

1 **THE USE OF BASALT AGGREGATES IN THE PRODUCTION OF**
2 **CONCRETE FOR THE PREFABRICATION INDUSTRY**

3 *Environmental impact assessment, interpretation and improvement*

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12

13 **Abstract**

14 This study aims at environmentally assessing the most significant input and output flows related to
15 the production of concrete using basalt aggregates. For this purpose, Life Cycle Assessment (LCA)
16 was applied according to the ISO 14040:2006 and 14044:2006. All data used was collected on site
17 and processed by SimaPro 7.3.3 accessing the Ecoinvent v.2.2 database and using the Impact 2002+
18 method. The LCIA results show that the most impacting phase is the production of the basalt
19 aggregates, with “Human Health” being the most affected damage category, because of the
20 emission in air of 2.7 kg of particulates (grain size < 2.5 µm). In addition to this, the concrete
21 production causes, mainly, the emission in air of 465 kg of Carbon Dioxide and the consumption of
22 37.37 kg of crude oil, affecting, the damage categories “Climate Change” and “Resources”.
23 Regarding “Ecosystem Quality”, the occurred damage is due to the emission in air of 29.6 g of
24 Aluminum and into soil of 251 mg of Zinc. Based on the obtained results, the solution of increasing
25 the amount of water used for particulates removal during the basalt extraction phase was
26 considered, thereby allowing for reducing damage by 17%. In addition to this, the hypothesis of
27 using limestone aggregates instead of the basalt ones was assessed from both technical and
28 environmental perspectives. The analysis developed highlighted a total damage decrease of 67%
29 (from 0.359 pt to 0.116 pt).

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31 *Key words:* concrete, basalt, life cycle assessment, environmental sustainability, particulates
32 emission, impact indicators
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35 **1. Introduction**

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

47 According to Habert et al. [1], the building materials sector is one of the largest CO₂-emitting and
48 resources consuming industrial sector in the world. Concrete is the single most world-widely used
49 building material mainly because of its strength and durability, among other benefits. Concrete is
50 used in nearly every type of construction, including homes, buildings, roads, bridges, airports and
51 subways, just to name a few [2]. To ensure the future competitiveness of concrete as a construction
52 material, it is essential to improve the sustainability of concrete structures. For this purpose,
53 environmental impact and resources consumption reduction-potentials can be found in the field of
54 concrete construction, especially in raw-materials production and concrete manufacturing
55 technology [3]. In this context, Life Cycle Assessment (LCA) can be used as a design support-tool
56 for assessing environmental impacts and improvement potentials in concrete production. In this
57 way, it will be possible to make concrete itself more environmentally sustainable so that it can
58 perform well compared to other construction materials. A literature review was developed for
59 highlighting the most relevant research studies dealing with the environmental sustainability matter
60 in the production of concretes. In particular, the following papers were found: Knoeri et al. [4],
61 regarding the application of LCA for comparing recycled and conventional concrete for structural
62 applications; Cazacliu and Ventura [5], in which LCA was applied for assessing technical and
63 environmental effects of concrete production, comparing dry batch with central mixed plant;
64 Garcia-Rey and Yepes [6], about the application of LCA on concrete structures for assessing and
65 improving the environmental performance associated with the construction phase; Habert et al. [1],
66 where LCA was used for demonstrating that the use of high performance concrete for bridges
67 construction causes less environmental impacts than the traditional one; Jonsson et al. [7], dedicated
68 to the application of LCA for assessing the environmental sustainability of both concrete and steel

