THE USE OF BASALT AGGREGATES IN THE PRODUCTION OF CONCRETE FOR THE PREFABRICATION INDUSTRY

Environmental impact assessment, interpretation and improvement

Carlo Ingrao [a, *], Agata Lo Giudice [b], Caterina Tricase [c], Charles Mbohwa [b], Roberto Rana [c]

[a] Department of Civil and Environmental Engineering (DICA), University of Catania, Viale A. Doria 6, 95125 Catania, Italy;
[b] Department of Quality and Operations Management, Faculty of Engineering and the Built Environment, University of Johannesburg. APB Campus, P. O. Box 524, Auckland Park 2006, Johannesburg, South Africa;
[c] Department of Economics, University of Foggia, Via Romolo Caggese, 1 - 71121 Foggia, Italy

Abstract

This study aims at environmentally assessing the most significant input and output flows related to the production of concrete using basalt aggregates. For this purpose, Life Cycle Assessment (LCA) was applied according to the ISO 14040:2006 and 14044:2006. All data used was collected on site and processed by SimaPro 7.3.3 accessing the Ecoinvent v.2.2 database and using the Impact 2002+ method. The LCIA results show that the most impacting phase is the production of the basalt aggregates, with "Human Health" being the most affected damage category, because of the emission in air of 2.7 kg of particulates (grain size < 2.5 μm). In addition to this, the concrete production causes, mainly, the emission in air of 465 kg of Carbon Dioxide and the consumption of 37.37 kg of crude oil, affecting, the damage categories "Climate Change" and "Resources". Regarding "Ecosystem Quality", the occurred damage is due to the emission in air of 29.6 g of Aluminum and into soil of 251 mg of Zinc. Based on the obtained results, the solution of increasing the amount of water used for particulates removal during the basalt extraction phase was considered, thereby allowing for reducing damage by 17%. In addition to this, the hypothesis of using limestone aggregates instead of the basalt ones was assessed from both technical and environmental perspectives. The analysis developed highlighted a total damage decrease of 67% (from 0.359 pt to 0.116 pt).

Key words: concrete, basalt, life cycle assessment, environmental sustainability, particulates emission, impact indicators

[*] Corresponding author. Tel.: +39 392 0749606; *E-mail address*: ing.ingrao@gmail.com

1. Introduction

Concrete is an artificial conglomerate consisting of a mixture of a binder, water and aggregates (sand and gravel) which, depending on the need, can be integrated with additives, in order to modify its physicochemical and mechanical properties. Nowadays, cement is the binder mainly used for the concrete production even if, in the past, lime was sometimes used. Cement, when mixed with water, hydrates and hardens, giving to the mixture (concrete) hardness values as high as that for rocks. Concrete is the most world-widely used building material, mainly used for the construction of buildings and their main elements and parts, such as floors, load-bearing structures, foundations, side walls and pavements. It has good compressive resistance, while its behaviour to traction is considerably poor: for this reason, it is commonly reinforced by using steel strands. Steel reinforcement is, always, appropriately designed based on the traction effort magnitude and it is installed before concrete is cast.

According to Habert et al. [1], the building materials sector is one of the largest CO_2-emitting and resources consuming industrial sector in the world. Concrete is the single most world-widely used building material mainly because of its strength and durability, among other benefits. Concrete is used in nearly every type of construction, including homes, buildings, roads, bridges, airports and subways, just to name a few [2]. To ensure the future competitiveness of concrete as a construction material, it is essential to improve the sustainability of concrete structures. For this purpose, environmental impact and resources consumption reduction-potentials can be found in the field of concrete construction, especially in raw-materials production and concrete manufacturing technology [3]. In this context, Life Cycle Assessment (LCA) can be used as a design support-tool for assessing environmental impacts and improvement potentials in concrete production. In this way, it will be possible to make concrete itself more environmentally sustainable so that it can perform well compared to other construction materials. A literature review was developed for highlighting the most relevant research studies dealing with the environmental sustainability matter in the production of concretes. In particular, the following papers were found: Knoeri et al. [4], regarding the application of LCA for comparing recycled and conventional concrete for structural applications; Cazacliu and Ventura [5], in which LCA was applied for assessing technical and environmental effects of concrete production, comparing dry batch with central mixed plant; Garcia-Rey and Yepes [6], about the application of LCA on concrete structures for assessing and improving the environmental performance associated with the construction phase; Habert at al. [1], where LCA was used for demonstrating that the use of high performance concrete for bridges construction causes less environmental impacts than the traditional one; Jonsson et al. [7], dedicated to the application of LCA for assessing the environmental sustainability of both concrete and steel building frames; Zabalza Bribian et al. [8], in which, it was possible to prove that the use of the best available construction technique and of eco-innovation in the manufacturing plants can significantly allow the reduction of the damage due to the construction products from an LCA perspective; Nässen et al. [9], where concrete and wood were compared considering the carbon dioxide emissions as well as the use of resources, materials and energy during the life cycle; López-Mesa et al. [10], about the application of LCA for comparing on equivalent building structures, the use of pre-cast and cast-in-situ concrete; Proske et al. [3], presenting mix design principles and laboratory tests to show how concrete can be eco-friendly if produced with a reduced content of water and cement; Van den Heede and De Balie [11] where a comparative assessment based on an LCA approach was carried out between traditional and “green” concretes; Valipour et al. [12] where the environmental impact on the global warming potential of concrete containing zeolite was assessed compared to conventional one applying the life-cycle assessment method; Habert et al. [13] where LCA was applied for environmentally assessing the geo-polymer concrete production reviewing current research trends; Pelisser et al. [14] dealing with the study of the utility of recycled tire rubber for lightweight concrete with added metakaolin, with the dual purpose of reducing cement consumption while achieving satisfactory strength; Blakendaal et al. [15] reporting an LCA application example for assessing measures oriented to the environmental impact reduction of both concrete and asphalt; Mingnan et al. [16] dedicated to the environmental assessment of ready-mixed concrete production in China; Yang et al. [17] reporting an evaluation procedure for the CO_2 reduction of alkali-activated concrete. Furthermore, Ortiz et al. [18] reviewed all the studies (from 2000 to 2007) about the application of LCA within the building sector.

