Eco-Efficient Concrete Using Industrial Wastes: A Review

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Abstract. Concrete is one of the most widely used construction materials in the world. However, the production of Portland cement as the essential constituent of concrete requires a considerable energy level. Also releases a significant amount of chemical carbon dioxide emissions and other greenhouse gases (GHGs) into the atmosphere. Global demand will increase almost 200 % by 2050 from 2010 levels. Thus, seeking an eco-efficient and sustainable concrete may be one of the main roles that the construction industry should play in sustainable construction.
Portland cement can be partially replaced by cementitious and pozzolanic materials, especially those of industry by-products such as fly ash, GGBS, silica fume, ceramic waste powder and metamorphic rock dust from stone cutting industry. The aggregates are also conserved by replacing them with recycled or waste materials (among which recycled concrete), ceramic waste, post-consumer glass, and recycled tires. All of the previous alternatives are, currently, the most used. This paper summarizes current knowledge about eco-efficient concrete, by reviewing previously published work.

Introduction

Concrete is the most used construction material on Earth, its consumption reaching almost 10.000 million tons per year [1]. The projections for the global demand of the main binder of concrete structures, Portland cement, show that in the next 40 years, concrete production will keep on rising [2]. China, for instance will need 40 billion square meters of combined residential and commercial floor space over the next 20 years which is equivalent to adding one New York city every two years or the area of Switzerland [3].

Portland cement production represents 74-81% of the total CO_2 emissions of concrete, aggregates, in turn, represent 13-20% of the total, therefore batching, transport and placement activities have no relevant expression in terms of carbon dioxide emissions [4,5].

The production of one tonne of Portland cement generates 0.55 tonnes of chemical CO_2 and requires an additional 0.39 tonnes of CO_2 in fuel emissions for baking and grinding, all accounting for a total of 0.94 tonnes of CO_2 [6]. Other authors [7] report that the cement industry emitted in 2000, on average, 0.87 kg of CO_2 for every kg of cement produced. Josa et al. [8] used the 1992 CML methodology to assess the LCI of Portland cement produced in Holland, Switzerland, Sweden, Finland and Austria. The production of 1kg of Portland cement can generate a maximum 800g of CO_2 in Type I cement. The same cement has SO_2 and NOx emissions ranging from 1.1 to 3.4 g of equivalent SO_2. However, a certain level of variability between different plants exists, Chen reports almost 20% variations for global warming [9].

Some authors suggest that the eco-efficiency of concrete could be made by the assessment of the amount of cement needed to generate a unit of compressive strength [10]. Daminelli et al. [11] suggest two indicators to measure the eco-efficiency of cement in concrete. The binder intensity (bi), that measures the amount (kg/m^3) of binder to deliver 1MPa of compressive strength for concrete specimens with 28 days curing and the CO_2 intensity index (ci) that measures the amount (kg/m^3) of carbon dioxide emissions to deliver 1MPa of compressive strength. The minimum values of bi and ci are 5 kg/m^3/MPa and 1,5 kg/m^3/MPa respectively.

Although concrete batching, transport and placement activities are responsible for very small amounts of the total concrete CO_2 emissions, other environmental impacts must be considered. This is the case of the high water consumption involved in the washing of the ready-mixed concrete trucks. Between 700-1300 l [12] of sludge water is needed, to in a single day, for each truck. Sludge water has a high level of solids and high alkalinity thus representing a hazardous waste [13]. These authors further state that concretes containing sludge water even present lower capillary water absorption. However, other authors [14] used sludge water and found higher reductions in compressive strength. Also, other factors can contribute to the eco-efficiency of concrete production as the choice of the mixing process [15].

Concrete has the ability to capture CO_2 by a carbonation process. Although carbonation levels for current concrete structures are low, some authors found that after demolition they could almost double, going from 33% to 59% [16]. More recently, Collins [17] analyzed a concrete bridge with a primary life of 100 years showing that if carbonation is not considered in the LCA assessment, CO_2 emissions of concrete can be overestimated by 13-48%.

Since binder production represents the major part of the environmental impacts of concrete this means that investigations on binder replacement by pozzolanic additions or about eco-efficient binders would lead to an eco-efficient concrete. The durability of concrete structures plays also a major role in the eco-efficiency of concrete. In fact, current concrete structures presents higher permeability which allows water and other aggressive elements to enter. This leads to carbonation and chloride ion attack resulting in corrosion problems thus leading to expensive conservation actions or building new structures. Therefore, if we increase concrete durability from 50 to 500 years, we will reduce the environmental impact by a factor of 10 [18].

