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Environmental life cycle assessment of lightweight concrete to support recycled materials selection for sustainable design

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HIGHLIGHTS

- A LCA is performed for artificial lightweight aggregates produced from waste sources.
- The environmental impacts of different types of lightweight concrete are investigated.
- Artificial aggregates produced from natural raw materials determine the highest environmental impact in concrete material.
- Lightweight aggregates produced from industrial waste raw materials provide environmental benefits due to the avoided impacts.

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ABSTRACT

The constant increase in consumption of aggregates for concrete production represents a major environmental issue in the construction industry. Recycled wastes might be used as raw materials in the manufacturing of artificial LightWeight Aggregates (LWAs) in substitution and/or in combination with aggregates produced using natural sources for several end-uses, thus saving non-renewable resources. In this study, a Life Cycle Assessment (LCA) is performed for different LWAs manufactured with raw materials supplied by nature or waste. Then, the LCA is conducted on different concretes made of the different LWAs.

1. Introduction

Concrete is the most consumed material in the construction sector and the second most consumed substance on Earth after water. The estimated worldwide concrete consumption was 32 million m^3 in 2013 [1]. Consequently, the consumption of aggregates, which represent the major component in concrete mixes, is constantly and rapidly increasing with the rise in concrete production and utilization. For example, it was estimated that 150 million tons of aggregates were produced in 2013 in the countries of European Union [1]. Inevitably, these considerations give rise to common environmental issues related to the depletion of natural resources and, consequently, to the availability of aggregates.

In the last decades, waste reuse/recycling has been considered as a valuable option to substitute the conventional aggregates in concrete production as well as to reduce waste generation. Construction and Demolition waste (C&D) recycling, for example, has the potential to reduce the amount of waste disposed in landfills and to preserve natural resources by avoiding new raw material production; this practice has been successfully used in ordinary concrete production [2–7].

The environmental comparison between normal/conventional and recycled concrete (produced using waste as raw materials) has been performed in several studies [8–16] and the results showed clear environmental benefits for all recycled concrete options, mainly due to the avoided impacts associated with the avoided disposal of waste. For instance, some studies have clearly

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showed the environmental benefits related to the uses of glasses and plastic waste as raw materials for aggregates production in ordinary concrete [17–21].

It has been also reported that cement is the largest contributor to the overall life cycle environmental burden of all concrete types (conventional and recycled ones). This evidence has forced the research community to develop proper environmental friendly solutions and new low-CO_2 binders capable of reducing the environmental impacts associated with the cement industry [22–25].

Besides cement component, aggregates are typically the second largest contributors in normal concrete production [11,14,15] while transport phase influences the overall environmental profile of concretes depending on the transport distances and transport vehicle type [10].

As far as LightWeight Aggregates (LWAs) are concerned, they are usually produced starting from minerals, including natural rock materials such as shale, clay, or slate. These raw materials are thermally expanded to about twice the original volume to get final aggregate density. The resulting material has properties similar to natural (bulk) aggregates, but is less dense and consequently yields a lighter concrete product. Indeed, the main difference between ordinary and lightweight concrete is the bulk density. In the former, this value usually ranges between 2200 and 2600 kg/m^3, while in the latter it ranges between 300 and 2000 kg/m^3 [26]. This difference results in the reduction of dead weights on structure, and also provides a better thermal and acoustic insulation. Several research activities have investigated the possibility of replacing LWAs manufactured with natural raw materials with recycled ones for the production of lightweight concretes. However, the authors of most of these studies focus intensely on the chemical, physical, and mechanical properties/performances of new Recycled Lightweight Aggregate Concretes (RLACs) whereas their environmental performance is usually not considered, even though they investigate the possibility of using waste products deriving from industrial processes [27–33]. Several experimental studies [31–33] have also showed opportunities for the reuse of industrial wastes, such as muds coming from both ornamental stone (granite sludge from sawing and polishing operations) and ceramic production (porcelain stoneware tile polishing sludge); starting from these wastes, the manufacturing of LWAs was demonstrated to be suitable for constituents of structural and/or thermo-insulating lightweight concretes.