The literature review was useful in creating a better understanding of the state of the art of concrete production environmental assessment. Besides, it highlighted that a number of concretes have been assessed over the years from a technical and environmental perspective, but studies regarding the application of LCA to basalt aggregates based concrete were not found. From this point of view, an uncovered gap in the literature was observed, thereby highlighting the need of similar LCA applications. In this context, this paper deals with the environmental assessment of the input and output flows related to the production of concrete using basalt aggregates. For this purpose, LCA was considered a valid tool to be used because, as defined by the International Organization for Standardization in the ISO 14040:2006 [19], it is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

2. The origin of concrete: an historical review

It is difficult to go back to the origins of the conglomerate building technique, as it seems that, during the Assyrian and the Egyptian ages, buildings were constructed using fine materials. Greeks also, already, knew this technique, adopted for the construction of the Argos aqueduct, Sparta tank and for other buildings, traces of which still remain. The Romans gave a big boost to this technique, using it for different constructions (for example: roads, foundations and masonry buildings) which, still survive in a good state of preservation. As far as the binder used is concerned, its invention is not of the Roman Age: it can be traced back to the third millennium BC when, in Egypt, gypsum mortar was used for the construction of masonry walls in blocks of stone. Until mortar was made using just lime, the hardening of the concrete was extremely slow, as the gradual consolidation of a lime mortar depends on the reaction between calcium hydroxide and carbon dioxide present in the air. The great revolution in this field occurred when lime was replaced by Pozzolan. Its chemical and physical characteristics were such that concrete hardened even in water, with no need for contact with the air. This allowed the production of high strength and fast hardening mortars. This finding, dating back to the first century BC, enabled the Romans building technique to be improved The decline of the Roman Empire, resulted in the inexorable decline in the quality of construction, especially in the suburbs of Rome. Pozzolan was no more used so the way of producing concrete, and the technology was forgotten. Such decline continued throughout the Middle Ages.

The discovery of the hydraulic lime (by the British Engineer John Smeaton) was a significant step forward in concrete production techniques. Such discovery marked the transition from the Roman concrete to the modern concrete. A synthesis process was developed for obtaining first hydraulic lime and then Portland cement. In 1860, based on the definition of the chemical composition of cement by M. Chatelier, industrial production of concrete was allowed and, since then, it has been under continuous development and innovation [20, 21].

3. Ready-mixed concrete: production data, main uses and mechanical properties

Ready-mixed concrete is produced in mixing plants located in buildings construction sites or in external appropriately equipped yards. According to the most recent statistics provided by the European Ready Mixed Concrete Organization (ERMCO), ready-mixed concrete market was heavily influenced by the economic dynamics which characterized the European Union in the last years. The crisis determined substantial changes in production levels: between 2009 and 2010, ready-mixed concrete production decreased by 4.3%: in 2011, there was a slight increase of 2.7%. In this context, Italy, one of the leading countries in this sector, since 2008 has been recording decreased production. Concrete production decreased from 66 Mm^3 (2008) to 40 Mm^3 (2012) [22]. Two different types of concrete can be identified: light and normal. Such a definition refers to its specific weight after drying, assuming values between 800 and 2,000 kg/m^3, in the first case, while varying from 2,000 to 2,600 kg/m^3 in the second case. In particular, “light concrete” is mainly used, also in the form of blocks, for houses construction: such blocks are used for partitions and provide protection from noise and fire. "Normal concrete" is constantly used in the industrial and commercial buildings construction, as well as in the infrastructural designs. It is strong, durable and fire resistant; it also presents good characteristics in terms of acoustic insulation, mechanical vibrations absorption and thermal capacity. Concrete resists moisture and the change of weather conditions, as well as mechanical wear, breakage and high temperatures. It is also able to absorb noise, reduce the internal temperature fluctuation in buildings, and to provide protection against different types of radiation and rise in sea level. Besides, concrete can be used for infrastructural applications such as roads, bridges, road safety barriers, tunnel and galleries, noise barriers; power plants, where potentially damaging fuels are stored; and silos and storage tanks. According with the laws and regulations in force, for the correct design and manufacturing of reinforced concrete structures, concrete is supposed to be specified based on "compressive resistance" and "texture". Compressive resistance is determined by mono-axial crushing tests using specific samples: these can be cubic or cylindrical. If the samples are cubic, they have a side length equal to 150 mm, while, cylindrical samples have a 150 mm diameter and a 300 mm height. Depending on which type of sample is used, the compressive resistance can be expressed as R_{ck} or f_{ck}: the two values are linked to each other by the following relation: $f_{ck}=0.83R_{ck}$. The Standards EN 206-1:2006 and UNI 11104:2004 [23, 24] have identified for both normal and heavy concrete, 18 classes from C8/10 to C100/120. The "texture" is an index of the main properties of the concrete behaviour in the time between its production and when it is cast in situ inside the formwork. In particular, in Italy this index is, commonly, expressed as spreading classes. This characteristic needs to be properly evaluated, depending on the structure to be built and for making the cast in-situ operations easier. Such tests can be done in the building construction yard or in appropriately equipped laboratories. In both cases, the Abrams cone is used. The aim of the test is to assess the deformation that concrete undergoes because of its weight, when the metal support is removed [25].

4. Material and methods

For the present analysis, an E-LCA (Environmental Life Cycle Assessment), word-widely known as LCA, was carried out since allowing for highlighting and assessing both critical points and margins for improvement in products' life cycle. This methodology aims in fact at addressing the environmental aspects of a product and their potential environmental impacts throughout its life cycle [26]. The study was developed according to the requirements of the ISO standards 14040:2006 and 14044:2006 [27] and it is divided in the following phases: 1) goal and scope definition, identifying the purpose of the study, the expected product of the study, system boundaries, functional unit (FU) and assumptions; 2) Life Cycle Inventory (LCI) Analysis, involving the compilation and quantification of both input and output flows and includes data collection and analysis; 3) Life Cycle Impact Assessment (LCIA), aiming to understand and evaluate the environmental impacts based on the inventory analysis within the framework of the goal and scope of the study; 4) Life Cycle Interpretation (LCI), in which the results from the impact assessment and the inventory analysis are analysed and interpreted for establishing recommendations so as to be consistent with the goal and scope of the study. The data collected during the LCI development were loaded into the SimaPro 7.3.3 software [28], accessing the Ecoinvent v.2.2 database [29] and then processed using the Impact 2002+ method for carrying out the LCIA. This method was used because, according to the ILCD Handbook "Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (LCA)" [30], it proposes a feasible implementation of a combined midpoint/damage approach, linking all types of Life Cycle Inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories, as shown in table 1. Additionally, it calculates the non-renewable energy consumption which represents a fundamental aspect to be considered and recognizes carbon dioxide as the emitted substance having the greatest responsibility for the greenhouse effect and climate change. Finally, the method is set-up so as to be more comprehensible for insiders and also more accessible if compared to other methods [31].