This manuscript carried out a literature review on investigations that contribute to the eco-efficiency of concrete, namely, partial replacement of cement by pozzolans and replacement of natural aggregates by non reactive wastes.

Portland cement Concrete

Concrete with pozzolans. The use of pozzolanic materials in construction dates back to thousands years ago. Roy [19] suggests that calcined clays mix with slaked lime (calcium hydroxide) were the first hydraulic binder made by men. Malinowsky [20] reports ancient constructions from 7000 B.C in the Galilei area (Israel) using this type of binder. The eruption of Thera in 1500 BC, which destroyed part of Santorini island, was responsible for the appearance of large amounts of ashes used by the Greeks to make mortars that revealed hydraulic properties. However, the Romans already knew that artificial pozzolans were needed to produce high performance mortars, so their use was not conditioned by the availability of natural pozzolans [21]. In reality, Roman mortars used for the Hadrian´s wall in Britain were made of crushed ceramic material mixed with lime binder [22]. Crushed ceramics seem also to have been preferred from early Hellenistic to early Byzantine times in mortars related to water-bearing constructions and to protect the inside of walls from moisture (typically in baths, canals and aqueducts) [23]. However, the appearance of Portland cement in the XIX century, as it possesses a fast setting and higher early strength, was responsible for the decline of the use of lime-pozzolan binders. Despite recent advances in kiln design and alternative, low energy clinkers, it seems likely that the greatest carbon reduction within the industry are likely to be made by the inclusion of supplementary cementing materials [24].

Several standards define pozzolans as siliceous and aluminous materials which have very little or no cementitious characteristics but when finely divided, and in the presence of water, react with calcium hydroxide to form cementitious compounds [25]. The pozzolanic reactivity is a rather complex property which relies on the amorphous state of silica and aluminum, being higher with higher amorphous state. Generally speaking, the aluminosilicate species of the pozzolans will react with calcium hydroxide to form calcium silico aluminate phases. Pozzolans can be of natural origin or artificial, like calcined clays or industrial by-products. Natural pozzolans came from silicon rich magma that has solidified very rapidly thus remaining in an amorphous state. As to artificial pozzolans, they became structurally instable because of the hydroxyl groups left out due to the

calcination. The pozzolanic activity of calcined clays is very much dependent of the loss of structural water which favors the creation of an amourphous structure. As to the pozzolanic industrial by-products such as fly ash or silica fume a similar process occurs since these materials have a very high content of silicon and aluminum [26]. Several pozzolan by-products are described below:

Fly ash -FA

Some supplementary cementitious material, like FA (a by-product from coal-fired electricity production), have very slow hydration characteristics thus providing very little contribution to early age strength [27]. FA is one the most used pozzolanic by-products, and although current replacement levels are below 40%, some authors showed that it is feasible to use more than 50% [28] as cement replacement.

Silica fume - SF

SF is a by-product of the production of the silicon metal that possesses high pozzolanic activity. This by-product contributes for a denser concrete microstructure enhancing both strength and durability [29].

Rice husk ash - RHA

RHA is a highly reactive pozzolan obtained when rice husks are calcinated below the crystallization temperature, at 780 ºC. RHA based concrete has high strength and high durability performance [30]. Since each tonne of rice generates 40 kg of rice husk ash[31], this means that annual world rice production of almost 600 million tonnes can generate almost 20 million tones of RHA.

Sewage sludge ash-SSA

SSA is a siliceous material obtained by the calcination of water treatment wastes. Its pozzolanic activity depends on the chemical composition of the waste and the calcination temperature [32]. The production of sewage sludge from waste water treatment plants is increasing all over the world. This kind of sludge includes the solid material left from sewage treatment processes. The total production of sewage waste for the United States of America and the European Union approaches 17 Mt of dry solids per year [33]. The expected growth of world population and also, the increase in the volume of waste water shows that sewage sludge ash will rise at a very fast pace in the next years.

Waste ceramics and tungsten mine wastes

Several authors already confirmed the pozzolanic reactivity of ceramic wastes [34].In Europe, the amount of wastes in the different production stages of the ceramic industry reaches some 3 to 7% of its global production. This means millions of tons of calcined-clays per year that can be used as Portland cement replacement. Some authors [35] show that tungsten mine waste is an aluminosilicate source with $(SiO_2+Al_2O_3+Fe_2O_3) > 70\%$ presenting pozzolanic properties when submitted to a thermal treatment.

