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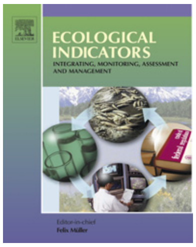

Specific emergy of cement and concrete: An energy-based appraisal of building materials and their transport

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ABSTRACT

Use and production of building materials, such as cement and concrete, is a major cause of global ecological problems with special reference to the overexploitation of non-renewable natural resources due to high temperature production processes, fossil fuels combustion, extraction of raw materials and non-recycling. In this paper, an environmental accounting method was applied to the production of cement and concrete in order to evaluate its dependence on natural resources even non-renewable and heavily relied on external inflows. The main steps of the production process (1) cement production, (2) transport of materials and (3) concrete mixing, were assessed by the *emergy analysis* (spelled with an "m"). This was performed to measure the amount of environmental resource use in terms of equivalent solar energy, extending the energy hierarchy principle to building materials. The resulting unit emergy values of cement and concrete were compared with previous emergy assessments in order to highlight how emergy analysis is sensitive to local context and reference system's boundaries. An Emergy Investment Ratio (EIR) was assessed and presented as a synthetic indicator of sustainability. Results showed a high dependence of cement and concrete production on external resource flows. Furthermore, the high value of EIR suggested a weak competitive capacity due to a high sensitivity to external instabilities.

1. Introduction

Large quantities of concrete (and cement) are traditionally used for building construction, for example, for building structural frames, groundwork, floors, roof, and prefabricated elements (see for a deeper discussion: Pulselli et al., 2007).

The world cement production has been increasing constantly since the early 1950s, especially in developing countries. World cement production was about 2100 million - tonnes in 2004, with a yearly growth of about 7–8%; it was doubled in less than 20 years. Asia has been the driving force with China and India currently the main cement producers (respectively: 930 million and 128 million tonnes or 44% and 6%, respectively, of world production).

The EU (25 Member States) produced about 11% of world cement production in 2004 (233 million tonnes). EU is a net cement exporter. With respect to local use of cement, EU (except The Netherlands) exports more than it imports. New cement plants have also been established in Eastern Europe and the USA by EU investments (CEMBUREAU, 2005).

According to the Italian Cement Association (AITEC, 2004), Italy is the biggest cement producer in EU (about 46,052,681 tonnes in 2004) and the eighth producer in the world. Italy is the eleventh cement exporter in the world, exporting to the USA, Middle East and other European countries. Italy had 89 cement plants in 1999.

The cement industry releases about 5% of the world CO_2 emissions. The environmental impact due to the emission of pollutants, particulate, ash and carbon dioxide has been

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largely investigated in the last years (among the others: Kjellsen et al., 2005; Pade and Guimaraes, 2007), as well as cement and concrete life cycle (among the others: Vold and Ronning, 1995; Nisbet and Van Geem, 1997; Josa et al., 2004; Josa et al., 2007) and concrete ecological footprint (Bastianoni et al., 2007).

This study concerns the intensive use of non-renewable mineral resources and fossil fuel in the (high temperature) production of cement and concrete (getting worse by non-recycling) and, in particular, it aims to evaluate the amount of environmental resource inflows to the production process. A common cement and concrete mixture was assessed as a case study, considering standard processes for Portland cement production and transport (Portland cement is the most common type produced for the building industry: 73.3% of total production) in the Italian context. Concordance or discordance between the present calculation and previous computed values (Björklund et al., 2001; Buranakarn, 1998; Brown and Buranakarn, 2003; Brown and McClanahan, 1992) highlights that the character of emergy accounting is particularly sensitive to context and systems boundaries. The high environmental impact, in terms of environmental resource exploitation, due to the use of cement and concrete in contemporary architecture, as shown in previous studies (Pulselli et al., 2006, 2007), let us implement a new assessment of cement and concrete production in order to provide a deeper evaluation of their sustainability/unsustainability in the Italian/European context.

2. Methodology

The emergy analysis allows to overcome the diversity of metrics used for quantifying different inputs by normalizing all products and services to a unit that represents the quantity and quality of work created and maintained by the system (Tilley and Swank, 2003). It uses the thermodynamic basis of all forms of energy and materials, but converts them into equivalents of one form of energy. Solar energy is used as the common denominator through which different types of resources (energy or matter) can be measured and compared. Inputs to a process are therefore normalized to a unit, namely the *solar emergy joule* or *solar emjoule* (sej). Based on this unit, emergy is defined as the quantity of solar energy that was used, directly or indirectly, to obtain a final product or service (Odum, 1971, 1983, 1988, 1996; Brown et al., 2004); it is a measure of the global processes required to make a product or service, expressed in units of solar energy (solar irradiation). The more work done to produce something, or the more energy transformed, the higher the emergy content of the product (Brown and Ulgiati, 1999). In other words, emergy is the "energy memory" that has been used throughout a sequence of different processes going into a product. Emergy is therefore not a state function, because it considers the specific path from the initial to the present state.