Table 1 Impact and damage categories contemplated in Impact 2002+

Damage Category	Impact Category
Human Health	Carcinogens
	Non-carcinogens
	Respiratory inorganics
	Respiratory organics
	Ionizing radiations
	Ozone layer depletion
Ecosystem Quality	Aquatic eco-toxicity
	Terrestrial eco-toxicity
	Terrestrial acidification/nitrification
	Aquatic acidiphication
	Aquatic eutrophication
	Land occupation
Climate Change	Global warming
Resources	Non-renewable energy
	Mineral extraction

The impact assessment phase was carried out including both the mandatory and the optional elements. Doing so, it was possible to express the results with equivalent numerical parameters (points) so as to be able to represent quantitatively the environmental effects of the analysed system. Damage and impact categories, processes, and both emitted-substances and used-resources can be easily compared to each other based on the damage unit-point. The impact categories represent the negative effects to the environment through which the damage (due to an emitted substance or an used resource) occurs, while the damage categories are obtained by grouping the impact categories into major ones and represents the environmental compartments suffering the damage.

The total damage is the one associated to the production of 1 cubic metre of concrete and can be calculated summing the contributions of the processes and materials included in the system boundaries or of the damage and impact categories or even of all substances emitted and resources used.

4.1 Goal and scope definition

The main goal of the study is to investigate, from a technical and environmental point of view, the production of concrete when basalt aggregates are used. For this purpose, since specific data and information were needed for carrying out the study, a Firm, leader in the prefabricating sector, was involved. The study was developed because: 1) such a concrete-type is largely used in the territory in which the Firm is located and so environmental considerations on its production technology were believed necessary and useful; 2) the research was considered of high scientific value; and, last but not least, 3) considered original and appealing to due to the absence of similar studies in the literature, as confirmed by the literature review done.

For achieving the goal, LCA was applied with the aim of qualifying and quantifying the environmental impacts due to the production of the analysed concrete, so as to highlight the highest ones and the alternative solutions for reducing them. In addition to this, the study aims at identifying the impact indicators best representing concrete production when basalt aggregates are used. This is believed extremely important, because such indicators are to be taken into account when environmental sustainability criteria are adopted for designing a structure which this concrete is used for.

The study will also contribute to the field adding value to the international knowledge and representing a fundamental support-tool for decision making. Thanks to this study, LCA practitioners, concrete producers, concrete-works designers, owners and buyers will learn more about the input/output flows involved in the system analysed and the consequential environmental impacts.

Furthermore, the development of this study was the occasion for the Firm to re-examine the merits of the environmental issues associated to the production of concrete and, in turn, of the prefabricated artefacts which it is used for.

Finally, it should be noticed that the present environmental analysis required an accurate study of the technical assessment commonly developed by the Firm for assuring concrete overall quality. Both the phases of technical and environmental assessment were realised in collaboration with the Firm involved in the project.

As established by the ISO standard 14040:2006, the “Goal and scope definition” phase includes also the Functional Unit (FU) choice and the system boundaries definition. In this case, 1 m^3 of concrete produced was chosen as the functional unit, while the system boundaries included: *the water use*; *the production and supply of the input materials in the amount required for producing the functional unit chosen; the energy consumption per m^3 of concrete and the use of the concrete mixing plant for the associated share.* Fig. 1 shows the system boundaries with the indication of the main input flows: the different thickness of the arrows refers to the input flow size in terms of supplied amount (kg*km).

