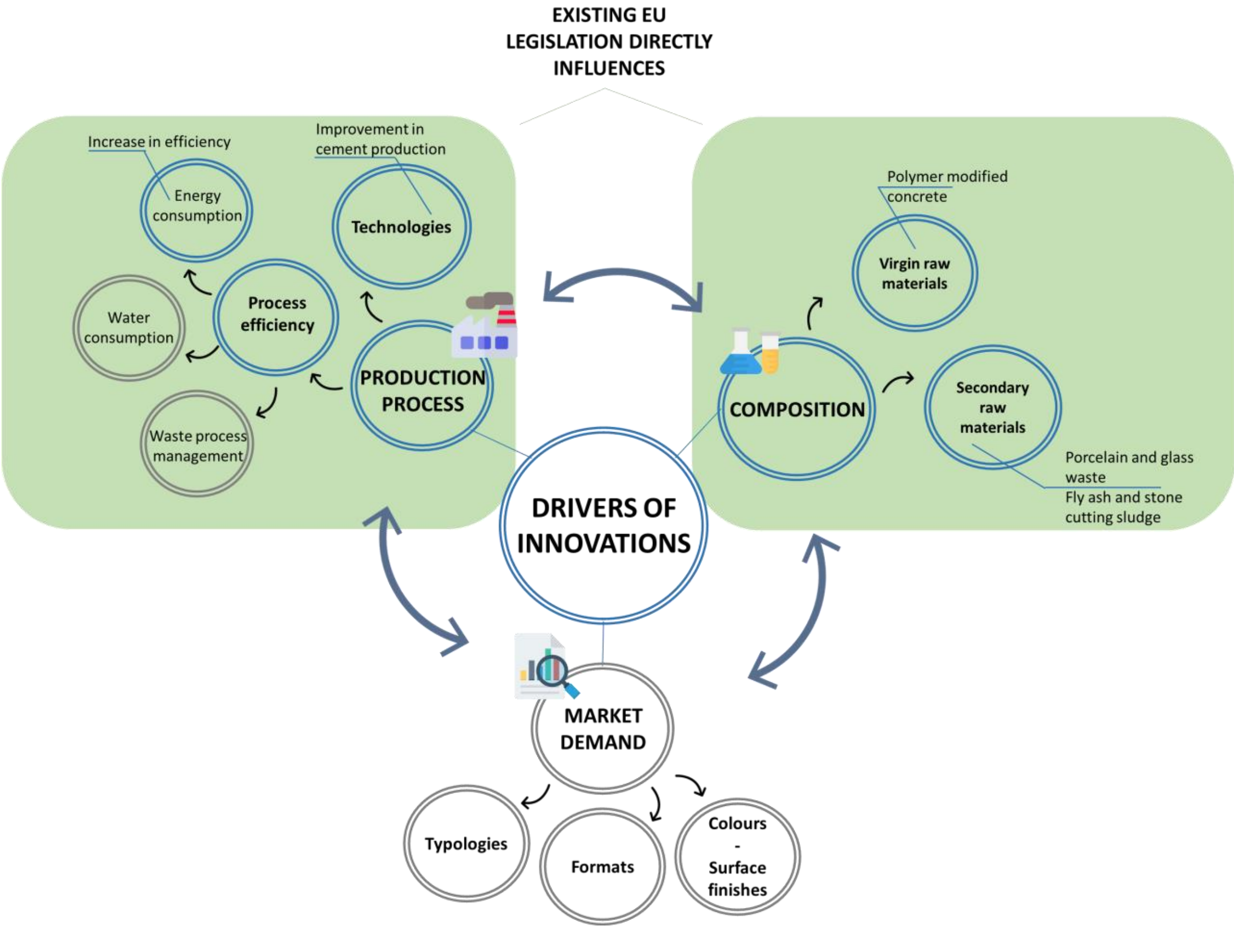


Figure 85. Main improvements and innovations for terrazzo tiles.

7.4.1 Manufacturing process

For cement-bonded terrazzo tiles, the manufacturing process is most likely to be using the same dry-cast concrete technology that is described in Figure 68 in the corresponding section for concrete paving units. The main stages of the production process are described below.

<u>Delivery and storage of raw materials</u>

Quality control of ingredients is of fundamental importance as deviations in ingredient quality may affect the appearance of the finished product. Care must be taken with the exposure of hygroscopic raw materials to atmospheric humidity, especially with cements where the absorbance of moisture actually causes premature cement hydration on grain surfaces to a minor degree.

The granulometry of aggregates has a fundamental effect on the mix ratios required for the process and on the appearance and properties of the final product. The terrazzo tile producer may directly specify the granulometry when purchasing aggregates or apply some in-house crushing and sieving processes when necessary.

In all cases, the recommendations of the raw material supplier should be followed with regards to storage conditions and the maximum storage times before the material should be used.

Dosing and mixing

In cases where dual-layered terrazzo tiles are produced, there are two separate dosing and mixing processes going on in parallel – one for the facing layer and one for the bed layer.

The facing layer will contain white (or occasionally grey) cement, filler, sand, high specification aggregates (siliceous or calcareous) and special additives. The bed layer will generally never use the more expensive white cement and will tend to use lower specification aggregates (siliceous or calcareous). For the cement used in the bed layer, there are a wider range of compositions available which may include waste materials or industrial by-products as partial substitutes for the cement (for example CDW142 and stone cutting sludge143).

In both processes, the raw materials are combined together in very specific doses to achieve mixes that are fit for the processing equipment to be used and that will result in satisfactory finished products based on the manufacturer's experience.

The dosing equipment is semi or fully automated in order to ensure greater mix precision and more consistent batches. One possible exception to the automated dosing process may be with pigments dosed for the facing layer, which may sometimes be weighed out manually and to the nearest 0.1g.

The quantity of water added is carefully controlled to ensure that the manufacturing process will operate correctly. Just enough water should be added to the facing layer mix to ensure that the mix spreads out evenly across the mould during vibration.

The containers with the facing layer mix and the bed layer mix tend to operate in a semi-continuous manner. Ingredients are periodically dosed into the container from above and the homogenous concrete mixture is dispensed from the bottom of the container into a mould in regular steps. The exact mixing time required will be based on the experience of the manufacturer but must be sufficient to ensure homogeneity of the mix (especially regarding the uniform distribution of pigments in the facing layer mix).

Dosing and vibro-pressing

The aim of the dosing equipment is to also dispense the same volume of mix into the empty mould. The facing layer mix is dosed first and the mould is normally vibrated (with or without vacuum) to ensure the complete distribution of the material across the entire mould, at a uniform thickness and with any entrained air bubbles being removed. The pressing action ensures that the aggregates are closely packed. Both the vibration and pressing actions ensure that a low water to cement ratio can be used which in turn, ensures that a stronger and less porous concrete will form.