69 building frames; Zabalza Bribian et al. [8], in which, it was possible to prove that the use of the best
70 available construction technique and of eco-innovation in the manufacturing plants can significantly
71 allow the reduction of the damage due to the construction products from an LCA perspective;
72 Nässen et al. [9], where concrete and wood were compared considering the carbon dioxide
73 emissions as well as the use of resources, materials and energy during the life cycle; López-Mesa et
74 al. [10], about the application of LCA for comparing on equivalent building structures, the use of
75 pre-cast and cast-in-situ concrete; Proske et al. [3], presenting mix design principles and laboratory
76 tests to show how concrete can be eco-friendly if produced with a reduced content of water and
77 cement; Van den Heede and De Balie [11] where a comparative assessment based on an LCA
78 approach was carried out between traditional and “green” concretes; Valipour et al. [12] where the
79 environmental impact on the global warming potential of concrete containing zeolite was assessed
80 compared to conventional one applying the life-cycle assessment method; Habert et al. [13] where
81 LCA was applied for environmentally assessing the geo-polymer concrete production reviewing
82 current research trends; Pelisser et al. [14] dealing with the study of the utility of recycled tire
83 rubber for lightweight concrete with added metakaolin, with the dual purpose of reducing cement
84 consumption while achieving satisfactory strength; Blakendaal et al. [15] reporting an LCA
85 application example for assessing measures oriented to the environmental impact reduction of both
86 concrete and asphalt; Mingnan et al. [16] dedicated to the environmental assessment of ready-mixed
87 concrete production in China; Yang et al. [17] reporting an evaluation procedure for the CO₂
88 reduction of alkali-activated concrete. Furthermore, Ortiz et al. [18] reviewed all the studies (from
89 2000 to 2007) about the application of LCA within the building sector.

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

100 **2. The origin of concrete: an historical review**

101 It is difficult to go back to the origins of the conglomerate building technique, as it seems that,
102 during the Assyrian and the Egyptian ages, buildings were constructed using fine materials. Greeks

103 also, already, knew this technique, adopted for the construction of the Argos aqueduct, Sparta tank
104 and for other buildings, traces of which still remain. The Romans gave a big boost to this technique,
105 using it for different constructions (for example: roads, foundations and masonry buildings) which,
106 still survive in a good state of preservation. As far as the binder used is concerned, its invention is
107 not of the Roman Age: it can be traced back to the third millennium BC when, in Egypt, gypsum
108 mortar was used for the construction of masonry walls in blocks of stone. Until mortar was made
109 using just lime, the hardening of the concrete was extremely slow, as the gradual consolidation of a
110 lime mortar depends on the reaction between calcium hydroxide and carbon dioxide present in the
111 air. The great revolution in this field occurred when lime was replaced by Pozzolan. Its chemical
112 and physical characteristics were such that concrete hardened even in water, with no need for
113 contact with the air. This allowed the production of high strength and fast hardening mortars. This
114 finding, dating back to the first century BC, enabled the Romans building technique to be improved
115 The decline of the Roman Empire, resulted in the inexorable decline in the quality of construction,
116 especially in the suburbs of Rome. Pozzolan was no more used so the way of producing concrete,
117 and the technology was forgotten. Such decline continued throughout the Middle Ages.
118 The discovery of the hydraulic lime (by the British Engineer John Smeaton) was a significant step
119 forward in concrete production techniques. Such discovery marked the transition from the Roman
120 concrete to the modern concrete. A synthesis process was developed for obtaining first hydraulic
121 lime and then Portland cement. In 1860, based on the definition of the chemical composition of
122 cement by M. Chatelier, industrial production of concrete was allowed and, since then, it has been
123 under continuous development and innovation [20, 21].

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

125 Ready-mixed concrete is produced in mixing plants located in buildings construction sites or in
126 external appropriately equipped yards. According to the most recent statistics provided by the
127 European Ready Mixed Concrete Organization (ERMCO), ready-mixed concrete market was
128 heavily influenced by the economic dynamics which characterized the European Union in the last
129 years. The crisis determined substantial changes in production levels: between 2009 and 2010,
130 ready-mixed concrete production decreased by 4.3%: in 2011, there was a slight increase of 2.7%.
131 In this context, Italy, one of the leading countries in this sector, since 2008 has been recording
132 decreased production. Concrete production decreased from 66 Mm³ (2008) to 40 Mm³ (2012) [22].
133 Two different types of concrete can be identified: light and normal. Such a definition refers to its
134 specific weight after drying, assuming values between 800 and 2,000 kg/m³, in the first case, while
135 varying from 2,000 to 2,600 kg/m³ in the second case. In particular, “light concrete” is mainly used,
136 also in the form of blocks, for houses construction: such blocks are used for partitions and provide