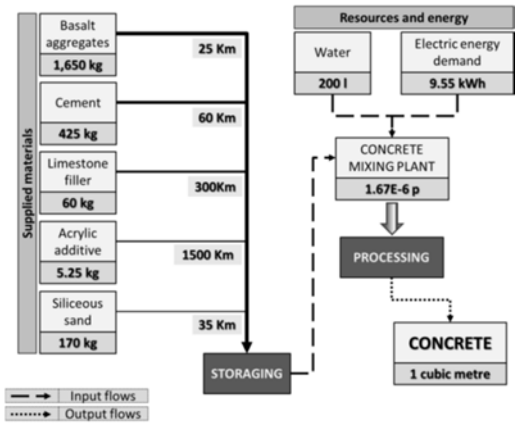

Fig. 1. System boundaries and input flows

4.1.1 Concrete production and testing

The mix object of this study is, conventionally, labelled as F1 by the Firm. It is used only for pre-stressed reinforced concrete elements and it is obtained by processing the resources and materials identified during the inventory data collection. The Firm produces, also, other concrete recipes on the basis of the characteristics (mainly artefacts dimensions and concrete design strength) of the precast artefacts which they are used for. For the F1 mix, a Portland cement with 52.5 N/mm^2 strength is used in accordance with the requirements of the standard EN 197-1:2011 [32]. Aggregates are those elements not taking part in the chemical processes of concrete setting and hardening, but they are bulk-added to the mixture with variable grain size. Generally representing 70% of hardened-concrete total volume, they can be considered as the concrete skeleton and an essential component for assuring appropriate values of concrete strength, deformability and durability. The F1 mix is produced using both fine and coarse aggregates in the form of sand and gravel in compliance with the standard UNI EN 206-1:2006. Their maximum dimension never exceeds 40 mm. Besides a correct particle-size distribution, these aggregates are characterized by high values of mechanical strength and low values of porosity; furthermore, they do not contain clay or organic (hydration reactions are not compromised). As indicated earlier, different aggregate types can be used: generally, normal concrete is made using limestone aggregates but in this case, since the Firm is located on the slopes of a Volcano, basalt aggregates are used. After production, the concrete is used on site for the production of prefabricated artefacts: it is not sold and not transported to other Companies nor it is used by the Firm itself for cast-in-situ works in external construction yards. Water plays an important role in cement hydration. In this case, tap water is used in accordance with the standard UNI EN 206-1:2006: the water used is clear, sulphate and chloride salts free and unaggressive and it is used with a water/cement (w/c) ratio of 0.5. It is important to observe that fluid concrete allows reducing the acoustic impact arising from the vibrating process that concrete is commonly subjected to once it is cast within the formwork. For obtaining a more fluid concrete, increasing the w/c ratio is not the proper solution, since it causes the reduction of concrete strength and the increase of concrete shrinkage. In such cases, additives are generally used: they allow the obtaining of more workable mixtures without the need of increasing the w/c ratio. For producing the F1 mix, an acrylic fluidizing material is used in an amount of more than 5 kg per m^3 of concrete. The Firm has a permanent system of production control so as to be able to produce concrete in compliance with the requirements of Italian Decree 14 January 2008. The adopted control system was planned according to the standard ISO 9001:2008 [33] and refers to the indications reported within the guidelines on ready-mixed concrete drafted by Public Work Superior Council. Furthermore, such a control system was also certified by an accredited organization operating in accordance with the standard ISO/IEC 17021:2006 [34]. One of the main aspects characterizing the control system adopted by the Firm is the development of a series of laboratory tests for continuous concrete quality monitoring from fresh concrete preparation to the next phases of curing and hardening. After testing aggregates grain-size to ensure the best distribution in the cement mix, fresh concrete is checked in terms of texture by performing the slump test (always super-fluid concrete, with a slump $\geq$ 220 mm). This is done after verifying that concrete has the requested characteristics in terms of cohesiveness and aggregates dimensions. Furthermore, for monitoring hardened concrete quality and strength, laboratory tests are performed by the Firm, in accordance with the standard EN 12390-1:2012 [35]: cubic samples with 150 mm side length are used for this purpose. Four samples were tested. This was done starting with levying the required amount of concrete from the same cast used for pre-stressed artefacts production. The samples preparation started with half-filling the PVC cubic moulds with concrete. When this was done, each mould was placed on a vibrating table, working for 20 seconds at the power of 165 W, for better compaction. After that, the moulds were totally filled and then a new concrete vibrating and compaction phase was triggered. The prepared concrete cubic samples were placed inside a curing chamber. The optimal conditions were set up to allow this phase to be developed under the best conditions so that the concrete would acquire, after 28 days of curing, compressive resistance values (R_c), equal to, if not superior, to the low limits (R_{ck}). This means that temperature and humidity were maintained at values of 20 °C and 90%. After curing, four compression tests (in two different places - Place 1 and 2) were performed. Place 1 is part of the concrete production Firm, while Place 2 is an accredited laboratory dealing with mandatory control tests execution and results certification as established by Italian Decree 14 January 2008 for construction materials, such as reinforced concrete, precast reinforced concrete and steel. All the samples were subjected to a 0.5 N/mm^2 load gradient using a standard hydraulic press. Table 2 reports the results recorded during the two test sessions: they show compressive resistance values hugely greater than the 55 MPa limit established by the Italian regulation. Furthermore, there is evidence that the concrete was well-manufactured: the average value remained, almost unchanged in the two test sessions.

Table 2 Concrete compressive resistance values recorded during sample test sessions

Number of sample	*Test laboratory location*	*Mass (kg)*	*Compression force (kN)*	*Compressive strength (MPa)*	*Crushing time (s)*
1	**Place 1**	**8.346**	**1,986.3**	**88.28**	**177**
2		**8.424**	**1,967.5**	**87.46**	**175**
3	**Place 2**	**8.388**	**1,954.8**	**86.88**	**174**
4		**8.456**	**2,088.9**	**92.84**	**185**
Arithmetic average		***8.403***	***1,999.375***	***88.865***	***177.75***

4.2 Inventory analysis

The Life Cycle Inventory (LCI) analysis quantifies the use of resources and energy and environmental releases associated with the system being evaluated [36]. This phase was developed collecting all the useful and available data regarding the concrete production in accordance with the Firm's practice. This phase allowed the researchers to quantify the use of the main input resources and materials and the energy consumption, as well as of the involved transportation. In developing this phase, great importance was given to using on-site collected data which was supplied by the Firm, together with other useful information regarding the techniques adopted for the concrete production process. Before being used, data was carefully verified, by experts in the sector, for assuring its quality and reliability. Furthermore, the maximum level of detail was assured: all the processes and materials considered significant in contributing to the damage were in fact accounted for. The processes contributing more than 0.35% to damage were in fact accounted for so as to include those processes which, though resulting far less impacting compared to the others, were believed important for the study consistency. In Table 3, all the main input flows linked to the concrete production are reported and commented.

Table 3 Inventory data concrete production

Process under study	**Basalt-based concrete production**		Corresponding file name in SimaPro 7.3.3: "CI_UNIFG_Concrete production"
Functional Unit (F. U.)	**1**	**m^3**	Basalt aggregates based concrete. Specific weight 2,500 kg/m^3
Input flow	**Physic amount**	**Measure unit**	**Comment**
Raw materials and resources			
Ground water at users	**200**	**l**	This process, taken from Ecoinvent v.2.2, using ground, river and lake water, considers the infrastructure and energy consumption for water treatment and transportation to the end user.
Portland cement	**0.425**	**t**	The Portland cement used has a 52.5 (CEM II) strength class and the following composition: clinker 91%, gypsum 6%, additional milling substances 3%.
Basalt gravel	**0.650**	**t**	This input material is used by the Firm (and also by most of the Firms located on the slopes of a Volcano) to give the concrete high strength. Furthermore, because the Firm site is 25 km close to the yards for basalt extraction from quarry and lava stone processing, this makes transportation less impacting. The basalt inert is peculiar of the Sicilian territory and it is not listed in the Ecoinvent v.2.2 database. For this reason, it was necessary to create the manufacturing process life cycle, starting from the basalt extraction from pit, also including lava stone crushing and then inert washing. This was done using the same process for limestone in the Ecoinvent v.2.2 database, replacing the item "Lime, at mine" with the one "Basalt, at mine". In doing this, any eventual difference in the manufacturing process was considered negligible. The process so created was named as "CI_UNIFG_Basalt inert".
Basalt sand	**1**	**t**	This sand is obtained by inert milling: sand is washed, too. In this case, we proceeded as done for the basalt inert. The process, named "Limestone, milled, loose, at plant", taken from the Ecoinvent v.2.2 database, was used, replacing the item "Limestone, crushed, for mill" from the abovementioned database, with "basalt inert". The process so created was named as "CI_UNIFG_Basalt sand".
Siliceous sand	**0.170**	**t**	
Limestone filler	**0.050**	**t**	
Acrylic additive for concretes	**5.25**	**kg**	The additive is used in order to ensure that the concrete flows better once casted inside the formwork
Electricity			
Electricity MV, use in Italy + import	**9.55**	**kWh**	This is referred to the consumption of electric energy associated to the functioning of the concrete mixing plant
Processing plants			
Concrete mixing plant	**1.67E-6**	**p**	This is the plant share for processing 1 m^3 of concrete. The calculation was developed considering that the amount of concrete produced in average every year is equal to 30,000 m^3 and that the lifetime of the concrete mixing plant is 20 years. For representing such industrial machine, the Ecoinvent v.2.2 database has been accessed using the existing item "Concrete mixing plant".
Transports			
Cement	**25.5**	**t*km**	For all the raw materials, transportation is done by means of Euro 4, 28 t lorry. The alongside values were calculated multiplying the relative amount for the travelled distance; in particular: - 60 km for cement; - 25 km for basalt inert; - 25 km for basalt sand; - 35 km for siliceous sand; - 300 km for limestone filler; - 1,500 km for acrylic additive for concretes.
Basalt inert	**16.25**		
Basalt sand	**25**		
Siliceous sand	**5.95**		
Limestone filler	**18**		
Acrylic additive for concretes	**7.875**		