In cases where low-relief surface features are to be introduced, it is necessary to place a fitting at the bottom of the mould that would impart the desired surface features to the facing layer.

A semi-dry mortar that will become the bed layer is then introduced on top in a slight excess quantity. It may be "pre-pressed" at this point prior to any excess mortar being swept away as the bed layer is mechanically levelled to match the top of the mould. It is worth noting that the water content of the bed layer has to be carefully controlled and

[142] Qasrawi, H. (n.d.). The Use of Recycled Building Rubble in the Reconstruction of Demolished Buildings. [online] Available at: https://pdfs.semanticscholar.org/980f/089a5d57c1008fd256413903542599db25b4.pdf

[143] Alzboon, Kamel & Tahat, Montasser. (2009). Recycling of Stone Cutting Waste in Floor Tiles Production. Trends in Applied Sciences Research. 1. 64-70.

the bed layer mix must be dry enough to ensure a sufficient absorption of water from the facing layer below.

The two layers are then pressed together in the mould using a hydraulic press. The press itself may contain a customised stamp that imprints the manufacturers name, brand and or batch ID onto the face of the bed layer. The time and pressure of the pressing stage will be chosen based on the experience of the manufacturer and must be sufficient to ensure the sufficient adherence of the two layers so that the piece will remain perfectly intact during the demoulding process, which will happen just a few seconds after pressing.

Demoulding and curing

Demoulding can be carried out automatically or manually. The demoulded tiles or slabs are stored on porous and stackable trays prior to their transfer to the curing chamber.

The curing process is necessary to allow the cement in the pressed tiles and slabs to hydrate and set under standard conditions of temperature and relative humidity. It is precisely the hydration of the cement that imparts the mechanical strength of the tile.

There are different options available for curing which generally either:

- **Normal:** typically the temperature is controlled at near ambient temperature (typically 20-30°C) and a minimum relative humidity is maintained (typically >90%) which results in the tiles/slabs being ready for further handling/treatment in 2-3 days.
- **Accelerated:** whilst still ensuring sufficient relative humidity, a moderately elevated temperature is applied in the curing chamber (around 40°C) which accelerates the hydration reactions of the cement to the extent that they are ready for further handling/treatment within 1-2 days instead of 2-3 days.

It is also worth noting that the Portland cement hydration reactions are not completed after 1-3 days but will actually continue in a gradual manner at least until 28 days, further increasing the mechanical strength of the tile and refining its porosity as the calcium-silicate-hydrate gel continues to grow and be generated from unreacted or partially reacted cement grains.

Secondary treatment

These types of treatments are commonly applied to the facing layer of terrazzo tiles according to the specifications of the client or in order to comply with certain technical standards. The treatments are either polishing, shot-blasting or washing, which have already been previously described.

Depending on the production process and the required precision for tile dimensions, the evenness of the bed face of the tile may be refined.

Packaging and labelling

The final stage of the production process is a final visual check of the tiles prior to their packing into cardboard boxes, sealing with cable tiles and then stored on pallets with or without plastic film wrap. This stage of the process may be manual, semi-automatic or fully automatic. Each box and/or pallet should be labelled with information about the relevant product class.

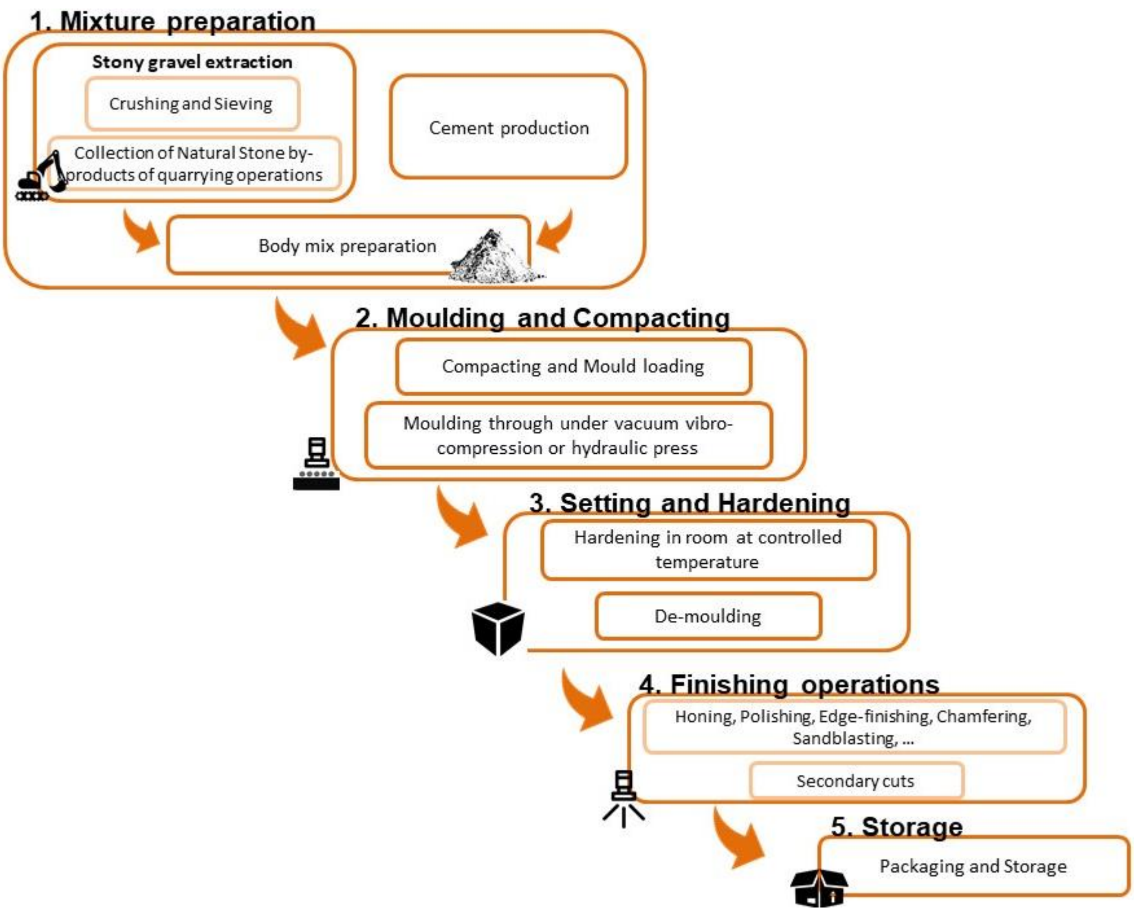


Figure 86. Main stages of the cement-based terrazzo tile manufacturing process.