137 protection from noise and fire. “Normal concrete” is constantly used in the industrial and
138 commercial buildings construction, as well as in the infrastructural designs. It is strong, durable and
139 fire resistant; it also presents good characteristics in terms of acoustic insulation, mechanical
140 vibrations absorption and thermal capacity. Concrete resists moisture and the change of weather
141 conditions, as well as mechanical wear, breakage and high temperatures. It is also able to absorb
142 noise, reduce the internal temperature fluctuation in buildings, and to provide protection against
143 different types of radiation and rise in sea level. Besides, concrete can be used for infrastructural
144 applications such as roads, bridges, road safety barriers, tunnel and galleries, noise barriers; power
145 plants, where potentially damaging fuels are stored; and silos and storage tanks. According with the
146 laws and regulations in force, for the correct design and manufacturing of reinforced concrete
147 structures, concrete is supposed to be specified based on “compressive resistance” and “texture”.
148 Compressive resistance is determined by mono-axial crushing tests using specific samples: these
149 can be cubic or cylindrical. If the samples are cubic, they have a side length equal to 150 mm,
150 while, cylindrical samples have a 150 mm diameter and a 300 mm height. Depending on which type
151 of sample is used, the compressive resistance can be expressed as R_{ck} or f_{ck} : the two values are
152 linked to each other by the following relation: $f_{ck}=0.83R_{ck}$. The Standards EN 206-1:2006 and UNI
153 11104:2004 [23, 24] have identified for both normal and heavy concrete, 18 classes from C8/10 to
154 C100/120. The “texture” is an index of the main properties of the concrete behaviour in the time
155 between its production and when it is cast in situ inside the formwork. In particular, in Italy this
156 index is, commonly, expressed as spreading classes. This characteristic needs to be properly
157 evaluated, depending on the structure to be built and for making the cast in-situ operations easier.
158 Such tests can be done in the building construction yard or in appropriately equipped laboratories.
159 In both cases, the Abrams cone is used. The aim of the test is to assess the deformation that concrete
160 undergoes because of its weight, when the metal support is removed [25].

161 **4. Material and methods**

162 For the present analysis, an E-LCA (Environmental Life Cycle Assessment), word-widely known as
163 LCA, was carried out since allowing for highlighting and assessing both critical points and margins
164 for improvement in products’ life cycle. This methodology aims in fact at addressing the
165 environmental aspects of a product and their potential environmental impacts throughout its life
166 cycle [26]. The study was developed according to the requirements of the ISO standards
167 14040:2006 and 14044:2006 [27] and it is divided in the following phases: 1) goal and scope
168 definition, identifying the purpose of the study, the expected product of the study, system
169 boundaries, functional unit (FU) and assumptions; 2) Life Cycle Inventory (LCI) Analysis,
170 involving the compilation and quantification of both input and output flows and includes data

171 collection and analysis; 3) Life Cycle Impact Assessment (LCIA), aiming to understand and
 172 evaluate the environmental impacts based on the inventory analysis within the framework of the
 173 goal and scope of the study; 4) Life Cycle Interpretation (LCI), in which the results from the impact
 174 assessment and the inventory analysis are analysed and interpreted for establishing
 175 recommendations so as to be consistent with the goal and scope of the study. The data collected
 176 during the LCI development were loaded into the SimaPro 7.3.3 software [28], accessing the
 177 Ecoinvent v.2.2 database [29] and then processed using the Impact 2002+ method for carrying out
 178 the LCIA. This method was used because, according to the ILCD Handbook “Analysis of existing
 179 Environmental Impact Assessment methodologies for use in Life Cycle Assessment (LCA)” [30], it
 180 proposes a feasible implementation of a combined midpoint/damage approach, linking all types of
 181 Life Cycle Inventory results (elementary flows and other interventions) via 14 midpoint categories
 182 to four damage categories, as shown in table 1. Additionally, it calculates the non-renewable energy
 183 consumption which represents a fundamental aspect to be considered and recognizes carbon dioxide
 184 as the emitted substance having the greatest responsibility for the greenhouse effect and climate
 185 change. Finally, the method is set-up so as to be more comprehensible for insiders and also more
 186 accessible if compared to other methods [31].

187
 188 **Table 1** Impact and damage categories contemplated in Impact 2002+

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

189
 190 The impact assessment phase was carried out including both the mandatory and the optional
 191 elements. Doing so, it was possible to express the results with equivalent numerical parameters
 192 (points) so as to be able to represent quantitatively the environmental effects of the analysed system.
 193 Damage and impact categories, processes, and both emitted-substances and used-resources can be
 194 easily compared to each other based on the damage unit-point. The impact categories represent the
 195 negative effects to the environment through which the damage (due to an emitted substance or an

196 used resource) occurs, while the damage categories are obtained by grouping the impact categories
197 into major ones and represents the environmental compartments suffering the damage.