Recycled glass-RG

Finely ground waste glass having a particle size finer than 38 µm has pozzolanic behavior, furthermore concrete containing ground glass exhibits a higher strength at both early and late ages compared to fly ash concrete. Dyer & Dhir [36] refer that the high sodium content of the material raises concerns about whether the release of this element could ultimately exacerbate alkali-silica reaction (ASR). They also show that powdered container glass is not suitable for controlling alkali-silica reaction.

Fluidized bed cracking catalyst - FBCC

Catalysts are widely used in the petrochemical industry. Usually, when the catalytic properties of this product are degraded, the deactivated catalyst must be replaced. Some authors [37] showed that FBCC (a waste from the petrochemical industry) is a zeolite material containing more than 50% SiO_2 and about 40% Al_2O_3. This material improves concrete strength and increases its durability [38].

Non reactive wastes as aggregate replacement

Although the use of construction and demolition wastes (C&DW) for the replacement of natural aggregates has been studied for almost 50 years, today we still see that too many structures are made with raw aggregates. The reasons for that rely in the low cost of raw aggregates, the lack of

incentives or the existence of low deposition costs and even, sometimes the lack of technical regulations. Recycled aggregates manufactured in laboratory are not contaminated with other wastes contrary to what happens with aggregates obtained from C&DW. Corinaldesi & Moriconi [39] showed that is possible to use 100% recycled aggregates without compressive strength loss as long as fly ash or silica fume are also used with a W/C=0.4.

Vegetable wastes. Several authors [40] used pine wastes to produce lightweight concrete. The wood waste particles have a dimension between 5mm to 10mm and have previously been immersed in sodium silicate. This treatment increases the adhesion between the waste and the cement paste and also, prevents the attack from insects or fungi.

Tyre rubber wastes. An estimated 1000 million tyres reach the end of their useful lives every year [41]. At present, enormous quantities of tyres are already stockpiled (whole tyre) or landfilled (shredded tyre), 3000 millions inside EU and 1000 millions in the US [42]. Waste tyres disposal areas contribute to the reduction of biodiversity, furthermore, the tyres hold toxic and soluble components [43]. The implementation of the Lanfill Directive 1999/31/EC [44] and the End of Life Vehicle Directive 2000/53/EC [45] banned the landfill disposal of waste tyres creating the driving force behind the recycling of these wastes. In the last years several authors investigated the replacement of natural aggregates by rubber aggregates. Rubber aggregates are obtained from waste tyres using two different technologies: mechanical grinding at ambient temperature or cryogenic grinding at a temperature below the glass transition temperature [46]. The first method generates chipped rubber for coarse aggregates replacement. As for the second method, it usually produces crumb rubber [47] to replace fine aggregates. Guneyisi et al. [48] mentioned that the strength of concretes containing silica fume, crumb rubber and tyre chips decreases with rubber content. These authors suggest that it is possible to produce a 40MPa concrete replacing a volume of 15% of aggregates by rubber waste.

PET wastes. These wastes represent one of the most common plastics that can be found in solid urban waste. In 2007 the world´s annual consumption represented 250.000 million terephthalate bottles (10 million tons of waste) with a growth increase of 15%. In the United States 50.000 million bottles are landfilled each year. Since PET waste is not biodegradable, it can remain in nature for hundreds of years [49]. Choi et al. [50] mentioned that the replacement of fine aggregates for treated PET/GBFS aggregates (5-15mm) leads to a decrease in the compressive strength. For a 25% replacement, the mixtures with a W/C=0.45 and 3 curing days lost just 6.4% in compressive strength. For 28 curing days the compressive strength loss reaches just 9,1%. Increasing the replacement percentage increases compressive strength loss but not in a proportional manner, for instance, for a 75% replacement the mixtures with a W/B=0.45 and 3 curing days lost just 16.5% in compressive strength. This means that these treated PET aggregates perform in almost a similar way as natural aggregates.

Conclusions

Portland cement production represents the majority of total CO_2 emissions of concrete so the use of pozzolans as cement replacement can allow major carbon dioxide reductions and also increase the service life of concrete structures, furthermore, in the case of waste pozzolans it also reduces the disposal areas. New investigations are needed in order to maximize the volume of pozzolans used by the construction industry. Research is also needed about the synergetic effect between different pozzolans. As to the aggregates, which represent 13-20% of carbon dioxide emissions they can be replaced by several non reactive wastes.

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