The initials "CI_UNIFG_" indicate those processes which were specially created for the study so as to be able to represent well the production of the analysed concrete.

4.2.1 Input data and damage allocation

All input flows were allocated on the concrete production using appropriately defined procedures and tools: as a matter of fact, interviews to the Firm's technicians during concrete production site investigation were made and check-lists were used for recording data and information. With regard to the total damage, because of the absence of co-products linked to the production of the examined concrete type, in accordance with the ISO standards 14040:2006 and 14044:2006, this was entirely allocated to the functional unit, namely 1 m^3 of basalt-based concrete produced. With regard to the total damage, because of the absence of co-products in all the phases of the examined packaging system production, in accordance with the ISO standards 14040:2006 and 14044:2006, no allocation was done. 100% total damage corresponds in fact to 1 m^3 of ready-mixed concrete produced, i.e. 2,500 kg.

5. Results and discussion

5.1 Life Cycle Impact Assessment

It was found that the total damage is equal to 0.359 pt and is mainly due to the production of both fine and course basalt aggregates which accounted for 46.2% and 29.4% and of Portland cement for 16.4%. Other contributions can be attributed to the transportation of the input raw materials (4.29%) and to the lime mortar production (1.76%). Fig. 2 shows the single score evaluation per impact categories.

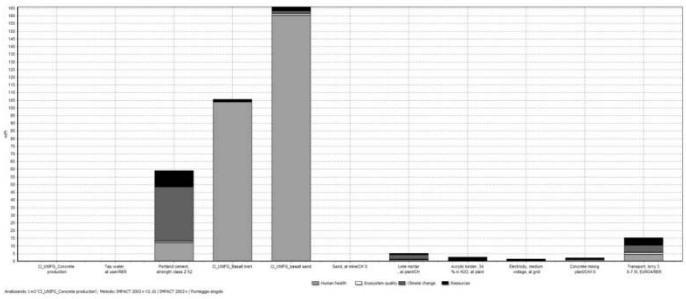

Fig. 2. Single score evaluation per impact categories - Impact 2002+

In terms of damage categories, the total damage is divided as follows: 79.1% *Human Health*; 13.3% *Climate Change*; 6.33% *Resources*; and 1.27% *Ecosystem Quality*. In Table 4, each damage category has been allocated a corresponding weighing point and the damages assessment value with the relative unit. Fig. 8 shows a histogram in which all the damage categories were associated to the processes characterizing the concrete production.

Table 4 Weighing points and the damages assessment values for each damage category

Damage category	Weighing points	Damages assessment	Units
Human Health	**0.284**	**0.00201**	DALY
Climate Change	**0.0476**	**471**	kgeqCO_2
Resources	**0.0227**	**3.45E3**	MJ primary
Ecosystem Quality	**0.00485**	**66.5**	PDF*m^2*y

DALY (Disability-Adjusted Life Year): a measure of the overall severity of a disease, expressed as the number of years lost due to illness, disability or premature death.
PDF (Potential Damage Fraction): the fraction of species that have a high probability of not surviving in the affected area due to unfavourable living conditions.

The most impacting substances are listed in Table 5, with the reported amounts referred to the production of 1 m^3 of concrete.

Table 5 Substances emission and resources consumption

Substance/resource	Emission compartment	Amount	Unit
HUMAN HEALTH			
Particulates, <2.5 µm	air	**2.69**	kg
CLIMATE CHANGE			
Carbon dioxide, fossil	air	**465**	kg
RESOURCES			
Oil, crude, in ground	---	**37.37**	kg
Uranium, in ground	---	**1.21**	g
Coal, hard, unspecified, in ground	---	**31.66**	kg
Gas, natural, in ground	---	**9.28**	m^3
ECOSYSTEM QUALITY			
Aluminium	air	**29.6**	g
Zinc	soil	**251**	mg

In particular, it should be noted that: the emission to air of particulates, accounting for 93.6% on the damage occurred under category "Human Health", is due to 59.7% and 38.8% for basalt sand and gravel and, in particular for about 100% due to the extraction of basalt from the pit. In addition to this, Carbon dioxide, emitted to air in the amount reported in Table 4, represents the 98.5% of the damage affecting "Climate Change" and can be mostly attributed to the Portland cement production. Regarding the damage associated to "Resources", it is caused: for 49.6% by the consumption of crude oil, due, in turn, to the production of cement 39.7%; and basalt sand 10.5%, both in the amounts required for producing 1 m^3 of concrete, as well as to the involved transportation accounting for 34.5%; for 19.6% caused by the consumption of Uranium, accounting for 52.8% and 21.3% from the production of cement and basalt sand and 10.5% from the input materials transportation; for 17.6% by the consumption of hard coal, mainly because of Portland cement production accounting for 72.2%; for 10.8% by the use of natural gas and, in particular, to the production of Portland cement 28.7%, acrylic additive 20.3%, of basalt sand 9.23%, and to the transportation of the raw materials 17.6% and to electricity consumption accounting for 12.2%. Aluminium and Zinc affect "Ecosystem Quality" by 45.6% and 17.7%. In particular, in the first case, the highest contribution can be attributed to 41.1% due to basalt sand, 26% due to basalt gravel and 23% due to Portland Cement production, while in the second, it is mostly due (for 92.4%) to the transportation linked to the raw materials supply. Furthermore, it is important to highlight that, in this case, Radon 222, generally acknowledged to be a significant source of impact when basalt is present, represents only about 0.0465% of the damage associated to "Human Health" and it is emitted, to air, in the amount of 3.9E4 kBq per m^3 of concrete produced. The impact categories containing the substances and resources listed in Table 4 are the ones causing the highest damages; they have been listed in Table 6, indicating, for each of them, the corresponding characterization value and the weighting point.

