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Life Cycle Thinking in decision-making for sustainability: from public policies to private businesses

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Concrete design optimization by LCA: a critical analysis

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Abstract

In today's societies, concrete is ever more frequently used, but its production demands a large amount of power that creates environmental pollution. The main material composing concrete is cement which is made from clinker. The necessary high production temperatures cause emissions of CO_2. Simultaneously, very significant amounts of demolished concrete produced from deteriorated and obsolete structures create severe ecological and environmental issues. One of the ways to solve these problems is to use this 'waste' concrete as an aggregate. Various authors have studied the effects of mixing a portion of recycled aggregates with concrete and they found that this solution has a positive effect on environmental impacts reduction. Preservation of the environment and conservation of the rapidly diminishing natural resources should be the essence of sustainable development.

1 Introduction

Nowadays, concrete is the most used building material all over the world, but the presence of clinker in the concrete mixture makes this material harmful to the environment. The production of concrete requires a large amount of energy that causes environmental pollution. Cement with a lower environmental impact in terms of carbon footprint, embodied energy and water use should be utilised with the aim to design in a more ecological way. (Fantilli et al., 2015).

If we analyse the life cycle of concrete, we can see that at the end-of-life it becomes the so-called "construction and demolition waste" (C&D). This means that after its lifespan, concrete is demolished and most often disposed of in a landfill (Corinaldesi and Moriconi, 2014).

With the desire to draw the attention to this alarming and worldwide overbuilding, the main target of this work is to gather the basic principles regarding concrete, its production, its life cycle and its environmental impact. This paper wants to be a review of the previous papers concerning the concrete topic that it is possible to find in the scientific literature and it is structured as follow. In section 2 after a general description of the main concrete components, a concise definition of LCA is given with direct reference to the concrete LCA. The environmental impact of concrete is analysed in section 3 with a separate analysis of the environmental impact of each of the concrete mix design components. Cement firstly and successively the aggregates. Section 4 shows the feasible use of recycled aggregates with a description of the properties that characterize aggregates made from construction and demolition (C&D) waste and of the environmental impact own of the recycled aggregates. As a conclusion of this review work, the sustainable design is presented in section 5 with reference to a new design philosophy oriented towards the analysis of the whole life-cycle.

2 Concrete

a. A general description

Worldwide concrete consumption has increased over the years. In 2016 it rose by 1,7% and reached 3,97 billion tons, 66 million more than 2015 (AITEC, 2016). This makes concrete one of the most common building materials on the market. The main ingredients in concrete are aggregate (70-80%), cement (10-2%) and water (7-9%), and to enhance specific characteristics, chemical admixtures (less than 1%) are added (Sjunnesson, 2005). In the cement production process, which is the main component of concrete with the role of hydraulic binder, not only do natural resources such as limestone and clay become depleted, but environmentally relevant gaseous substances are also emitted during clinker manufacturing through pyro process, due to large amounts of energy use (Kim et al., 2016). Additionally, the extraction of natural aggregates can lead to soil erosion or ecosystem destruction, while the waste sludge and wastewater emitted from a concrete batch plant have harmful effects on the water ecosystem (Cucchiella et al., 2014).

b. LCA of concrete

The life cycle assessment, LCA, is the investigation and the evaluation of the environmental impacts of a product, process or service. LCA evaluates all stages of a product’s life and considers each stage interdependently, meaning that one operation leads to the next (Lemay, 2011). The environmental impact assessment on concrete was based on the life cycle assessment process suggested in the ISO 14040 (ISO 14040:2006). Some environmental problems arising from concrete use are global warming, ozone depletion, photochemical ozone creation, abiotic depletion, eutrophication, and acidification.

3 Environmental impact of concrete

Concrete is the most heavily consumed material in the construction sector and the second most heavily consumed substance on Earth after water (Weil et al., 2006). As a consequence, it is obvious that the construction sector employs a lot of power and emits large amount of greenhouse gases like CO_2 into the atmosphere. Indeed, power is required for the extraction, transport, production, and manufacturing of building materials and components (Corinaldesi and Moriconi, 2014).

a. Environmental impact of cement

The fundamental raw material in the production of Portland cement is limestone. The very high temperatures of the cooking process (some phases reach 1450°C) causes the chemical reaction in which the limestone is broken down into the fundamental components: CaO and CO_2. Other CO_2 emissions come from the carbon contained into the fuel used to reach the high temperature needed to produce the clinker. 60% of the CO_2 emissions derive from the limestone decarbonisation, while the remaining 40% derives from the combustion of the fossil fuels (Corinaldesi and Moriconi, 2014).

b. Environmental impact of aggregates

Aggregates form more than 80% of the weight of a typical concrete mixture. The extraction of a ton of natural aggregates needs 20 MJ of energy by fossil fuel and 9 MJ of electric energy, while smashing a ton of aggregates needs 120 MJ and 50 MJ (Worrell et al., 1994), respectively. So, the use of natural aggregates instead of smashed aggregates in concrete production involves a lower consumption of fossil fuels and smaller CO_2 emissions, but the insufficient availability and the resulting environmental impact constitute a very difficult problem to solve.