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

202 *4.1 Goal and scope definition*

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

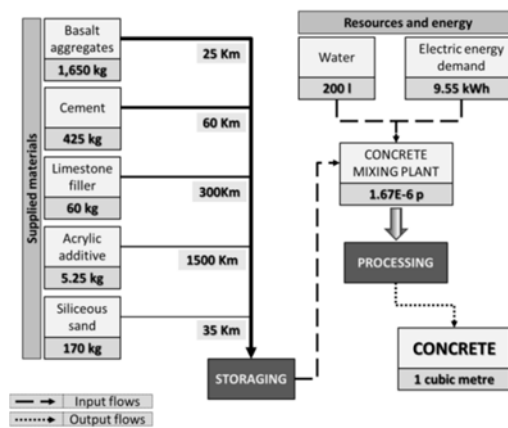
211 For achieving the goal, LCA was applied with the aim of qualifying and quantifying the
212 environmental impacts due to the production of the analysed concrete, so as to highlight the highest
213 ones and the alternative solutions for reducing them. In addition to this, the study aims at
214 identifying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

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

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

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

230 As established by the ISO standard 14040:2006, the “Goal and scope definition” phase includes
 231 also the Functional Unit (FU) choice and the system boundaries definition. In this case, 1 m³ of
 232 concrete produced was chosen as the functional unit, while the system boundaries included: *the*
 233 *water use; the production and supply of the input materials in the amount required for producing*
 234 *the functional unit chosen; the energy consumption per m³ of concrete and the use of the concrete*
 235 *mixing plant for the associated share.* Fig. 1 shows the system boundaries with the indication of the
 236 main input flows: the different thickness of the arrows refers to the input flow size in terms of
 237 supplied amount (kg*km).



238
 239 **Fig. 1.** System boundaries and input flows

240 **4.1.1 Concrete production and testing**

241 The mix object of this study is, conventionally, labelled as F1 by the Firm. It is used only for pre-
 242 stressed reinforced concrete elements and it is obtained by processing the resources and materials
 243 identified during the inventory data collection. The Firm produces, also, other concrete recipes on
 244 the basis of the characteristics (mainly artefacts dimensions and concrete design strength) of the
 245 precast artefacts which they are used for. For the F1 mix, a Portland cement with 52.5 N/mm²
 246 strength is used in accordance with the requirements of the standard EN 197-1:2011 [32].
 247 Aggregates are those elements not taking part in the chemical processes of concrete setting and
 248 hardening, but they are bulk-added to the mixture with variable grain size. Generally representing
 249 70% of hardened-concrete total volume, they can be considered as the concrete skeleton and an
 250 essential component for assuring appropriate values of concrete strength, deformability and
 251 durability. The F1 mix is produced using both fine and coarse aggregates in the form of sand and
 252 gravel in compliance with the standard UNI EN 206-1:2006. Their maximum dimension never
 253 exceeds 40 mm. Besides a correct particle-size distribution, these aggregates are characterized by
 254 high values of mechanical strength and low values of porosity; furthermore, they do not contain
 255 clay or organic (hydration reactions are not compromised). As indicated earlier, different aggregate
 256 types can be used: generally, normal concrete is made using limestone aggregates but in this case,