Table 6 Weighting points and the characterization values of most significant impact categories

Impact category	Weighting points	Characterization	Unit of measurement
Respiratory inorganic	**0.281**	**2.84**	$kg_{eq}P.M._{2.5}$
Global warming	**0.0476**	**471**	$kg_{eq}CO_2$
Non-renewable energy	**0.0227**	**3.45E3**	MJ primary

5.2 Life Cycle Impact Interpretation

The study showed: the process in the concrete production that has the most environmental impacts; the most damage category impact among those considered by the method chosen for the impact assessment development; the most impacting substances emitted and resources used; the processes causing the emission and consumption of the abovementioned substances and resources; and the most significant impact categories. It can be said in fact that the most environmental impacts are due to the extraction of basalt from quarry for producing aggregates and to cement production. The most affected damage category is "Human Health", while the most significant impact categories for the environmental assessment are: "Respiratory Inorganics (RI)", "Global Warming (GW)" and "Non-Renewable Energy (NRE)". As reported in Table 4, the emitted substances with the most environmental impacts are: Particulates (grain size < 2.5 μm), Carbon dioxide, Aluminium and Zinc, affecting "Human Health", "Climate Change" and "Ecosystem Quality". In terms of primary resources, those used with the most environmental impacts are: crude oil, Uranium in ground, hard coal in ground, gas natural in ground. Finally, transportation affects "Resources" for 33.2%, "Climate Change" for 29.3%, "Human Heath" for 28.3% and "Ecosystem Quality" for 9.2%. A flow chart of the damages arising from all the processes composing the basalt-based concrete production is also shown in Fig. 3.

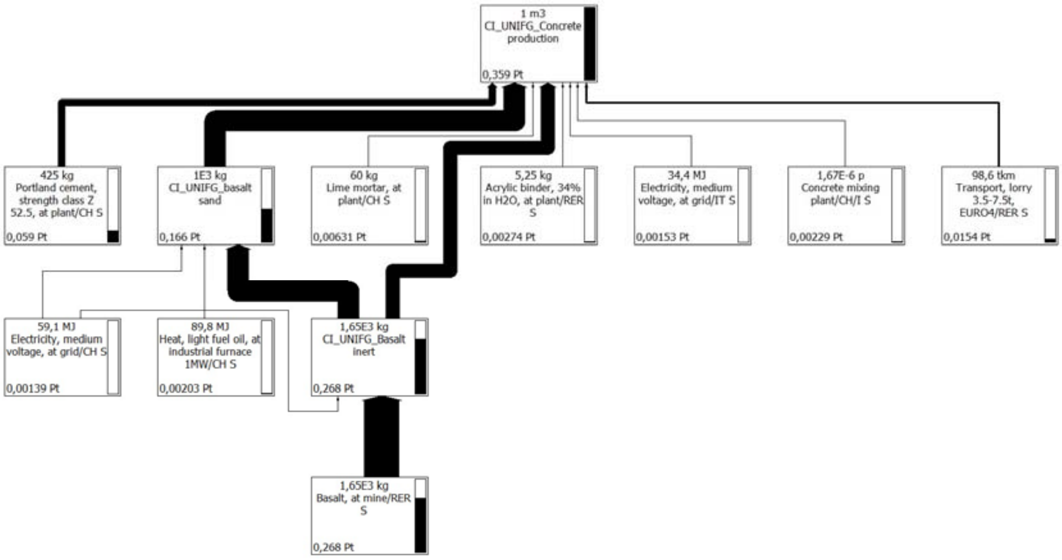

Fig. 3. Concrete production: damages flow – Impact 2002+

5.3 Improvement hypothesis

This is the phase of LCA in which improvement solutions are identified and assessed from an environmental point of view for reducing the total damage and, so, for increasing the sustainability level of the product under examination. On the basis of the obtained results, the solution of increasing the amount of water used for particulates removal during the basalt extraction phase was considered: an increase of 30% was chosen, because it was believed to be sensible. This percentage is equal to 0.000012 m^3 and it was thought for capturing the particulates amount resulting from the extraction of 1 kg of basalt stone. As shown in Fig.4, this solution allowed a reduction of the total damage of 17%, which means from 0.359 pt to 0.297 pt.

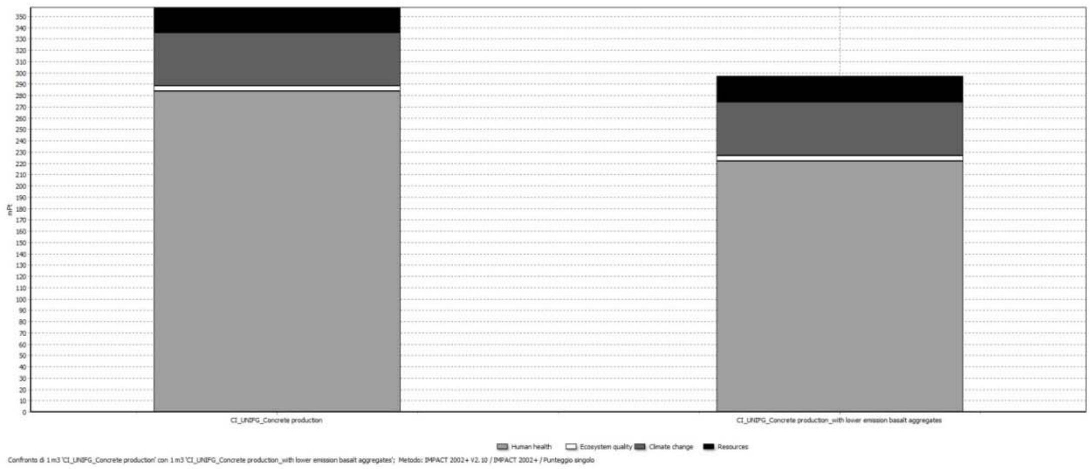

Fig. 4. Comparison with low particulates emission basalt-based concrete – Single score evaluation per Damage Category - Impact 2002+

Also in this case, “Human Health” is the most affected damage category, but the associated damage is reduced from 0.284 pt to 0.222 pt. This is because the amount of the emitted particulates (grain size < 2.5 μm) decreased by 23.4% (from 2.69 kg to 2.06 kg). The new results justify the use of a more water.

