A Systemic Approach to Concrete Constructions

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Abstract. In recent years the term design has been overexploited in popular magazines, newspapers and on television. Schools and universities have increased the courses on offer which now include very different design disciplines, from social design to systemic design. The latter, in particular, is the ability to outline and plan the flow of matter and energy from one system to another, within metabolization processes which reduce the ecological footprint and generate a remarkable economic flow. Today designers are asked to strategically design a scenario that doesn't focus only on product innovation as an end in itself, but involves developing broader issues which require the input and expertise of other fields of learning. These issues necessarily include non-traditional economic and industrial models (i.e. Circular Economy, Blue Economy and Bioeconomy). This paper aims to create bridges between the world of construction engineering and design practices based on non-linear industrial models. It stimulates a discussion about systemic design challenges in relation with the concrete structures, evidencing some challenges, open questions and possible new directions.

Keywords: Concrete structures · Systemic design · Construction · Environment

1 Introduction

Systemic Design (SD) is the ability to outline and plan the flow of matter and energy from one system to another, within metabolization processes which reduce the ecological footprint and generate a remarkable economic flow [1]. Its roots are in cybernetics and the complexity of systems and it regards the study of industrial and agricultural processes with an eye to transforming the output of a process in a chain mechanism whose goal is the total elimination of manufacturing waste. The final objective is providing benefits for the whole community: total reduction of the production output, creation of new job placements, new virtuous cooperation among people and better environmental quality. This model takes the inspiration from the foundations of the generative science. More than ever before we need to design products, systems and services efficiently and in an ecologically correct manner. We cannot ignore anymore the complex relationship between action and reaction in natural and artificial systems. Architects and Engineers were already aware of this in the fifties, when they realised how complex and difficult design actually was: "(…) problems have

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a background of needs and activities which is becoming too complex to grasp intuitively" Christopher Alexander wrote in his milestone book Notes on the Synthesis of form [2]. Too many variables became involved and an interdisciplinary approach was needed with the input by experts from more than one field of learning. The process that gradually developed and grew during that period helped to break down disciplinary barriers and moved in the opposite direction to the monodisciplinary and specialist approach of the first half of the nineteenth century, an approach that had been adopted to counter the boom in knowledge, especially scientific knowledge. Today designers are asked to strategically design a scenario that doesn't focus only on product innovation as an end in itself, but involves developing broader issues which require the input and expertise of other fields of learning. These issues necessarily include non-traditional economic and industrial models.

This paper aims to create links between the world of construction engineering and design practices based on non-linear industrial models. It tackles the issue of sustainability in the field of concrete structure applying a systemic approach to satisfy both sustainable and mechanical requirements. The paper offers a critical reading of some case studies and stimulates a discussion about systemic design challenges in relation with the concrete world, evidencing some challenges and new directions toward sustainability.

2 Challenges in Concrete Structures

As shown in Fig. 1, concrete is a composite material made of cement (the binder), water, stone aggregates, and additives. Although concrete is the most widely used material on the earth after water, it is not environmental friendly. Indeed, the production of cement requires high amounts of energy, water and natural resources [3]. Thermal energy usually constitutes around 90% of total energy and is used for activities such as the clinker burning unit and to dry out raw materials. Producing clinker entails carbonizing limestone, which takes place at about 900 °C during which the limestone decomposes into CaO and CO_2. Temperatures of around 1400 °C are needed to decarbonize and later sinter raw meal (Fig. 2). The remaining 10% of the energy is electricity, which is mainly needed to grind coal, raw meal and cement. Water consumption in the cement plant is due to the preparation of the slurry in wet-process kilns. Water is fundamental also for the treatment of the exhausted gas, the quenching of the cement, the cooling down of engines and the dust abatement. It must be remarked that also the other components of concrete are consumed faster than they can be replenished