257 since the Firm is located on the slopes of a Volcano, basalt aggregates are used. After production,
258 the concrete is used on site for the production of prefabricated artefacts: it is not sold and not
259 transported to other Companies nor it is used by the Firm itself for cast-in-situ works in external
260 construction yards. Water plays an important role in cement hydration. In this case, tap water is
261 used in accordance with the standard UNI EN 206-1:2006: the water used is clear, sulphate and
262 chloride salts free and unaggressive and it is used with a water/cement (w/c) ratio of 0.5. It is
263 important to observe that fluid concrete allows reducing the acoustic impact arising from the
264 vibrating process that concrete is commonly subjected to once it is cast within the formwork. For
265 obtaining a more fluid concrete, increasing the w/c ratio is not the proper solution, since it causes
266 the reduction of concrete strength and the increase of concrete shrinkage. In such cases, additives
267 are generally used: they allow the obtaining of more workable mixtures without the need of
268 increasing the w/c ratio. For producing the F1 mix, an acrylic fluidizing material is used in an
269 amount of more than 5 kg per m³ of concrete. The Firm has a permanent system of production
270 control so as to be able to produce concrete in compliance with the requirements of Italian Decree
271 14 January 2008. The adopted control system was planned according to the standard ISO 9001:2008
272 [33] and refers to the indications reported within the guidelines on ready-mixed concrete drafted by
273 Public Work Superior Council. Furthermore, such a control system was also certified by an
274 accredited organization operating in accordance with the standard ISO/IEC 17021:2006 [34]. One
275 of the main aspects characterizing the control system adopted by the Firm is the development of a
276 series of laboratory tests for continuous concrete quality monitoring from fresh concrete preparation
277 to the next phases of curing and hardening. After testing aggregates grain-size to ensure the best
278 distribution in the cement mix, fresh concrete is checked in terms of texture by performing the
279 slump test (always super-fluid concrete, with a slump \geq 220 mm). This is done after verifying that
280 concrete has the requested characteristics in terms of cohesiveness and aggregates dimensions.
281 Furthermore, for monitoring hardened concrete quality and strength, laboratory tests are performed
282 by the Firm, in accordance with the standard EN 12390-1:2012 [35]: cubic samples with 150 mm
283 side length are used for this purpose. Four samples were tested. This was done starting with levying
284 the required amount of concrete from the same cast used for pre-stressed artefacts production. The
285 samples preparation started with half-filling the PVC cubic moulds with concrete. When this was
286 done, each mould was placed on a vibrating table, working for 20 seconds at the power of 165 W,
287 for better compaction. After that, the moulds were totally filled and then a new concrete vibrating
288 and compaction phase was triggered. The prepared concrete cubic samples were placed inside a
289 curing chamber. The optimal conditions were set up to allow this phase to be developed under the
290 best conditions so that the concrete would acquire, after 28 days of curing, compressive resistance

291 values (R_c), equal to, if not superior, to the low limits (R_{ck}). This means that temperature and
 292 humidity were maintained at values of 20 °C and 90%. After curing, four compression tests (in two
 293 different places - Place 1 and 2) were performed. Place 1 is part of the concrete production Firm,
 294 while Place 2 is an accredited laboratory dealing with mandatory control tests execution and results
 295 certification as established by Italian Decree 14 January 2008 for construction materials, such as
 296 reinforced concrete, precast reinforced concrete and steel. All the samples were subjected to a 0.5
 297 N/mm² load gradient using a standard hydraulic press. Table 2 reports the results recorded during
 298 the two test sessions: they show compressive resistance values hugely greater than the 55 MPa limit
 299 established by the Italian regulation. Furthermore, there is evidence that the concrete was well-
 300 manufactured: the average value remained, almost unchanged in the two test sessions.

301 **Table 2** Concrete compressive resistance values recorded during sample test sessions

<i>Number of sample</i>	<i>Test laboratory location</i>	<i>Mass (kg)</i>	<i>Compression force (kN)</i>	<i>Compressive strength (MPa)</i>	<i>Crushing time (s)</i>
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
<i>Arithmetic average</i>		8.403	1,999.375	88.865	177.75

302

303 4.2 Inventory analysis

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

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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
<i>Raw materials and resources</i>			
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
<i>Electricity</i>			
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
<i>Processing plants</i>			
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".
<i>Transports</i>			
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: <ul style="list-style-type: none"> - 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.

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327 4.2.1 Input data and damage allocation

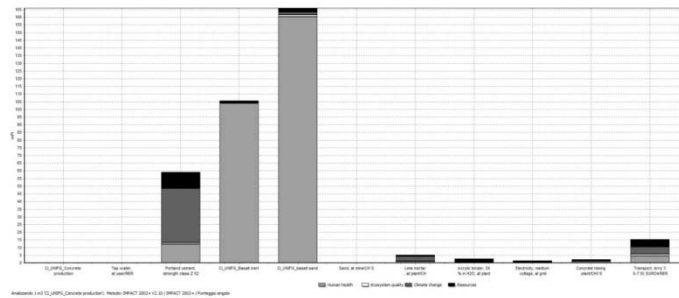
328 All input flows were allocated on the concrete production using appropriately defined procedures
329 and tools: as a matter of fact, interviews to the Firm's technicians during concrete production site
330 investigation were made and check-lists were used for recording data and information. With regard
331 to the total damage, because of the absence of co-products linked to the production of the examined
332 concrete type, in accordance with the ISO standards 14040:2006 and 14044:2006, this was entirely

333 allocated to the functional unit, namely 1 m³ of basalt-based concrete produced. With regard to the
 334 total damage, because of the absence of co-products in all the phases of the examined packaging
 335 system production, in accordance with the ISO standards 14040:2006 and 14044:2006, no
 336 allocation was done. 100% total damage corresponds in fact to 1 m³ of ready-mixed concrete
 337 produced, i.e. 2,500 kg.