The ratio of the total emergy used to the energy of the product, gives a unit emergy value, namely specific emergy or transformity, in units sej/g or sej/J, respectively. Specific emergy can be used to "convert" a given product into emergy. Mass quantities (g) or energy quantities (J) multiplied by the specific emergy give an emergy content (sej). Moreover, specific emergy can be conceived as an indicator that represents the position that a given transformation process (and its product) occupies in the hierarchical network of the earth's biosphere (Odum, 1996).

Furthermore, through a classification of emergy inflows to the investigated process based on their origin, from within or outside the system, some emergy-based indicators can be assessed. This classification depends on the choice of the system's boundaries. In particular, an Emergy Investment Ratio (EIR) is calculated as the emergy of the external purchased inputs supporting a given system in relation to all local emergy ($EIR = F/L$, where F is the external inflow and L is the withdrawal from local flows and storages). Considering the present case study, this can inform on cement and concrete level of sustainability referring to their dependence on external inputs coming from other economic systems. This is moreover enhanced by the fact that most of the inputs to the production process are non-renewable.

Studies concerning emergy evaluation were presented in literature with reference to regions (Campbell et al., 2004; Higgins, 2003; Pulselli et al., 2008, 2007-a; Ulgiati et al., 1994), economic and technological issues (Brown and Ulgiati, 1997), resources (Ulgiati et al., 1995), fuels (Bastianoni et al., 2005a) ecosystems (Bastianoni et al., 2005b; Odum and Odum, 2003; Geber and Björklund, 2002; Tilley and Swank, 2003; Ton et al., 1998), agricultural systems (Rydberg and Jansen, 2002; Ulgiati et al., 1993), buildings and housing (Buranakarn, 1998; Meillaud, 2003; Pulselli et al., 2006).

In the last case, calculation was performed for evaluating building manufacturing (Pulselli et al., 2007). In particular, the construction of a contemporary building with very common characteristics was analysed in order to provide general information concerning a widespread architecture, such as that of many growing neighbourhoods and suburbs of contemporary cities in Italy and in most of southern Europe. Quantity of materials, land, energy, human work to the building process was assessed through an emergy analysis and outcomes highlighted that certain materials have higher impacts than others in terms of environmental resource use. Concrete was found to be the material mostly used in contemporary architecture since about 260 kg are generally embodied in a built cubic metre, versus about 76 kg of brick, 21 kg of mortar, 11 kg of plaster, 10 kg of stone, 8 kg of steel and about 10 kg of other materials. In terms of emergy, concrete was 4.8×10^{14} sej/m^3 corresponding to the 45% of the total emergy of a built cube metre (1.07×10^{15} sej). Moreover, in a comprehensive balance, emergy inflow to building manufacturing, maintenance and use was 43.52×10^{12} sej/year/m^3. Emergy inflow due to building manufacturing corresponds to 49% (considering a 50 years building lifetime), while maintenance is 36% (maintenance needs material use as well) and building use is 15%. This highlights the importance of material choice in building construction.

Considering a region, the use of non-renewable resources by the building industry can be assessed through emergy. This would stress the environmental concern of building materials, particularly concrete. For example, in the case of the municipality of Ravenna – north-western Italy – (Pulselli et al., 2004, 2006) a region of about 653 km^2 with a population of

142,000 persons, (217 persons/km^2), the built environment grows with a rate of 217,722 m^3/year that corresponds to an emergy flow of 2.33×10^{20} sej/year for building manufacturing. This emergy inflow highlights an intensive use of environmental resources by the building industry at a local level that mainly corresponds to building materials, particularly concrete. These results call to a deeper analysis of cement and concrete production in order to provide more valuable evaluation of the building industry in the European context.

2.1. *Compared unit emergy values of cement and concrete production*

Since emergy is not a state function, it depends on the various steps in a process. Differences in comparable studies can be observed in the accounts of different authors depending on different objectives, systems boundaries and context.

Differences from this study depend on the following considerations:

(1) *Context*: this study focuses on production processes of Italian industry of cement and concrete. It could be potentially expanded to standard procedures in Western Europe, but most of the previous calculated specific emergy values were assessed in the USA. For instance, referring to the process of concrete production, a distance of 50 km from the quarry and the cement plant to the building yard is an average value for Italy and most of Europe but it may be underestimated for the USA.

(2) *System*: we made an assessment of a specific process considering the production of a given quantity of cement (23 tonnes), its transport to the building yard, and the concrete production, as shown in Fig. 1. The choice of this system makes some factors negligible, such as the assessment of the entire national infrastructures for transport (roads and other services). This calculation could have a relevant meaning for assessing the entire national transport system with its infrastructures, services and vehicles (all the categories), with reference to their construction, maintenance and use (considering their entire life time), but it was not considered in this case, because the infrastructure use should be allocated to a short trip of a unique vehicle.