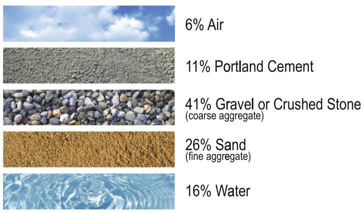


Fig. 1. Composition of concrete

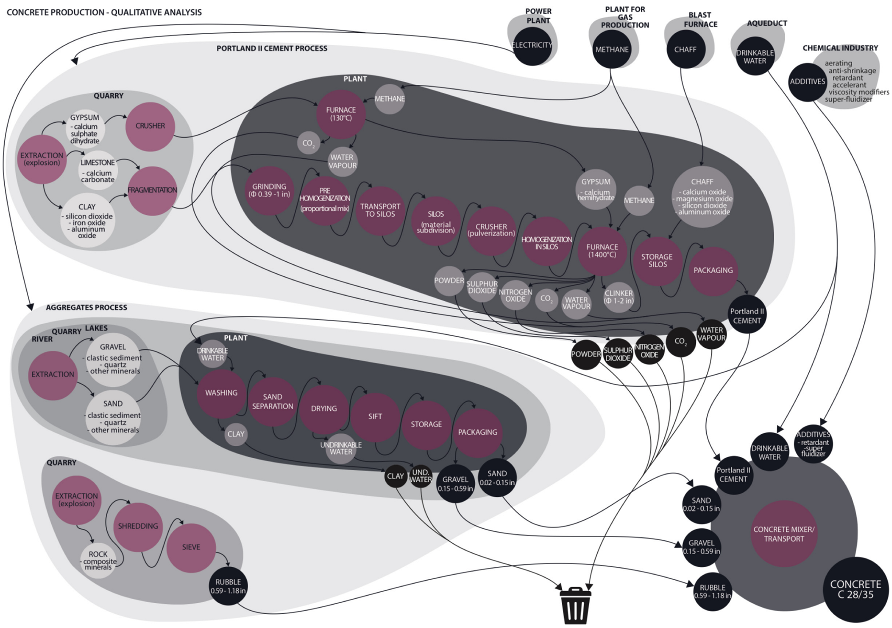


Fig. 2. Concrete production: qualitative analysis

(resource depletion). The world consumption of aggregates exceeds 40 billion tonnes per year, which is twice the amount of sediment carried by all the rivers in the world. Thus, to reduce the impact of concrete on biodiversity, land losses, water supply, climate changes, extreme events, etc., clean technologies need to be applied to concrete production. For these reasons, several efforts are directed to reduce the use of natural raw materials for cement production (limestone, marl, clay, sand, schist, gypsum and pozzolana) or substitute them with byproducts and non hazardous wastes. The literature review provides some interesting examples of "new" materials deriving from external production processes: fly ash, slag, sludge, chemical gypsum, incinerator slag, mill scales and alumina dust. These are all outputs of production processes transformed in input for the cement industry satisfying quality requirements.

Cement manufacturing is highly energy and produces intensive CO2 emissions. This industry is one of the major causes of global warming on the planet: the direct emission factor of CO2 in the cement plant mainly depends on the extreme heat required to produce clinker. Therefore it seems urgent reducing its quantity or replacing it with secondary raw materials. Cement, as seen above, could be an interesting repository of industrial, and even agricultural, waste products: i.e., silica fume, steel slag and husk ash. In particular, ash from burning of rice husks is one of the most cutting-edge product deriving from agricultural waste, even if its limited availability. The rice husks are burned without oxygen at a temperature of 800 °C. The product resulting from this process is practically pure silicon. 20% of cement conventionally used in the preparation of concrete could be replaced with this silicon of vegetable origin, which moreover provides protection against corrosion and strengthens the concrete (Fig. 3).