338 5. Results and discussion

339 5.1 Life Cycle Impact Assessment

340 It was found that the total damage is equal to 0.359 pt and is mainly due to the production of both
 341 fine and course basalt aggregates which accounted for 46.2% and 29.4% and of Portland cement for
 342 16.4%. Other contributions can be attributed to the transportation of the input raw materials (4.29%)
 343 and to the lime mortar production (1.76%). Fig. 2 shows the single score evaluation per impact
 344 categories.



345
 346 **Fig. 2.** Single score evaluation per impact categories - Impact 2002+

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

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

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

353 DALY (Disability-Adjusted Life Year): a measure of the overall severity of a
 354 disease, expressed as the number of years lost due to illness, disability or
 355 premature death.

356 PDF (Potential Damage Fraction): the fraction of species that have a high
 357 probability of not surviving in the affected area due to unfavourable living
 358 conditions.

359 The most impacting substances are listed in Table 5, with the reported amounts referred to the
 360 production of 1 m³ of concrete.

361
362

Table 5 Substances emission and resources consumption

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

363

364 In particular, it should be noted that: the emission to air of particulates, accounting for 93.6% on the
 365 damage occurred under category “Human Health”, is due to 59.7% and 38.8% for basalt sand and
 366 gravel and, in particular for about 100% due to the extraction of basalt from the pit. In addition to
 367 this, Carbon dioxide, emitted to air in the amount reported in Table 4, represents the 98.5% of the
 368 damage affecting “Climate Change” and can be mostly attributed to the Portland cement
 369 production. Regarding the damage associated to “Resources”, it is caused: for 49.6% by the
 370 consumption of crude oil, due, in turn, to the production of cement 39.7%; and basalt sand 10.5%,
 371 both in the amounts required for producing 1 m³ of concrete, as well as to the involved
 372 transportation accounting for 34.5%; for 19.6% caused by the consumption of Uranium, accounting
 373 for 52.8% and 21.3% from the production of cement and basalt sand and 10.5% from the input
 374 materials transportation; for 17.6% by the consumption of hard coal, mainly because of Portland
 375 cement production accounting for 72.2%; for 10.8% by the use of natural gas and, in particular, to
 376 the production of Portland cement 28.7%, acrylic additive 20.3%, of basalt sand 9.23%, and to the
 377 transportation of the raw materials 17.6% and to electricity consumption accounting for 12.2%.
 378 Aluminium and Zinc affect “Ecosystem Quality” by 45.6% and 17.7%. In particular, in the first
 379 case, the highest contribution can be attributed to 41.1% due to basalt sand, 26% due to basalt
 380 gravel and 23% due to Portland Cement production, while in the second, it is mostly due (for
 381 92.4%) to the transportation linked to the raw materials supply. Furthermore, it is important to
 382 highlight that, in this case, Radon 222, generally acknowledged to be a significant source of impact
 383 when basalt is present, represents only about 0.0465% of the damage associated to “Human Health”
 384 and it is emitted, to air, in the amount of 3.9E4 kBq per m³ of concrete produced. The impact
 385 categories containing the substances and resources listed in Table 4 are the ones causing the highest

386 damages; they have been listed in Table 6, indicating, for each of them, the corresponding
387 characterization value and the weighting point.