(3) *Approximation*: in this case study, the emergy/money ratio was not used in the assessment because inputs were collected in energy and mass units and approximation due to economic values (to be processed through the emergy/money ratio) was not necessary. The emergy/money ratio is an emergy-based indicator aimed to measure the amount of environmental resources used (in sej) per unit of GDP (in $ or €). This ratio is usually based on a national evaluation (total emergy use in a specific country/national GDP) that is too general with respect to a specific process.

In particular, considering (a) Björklund et al. (2001), (b) Buranakarn (1998) and (c) Brown and Buranakarn (2003), (d) Brown and McClanahan (1992); differences are as follows:

(a) Differences in Björklund et al. (2001) are due to:

  (1) *Context*: the authors used values of solar transformity specific for a national context. For example, the transformity of electricity is very specific as it was assessed according to the production processes in Sweden that includes nuclear (33%—here accounted with the transformity of the average world electricity production) and hydroelectric power (66%).

  (2) *System*: the emergy assessment of cement production does not consider the entire production process presenting a relevant approximation. A few main inputs, especially relative to a material use (only limestone and quarts), electricity and oil were accounted, while inputs to transport, packaging, services, such as human work, machinery and fuel were not assessed.

  (3) *Approximation*: in the process of electricity production a few inputs, such as human work, were assessed through an emergy/money ratio.

(b) Differences in Buranakarn (1998) are due to:

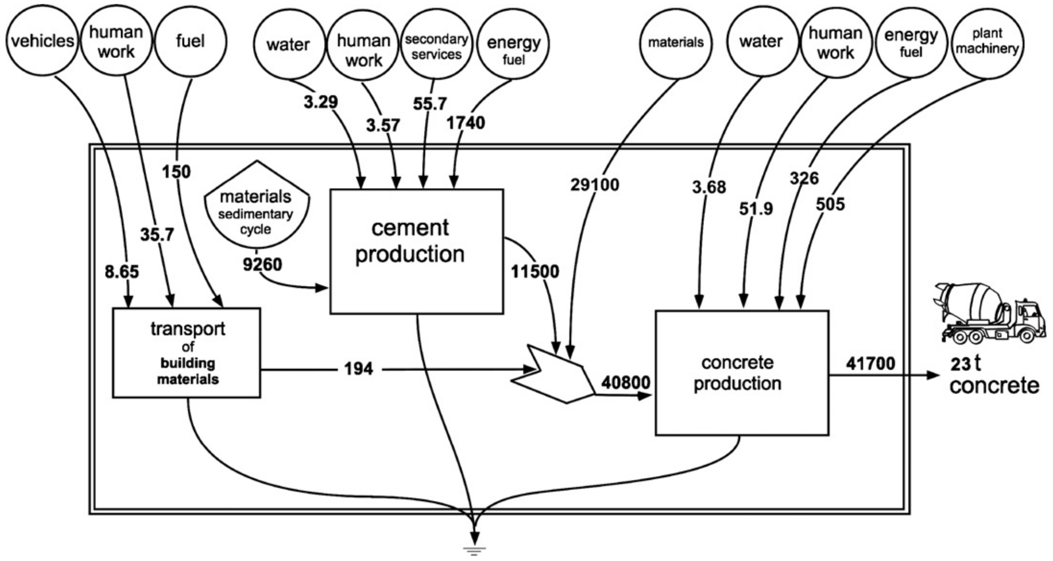

Fig. 1 – Energy system diagram of concrete production. Values are in sej × 10^{12}.

(1) *Context*: specific emergy was assessed in the USA.
(2) *System*: a complicate assessment of roads, vehicles and infrastructures use, was provided considering the entire national transportation system. The author calculated the total length of the national highways and their production process (materials, energy, human work, other services), considering the annual cost of their construction. This value (in sej/km) was divided by the percentage of trucks relative to the total weight of vehicles (cars, buses, trucks, others). The same for railways (by trains) and sea services (by boats). This is the percentage of the total emergy of the national transportation system due to freight, in general. It is not clear how to allocate this general assessment to a mass unit of cement and concrete and why it has about 20% of incidence relative to the final value of the transformity. Overall, it is not considered the life time of roads, infrastructures and vehicles.
(3) *Approximation*: human work and other services were assessed through an emergy/money ratio.

(c) Differences in Brown and Buranakarn (2003):

This assessment is mostly based on Buranakarn, 1998 but it also accounts for the phases of material use, demolition, disposal and reuse. Therefore, this analysis concerns with further inputs to the process that needs specific procedures. The present work, on the contrary, has the aim of determining the transformity of concrete, from the cradle to the final grade concrete used in building construction and without exploring its entire lifecycle until the grave.

