

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 and 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 construction industry should play in sustainable construction. To make the concrete more eco-efficient, different life cycle phases of concrete products can be brought to bear such as extraction of raw material, production of constituents, production of concrete, transportation, erection, maintenance, demolition and recycling.

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 are 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, 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]. For instance China will need 40 billion square meters of combined residential and commercial floor space over the next 20 years - equivalent to adding one New York every two years or the area of Switzerland [3].

Portland cement production represents 74-81% of the total CO₂ emissions of concrete, the aggregates represent 13-20%, 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 CO₂ and requires an additional 0,39 tonnes of CO₂ in fuel emissions for baking and grinding, accounting for a total of 0,94 tonnes of CO₂ [6]. Other authors [7] report that the cement industry emitted in 2000, on average, 0,87 kg of CO₂ 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 CO₂ in Type I cement. The same cement has SO₂ and NO_x emissions ranging from 1.1 to 3.4 g of equivalent SO₂. However, a certain level of variability between different plants exists, Chen report 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/m³) of binder to deliver 1MPa of compressive strength for concrete specimens with 28 days curing and the CO₂ intensity index (*ci*) that measures the amount (kg/m³) of carbon dioxide emissions to deliver 1MPa of compressive strength. The minimum values of *bi* and *ci* are 5 kg/m³/MPa and 1,5 kg/m³/MPa respectively.

Although concrete batching, transport and placement activities are responsible for very small amounts of CO₂ to total concrete emissions, other environmental impacts must be considered such as the high water consumption to wash 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 representing a hazardous waste [13]. This author's state that concretes with sludge water even has lower capillary water absorption. However, other authors [14] used sludge water and found higher reductions in compressive strength. 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 CO₂ 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 CO₂ 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 because current concrete structures presents a higher permeability that allows water and other aggressive elements to enter, leading 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 would reduce the environmental impacts 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 reveal having hydraulic properties. However, the Romans already knew that artificial pozzolans were needed to produce mortars with a high performance, so their use was not conditioned by the availability of natural pozzolans [21]. The 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 be 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, having 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 savings from the industry are likely to be made by the inclusion of supplementary cementing materials [24].

Pozzolanic admixtures react with calcium hydroxide generating additional CSH phases, leading to more compact concretes with increase durability. Several standards define pozzolans as siliceous and aluminous materials which have very little or no cementitious characteristics but when finely divide an in the presence of water react with calcium hydroxide to form cementitious compounds [25]. The pozzolanic reactivity is a rather complex property which rely 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 have solidify very rapidly remaining in an amorphous state. As to artificial pozzolans they became structurally instable

because 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 amorphous structure. To the pozzolanic industrial by-products such as fly ash or silica fume a similar process occurs because 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 fly 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 from the production of the silicon metal with 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 °C. RHA based concrete has high strength and high durability performance [30]. Since each tonne of rice generates 40 kg of rice [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 are 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 meaning 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 $(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3) > 70\%$ with pozzolanic properties when submitted to a thermal treatment.

Recycled glass-RG

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

Fluidized bed cracking catalyst - FBCC

Catalysts are widely used in petrochemical industry and 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 . It 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 to 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 use of low deposition costs and even sometimes the lack of technical regulations.

Recycled aggregates manufactured in laboratory are not contaminated with other wastes as it 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, 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 been previously 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 also the tyres hold toxic and soluble components [43]. The implementation of the Landfill 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 to replace coarse aggregates. As for the second method it usually produce 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. This wastes represents one of the most common plastics 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 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 CO₂ 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. Investigations are 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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