7.4.2 Innovations and improvements

In the terrazzo tiles sector, during the past decade, neither technological breakthrough nor major changes in the production technologies have occurred. However, progress and improvements in the already existing technologies for the cement production as well as in the moulding and compacting processes led to a decrease in energy consumption.

The only recent innovative elements encountered are in the mixture composition. In particular, two types of innovation can be distinguished. The first concerns the use in the mixture of recycled material, while the second concerns the introduction of polymeric compound in the cement to form "Polimer Modified Concrete" (this corresponds to the "polyacrylate" market shown share in Figure 84).

Various types of recycled or ceondary materials may be incorporated into the mixture such as porcelain waste and glass composites, but also fly ash144 and stone cutting sludge145, which helps cutting down the use of virgin aggregates and cement. Polimer Modified Concretes, consisting in water dispersed latex blended with concrete, are

[144] Green Initiative. (2018). Tectura Designs. Retrieved from http://www.tecturadesigns.com/why-tectura/green-initiative

[145] Al-Zboon, K., Tahat, M., Abu-Hamatteh, Z., & Al-Harahsheh, M. (2009). Recycling of stone cutting sludge in formulations of bricks and terrazzo tiles. Waste Management & Research, 28(6), 568-574. http://dx.doi.org/10.1177/0734242x09350246

instead used to produce thin tiles (< 1 cm) or to produce large format made of very small stone aggregates[146].

7.5 Life Cycle Assessment: Terrazzo tile

The life cycle assessment of cement-based terrazzo tiles that are produced using the dry-cast vibro-compression process can be expected to be very similar to that of concrete paving units. The use of white cement is much more likely in terrazzo tiles since good surface brightness is generally important for the visual impact of the deliberately exposed aggregates in the facing layer.

Regarding epoxy-based terrazzo tiles, the authors were unable to find any results or raw process data that would explain the technology involved in epoxy-based terrazzo tile production.

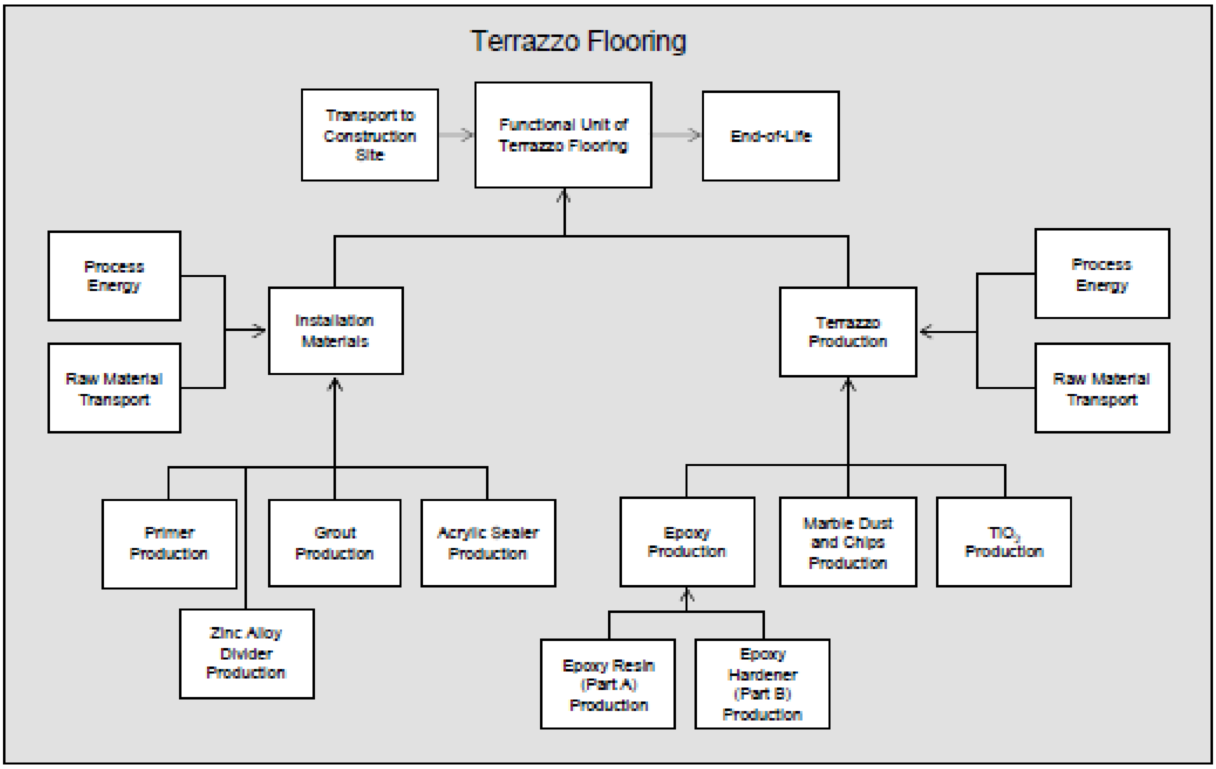


Figure 87. Terrazzo flooring system boundaries (Source: BEES147).

The system boundary goes well beyond a simple factory production of floor tiles and is referring to a product type that is mixed and poured onsite, which is not intended to be included in the scope since assessment and verification of the choice and quantities of binder and aggregates would need to be verified on a job by job basis. A typical composition of epoxy-terrazzo was stated as:

- 67% marble dust (or other crushed rock or glass cullet)
- 10% marble chips (or other coarse aggregates)

[146] Breton. Bretonterastone tile and slab plant. Natural stone surfaces by Brton technology. Breton Technologies and Plants for producing slabs and tiles made of agglomerate stones with cement. (p. 15). Retrieved from https://www.breton.it/en/engineered-stone/bretonterastone-slabs

[147] Building for Environmental and Economic Sustainability (BEES), Generic boundaries for terrazzo flooring. Accessed online: https://ws680.nist.gov/bees/ProductListFiles/Generic%20Terrazzo.pdf

- 22% epoxy resin;
- 1% pigment (although could be up to 15% depending on the degree of colour requested in final product).

Terrazzo flooring is expected to have a long service life (75 years) with periodic maintenace worth surface cleaning and polishing depending on how intensively the surface is used and whether it is indoors or outdoors. Indoor surfaces will tend to require a higher surface gloss that requires intermittent polishing every 5-10 years or o.

Ignoring the other materials involved in the floor base installation (beyond the scope of the EU Ecolabel), the main environmental impacts can be expected to be associated with the embodied energy and impacts of the epoxy resin and related curing chemicals.

With cement-based terrazzo, the main life cycle impacts are likely to be similar to those identified for concrete paving units, which emphasise the importance of cement on the overall LCA impact.