Furthermore, in the present study, some factors in the process of concrete production were considered to have negligible effects in terms of resource use and were not included. For example, infrastructures, machinery in cement plants, vehicles assembly lines, and other secondary chain of processes; were not accounted because, if allocated to a unit mass of product and to the time segment of their use, the emergy accounting of these secondary processes would provide negligible effects.

(d) Differences in Brown and McClanahan (1992):

(1) *Context*: specific emergy was assessed in Thailand, with reference to locally available energy sources. This analysis was conducted in 1992, using data of 1983. Since changes occurred in concrete production relative to technological innovation and market growth, an up to date assessment should be expected.
(2) *System*: emergy analysis was here oversimplified with respect to our purposes since authors considered a few aggregated issues such as, for example, reef (limestone) as material flow, petroleum and electricity as energy flow and other goods and services, the latter assessed in terms of money flow (through an emergy/money ratio). In addition, concrete aggregate (gravel and sand), which consist of 89% by weight of final concrete, were assessed in the article under the voice ''mining and transit'', in terms of Joule, that does not clearly corresponds to a material flow. Transport of cement to the building yard was not assessed.
(3) *Approximation*: good and services for the cement production were assessed through an emergy/money ratio.

Beside these differences, the specific emergy of concrete was calculated in this paper in order to provide a valid information for future emergy assessments of the building industry. Specific emergy is an intensive quantity that represents the environmental resource use due to a given product (in this case a building material) and can be used for emergy-based evaluation of any wider system involving concrete, for example, a building manufacturing process, a building metrical computation or even the building industry itself. Thus specific emergy works for emergy-based environmental accounting of systems of varying complexity. In particular, an emergy analysis of building manufacturing accounted through the specific emergy of cement and concrete presented in this paper is available in the literature cited above (Pulselli et al., 2007).

3. Results

An energy system diagram of concrete production, based on the energy system symbols of Howard Odum (1971, 1983, 1996), is shown in Fig. 1. The main inputs, interactions and transformation processes to obtain a unit of concrete are represented.

In the diagram, arrows are energy and matter inflows for cement production, transportation and concrete production, such as materials, water, fuel, electricity, human work, machinery, plant and vehicles. Cement and other materials, except water, convert to the process of concrete production, through transport. Concrete production may take place on the building yard. The outcoming arrow represents the final product, concrete for casting.

In this scheme, the analysis is divided into three main phases:

Cement production.
Transport of building materials.
Concrete production.

Data were gathered for each phase and multiplied by specific emergy values so that all inputs were in solar emergy joules. The results are in solar emergy joules per mass of concrete produced (sej/g). Values related to each arrow are reported in the diagram in sej as a preview of the final results. More detailed discussion of these values will be given later in this paper.

The values of specific emergy of cement and concrete apply to Italy (a common method of production of Portland cement and of mixing concrete).

3.1. *Emergy analysis of cement production*

Analysis of cement production first requires data collection. Quantities of raw materials, consumption of fuels and electricity, hours of human work, quantities of materials for packing and carriage and other secondary services were obtained per unit of product. Data of the cement production was collected in a cement plant in central Italy that was used as a case study (CEMENTIR, 2006).

Traditional materials for making cement are limestone, chalk, shale, clay and sand that are reduced and proportioned to obtain Portland cement of specific chemical composition. The quarry is usually close to the cement plant and the raw materials are extracted and stored separately to be proportioned, blended and grinded. A critical step of the process is clinker production by fusion of raw materials (limestone, chalk, shale, clay, sand). A ground mixture is obtained with a rotating cylindrical kiln in which heat exchanges cause chemical chain reactions. This transformation process is the main step of cement production. The kiln should have a temperature of 1450 °C and consumes almost 90% of the energy required for the whole cement production. Energy consumption can therefore be expected to have a significant impact on the annual economic and environmental costs of a cement plant. Clinker is a basic-product that is finally combined with other materials to obtain different kinds of cement with different properties.

The cement plant we studied has a production capacity of about 715,000 tonnes/year of final grade cement. Data on the flows of energy and matter that supply the production process were collected over a year. Emergy of cement production is mainly due to inputs such as energy, materials, secondary materials for quarrying, packing materials, water, human work. Yearly inputs were estimated in units of mass and energy. Data in energy units was processed as follows:

- Electricity use (82 GWh/year): (82,000,000 kWh·3600 J/kWh) = 2.93×10^{14} J.
- Pet-coke (54,000 tonnes/year): (54,000,000 kg·43,020.79 J/kg) = 2.31×10^{15} J.
- Oil (1500 tonnes/year): (1,500,000 kg·41,818 J/kg) = 2.31×10^{15} J.
- Human work (104,400 working hours/year): (1740 h·60 workers·125 kcal/h·4.186 J/kcal) = 5.42×10^{10} J.