Preservation of the environment and conservation of the rapidly diminishing natural resources should be the essence of sustainable development. Continuous industrial development poses serious problems of construction and demolition waste disposal (Topcu and Guncan, 1995). On the one hand, there is critical shortage of natural aggregates for production of new concrete, on the other the enormous amounts of demolished concrete produced from deteriorated and obsolete structures creates severe ecological and environmental issues. One of the ways to solve this problem is to use this ‘waste’ concrete as an aggregate (Khalaf et al., 2004; Raeis Samiei et al., 2015), the so-called recycled concrete aggregate (RCA).

Concrete debris was once routinely shipped to landfills for disposal, but recycling is increasing due to improved environmental awareness, mandatory laws and economic benefits (Wikipedia, 2018).

The cement industry has integrated sustainable development into their global operations, with the aim to create a concrete with a smaller environmental impact. They have become leaders in industrial ecology and innovators in carbon dioxide management (The cement sustainability initiative, 2002).

4 Concrete with recycled aggregates

Construction and demolition (C&D) waste has become the largest (Schachermayer et al., 2000) and increasing (Muller 2006; Hashimoto et al., 2007) waste fraction in industrialized countries. It is estimated that the annual generation of C&D waste in the EU could be as much as 450 million tons, which is the largest single waste stream, apart from farm waste. Even if earth and some other wastes were excluded, the construction and demolition waste generated is estimated to be 180 million tons per year, and considering a population of approximately 370 million, the per capita annual waste generation is about 480 kg (Rao et al., 2007).

Thus, C&D waste reuse as concrete aggregates has been considered as a valuable option to substitute the primary aggregates in concrete production as well as reducing the C&D waste deposition, where space for landfills is increasingly scarce (WBCSD, 2009). In the European Union, where the average

C&D waste recycling rate is 33% (Eurostat, 2017), the most recent waste legislation established a material recovery rate target of 70% for 2020 for this group of wastes (including reuse, recycling or other material recovery) (EC, 2008).

a. Properties of aggregates made from C&D waste

Recycled concrete aggregates can be produced from (a) recycled precast elements and cubes after testing, and (b) demolished concrete buildings. In the former case, the aggregate might be relatively clean, with only the cement paste adhering to it, whereas in the latter case the aggregate might be contaminated with salts, bricks and tiles, sand and dust, timber, plastics, cardboard and paper, and metals. It has been shown that, after separation from other waste types, and sieving, contaminated aggregates can be used as a substitute for natural coarse aggregates in concrete (Nagataki et al., 2004). As with natural aggregate, the quality of recycled aggregates, in terms of size distribution, absorption, abrasion, etc. also needs to be assessed before using the aggregate (Rao et al., 2007).

b. Environmental impact according to recycled aggregate

Kim et al. (2016) analysed, among others, the effect of recycled aggregates mixed into concrete and they concluded that there was an increase in some environmental categories.

Indeed, as the recycled aggregate portion of concrete increased, the potential for acidification (AP), eutrophication (EP), ozone depletion (ODP), and abiotic depletion (ADO) decreased, while the potential for global warming (GWP) and photochemical ozone creation (POCP) increased (Jongsuk et al., 2014).

In more detail, Kim et al. (2016) have demonstrated that, when the recycled aggregate mixing ratio was increased, GWP increased to up to about 14%~29% compared to concrete in which only natural aggregates were mixed. This was because, in the production process of recycled aggregates, major impact substances in terms of global warming potential (GWP), such as CO_2, CH_4, and N_2O, were emitted more than in the case of natural aggregate production process. On the other end, when the mixing ratio of recycled aggregate was increased to 10%, 20%, and 30%, compared to the concrete in which only natural aggregates were used, AP, EP, ODP, and ADP were reduced to about 9%~29%. A fine analysis of the reasons of this outcome revealed that in the manufacturing process of recycled aggregates, lower amounts of substances such as NOx, NH_3, SO_2, NH_4, halon, and CFC, which greatly affect the impact categories of AP, EP, ODP, and ADP, were emitted with respect to the production process of natural aggregates. In particular, as a large quantity of natural resources is not used in waste concrete recycling, it was found that also abiotic depletion potential (ADP) was significantly reduced. As the recycled aggregate mixing ratio was increased, compared to OPC (Ordinary Portland Cement), POCP was found to be reduced to about 2%~9%. CH_4, CO, S, and C_4H_{10}, the major impact materials of photochemical ozone creation potential

(POCP) in recycled aggregate production process, were emitted less than in the case of natural aggregate production process, but there was not much difference (Kim et al., 2016).