8 SUMMARY TECHNOLOGICAL INNOVATIONS IN THE HARD COVERING MANUFACTURING SECTOR

Improvements and innovations have been reported for the considered hard coverings products along the report. As a general trend, the technology is developing more efficient and less energy demanding processes, as well as incorporating secondary materials in their formulations. Three main drivers of innovation have been identified for all the hard coverings products (Figure 88). These areas are not independent but are strictly interlinked, constantly influencing each other. Changes in market demand lead to improvements and innovations in technology, but at the same time, increase in process efficiency allows to stay competitive on the market. Besides, legislation always plays a relevant role to force changes in the production process and in raw material choice. A preliminary review of existent legislation has been carried out in the proposal. Green squared boxes highlight the areas of influence of existing EU legislation.

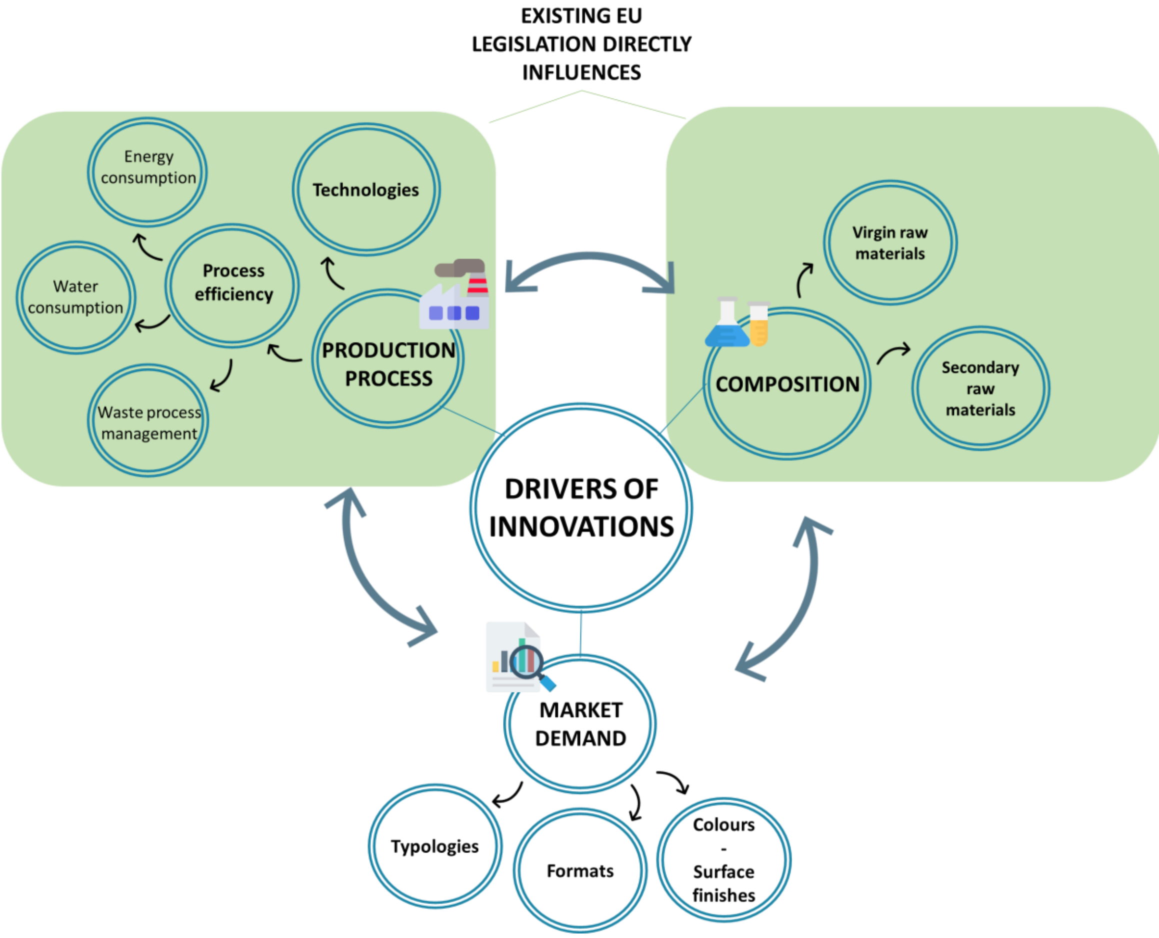


Figure 88. Main drivers of innovations and related areas of improvements for the hard coverinngs products.

Among the others, ceramic tiles have undergone deep changes ranging from the technological point of view (firing kilns, digital glazing machines) to the formats (larger slabs and thinner tiles) and typologies (fiber reinforced and titania coated tiles).

Use of secondary raw materials

Many technologies are moving towards the incorporation of secondary raw materials in the formulation .This brings many environmental benefits, such as:

- reduced raw materials extraction volume;
- reduced energy demand for raw materials processing;
- lower emissions;
- landfill space saving.

Moreover, including secondary raw material, either pre- or post- consumer, in the Ecolabel criteria might be important to draw the interest of a higher number of industries.

As already mentioned, the supply chain of these secondary materials must not offset the benefits arising from reduction in raw material demand and less production process.

Energy efficiency

In all cases it is observed that more efficient production processes are being introduced. This is mainly due to more modern processes and better designed kilns which reuse waste heat in other steps of the manufacturing process.

As far as ceramic tiles are concerned, since the array of products available has been greatly expanded, both for slab thickness and size, it may be necessary to differentiate the firing limit for product categories.

In concrete paving units, since many industries are using always more alternative fuels for the cement production process, as already seen in Paragraph 5.4.3, the process energy requirement will be furtherly investigated in the Life Cycle Assessment (Task 3).

Annexes

I Data collection

The data presented have been collected mainly contacting relevant EU hard flooring manufacturing associations. Also single manufacturers and national associations have been contacted, as well as literature research. For those product groups for which no public market data were available, EUROSTAT data have been considered, but it has to be emphasized that such data are not perfectly suitable for the aim of this study, since they are referred to HFC macro-categories, not completely comparable with the ones addressed by the EU Ecolabel. For those products included in the PRODCOM code [148] available data has been also considered. Table 40 presents the relevant PRODCOM classification for hard coverings and products.