388

389

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

Impact category	Weighting points	Characterization	Unit of measurement
<i>Respiratory inorganic</i>	0.281	2.84	kg _{eq} P.M. _{2.5}
<i>Global warming</i>	0.0476	471	kg _{eq} CO ₂
<i>Non-renewable energy</i>	0.0227	3.45E3	MJ primary

390

391 5.2 Life Cycle Impact Interpretation

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

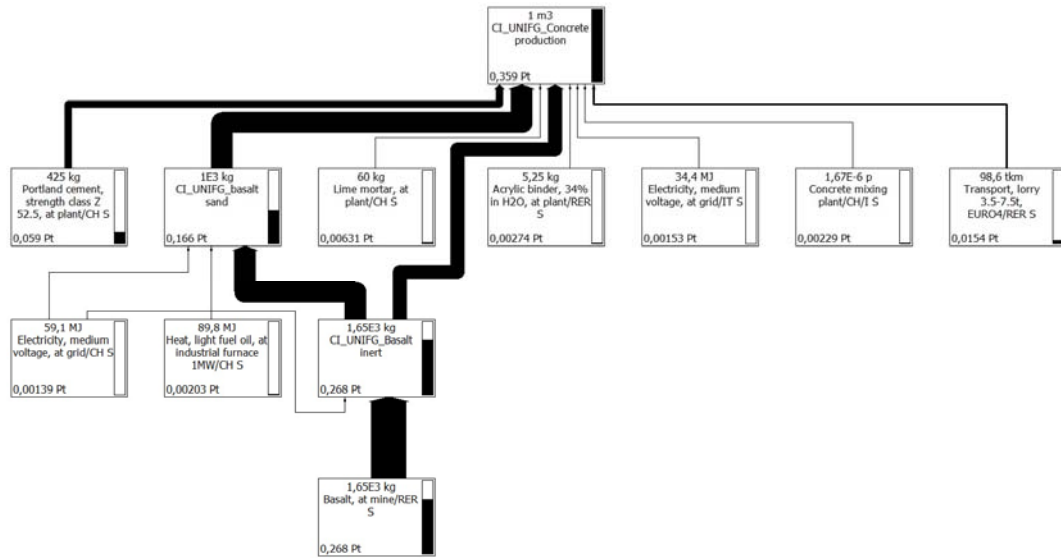


Fig. 3. Concrete production: damages flow – Impact 2002+

409

410

411 *5.3 Improvement hypothesis*

412 This is the phase of LCA in which improvement solutions are identified and assessed from an
 413 environmental point of view for reducing the total damage and, so, for increasing the sustainability
 414 level of the product under examination. On the basis of the obtained results, the solution of
 415 increasing the amount of water used for particulates removal during the basalt extraction phase was
 416 considered: an increase of 30% was chosen, because it was believed to be sensible. This percentage
 417 is equal to 0.000012 m³ and it was thought for capturing the particulates amount resulting from the
 418 extraction of 1 kg of basalt stone. As shown in Fig.4, this solution allowed a reduction of the total
 419 damage of 17%, which means from 0.359 pt to 0.297 pt.

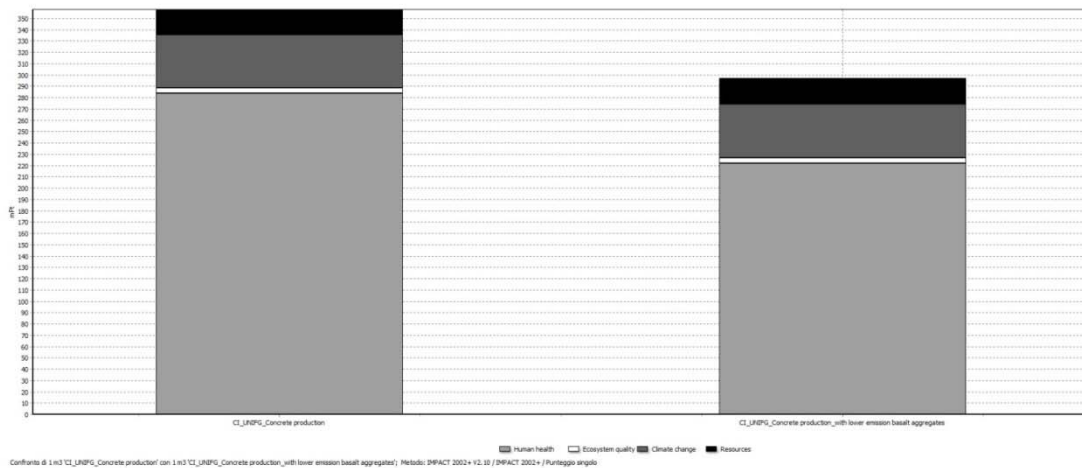


Fig. 4. Comparison with low particulates emission basalt-based concrete – Single score evaluation per Damage Category - Impact 2002+