The emergy analysis of cement production is shown in Table 1.

The values used in the following tables are referred to: a (Odum, 1992), b (Bastianoni et al., 2005a), c (Odum, 1996), d (Brown and Arding, 1991), e (Buranakarn, 1998), f (Tiezzi, 2001), g (Ulgiati et al., 1993). Specific emergies (transformities) are relative to the 15.83×10^{24} sej/year baseline.

The total emergy for the production of 710,000 tonnes/year of cement is 2.16×10^{21} sej. In this process, the emergy of materials created by the natural sedimentary cycle is about 84% of the total emergy. Emergy as electricity and fuels is about 15%. The total emergy used was expressed per unit of product to obtain the specific emergy, an intensive quantity. The specific emergy of cement is 3.04×10^9 sej/g.

Table 1 – Calculation of specific emergy of cement from emergy assessment of the production process: 715,000 tonnes/year cement production

Item	Input	Unit	Specific emergy (sej/unit)	Reference	Emergy (sej)
Energy inputs					
Electric energy	2.93×10^{14}	J	2.07×10^{5}	a	6.07×10^{19}
Pet coke	2.31×10^{15}	J	1.13×10^{5}	b	2.61×10^{20}
Oil	6.23×10^{13}	J	9.3×10^{4}	b	5.79×10^{18}
					3.27×10^{20}
Materials					
Limestone	8.04×10^{11}	g	1.68×10^{9}	c	1.35×10^{21}
Clay	1.89×10^{11}	g	1.68×10^{9}	c	3.17×10^{20}
Chemical gypsum	2.78×10^{10}	g	1.68×10^{9}	c	4.67×10^{19}
Pozzolan stone	5.66×10^{10}	g	1.68×10^{9}	c	9.51×10^{19}
Other stone	5.96×10^{9}	g	1.68×10^{9}	c	1.00×10^{19}
					1.82×10^{21}
Special materials for quarrying					
Explosive (chemicals)	2.18×10^{7}	g	6.38×10^{8}	c	1.39×10^{16}
Packing materials					
Paper bag	1.51×10^{9}	g	6.55×10^{9}	d	9.89×10^{18}
Polyethylene	6.65×10^{7}	g	8.85×10^{9}	e	5.89×10^{17}
Pallets	1.31×10^{3}	g	2.40×10^{9}	e	3.15×10^{12}
					1.05×10^{19}
Water input	3.18×10^{11}	g	1.95×10^{6}	f	6.20×10^{17}
Human work	5.42×10^{10}	J	1.24×10^{7}	g	6.73×10^{17}
Emergy of cement	7.10×10^{11}	g	–		2.16×10^{21}
Specific emergy of cement	1.00	g	3.04×10^{9}		

3.2. Emergy analysis of materials transport

Cement is the binder that is mixed with water and other inert materials to obtain concrete for buildings. This blending process can take place either in the building yard or in a ready-mix plant requiring simple equipment and a procedure with a few steps; transport of materials to the site of concrete production is therefore a necessary step. The process can be conceived as a transformation process: the state of materials including their position in space, changes. We therefore inducted the emergy used for transport of materials per unit mass. This measure is valid for different kinds of inert materials, for example liquid, powder, gravel, rubbles, fragments, bricks or blocks. It is presumably also valid for transport of different types of products, not only building materials.

The results depend on the distance from the source to the site and give a measure of the environmental impact due to transport. Since emergy flows are assessed for a covered distance, local building materials will have a lower environmental impact than remote resources.

Specific emergy for transport per unit weight of material was assessed assuming a round trip of 100 km. This average distance of 50 km from the source to the site is a likely general assumption for Italy and for Europe. The accounting procedure can be adapted to specific cases.

Emergy of transport is due to:

- Vehicle use: a truck for carrying building materials was assessed according to its weight divided into percentages of different materials (given by Buranakarn, 1998), its performance (fuel consumption) and its maximum capacity. For example, an *Iveco Trakker* was taken as a case study (9200 kg tare weight, 23,000 kg capacity, 900,000 km estimated life).

$$\frac{9200\,\text{kg}\,(\text{tare weight})\cdot 100\,\text{km}\,(\text{distance})}{900{,}000\,\text{km}\,(\text{life-use})}$$

- Fuel consumption (2.5 km/l equivalent to 0.4 l/km) was calculated for a distance of 100 km.

$$(838.78\,\text{kg/m}^3\,(\text{diesel density})\cdot 43{,}020.79\,\text{J/kg}\,(\text{diesel heat power})\cdot 0.4\,\text{l/km}\,(\text{l/km})\cdot 100\,\text{km}\,(\text{distance}))$$

- Human work (6 working hours including loading, trip and unloading) was estimated for a distance of 100 km.

$$(125\,\text{kcal/h}\,(\text{human metabolism})\cdot 4.186\,\text{J/kcal}\,(\text{energy per cal})\times 6\,\text{h}\,(\text{working hours}))$$

The emergy analysis of transport of building materials is shown in Table 2 for a fully loaded vehicle for a 100 km round trip.