Table 40. Relevant PRODCOM classification for hard covering products and parts

PRODCOM Code	Description
08.11	**Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate**
08.11.11	Marble and other calcareous ornamental or building stone
08.11.12	Granite, sandstone and other ornamental or building stone
08.11.20	Limestone and gypsum
08.11.40	Slate
23.31	**Manufacture of ceramics tiles and flags**
23.31.10	Ceramic tiles and flags
08.12	**Operation of gravel and sand pits; mining of clays and kaolin**
08.12.11	Natural sands
08.12.21	Kaolin and other kaolinic clays
08.12.22	Other clays, andalusite, kyanite and sillimanite; mullite; chamotte or dinas earths
23.61.11	Tiles, flagstones, bricks and similar articles, of cement, concrete or artificial stone
23.31.12	Prefabricated structural components for building or civil engineering, of cement, concrete or artificial stone
23.51	**Manufacture of cement**
23.51.11	Cement clinker
26.61	**Manufacture of concrete products for construction purposes**
26.61.11	Tiles, flagstones, bricks and similar articles, of cement, concrete or artificial stone
23.63	**Manufacture of ready-mixed concrete**
23.63.11	Ready-mixed concrete

[148] Product classifications according to Eurostat PRODCOM (http://epp.eurostat.ec.europa.eu/portal/page/portal/prodcom/introduction)

II LIFE CYCLE INVENTORY

Life Cycle inventory for natural stone

Functional unit of 1 ton of natural stone tile leaving the manufacturing process)

		References:					
	Industrial Flows:	Gazi et al., 2012 *[marble, quarry in center Italy; tile dimension: 0,4 x 0,4 x 0,02 m]*		Nicoletti et al., 2002 *[marble, quarry in northern Greece; tile dimension: thickness 0,018 m, 48,8 kg/m ²]*		Mendoza et al., 2014 *[granite, quarry in Northwest Spain; tile dimension: 0,6 x 0,6 x 0,02 m]*	
INPUT		Data	Notes	Data	Notes	Data/ton	Notes
Quarrying	Energy (MJ/ton)	16,67	Drill machine and pneumatic top-hammer (two generators powered by diesel fuel)	474,91	Electric Energy + Thermal energy; Extraction using diamond wire	86,16	Low voltage Electricity (MJ/ton)
		25,00	Diamond wire saw (two generators powered by diesel fuel)			415,97	Diesel
		12,50	Excavator and loader (two generators powered by diesel fuel)				
	Water (m³/ton)	1,29	Considering 80m3/day of water consumption;			0,54	Cooling water
	Ancillary Materials (kg/ton)					0,45	Explosives
						0,86	Steels
						0,24	Oil and grease
	Product (ton/ton)			4,64	Marble	3,21	Granite raw material
Transport	Energy (MJ/ton)	45,83	30 km distance; diesel fuel	153,06	50 km distance;		
Cutting and sawing	Energy (MJ/ton)	308,33	Block squaring with diamond monoblade; Block cutting into slabs in the multi-blade gang-saw	123,85	Electric energy for raw blocks cutting	1053,04	Low voltage electricity for Sawing
				143,87	Electric energy for standard block cutting	8,40	Diesel for Sawing
						676,95	Low voltage electricity for Cutting
						7,81	Diesel for Sawing
	Product (ton/ton)	30%	There is a 70% material loss	1,86	Refined blocks	1,94	Granite to Sawing
						1,33	Granite to Cutting
	Water (m³/ton)			1,10	65% ot the total water entering the processing plant is recycled water from the waste water treatment; the remaining 35% from the aqueduct	0,68	Cooling water for Sawing
						0,21	Cooling water for Cutting
	Ancillary materials (kg/ton)					76,74	Steels for Sawing
						22,98	Lime and/or Silica sand for Sawing
						0,29	Oil and grease for Sawing
						2,70	Steels for Cutting
						10,56	Timber for Cutting
						0,20	Oil and grease for Cutting
Finishing	Energy (MJ/ton)	220,83	Polishing; Edge profiling. (Please note that if the curing process would be included, the energy requirement would significantly increase, up to twice the current energy consumption value).	212,84	Polishing and buffing	118,30	Low voltage electricity for Polishing
						7,83	Diesel for Polishing
						43,01	Low voltage electricity for Sandblasting
						7,83	Diesel for Sandblasting
						2,56	Low voltage electricity for Flaming
						7,83	Diesel for Flaming
						294,41	Propane for Flaming
						2,27	Low voltage electricity for Bush hammering
						7,83	Diesel for Bush hammering

OUTPUT		Data	Notes	Data	Notes	Data	Notes
Quarrying	**Product ton/ton**	**30%**	On average only 30% of extracted products is og good enough quality to be transferred and processed in the manufacturing plant	**1,86**	Refined blocks	**1,94**	Granite
	Solid waste ton/ton	**70%**	Among this percentage there is solid waste and by-products	**2,78**	0,83 is used for filling drifts; 1,94 for external reuse	**0,06**	Granite sawdust
						1,22	Granite scrap
						0,00	Wastes - mix of elements
	Wastewater (ton/ton)					**0,54**	Wastewater - evaporated
Transport						**20 km**	Transportation of solid waste to recycling plants (or landfill) is 20 km
Cutting and **sawing**	**Product (ton/ton)**			**1,11**	Raw marble tiles	**1,36**	Granite from Sawing
						1,00	Granite from Cutting
	Solid waste (ton/ton)			**0,28**	0,056 goes to landfill; 0,220 for external reuse	**0,02**	Granite sawdust from Sawing
						0,09	Granite scrap from Sawing
						0,02	Wastes - mix of elements from Sawing
						0,00	Granite sawdust from Cutting
						0,32	Granite scrap from Cutting
						0,01	Wastes - mix of elements from Cutting
	Sludge (ton/ton)			**1,49**		**0,84**	Granite sludge from Sawing
						0,02	Granite sludge from Cutting
	Wastewater (ton/ton)					**0,37**	Wastewater - evaporated from Sawing
						0,20	Wastewater - evaporated from Cutting
Finishing	**Product (ton/ton)**			**1,00**	Marble tiles, polished and buffed	**1,33**	Granite from Finsihing operations
	Solid waste (ton/ton)					**0,00**	Granite sawdust from Polishing
						0,01	Wastes - mix of elements from Polishing
						0,03	Granite sawdust from Sandblasting
						0,03	Wastes - mix of elements from Sandblasting
						0,00	Granite sawdust from Flaming
						0,01	Wastes - mix of elements from Flaming
						0,03	Granite sawdust from Bush hammering
						0,01	Wastes - mix of elements from Bush hammering
	Sludge (ton/ton)			**0,37**		**0,05**	Granite sludge from Polishing
						0,04	Granite sludge from Flaming
	Wastewater (ton/ton)					**0,51**	Wastewater from Polishing
						0,28	Wastewater from Flaming

Life Cycle inventory for ceramic tiles

The following tables contains life cycle inventory values, results and indicator breakdown for thicknesses 3, 5, 15 and 20 mm to cover most of available formats and tile typology.