420

421

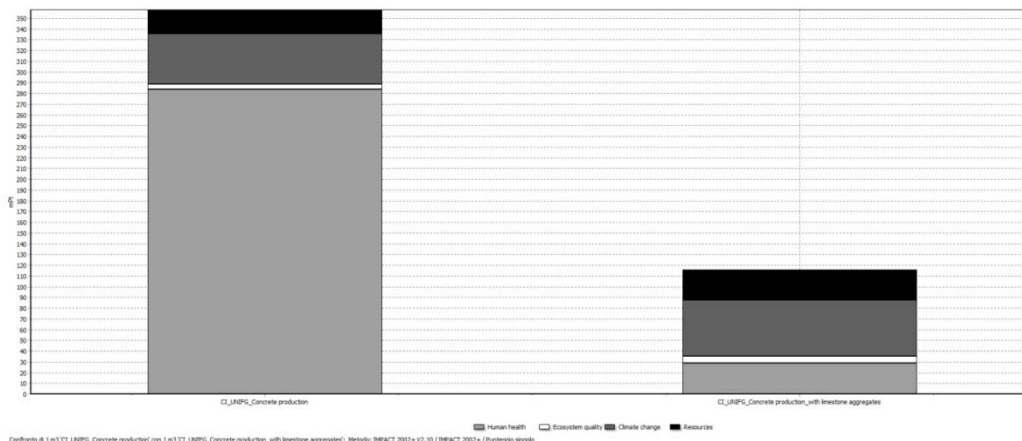
422

423

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

428 **6. Sensitivity analysis**

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



448 **Fig. 5** Comparison with limestone aggregates based concrete - Single score evaluation per Damage Category -Impact
 449 2002+
 450

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

459

460 **7. Conclusion**

461 In the most of the concrete environmental assessment studies highlighted by the literature review
462 developed, CO₂ is accepted to be the substance emitted to air that has the most environmental
463 impacts because of the production of Portland cement to be used for concrete. On the contrary this
464 study demonstrated that when concrete is produced from basalt aggregates, the highest
465 environmental impacts and damages are not due to CO₂ but due to particulates emissions caused by
466 the extraction of basalt from the pit: these emissions, represent the most important and
467 representative environmental impact indicator to be taken into consideration for decision making
468 when basalt is used. Regarding this aspect, the LCIA results highlighted that the use of basalt
469 aggregates appears not to be environmentally justifiable when compared with other aggregates (for
470 example, limestone) of equal quality and performance that do not compromise the concrete’s final
471 quality and strength. In fact, the basalt aggregates result in more environmental impacts than
472 limestone aggregates, although there is increased distance for the limestone aggregates supply
473 transportation. Also, even if solutions are adopted during the phases of basalt extraction and
474 processing for reducing the huge amount of particulates emitted in air, the hypothesis of using
475 limestone aggregates is to be preferred since it results in more environmental sustainable
476 production. This production alternative will need to be evaluated, from the economical point of
477 view, in a further study, compared with the technical and environmental aspects considered in this
478 paper. The economical analysis will be done in compliance with the Policy and (economic)
479 availability of data from the Firm involved, taking in consideration the price differences, mainly
480 linked to the use of a different type of aggregates and to the increased distance for its supply. As
481 done for this study, the application of the LCA methodology to the building and construction field
482 allows the identification and environmental assessment of alternative solutions for reducing the
483 damage associated with a product under examination. This approach is the basis of Green Economy
484 since it allows the diffusion, on the market, of eco-friendly and energy efficient products. As also

485 highlighted by Ortiz et al., SMEs should understand the importance of LCA not only for meeting
486 consumer demands for environmental friendly products, but also for increasing green construction
487 markets productivity and competitiveness. In this context, this LCA study could represent the starting
488 point for developing the Environmental Product Declaration (EPD) (III type voluntary
489 environmental label) of this kind of concrete in accordance with the standard ISO 14025:2006 [37].
490 Doing so, in addition to what is already mentioned above, would make it possible to facilitate any
491 comparison, in terms of materials use and constructive technique, with other concrete types, which
492 this labelling has already been applied to; encourage eco-friendly materials and products demand
493 and supply; boost the environmental improvement.

494

495 **Acknowledgements:** The authors would like to thank the Firm for supplying all the necessary
496 technical support to the ends of the study development.

497 **Contribution of authors**

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

502

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