The total emergy was 2.11×10^{14} sej. About 77% of the total emergy was due to fuel and 18.4% to human work. Only 4.5% of the total emergy was due to vehicles because their life was estimated at about 900,000 km, equivalent to 9000 full loaded trips.

The emergy for transport of building materials was expressed per unit weight of transported material in fully loaded vehicles. The resulting specific emergy of transport of building materials was 9.19×10^4 sej/g/km.

Table 2 – Calculation of the specific emergy of transport of building materials for a vehicle (25 tonnes capacity) on a 100 km round trip

Item	Input	Unit	Specific emergy (sej/unit)	Reference	Emergy (sej)
Vehicle tare weight					
Steel and iron (67.5%)	6.21×10^6	g	6.97×10^9	e	4.33×10^{16}
Aluminium (5.8%)	5.34×10^5	g	2.13×10^{10}	e	1.14×10^{16}
Rubber (4.2%)	3.86×10^5	g	7.22×10^9	c	2.79×10^{15}
Plastics (7.7%)	7.08×10^5	g	9.86×10^9	e	6.99×10^{15}
Glass (2.9%)	2.67×10^5	g	8.40×10^8	c	2.24×10^{14}
Copper (1.4%)	1.29×10^5	g	1.04×10^{11}	d	1.34×10^{16}
Zinc (0.5%)	4.60×10^4	g	1.04×10^{11}	d	4.78×10^{15}
Other metals (0.9%)	8.28×10^4	g	6.97×10^9	e	5.77×10^{14}
Other materials (9.1%)	8.37×10^5	g	1.68×10^9	c	1.41×10^{15}
Total (100%)	9.20×10^6	g	9.22×10^9	–	8.48×10^{16}
Emergy: vehicle life time	9.00×10^5	km			8.48×10^{16}
Emergy: vehicle use per 100 km	100	km			9.42×10^{12}
Fuel (diesel) per 100 km	1.44×10^9	J	1.13×10^5	b	1.63×10^{14}
Human work per 100 km	3.14×10^6	J	1.24×10^7	g	3.89×10^{13}
Emergy: transport per 100 km					2.11×10^{14}
Vehicle capacity	2.30×10^7	g			
Specific emergy per 100 km	1.00	g	9.19×10^6		
Specific emergy per km	1.00	g	9.19×10^4		

Table 3 – Calculation of the specific emergy of concrete by emergy assessment: 23 tonnes load

Item	Input	Unit	Specific emergy (sej/unit)	Reference	Emergy (sej)
Materials					
Water (8.2%)	1.89×10^6	g	1.95×10^6	f	3.68×10^{12}
Cement (16.39%)	3.77×10^6	g	3.04×10^9	Table 1	1.15×10^{16}
Sand (29.51%)	6.79×10^6	g	1.68×10^9	c	1.14×10^{16}
Gravel (45.9%)	1.06×10^7	g	1.68×10^9	c	1.77×10^{16}
					4.06×10^{16}
Transport (91.8%) per km	2.11×10^7	g	9.19×10^4	Table 2	1.94×10^{12}
Transport (91.8%) per 100 km	2.11×10^7	g	9.19×10^6	Table 2	1.94×10^{14}
Plant and machinery					
Cement mixer capacity (1full load)	2.30×10^7	g			
Cement mixer tare weight	9.20×10^6	g	9.21×10^9	Table 2	8.48×10^{16}
Cement mixer life time (9000 full loads)	9.00×10^4	n.			
Emergy: cement mixer use per load	1	n.			9.42×10^{12}
Storage bin per load	7.19×10^4	g	6.97×10^9	e	5.01×10^{14}
					5.11×10^{14}
Fuel per load	2.89×10^9	J	1.13×10^5	b	3.26×10^{14}
Human work	4.19×10^6	J	1.24×10^7	g	5.19×10^{13}
Emergy of concrete	2.30×10^7	g			4.17×10^{16}
Specific emergy of concrete	1	g	1.81×10^9		

To give an example, the emergy used by a vehicle that carries 16 tonnes of gravel from a quarry to a building yard (distance 120 km) and returns empty is:

$$(16,000,000\,\text{g}\,(\text{material quantity}) \cdot 240\,\text{km}\,(\text{distance}) \cdot 91,900\,\text{sej/g}\,(\text{specific emergy})) = 3.53 \times 10^{14}\,\text{sej}\,(\text{emergy of transport of materials})$$

3.3. *Emergy analysis of concrete production*

Concrete is a mixture of inert material of different sizes, such as sand and gravel, with water and cement (binder), that is cast into formwork where it sets. The quantity of cement, the size of the inert material and the percentage of water in the mixture give different results. Mixing therefore is a very important process for the technical properties of concrete which vary with the use to envisaged. For example, a high proportion of cement (about 300 kg/m^3) is used in reinforced concrete for building frames; a low proportion is used for building elements (about 150 kg/m^3) not intended to bear load.