3 mm thickness							
Input	**Flow**	**Body preparation**	**Pressing - drying**	**Glazing**	**Firing**	**Packing**	**Total**
Raw materials	Body raw materials (kg/m^2)	8					
	Glaze raw materials (kg/m^2)			0.2			0.2
Water	Water from well (l/m^2)	0.1	1.7	1.3	1.2	0.3	4.7
	Water from grid (l/m^2)	<0.1	0.4	0.2	0.2	0.1	0.9
Energy	Medium voltage electricity (MJ/m^2)	33.1	6.6		43.9		83.7
	Natural gas (MJ/m^2)	0.7	0.1		0.1		0.9
	Fuel Oil (MJ/m^2)	6	3.3	2	1.6	1.0	13.8
Packaging	Carton board (kg/m^2)					0.2	0.2
	LDPE film (kg/m^2)					0.02	0.02
Output							
Product	Ceramic tile (kg/m^2)					7	7
Waste	Hazardous waste (kg/m^2)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Non-hazardous waste (kg/m^2)	<0.1	0.1	0.6	<0.1	<0.1	1

5 mm thickness							
Input	**Flow**	**Body preparation**	**Pressing - drying**	**Glazing**	**Firing**	**Packing**	**Total**
Raw materials	Body raw materials (kg/m^2)	13					13
	Glaze raw materials (kg/m^2)			0.4			0.4
Water	Water from well (l/m^2)	0.2	2.8	2.2	2	0.6	7.8
	Water from grid (l/m^2)	<0.1	0.4	0.3	0.3	0.1	1.2
Energy	Medium voltage electricity (MJ/m^2)	47.6	9.5		63.1		120.2
	Natural gas (MJ/m^2)	1	0.2		1.3		2.5
	Fuel Oil (MJ/m^2)	8.6	4.8	2.9	2.3	1.4	20
Packaging	Carton board (kg/m^2)					0.2	0.2
	LDPE film (kg/m^2)					0.02	0.02
Output							
Product	Ceramic tile (kg/m^2)					12	12
Waste	Hazardous waste (kg/m^2)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Non-hazardous waste (kg/m^2)	<0.1	0.1	0.9	<0.1	<0.1	1

10 mm thickness							
Input	**Flow**	**Body preparation**[a]	**Pressing and drying**	**Glazing**	**Firing**	**Packing**	**Total**
Raw materials	Body raw materials (kg/m^2)	26	-	-	-	-	26
	Glaze raw materials (kg/m^2)	-	-	0.8	-	-	0.8
Water	Water from well (l/m^2)	<1	6	4	4	1	16
	Water from grid (l/m^2)	<0.1	0.7	0.5	0.5	0.6	2
Energy	Medium voltage electricity (MJ/m^2)	8	4	3	2	1	18
	Natural gas (MJ/m^2)	48	9.8	-	63	-	120
	Fuel Oil (MJ/m^2)	1	0.2		1		2
Packaging	Carton board (kg/m^2)	-	-	-	-	0.2	0.2

Input	Flow	Body preparation	Pressing - drying	Glazing	Firing	Packing	Total
	LDPE film (kg/m²)	-	-	-	-	0.02	0.02
Output							
Product	Ceramic tile	-	-	-	-	23	23
Waste[b]	Hazardous waste (kg/m²)	<0.1	<0.1	<0.1	<0.1	<0.1	
	Non-hazardous waste (kg/m²)	<0.1	0.2	2	0.05	0.03	2.2

[a] includes mixing, grinding and atomization

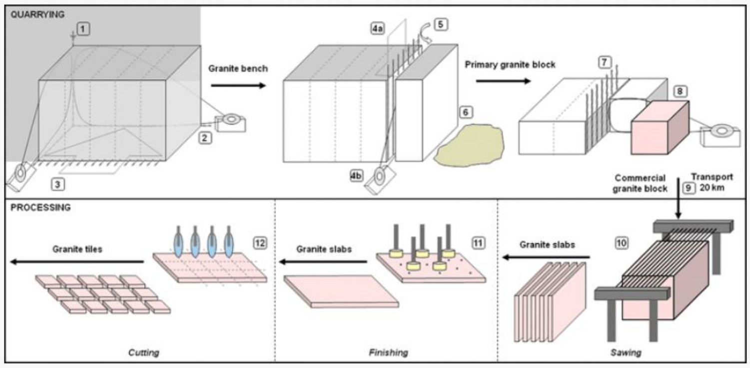
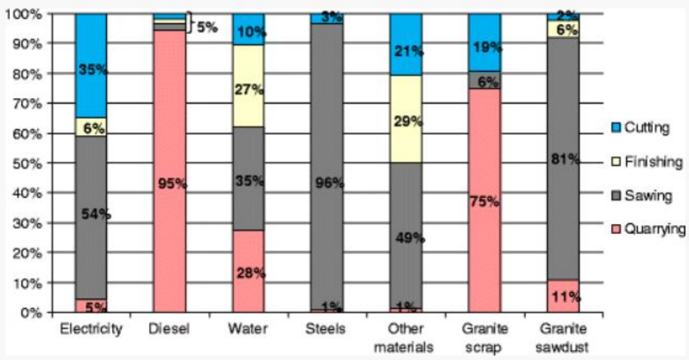
[b] process waste destination: 55% recycling in other industries; 45% landfill. Distance from treatment facility: 20 km.

15 mm thickness							
Input	**Flow**	**Body preparation**	**Pressing - drying**	**Glazing**	**Firing**	**Packing**	**Total**
Raw materials	Body raw materials (kg/m²)	38					38.1
	Glaze raw materials (kg/m²)			1			1
Water	Water from well (l/m²)	0.6	8.3	6.6	6.1	1.7	23.3
	Water from grid (l/m²)	0.1	1.3	1	0.9	0.3	3.5
Energy	Medium voltage electricity (MJ/m²)	64.8	13		86.0		163.7
	Natural gas (MJ/m²)	1.3	0.3		1.8		3.3
	Fuel Oil (MJ/m²)	11.7	6.5	3.9	3.2	1.9	27.2
Packaging	Carton board (kg/m²)					0.2	0.2
	LDPE film (kg/m²)					0.02	0.02
Output							
Product	Ceramic tile (kg/m²)					34	34
Waste	Hazardous waste (kg/m²)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Non-hazardous waste (kg/m²)	0.1	0.5	3.8	0.1	0.1	4