Knoeri et al. (2013) have also studied the impact assessment using two endpoint methods (Ecoindicator 99 and Ecological Scarcity 2006), and the GWP and the abiotic depletion potential (ADP) as midpoint indicators.

This study has also demonstrated that recycled concrete mixtures for structural concrete applications have significant environmental benefits compared to conventional concrete with the same cement type at endpoint level. Strongly reduced “respiratory inorganic” effects and a slight reduction of fossil fuel consumption are the main contributors to the Ecoindicator 99 reduction, while the Ecological Scarcity 2006 reduction is caused by natural resources preservation in addition to reduced emissions to air. Recycled concrete and conventional concrete have similar GWP due to higher cement content when recycled aggregates are used. On average, recycled concrete mixtures show around 30% environmental impacts reduction when assessed by Ecoindicator 99, Ecological Scarcity 2006 and ADP compared to conventional concrete mixtures, while the two options are on the same level regarding GWP (Knoeri et al., 2013).

These two results (Kim et al, 2016; Knoeri et al., 2013) could appear in contradiction with previous studies, which resulted in comparable or even higher environmental impacts of recycled concrete aggregates with respect to virgin ones (Marinkovic et al., 2010; Weil et al., 2006).

The difference might partly occur due to differences in construction practices among the countries (e.g. transport type and distances), but it is more likely to be related to different system definitions, particularly to the fact that the demolition process, C&D waste transport and landfilling, were largely excluded until that time.

5 A sustainable design

With the desire to find a solution to this alarming and worldwide pollution problem owed to the overbuilding, structural engineering could bring about profound changes in the design philosophy.

The traditional design procedure will be converted in an analysis of the whole life-cycle (Biondini and Frangopol, 2018), from the materia prima extraction to the end of the building lifespan.

One of the main issues facing sustainable building is that today’s demolition technologies do not produce directly reusable clean recycled materials. Usually, when a construction arrives at the end of its lifespan, it is demolished and transformed into demolished ruins. During this process, various materials are mixed and suitable careful procedures are needed to allow the reuse of debris (Corinaldesi and Moriconi, 2014).

It is possible to deal with this problem in two different ways:

- Designing with the aim of recycling the materials at the end of their life of service. The design procedure could include dismantling technique (DFD, design for dismantling) that allow an easier and direct reutilization of the materials and remove components after the building demolition (DFR, design for recycling).
- Adopting selective demolishing techniques for new buildings and selective destruction for existing buildings.

This kind of analysis needs to be included into an end-to-end design, previously mentioned.

To reach this ambitious goal to reduce the pollution problem owed to the overbuilding, it will be also useful to have a partnership among all the professional figures who contribute to the design and building of a structure. This would be the best way to fuse together the architectural, structural and functional needs in the aim of reducing environmental impacts that derive from the choices taken during the design phase.

The adoption of interoperable methodologies (the so call Building Information Modelling) appear to be the best way to reach this aim of new design philosophy (Fantilli et al., 2015).

6 Conclusions

The production of concrete requires a large amount of power that causes significant environmental pollution. With the desire to draw the attention to this alarming and worldwide environmental problem, the main target of this work was to gather the basic principles regarding concrete, its production, its life cycle and its environmental impact. The aim to design in a more ecological way calls for selecting cement with a lower environmental impact.

If we analyse the life cycle of this material, we can see that it belongs to the construction and demolition waste (C&D), this means that after its lifespan, it will be demolished and deposited in a landfill. One of the ways to solve this problem is to use this ‘waste’ concrete as an aggregate, the so-call recycled concrete.

Many authors have studied the effects of the recycled aggregates portion of concrete on resultant environmental issues. The outcomes of these studies are not conclusively in favour of the adoption of recycled concrete aggregates. As expected, with current recycling technologies some impact categories, but by no means all, are favoured by the use of RCA.

For this reason, it is important a larger degree of inter-operation between architectural, structural and functional needs during the design phase, implementing smart technologies for dismantling and recycling. To this purpose, Building Information Modelling (BIM methodologies) could reveal a highly effective tool.

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