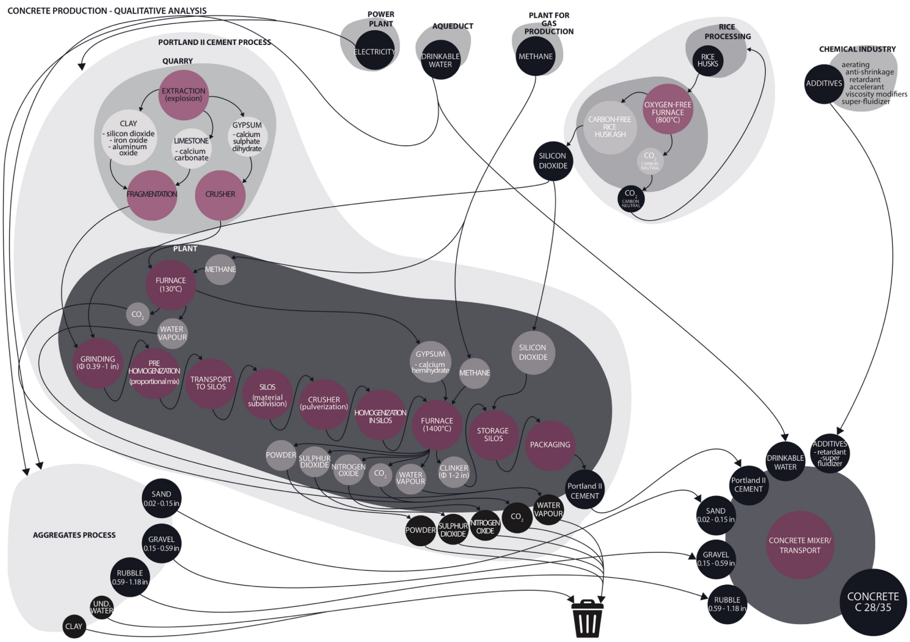


Fig. 3. 20% of cement conventionally used in the preparation of concrete could be replaced with silicon of vegetable origin

Regarding the energy field, cement manufacturing plant demands thermal energy provided by incineration of mainly fossil based fuels. This heavy amount of energy is often integrated by a contribution from the slaughterhouse waste (animal meal). Meal derived from animal meat and bones has a high calorific value to fuel kilns generating significant amounts of calcium salts, which may also be used in replacement of raw materials [4].

2.1 New Breakthroughs in Construction Engineering: The Frejus Highway Security Tunnel

A systemic design approach to building engineering was applied at the beginning of this century to the preliminary study for the construction of a security gallery (second tube) of the Frejus highway tunnel. This 12.9 km long infrastructure connecting the towns of Modane (France) and Bardonecchia (Italy) is one of the main Alpine crossings between France and Italy. It is still under construction and it will enter into service in 2019.

The systemic approach developed by Sitaf spa (Italian society managing the A32 highway and the Frejus Tunnel), Zeri Foundation, Università di Torino (Agricultural Sciences) and Politecnico di Torino (Design, Materials and Mechanical Engineering) raised by the necessity of finding systemic solutions to the excavation of tons of rocky materials and the impact of logistics activities on environment and society.

The main point of this project (unfortunately never implemented) consists in increasing the value of the rock chips (muck) which is mainly a waste and rarely used for construction applications [1]. Physical and chemical analysis of the rock demonstrates the presence of significant amount of calcareous schists potentially used in rice fields to cover the soil. This material has a potential of 230,000 tons of calcite and 150,000 tons of miche, that compensates for the lack of silicon caused by an intensive rice cultivation. The design research leads to a series of considerable benefits: better use of material properties, reversed decline of the impoverishment of soil quality, reduced use of plant protection products (pesticides) and improvement of the soil water retention.