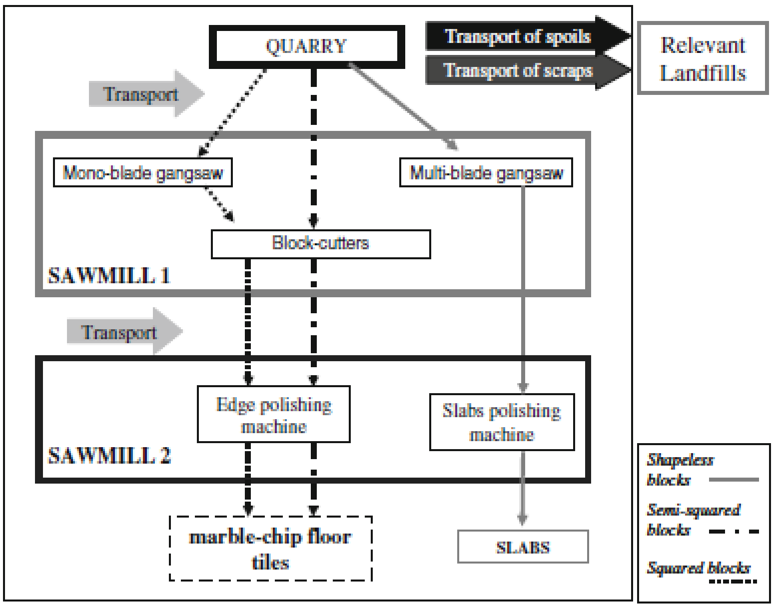
20 mm thickness							
Input	**Flow**	**Body preparation**	**Pressing and drying**	**Glazing**	**Firing**	**Packing**	**Total**
Raw materials	Body raw materials (kg/m²)	51					51
	Glaze raw materials (kg/m²)			1			1
Water	Water from well (l/m²)	0.8	11	8.8	8.1	2.3	31
	Water from grid (l/m²)	0.1	1.7	1.3	1.2	0.3	4.7
Energy	Medium voltage electricity (MJ/m²)	83.1	16.6		110.3		210
	Natural gas (MJ/m²)	1.7	0.3		2.3		4.3
	Fuel Oil (MJ/m²)	15	8.3	5.1	4.1	2.5	34.9
Packaging	Carton board (kg/m²)					0.2	0.2
	LDPE film (kg/m²)					0.02	0.02
Output							
Product	Ceramic tile (kg/m²)					45	45
Waste	Hazardous waste (kg/m²)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Non-hazardous waste (kg/m²)	0.1	0.5	3.8	0.1	0.1	4

II LCA case studies as result of the screening process

LCA case studies from natural stone products

Item1	***Observation***
Title	**Life cycle inventory analysis of granite production from cradle to gate**.
Authors	Joan-Manuel F. Mendoza., et al.
Reference and year	Resources, Conservation and Recycling 101 (2015) 1-8
Type of study	Cradle-to-gate
Scope	
Functional unit	**1m^2 of finished granite tiles dimensions 60 × 40 × 2cm used for indoor and outdoor applications**
System boundaries	 **Fig. 1** Simplified diagram of the basic stages of the production chain of granite tiles
Assumptions	
Data sources and quality	Primary data from local manufacturers for raw material supply. Year of data collection and quantity reported. Primary data from local manufacturers (quarrying facility) Primary data from local manufactures (processing facility)
Impact assessment categories/methods	Resource Depletion (material, energy and water)
Conclusions	The geometry of the pieces is a decisive factor for the different inputs and outputs of the production chain, for example sawdust generation. The total production of granite sawdust during sawing is inversely proportional to the thicknesses of the granite slabs to be produced, whereas the opposite scenario occurs in the cutting process. This relationship is an important aspect to be considered as it may also affect the energy, water and material demands during granite sawing and cutting The impact assessment results are shown in.  **Fig. 3** Relative contribution of each unit process to the most significant inputs and outputs of th granite production chain

Strengths and weakness of the whole study, general comments	The paper clearly shows that: Electrical energy, cooling water and steel are the major industrial requirements in which granite sawing is the most demanding process. The resource efficiency of the production chain is 0.31. Approximately 117 kg of granite are wasted per square meter of granite tiles that are produced (53 kg). The predominant source of granite waste is the sawdust that is generated during stone-cutting operations. *"granite sawing is the most ecologically relevant unit process of the granite production chain. Cleaner production strategies that focus on the sawing process can contribute to significantly reduce the environmental interventions related to the granite production chain. Further research is required to compile input and output data related to alternative sawing technologies, such as the use of diamond multiwire saw machines that are achieving higher relevance in the granite industry and seems to be a suitable strategy for improving the environmental performance of the production chain"*
Subject to independent review?	Publication in a peer-reviewed journal The International Journal of Life Cycle Assessment January 2014, Volume 19, Issue 1, pp 153–165

Item 2	***Observation***
Title	**Environmental performance of building materials: life cycle assessment of a typical Sicilian marble**.
Authors	Marzia Traverso & Gianfranco Rizzo & Matthias Finkbeiner
Reference and year	Int J Life Cycle Assess (2010) 15:104–114
Type of study	
Scope	LCA of Perlato di Sicilia, in order to quantify its environmental performance
Functional unit	**1m^3 of marble tiles (Perlato di Sicilia)**
System boundaries	
Assumptions	Pollutant emissions related to the electric energy production are those referring to the Italian energy system The value of the energy input of the explosive refers to the energy realized during the explosion The energy consumption and the environmental impact of all transport steps calculated starting from the known values of fuel consumption; Data of water consumption in the sawmills not available but the used water is totally recycled in both plants; The distance for the transportation of the products from sawmill 1 to sawmill 2 is about 6.5 km; Data from the production, use, and disposal of diamond wire not available

Data sources and quality	Primary data from a local manufacture plant
Impact assessment categories/methods	Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical oxidation (POCP),
Conclusions	In a comparison with the current EU Ecolabel, marble is competitive in terms of environmental aspects if applied properly. However , some aspect are not respected, i.e., the water used in the quarry that should be recycled more than 80% to avoid polluting ground waters but it is not recycled at all. Nevertheless, in the production and finishing steps is recycled 100% with no emissions in the surrounding ground water sources.
Strengths and weakness of the whole study, general comments	The paper shows that: Lack of studies and raw data information Effect of different types of stone are not considered in the study Study fro tiles but not considered other marble products,, such as slabs.
Subject to independent review?	Publication in a peer-reviewed journal