On the basis of the results reported in [31–33], the present study aims to investigate the environmental footprint of different lightweight concretes made of different LWAs by means of a Life Cycle Assessment (LCA) methodology [34,35]. In detail, the present paper is organized as follows:

1) The environmental performance of LightWeight Aggregates (LWAs) produced from natural and industrial waste raw materials is first calculated and compared. The LWAs manufactured with industrial waste raw materials are obtained starting from the following waste: Campanian Ignimbrite (Cab70), Dry Powder Mud (DPM), and granitoid orthogneiss SERizzo (SER); instead, the LWAs produced by natural raw materials are made of (expanded) clay.
2) Then, the environmental footprint of the Natural Lightweight Aggregate Concrete (NLAC) and Recycled Lightweight Aggregate Concrete (RLAC) made with the above mentioned lightweight inert options are assessed and the results are compared. The proposed lightweight concrete mixes have been selected from previous works of the authors [31–33] considering the hypothesis that those mixes should have the same physical and mechanical performances (for LCA comparative purposes).

2. Materials

Four artificial LightWeight Aggregates (LWAs) (Type A, Type B, Type C and Type NA) are investigated from an environmental point of view. The main difference among these LWAs is the raw material used for their production; indeed, three LWA types (Type A, B and C) are produced using industrial waste as raw materials (LWAs_R indicates recycled sources for raw materials), and one LWA type (Type NA) using clay as raw material (LWA_N indicates a natural source for raw material). Additional details of all artificial aggregate types are provided in the following sub-sections.

2.1. LWA_R

Raw materials (recycled wastes) used to produce LWA_R and afterwards used in RLAC mixes are the following:

1) Mud deriving from the processing (cutting and sawing) of commercial "zeolitite" (rocks with zeolite content higher than 50 wt.%), coming from a quarry site located near Comiziano, Naples-Italy (Campanian Ignimbrite, hereafter referred to as Cab70);
2) Mud deriving from the processing (cutting and sawing) of Serizzo (a granitoid orthogneiss, hereafter referred to as SER), from the Verbania-Cusio-Ossola district (Verbania, Italy);
3) Mud resulting from polishing porcelain tiles (Dry Powder Mud, hereafter referred to as DPM), from the Sassuolo industrial district (Modena, Italy).

Further information about chemical, mineralogical and technological characterization of each industrial waste can be found in [31–33].

The production process adopted to obtain LWA_R from the above described waste materials is composed of three main steps [31–33]:

1- Mixing of secondary materials: The raw materials require to be properly mixed (in terms of % w/w) in order to achieve the final physical and mechanical properties of the LWA_R. Moreover, the use of DPM and/or Cab70 waste material is needed in each LWA_R mix to guarantee a proper expansion process during thermal treatment. The resulting mixes of raw materials (% w/w) which are used to produce LWA_R in the RLAC (reported in the subsequent sections) are reported in Table 1 [31–33] and are named as "Type" as follows:

- Type A indicates LWA_R composed of 100% of Cab70 secondary material;
- Type B indicates LWA_R composed of 70% and 30% of Cab70 and DPM secondary materials, respectively;
- Type C indicates LWA_R composed of 50% of SER and 50% of DPM secondary materials.

2- Compaction and granulation: Compaction and granulation of secondary materials and their mix (Table 1) are obtained by means of dry granulation using a compactor apparatus and a briquettes breaker mill according to the following procedure. The powder material is moistened by adding 3% water by weight and poured into a feed screw hopper, where it is continuously conveyed to the compactor which generates the briquettes (Fig. 1a). These are further granulated and divided in order to obtain a grain size fraction ranging between 3 and 8 mm.

3- Thermal treatment: dynamic firing (rotative kiln). The materials coming from the compaction and granulation phase are thermally treated in dynamic conditions by a rotative kiln at the temperatures and for a duration reported in Table 1. During this thermal treatment, the compacted DPM raw material expands thanks to the presence of small amounts (about 3% in weight) of an abrasive substance, i.e. Silicon Carbide (SiC) contained in the mud coming from ceramic tile production; SiC is released at high temperatures from compacted material, producing CO_2 gas [31–33]. On the contrary, in the case of Cab70, the expansion of the compacted material is driven by the gas (H_2O steam) which is incorporated in the material itself. In Fig. 1b, the recycled LWAs are shown after the production steps.

2.2. LWA_N

Raw material used to produce artificial LWA_N is natural clay (Table 1). The production process used to obtain LWA_N is composed of three steps [36]: *Mixing process, Thermal treatment and Expansion process*. The mined clay is mixed with water, ground and sometimes granulated (*mixing process*) and then burned at reverse flow in a rotary furnace at 1200 °C (*Thermal treatment*). The material burns and expands with the help of heavy fuel oil (*Expansion process*). The pellets are rounded in shape and fall from the kiln in a grade of approximately 0–32 mm with an average dry bulk density of approximately 600 kg/m^3. The crushing resistance value is approximately 1.3 MPa (Table 1) [36] according to [37]. Table 1 reports the composition and the principal properties of LWA_N (named as Type NA).