For our study, concrete with medium performance was considered. Average percentages were obtained from the Portland Cement Association (1979): 8.20% water; 16.39% cement; 29.51% sand; 45.90% gravel.

Materials are carried to the site where the concrete is produced (usually in the building yard) by vehicles. Transport was assessed in relation to the quantity of materials transported (excluding water, inert materials are 91,2% by weight) and to the distance from source to site. At the site of concrete production, dry materials are stored in a tank (concrete bin) for proportioning and from the tank down to a truck (concrete mixer) for mixing. A concrete bin is a cylindrical steel tank on four pillars about 3 m above the ground. The concrete mixer is a special truck (in our case *Iveco Trakker*: 23,000 kg capacity) for mixing and for transporting ready-mixed concrete.

In our case study, the emergy of cement production was due to the following inputs, raw materials, transport, plant and machinery (a vehicle was used for concrete mixing), fuel, human work. Fuel consumption was assessed for concrete mixing in the truck separately from fuel for transport. Human work was expressed in working hours (2 h × 4 workers) from storage of materials in the bin to loading in the concrete mixer, ready for casting.

Table 3 shows the emergy analysis of a standard concrete production process considering a full load of 23 tonnes ready for casting.

The total emergy consumed by the process of concrete production was 4.17×10^{16} sej, 97.4% of which was embodied in the natural sedimentary cycles of building materials. Transport (0.47%), machinery (1.22%), fuel (0.78%) and human work (0.12%) were negligible secondary inputs.

Back to Fig. 1, the emergy values reported in the energy system diagram refer to the production of 23 tonnes of concrete equivalent to a full load of a standard cement mixer, including the emergy required to produce the necessary quantity of Portland cement (3.77 tonnes) and the emergy for transport of materials: cement (3.77 tonnes), sand (6.79 tonnes) and gravel (10.56 tonnes).

4. Discussion

The specific emergy of concrete was 1.81×10^9 sej/g while the specific emergy of cement was previously computed (Section 3.1) equal to 3.04×10^9 sej/g. These values have to be considered for an Italian or even European context. Standard processes for Portland cement production and transport of materials would differ with respect to other countries, such as

Table 4 – Specific emergy of concrete from different sources

Specific emergy (sej/g)	Reference
7.34×10^8	Björklund et al. (2001)
1.54×10^9	Buranakarn (1998)
3.70×10^9	Brown and Buranakarn (2003)
1.06×10^9	Brown and McClanahan (1992)
1.81×10^9	This study

the USA. Table 4 shows a series of concrete specific emergy values from the literature with relative references. Values of specific emergy are relative to the 15.83×10^{24} sej/year baseline as defined in the literature cited (Odum et al., 2000).

4.1. *Sensitivity analysis*

A sensitivity analysis on the calculation of specific emergy of concrete was performed, considering potential changes in the main inputs to the process.

Energy inputs and raw materials, especially limestone, are the main inputs in cement production.

A decrease of 20% of the energy inputs (including electricity, pet coke and oil) was hypothesised, for example, improving the energetic efficiency in the process. In this case, specific emergy would decrease of 9×10^7 sej/g for cement and 1×10^7 sej/g for concrete. Thus, a variation of a 20% of the total energy input would lead to a variation of about ±3.2%.

Since raw materials, especially limestone, are the main inputs, a different limestone/concrete ratio was considered in order to evaluate how results change.

In the present study, a gram of mined limestone is embodied in 5.4 g of concrete (limestone/cement = : 1.13; cement/concrete = 0.16) as in the following equation:

$$\text{Proportion of raw limestone in concrete} = \frac{1\,\text{g cement}}{1.13\,\text{g limestone}} \times \frac{1\,\text{g concrete}}{0.16\,\text{g cement}}$$

According to an average of world statistics (CEMBUREAU, 2005), a gram of mined limestone is embodied in 7.85 g of concrete, which leads to a decrease of cement and concrete specific emergy: from 3.04×10^9 sej/g to 2.43×10^9 sej/g (variation of 20%) and from 1.81×10^9 sej/g to 1.71×10^9 sej/g (variation of 5.5%), respectively.

4.2. *Emergy investment ratio*

Among emergy-based indicators we have chosen to discuss the value of the Emergy Investment Ratio (EIR), the emergy of the external purchased inputs supporting the system in relation to all local emergy. A high level of the EIR represents a sort of fragility of the system because of its dependence on inputs from other economic systems. In general, the degree of dependence on other systems shows a weakness in the competitive capacity (self-sufficiency and long term sustainability), because the availability of resources for development and maintenance is not under the system's control (Bastianoni et al., 2005b; Pulselli et al., 2008).