6. Sensitivity analysis

The sensitivity analysis was developed for assessing, from an environmental point of view, the use of limestone aggregates in comparison with the Firm’s current practice. The idea was in fact to replace basalt aggregates with those from limestone, leaving unchanged the amount required for producing concrete. Same was done both in quantitative and qualitative terms for the other component materials and the energy consumption linked to the mixing phase. On the contrary, the limestone extraction yard is about 100 km far away from the concrete production site, so a greater distance (compared to the basalt mine) was taken into account for the assessment. Doing so, it was possible to focus on the environmental impacts related to the phases of stones extraction from pit, aggregates production and transportation to the concrete production plant so as to be able to highlight the existing differences. This new solution was proposed to the Firm’s technicians who, after appropriate laboratory tests whose results cannot be reported here for reasons of confidentiality, confirmed its technical feasibility. It has to be underlined that this study is based on the assumption that the two aggregate types have the same intrinsic quality so that concrete overall quality and strength will not be compromised. Regarding the LCA development, the study settings remained unchanged in terms of FU and system boundaries, type and quality of inventory data, LCIA development criteria and method. As shown in Fig. 5, the solution proposed, although there was increased transportation distance (+75 km) for the limestone aggregates supply and the impacts linked to the limestone extraction and aggregates production, is environmentally sustainable. The total damage is reduced by 67% (from 0.359 pt to 0.116 pt) compared to the initial study.

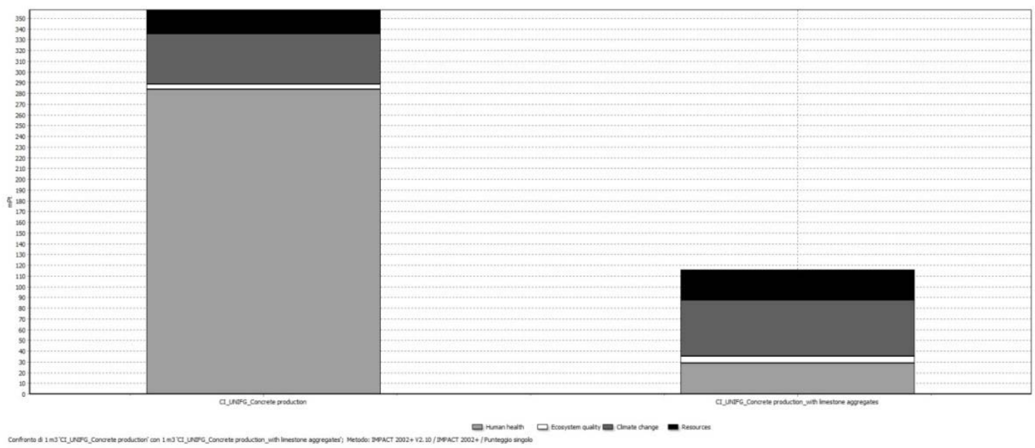

Fig. 5 Comparison with limestone aggregates based concrete - Single score evaluation per Damage Category -Impact 2002+

The damage that occurred due to "Human Health" was lowered a lot due to the emitted particulates amount reduction (from 2.69 kg to 0.0721 kg). In the process of limestone-based concrete production, the most impacted damage category turned out to be "Climate Change". This is because of the emission in air of Carbon dioxide mostly due to the Portland cement production which now represents the most environmental impacts in the concrete production. In addition to this, it has to be noted that the emitted amount of Carbon dioxide has increased by 45 kg compared to the initial study, because of the limestone aggregates production and transportation to the concrete mixing plant.

7. Conclusion

In the most of the concrete environmental assessment studies highlighted by the literature review developed, CO_2 is accepted to be the substance emitted to air that has the most environmental impacts because of the production of Portland cement to be used for concrete. On the contrary this study demonstrated that when concrete is produced from basalt aggregates, the highest environmental impacts and damages are not due to CO_2 but due to particulates emissions caused by the extraction of basalt from the pit: these emissions, represent the most important and representative environmental impact indicator to be taken into consideration for decision making when basalt is used. Regarding this aspect, the LCIA results highlighted that the use of basalt aggregates appears not to be environmentally justifiable when compared with other aggregates (for example, limestone) of equal quality and performance that do not compromise the concrete's final quality and strength. In fact, the basalt aggregates result in more environmental impacts than limestone aggregates, although there is increased distance for the limestone aggregates supply transportation. Also, even if solutions are adopted during the phases of basalt extraction and processing for reducing the huge amount of particulates emitted in air, the hypothesis of using limestone aggregates is to be preferred since it results in more environmental sustainable production. This production alternative will need to be evaluated, from the economical point of view, in a further study, compared with the technical and environmental aspects considered in this paper. The economical analysis will be done in compliance with the Policy and (economic) availability of data from the Firm involved, taking in consideration the price differences, mainly linked to the use of a different type of aggregates and to the increased distance for its supply. As done for this study, the application of the LCA methodology to the building and construction field allows the identification and environmental assessment of alternative solutions for reducing the damage associated with a product under examination. This approach is the basis of Green Economy since it allows the diffusion, on the market, of eco-friendly and energy efficient products. As also highlighted by Ortiz et al., SMEs should understand the importance of LCA not only for meeting consumer demands for environmental friendly products, but also for increasing green construction markets productivity and competiveness. In this context, this LCA study could represent the starting point for developing the Environmental Product Declaration (EPD) (III type voluntary environmental label) of this kind of concrete in accordance with the standard ISO 14025:2006 [37]. Doing so, in addition to what is already mentioned above, would make it possible to facilitate any comparison, in terms of materials use and constructive technique, with other concrete types, which this labelling has already been applied to; encourage eco-friendly materials and products demand and supply; boost the environmental improvement.