The project provides solutions for placing the material extracted from the tunnel. The approach changes the usual perspective of things: waste becomes resource and resources are used to generate new products. At the same time it works for preventing the soil impoverishment in the areas of Novara and Vercelli (Piedmont region). Generally, the intensive rice cultivations are focused on the maximum output of the plant, taking into account only the grain and not the whole plant. The objective is to increase the value of the whole rice biomass. The analysis of the cycle referred to the rice production shows two products which are not considered at all: the chaff (husk of grains) and the straw. The former is rich in silicon and germanium, the latter in cellulose and lignin. All these high value materials are obtained by the chaff steam explosion process. Germanium could be used in electric and electronic equipments, lignin is a great combustible material which produces clean energy: it comes from season crops and the combustion process produces an amount of carbon dioxide equal to the amount absorbed by the plant during its whole life. Finally, cellulose could be used as a row material in the production of “non oil” plastic material, while silicon could be exploited as semi-conductor in the production of photovoltaic panels.

Summing up, chaff and straw, first considered as a waste, useful only for combustion, are now row materials for applications in several technical fields. Even the muck, rich in natural substances, originally used as a filling material, could be exploited to avoid the excessive use of plant protection products.

3 The Ecodesign of Concrete Structures

Unlike other construction materials, it is impossible to tailor a concrete mixture that can be universally considered the most sustainable. This is due to the following reasons:

– The composition of structural concrete depends on the required performances (or functions), which are not always the same (e.g., one-way or two-way slabs are designed to resist to bending actions, whereas columns are mainly compressed).
– For a specific function, concrete is tailored in different ways, because the availability of natural resources is not the same in all the zones of the Earth.

Recently, rubber from end-of-life tires has been used to achieve a more favorable Life Cycle Assessment (LCA) of structural concrete [5]. In some European Countries, rich of stone quarries but poor of oil fields, such as Italy, it is more convenient to produce the clinker by burning this rubber. Whereas, in the Middle East (e.g., Qatar), where a large quantity of oil can be found, but aggregates for concrete are very scarce, it seems more appropriate the use of rubber in substitution of the natural stone aggregates. In the latter case, the so-called rubber concrete does not perform as the traditional concrete does, and sometimes it is not suitable for structural applications. Thus, LCA can only compare group of concretes available in a specific marked and tailored to fulfill specific requirements, or functions. Moreover, concretes should always be associated to a functional unit, which provides a reference for the inputs and outputs of LCA.

In the case of structural concrete, Damineli et al. [6] suggest the use of a functional unit of performance - the compressive strength f_c - instead of the unit of concrete volume or weight - 1 m^3 or 1 kg. The following indexes can therefore be used in the comparative analysis [6]:

- the Binder intensity indicator (bi_{cs}), which measures the total amount of binder, contained in a cubic meter of concrete, necessary to deliver 1 MPa of compressive strength,
- the CO_2 intensity indicator (ci_{cs}), defined as the amount of CO_2 released for the production of a cubic meter of concrete, to deliver 1 MPa of compressive strength.

As both bi_{cs} and ci_{cs} decrease with f_c (see Fig. 4a), high-strength concretes are in principle more sustainable than normal-strength concretes.

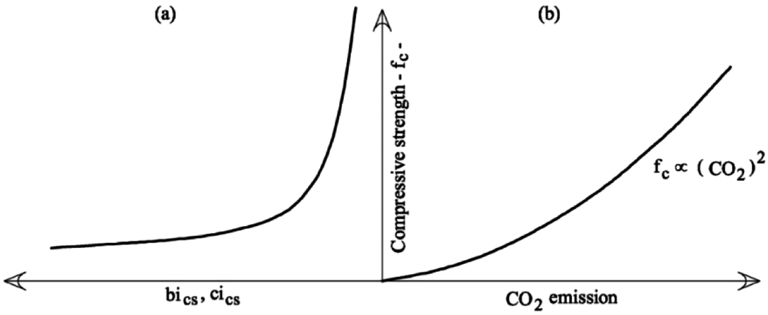
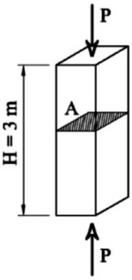


Fig. 4. Concrete strength as the functional unit of LCA: (a) the binder and the CO_2 intensity indicators *vs.* f_c [2]; (b) the amount of CO_2 released for the production of a cubic meter of concrete (with a strength f_c) [3].