LCA case studies from ceramic tiles

Item 1	***Observation***
Title	Life cycle assessment of a large, thin ceramic tile with advantageous technological properties
Authors	Martina Pini & Anna Maria Ferrari & Rita Gamberini & Paolo Neri & Bianca Rimini
Reference and year	Int J Life Cycle Assess (2014) 19:1567–1580
Type of study	LCA cradle to grave
Scope	To assess the environmental impacts of a large, thin ceramic tile reinforced with a fibreglass backing
Functional unit	**1 m2 of a black, large, thin ceramic tile reinforced with fibreglass backing (size 1,000 mm×1,000 mm× 3.5 mm).**
System boundaries	The analysis includes • raw material extraction and utilisation in green tile production; firing to produce the large, thin ceramic tile; pasting of the fibreglass backing; cutting of the ceramic slab into 1,000 mm×1,000 mm sized items; packing; final distribution; and end of life. • The production, maintenance and disposal of facilities as well as the environmental burdens related to the production of chemicals, additives, adhesives, packaging and other auxiliary materials • Emissions into the air and water as well as the solid waste produced in each step are all taken into account. • The transportation of the solid waste to a treatment facility The installation and use step are excluded
Assumptions	• Particulate emissions into the air in the production of the base and coloured slip are assumed to be 0.1 % of the clay and feldspars input into the hoppers. • The final distribution is assumed to be a scenario of 100 km from the producer to the customers, as is required by the Environmental Product Declaration (EPD) (EPD 2008). • The electrical energy supply is assumed to be the Italian mix electrical energy generated by Ecoinvent.
Data sources and quality	Primary data from a local manufacture plant (2008 production) Ecoinvent database (Ecoinvent v2 2009)
Impact assessment categories/methods	Energy consumpotion and GWP
Conclusions	• The phases of the life cycle with the highest environmental burdens are the base slip production (27.62 %) and the pasting process (21.31 %). • The major GHG emissions are related to the production of polyurethane, a component of the adhesive used in the pasting stage,

	and to the natural gas consumption in the firing process.
Strengths and weakness of the whole study, general comments	Very specific for reinforced ceramic tiles
Subject to independent review?	Publication in a peer-reviewed journal

LCA case studies from concrete paving units

Item 1	***Information***
Title	**Implementation of best available techniques in cement manufacturing: a life-cycle assessment study**.
Authors	Valderrama C, Granados R, Cortina JL, Gasol CM, Guillem M, Josa A
Reference and year	Journal of Cleaner Production 25:60-67.
Type of study	Real life industrial scale study of refurbished plant
Scope	Looking at the process and emissions associated with cement clinker production.
Functional unit	**Per kg clinker**
System boundaries	Cradle-to-gate for clinker production (not cement)
Assumptions	Considers both mass-based and value-based allocation for BFS and FA
Data sources and quality	A combination of primary data and inventory data from ecoinvent (v2.2) Raw materials : Ecoinvent v2.2 Manufacturing : Primary data
Impact assessment categories/methods	Global warming potential (IPCC), Acidification (CML 2000), Eutrophication (CML 2000), Abiotic depletion (CML 2000), Ozone layer depletion (CML 2000), Fresh water aquatic ecotoxicity (CML 2000), Photochemical oxidation (CML 2000).
Conclusions	By upgrading the production process (new mill, extra cyclone preheater and now with precalciner) the GWP was reduced by 5%, AP by 15%, EP by 17% and the other studied impact categories by 10-14%. The real observed reductions were not as high as expected in design calculations,
Strengths and weakness of the whole study, general comments	The paper shows that: BAT processes (precalciner, >4 stage preheaters and better milling) can deliver real environmental benefits in modern plants. That the benefits ranged from 5-17% depending on the impact category in question However, the scope only extended to clinker production and misses the missing (and any blending) when clinker is converted to cement.
Subject to independent review?	Publication in a peer-reviewed journal

Item 2	**Information**
Title	**An environmental evaluation of geopolymer based concrete production: reviewing current research trends**.
Authors	Habert G, d'Espinose de Lacaillerie JB, Roussel N
Reference and year	Journal of Cleaner Production (2011) 19:1229-1238.

Type of study	Comparison of LCA of conventional and geopolymer concrete
Scope	Cradle-to-gate LCI for production of different types of concrete
Functional unit	**1 m^3 of concrete**
System boundaries	Cradle-to-grave
Assumptions	No significant differences in durability of conventional and geopolymer concrete. 3 different allocation methods (i) none, (ii) mass-based, (iii) value-based.
Data sources and quality	A combination of primary data cited by relevant literature and LCI from ecoinvent databases Raw materials: Aggregates (Chen, 2009); sodium powder (Althaus et al., 2007); sodium silicate (Fawer et al., 1999); Metakoalin (MK, from NLK, 2002)Primary data from local manufacturers Manufacturing: Primary data from laboratory
Impact assessment categories/methods	CML01 baseline method used. Abiotic depletion, GWP, ozone layer depletion, human toxicity, freshwater toxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication impacts reported.
Conclusions	Geopolymer concrete may in some cases (i.e. no allocation) show a lower impact than conventional concrete but concrete using 70:30 blended cements was consistently better and conventional concrete was generally better than all of the geopolymer concretes from an environmental perspective. Within the geopolymer concretes the impacts were MK > FA > BFS.
Strengths and weakness of the whole study, general comments	The paper shows that: Geopolymer concrete should not be assumed to be better than conventional concrete from an environmental perspective. It is also important to look beyond GWP when assessing the performance of geopolymer concrete.
Subject to independent review?	Publication in a peer-reviewed journal

Item 3	**Information**
Title	**Life Cycle Assessment of Concrete Products for Special Applications Containing EAF Slag**
Authors	Anastasioua E. K., Liapisa A., Papachristoforoua M.
Reference and year	Procedia Environmental Sciences 38 (2017) 469 – 476
Type of study	LCA of concrete paving blocks with furnace (EAF) slag
Scope	Cradle-to-gate LCI for production of concrete paving blocks and EAF slag as aggregate. Software: Simapro.
functional unit	**1 m^2 of paving block**
system boundaries	Cradle-to-gate
Assumptions	
Data sources and quality	Primary data from local manufacturers for raw material supply. Primary data from production in laboratory. Year of data collection not reported. Raw material primary data from local manufacturers Manufacturing primary data from laboratory
Impact assessment categories/methods	Global warming potential (GWP)
Conclusions	The results indicate that material production is responsible of most of the CO_2 emissions, in particular attributed to cement production. For concrete paving blocks, there was a CO_2 emission reduction when aggregate was substituted by EAF slag. A further reduction could be achieved by reducing cement use in concrete mixtures.

Strengths and weakness of the whole study, general comments	The paper shows that: • cement has been identified as an environmental hot-spot in concrete paving block production • GWP decrease if aggregates are substituted by EAF slag. Beside emission reduction, incorporation of secondary raw materials leads to reduced raw material extraction and reuse of a waste (EAF slag). • Results are provided only for one indicator (GWP). Reduction of CO2 emissions is mainly associated to reduction of extraction operations and avoided impacts of EAF slag disposal
Subject to independent review?	Publication in a peer-reviewed journal

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