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Contribution of authors

This article has been thought, discussed and written by the five authors and it is the results of their common commitment. In particular, C. Ingrao, A. Lo Giudice and R. Rana contributed to bibliographical research, data collection-classification-evaluation, LCA development. C. Mbohwa and C. Tricase have contributed to planning and final review of the research study.

References

[1] Habert G, Arribe D, Dehove T, Espinasse L, Le Royc R. Reducing environmental impact by increasing the strength of concrete quantification of the improvement to concrete bridges. J. Clean Prod 2012; 35: 250-62.

[2] National Ready Mixed Concrete Association (NRMCA). Concrete CO2 Fact Sheet. NRMCA Publication Number 2PCO2, 2012.

[3] Proske T, Hainer S, Rezvani M, Graubner C. Eco-friendly concretes with reduced water and cement contents - Mix design principles and laboratory tests. Cement Concrete Res 2013; 51: 38-46.

[4] Knoeri C, Sanyé-Mengual E, Althaus H. Comparative LCA of recycled and conventional concrete for structural applications. Int. J LCA 2013; 18:909-18.

[5] Cazacliu B, Ventura A. Technical and environmental effects of concrete production: dry batch versus central mixed plant. J Clean Prod 2010; 18:1320-7.

[6] García-Rey J, Yepes V. Environmental Assessment of Concrete Structures. Int. J. Construction Engineering and Management 2012; 1: 33-41.

[7] Jonsson A, Bjorklund T, Tillman A. LCA of concrete and steel building frames. Int. J. LCA 1998; 3: 216-24.

[8] Zabalza Bribián I, Capilla AV, Aranda Usón A. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 2011; 46:1133-40.

[9] Nässén J, Hedenus F, Karlsson S, Holmberg J. Concrete vs. wood in buildings – An energy system approach. Build Environ 2012; 51: 361-9.

[10] López-Mesa B, Pitarch Á, Tomás A, Gallego T. Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors. Build Environ 2009; 44: 699-712.

[11] Van den Heede P, De Belie N. Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations. Cement Concrete Composites 2012; 34:431- 42.

[12] Valipour M, Yekkalar M, Shekarchi M, Panahi S. Environmental assessment of green concrete containing natural zeolite on the global warming index in marine environments. J. Clean. Prod 2014; 65:418-423.

[13] Habert G, d’Espinose de Lacaillerie JB, Roussel N. An environmental evaluation of geopolymer based concrete production: reviewing current research trends. J. Clean. Prod 2011; 19:1229-1238.

[14] Pelisser F, Barcelos A, Santos D, Peterson M, Bernardin AM. Lightweight concrete production with low Portland cement consumption. J. Clean. Prod 2012; 23:68-74.

[15] Blankendaal T, Schuur P, Voordijk H. Reducing the environmental impact of concrete and asphalt: a scenario approach, J. Clean. Prod 2014; 66:27-36.

[16] Mingnan Z, Xianzheng G, Feifei S, Minghui F. Life Cycle Assessment of ready-mixed concrete. Materials Science Forum 2013; 743-744: 234 – 8.

[17] Yang K, Song J, Song K. Assessment of CO2 reduction of alkali-activated concrete. J. Clean. Prod 2013; 39:265-272.

[18] Ortiz O, Castells F, Sonnemann G. Sustainability in the construction industry: a review of recent developments based on LCA. Constr Build Mater 2009; 23: 28-39.

[19] International Organization for Standardization (ISO), Environmental management - Life cycle assessment - Principles and framework ISO 14040, 2006.

[20] Bostenaru-Dan M, Pøikryl R, Török A. Materials, Technologies and Practice in Historic Heritage Structures. 2010. Springer, The Netherlands

[21] Palley R, Concrete: a Seven-Thousand-Year History. 2010. Quantuck Lane Press. New York

[22] ERMCO (European Ready Mixed Concrete Organization), [on line], XVI ERMCO Congress, 21-22June 2012 www.ingenio-web.it/immagini/CKEditor/120621_Nota_stampa_dati_settore_Ermco_giugno.pdf, [Accessed 07/10/ 2013].

[23] European Standard (EN) 206-1:2006, Concrete - Part 1: Specification, performance, production and conformity.

[24] Ente Nazionale Italiano di Unificazione (UNI) 11104:2004, Calcestruzzo - Specificazione, prestazione, produzione e conformità- Istruzioni complementari per l'applicazione della EN 206-1 (Italian Standard - Concrete - Specification, performance, production and conformity - Additional provisions for the application of EN 206-1).

[25] Decreto Ministeriale (D.M.) (infrastrutture) 14 gennaio 2008, Approvazione delle nuove norme tecniche per le costruzioni, pubblicato in G.U. n. 29 del 4 febbraio 2008. In Italian.

[26] Guinée B, Reinout H, Huppes G, Zamagni A, Masoni P, Ekvall T, Rydberg T. Life cycle assessment: past, present, and future, Environmental Science & Technology 2011; 45: 90-96.

[27] International Organization for Standardization (ISO), Environmental management - Life cycle assessment - Requirements and guidelines ISO 14044, 2006.

[28] SimaPro (2006). LCA software and Database Manual. Prè Consultants BV, Amersfoort, The Netherlands.

[29] Ecoinvent (2011). The Swiss Centre for Life Cycle Inventories. Ecoinvent v2.2.

[30] ILCD handbook. "Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (LCA)", European Union, 2010.

[31] Joillet O, Manuele M, Raphael C, Sébastian H, Jérome P, Gerald R, Rosenbaum R. IMPACT 2002+: a new life cycle impact assessment methodology. Int J LCA 2003; 8: 324 - 30.

[32] European Standard (EN) 197-1:2011, Cement - Part 1: Composition, specifications and conformity criteria for common cements

[33] ISO 9001:2008, Quality management systems -- Requirements

[34] ISO/IEC 17021:2006 Conformity assessment – requirements for bodies providing audit and certification of management system

[35] EN 12390-1:2012, Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds

[36] Lo Giudice A, Mbohwa C, Clasadonte MT, Ingrao C, Environmental assessment of the citrus fruit production in Sicily using LCA. Italian Journal of Food Science 2013; XXV: 202-212.

[37] International Organization for Standardization (ISO), Environmental labels and declarations - Type III environmental declarations -- Principles and procedures ISO 14025, 2006