The same results can also be obtained through the so-called material performance strategy, which consists of improving the performances to reduce the impact of concrete [7]. Indeed, the amount of concrete, and of the released CO_2 as well, reduces when concrete strength increases, although f_c is proportional to the power 2 of the CO_2 emissions per cubic meter of concrete (Fig. 4b). As an example, the environmental impact of two columns, made respectively with concrete of strength 40 MPa (type 1) and 60 MPa (type 2), are compared in Fig. 5a. The higher the strength, the larger the amount of CO_2 released by a cubic meter of concrete, but the lower the cross-sectional area A and the volume (of concrete and CO_2) of the entire column.

To increase f_c, the content of cement must be increased, whereas the amount of water should remain the same, or reduced by adding superplasticizers to concrete

(a)



	Concrete		
	type 1	type 2	type 3
P (kN)	3600		
f_c (MPa)	40	60	40
CO_2 (kg/m^3) concrete production	280	350	230
$A = P / f_c$ (m^2)	0.09	0.06	0.09
Volume = A· H (m^3)	0.27	0.18	0.27
CO_2 (kg) column production	75.6	63	62.1

(b)

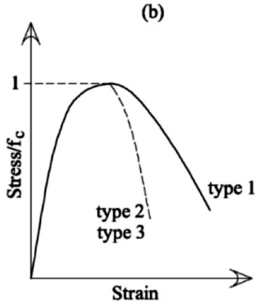


Fig. 5. The environmental impact of three concrete columns: (a) the production of carbon dioxide; (b) the stress-strain relationship of the concretes subjected to uniaxial compression.

mixtures. In addition, the porosity needs to be reduced by using, for instance, fine pozzolanic admixtures [8]. Such additives can also substitute Portland cement, the major responsible of the CO_2 production, without compromising the strength. This is the case of type 3 concrete (Fig. 4a), in which a part (18% in weight) of the cement contained in type 1 concrete has been substituted by the same amount of fly ash and silica fume [9]. In accordance with the substitution strategy suggested by Habert and Roussel [7], the impact of the type 3 column is lower than that of type 1 concrete, despite the same strength and volume of the column.

Nevertheless, concrete mixtures with higher strength show a more brittle behavior. Thus, the performance strategy (applied to type 2 concrete) causes a steeper softening response of concrete, as illustrated in the stress-strain diagrams reported in Fig. 5b. As a result, the column cast with type 2 concrete requires a larger amount of transversal rebar (whose area is in direct proportion to f_c [10]), with respect to the same column made with type 1 concrete. In such cases, the environmental advantage of decreasing the volume of concrete (due to the increment of strength) vanishes, because more stirrups or spirals are needed in compressed columns.

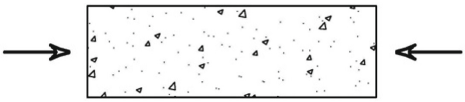
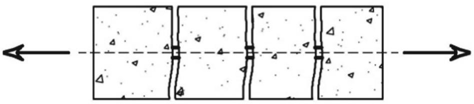
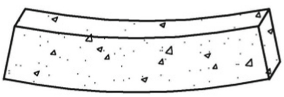
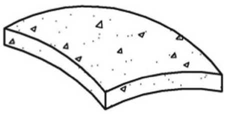
Similarly, the substitution of cement with pozzolanic admixtures can lead to a reduction of the mechanical performances. In particular, in concrete where part of cement is replaced by silica fume and fly ashes (i.e., type 3 concrete), the strength does not change (with respect to type 1 concrete) but the post-peak stage is more brittle, as in high strength concrete (i.e., type 2 concrete) [9].