In the case of the cement and concrete production, it was discovered, respectively, a low level and a high level of purchased resources with respect to the local resource availability. These results depend on the definition of the boundaries of the system. What is our system? Which of the inputs to the process is available inside the system and which one comes from outside the system? According to the energy system diagram, our reference system is a limited region where both the *quarry + cement factory* (they are usually close to each other) and the building yard are located, while materials for concrete production are imported from outside. The meaning of this indicator can change relative to the case studies.

In the phase of cement production, almost 16% of resources are imported from other sites. The EIR of cement production was assessed as follows:

$$\frac{4.76 \times 10^8\,\text{sej (purchased inputs)}}{2.57 \times 10^9\,\text{sej (local resources)}} = 0.19\,\text{(Emergy Investment Ratio)}$$

In the process of concrete production, almost 76.6% of resources are imported from other sites (this percentage could easily change if we consider materials local or imported from the outside). The EIR of concrete production was assessed as follows:

$$\frac{1.39 \times 10^9\,\text{sej (purchased inputs)}}{4.24 \times 10^8\,\text{sej (local resources)}} = 3.27\,\text{(Emergy Investment Ratio)}$$

Results highlight the importance of raw materials that could be local, in the case of cement, or both local and external, in the case of concrete. Their location, inside or outside the system, makes this indicator change. However, besides raw materials, purchased inputs have a relevant role in the production process, considering that they are mostly fuels.

Usually, in production systems also the Environmental Loading Ratio (ELR) is considered as the ratio of non-renewable to renewable emergy. In this case, ELR is close to infinite, therefore not relevant.

5. Conclusion

In this paper, an evaluation of building materials sustainability was presented through an emergy evaluation. The specific emergy of cement and concrete are 3.04×10^9 sej/g and 1.81×10^9 sej/g, respectively, in the Italian context.

The emergy analysis of cement and concrete production takes into account various steps in the process. More than procedures for materials production, the results highlight the impact of the use of quarry materials. These are seen as mineral resources with high specific emergy provided by natural sedimentary cycles and accounted in sej. In the case of cement, materials (limestone, chalk, shale, clay and sand) are about 84% of the total emergy, while emergy for the blast furnace is about 15%. In the case of concrete, materials (sand, gravel, crushed stone, cement) are about 97% of the total emergy. Thus emergy highlights the critical role of overuse of non-renewable resources in the building industry, since it accounts for the work of nature (sedimentary cycle), not only human work for quarrying (the only process accounted in economic analysis). The dominant contribution of mineral resources underlines the un-sustainability of the building industry. Non-renewable and non-recyclable materials such as cement and concrete are undergoing depletion.

Other procedures in the process of concrete production were accounted by the present emergy analysis though with less emphasis.

Transport of building materials was assessed separately because it is a transformation process (materials change position in space) with impacts that vary from case to case. The specific emergy of material transport was 9.19×10^4 sej/g/km. This was calculated to enable accounting of different kinds of materials, liquid, powder, rubble, gravel, fragments, bricks or blocks, according to quantity and distance from source to site. It is presumably also valid for the transport of other types of products. Although the emergy contribution of transport to concrete production less than 1%, the environmental cost (specific emergy) makes it possible to evaluate the energy saving available if local materials are chosen and to appreciate the importance of a traditional local architecture with local materials on a thermodynamic basis.

The Energy Investment Ratio was assessed as a sustainability indicator to evaluate the dependence on local or external sources. Raw materials have a relevant role in the emergy assessment of cement and concrete production and they are provided by Nature for free; they are not economically accounted despite their importance as highlighted by the emergy assessment. However, besides raw materials and their location inside or outside the system (this makes the EIR change), a relevant portion of external resources, especially fuels, are needed to produce cement and concrete. Thus, both the production processes strongly depend on purchased inputs.

In conclusion, specific emergy is presented as a measure of the environmental resource use due to building materials; it is an intensive parameter that provides a classification of building materials on the basis of an energy hierarchy. In general, emergy analysis combines quality (specific emergy) with quantity (energy or mass). For example, emergy analysis of construction process will depend on the choice of building materials (quality in terms of environmental cost due to use of energy and matter) and the building project itself (quantity of materials needed to build structural elements).

From a thermodynamic viewpoint, buildings are like reservoirs of energy spent in transformation processes to provide building materials and assemble them. Emergy provides a measure of building sustainability in terms of emergy investment. Many units of low quality energy are used to provide a high quality energy (high specific emergy). Energy is embodied through a chain of transformation processes and its memory is conserved in the building frame.

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