The above-mentioned brittle response indicates that, in some structures, compressive strength cannot be used as the functional unit of LCA, although f_c is adopted to classify structural concrete. Conversely, as suggested by Fantilli and Chiaia [9], the fracture toughness in compression must be the functional unit of the concretes used to cast columns. When referred to this mechanical property, the use of steel or plastic fibers also produces environmental advantages, because they bridge the cracks and increase the residual stresses in the post-peak stage of Fig. 5b. Conversely, with respect to the compressive strength, fibers do not produce any environmental benefit, because the production of CO_2 increases (a volume of steel is added to the mass of concrete) without modifying f_c [11].

The necessity of considering other performance parameters is also evident in reinforced concrete (RC) structures prone to cracking in aggressive environments. In such RC elements, to increase the chloride penetration resistance (and therefore the structural durability), cracks in the tensile zones need to be narrow. Hence, crack width is the structural performance that can be used as the functional unit of cracked RC structures [12], instead of f_c (which is a material performance). Nevertheless, Fantilli and Chiaia [13] showed that an effective LCA can also be performed among cracked structures by using the fracture energy of concrete in tension, instead of crack width. In concrete structures without rebar and subjected to bending actions, the optimal functional unit depends on the post-cracking response of concrete.

In beams and slabs made with traditional concrete having a strain softening in the post-cracking stage, flexural strength is more representative than compressive strength. In lightweight concrete slabs investigated by Fantilli et al. [14], the better performances can be observed when granulated rubber substitutes the traditional expanded clay

Table 1. The functional units of some concrete structures.

Type of concrete structure		Functional unit	Ref.
Compressed		Compressive strength	[2, 5]
		Fracture toughness in compression	[5, 9]
RC elments prone to crack in aggressive environments	 	Crack width	[8]
		Fracture toughness in tension	[9]
Beams and slabs without rebar	 	Flexural strength in strain softening concretes	[10]
		Maximum bending moment in strain hardening concretes	[11]

aggregate. On the contrary, if the comparative analysis is limited to the compressive strength, the use traditional aggregates (stone or expanded clay) is always more convenient than the rubber from end-of-life tires.

If high performance concretes are used to cast elements subjected to bending actions, the functional unit must be again a structural performance and not a material property (i.e., compressive or flexural strength). As in the case of high strength concrete (type 2 in Fig. 5a), the environmental cost (in term of CO_2 produced per cubic meter) is remarkably higher than that of traditional concrete. Thus, to assess the environmental benefit, the input and output of LCA must be referred to the ultimate (or the maximum) bending moment of beams and slabs made with ultra-high performance concrete [15].

It must be finally remarked that both the flexural strength and the ultimate bending moment depend on the post-peak behavior (and on the ductility) of concrete in tension. For this reason, the possible functional units of structural concrete, as summarized in Table 1, always take into account the fracture toughness of concrete, in a direct or indirect manner.

4 Conclusions

The analysis reported in the previous sections has mainly pointed out four conclusions:

- it does not exist a concrete which can be universally considered the most sustainable. Moreover, the design of concrete structure cannot be only based on the mechanical performances: a systemic approach is necessary when concrete structures have to satisfy both sustainability and mechanical requirements.
- when we talk about production in a SD perspective, we do refer not only to industrial production but also to agricultural production. Within the same territorial context, we need to ensure that agriculture, industry, and the community at large blend harmoniously with the natural system: this is the key to a production model of sustainable growth.
- in SD physical objects could disappear while the methodological process and metaproject become much more important. Open industrial systems are designed to avoid production waste: the focus moves to production in which the output becomes a resource (input) for another production process. Considering the all elements of a system (such as the one applied to the second tube of the Frejus Highway Tunnel), the next challenge would be to design links among different sectors, from agriculture to the cement industry. Is it really possible to trace a line between the tons of muck from the mountain and the rice husks burned to produce green cement? Who are the main professionals to be involved in the project? Where is the limit of a system?

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