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Multi-criteria decision analysis to assess the environmental and economic performance of using recycled gypsum cement and recycled aggregate to produce concrete: The case of Catalonia (Spain)

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ABSTRACT

The production of virgin raw materials used in construction and the generation of construction and demolition waste (CDW) are key environmental issues in the construction industry. Portland cement and concrete are used extensively in the construction sector. Processing of CDW to produce recycled gypsum cement and recycled aggregates (RA) and their use in the production of structural and non-structural concrete are one way of slowing natural resource depletion and reducing the amount of CDW landfilled. This study proposes the application of multi-criteria decision analysis (MCDA) to compare the production of "green" concretes made from recycled gypsum cement (RGC) and RA with the production of conventional concrete made from natural aggregate and ordinary Portland cement. The VIKOR MCDA method was employed to determine the best or a set of good alternative(s) for concrete production, considering environmental and economic criteria. The life cycle assessment method was used to select the environmental evaluation criteria, and the reference cost of producing concrete alternatives in Spain was used to determine economic criteria. The results of this study, in which environmental and economic criteria were considered of equal weight, or one of the two criteria was given greater weight, showed that the best option for structural and non-structural concrete was the use of RGC and RA. In both cases, the worst alternative was conventional concrete. In conclusion, we found that the use of RGC and RA in concrete production is positive because it replaces the original raw material, reduces the environmental impact, and lowers the economic costs.

1. Introduction

As civilization has developed and the world population has grown, one of the biggest environmental concerns has become the high consumption of natural resources and energy. One of the main consumers is the construction industry, since it requires large quantities of natural resources. According to USGS (2017), in 2015, the world production of ordinary Portland cement (OPC) was 4.1 billion metric tonnes. Although data differ from country to country, around half of the world's OPC is used to make concrete; the rest is used in mortars, screeds, stucco, coatings, soil stabilization and other applications (Smith et al., 2002). The cement industry, like any other construction industry, is tackling major challenges relating to energy resources, CO_2 emissions and the use of recycled materials instead of raw materials (Imbabi et al., 2012).

Considerable quantities of construction and demolition waste (CDW) are produced during the construction and demolition of buildings and civil infrastructure (Chen and Weisheng, 2017). CDW is one of the main waste streams in the EU, accounting for around 900 million tonnes per year (Eurostat, 2010; Ossa et al., 2016). Accordingly, special attention is devoted to CDW management at global and European level. In European legislation, this issue is addressed in Directive 2008/98/EC, which set the target for the recovery and recycling of non-hazardous CDW at a minimum of 70% of its weight by 2020.

CDW consists of numerous materials, including concrete, brick, gypsum, wood, glass, metal, plastic, solvents, asbestos and excavated soil, much of which can be recycled. However, most of this waste ends up in landfill, even though the space available for landfill is increasingly scarce (Hiete et al., 2011).

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List of notations

CDW	Construction and demolition waste
RA	Recycled aggregates
MCDA	Multi-criteria decision analysis
RGC	Recycled gypsum cement
OPC	Ordinary Portland cement
RG	Recycled gypsum
GW	Gypsum waste
NG	Natural gypsum
NAC	Natural aggregate concrete
RAC	Recycled aggregate concrete
LCI	Life cycle inventory
NG	Natural gypsum
RA	Recycled aggregate
RGC	Recycled gypsum cement
LCA	Life cycle assessment
SC	Structural concrete
NC	Non-structural concrete
NA	Natural aggregate
RMA	Recycled mixed aggregate
NGC	Natural gypsum cement
NCA	Natural coarse aggregate
NFA	Natural fine aggregate
RCCA	Recycled concrete coarse aggregate
RMCA	Recycled mixed coarse aggregate
GWg	Global warming
OD	Ozone depletion
A	Acidification
E	Eutrophication
RO	Respiratory organics
ME	Mineral extraction
C	Carcinogens
NC	Non- carcinogens
NRE	Non-renewable energy
RI	Respiratory inorganics
LO	Land occupation

Due to the considerable environmental and economic impact of the construction industry on resource depletion and waste generation, new strategies must be found for producing construction materials that are not based on original raw material, and for managing CDW in such a way that dependency on landfill is reduced. The use of recycled material from CDW is becoming a crucial strategic step for managing CDW, to improve the sustainability of the construction industry (Lu and Yuan, 2011; Ghanimeh et al., 2016).

Within this framework, it should be noted that after clay materials, gypsum waste (GW) is the second largest contributor to the CDW stream (Godinho-Castro et al., 2012). Over 15 million tonnes of gypsum waste is sent to landfill annually in Europe, the USA and Asia (GRI, 2014). In 2002, EU Council Decision 33/2002 strengthened criteria for deciding which waste could be landfilled and in which type of landfills. It was decided that non-hazardous gypsum-based materials should be disposed of only in landfills for non-hazardous waste in cells (due to the risk of hydrogen sulphide gas generation). Full implementation of the Council Decision on Waste Acceptance Criteria in all EU countries will significantly increase the cost of landfilling and will lead to an increase in the availability of recycled gypsum (RG). Therefore, it is important to recycle or reuse GW to fulfil current legislation and protect the health and welfare of human beings against environmental pollution.

The use of RG instead of natural gypsum (NG) in ordinary Portland cement (OPC) manufacture, together with its use in plasterboard plants, are feasible alternatives to meet the environmental challenges of managing RG from CDW. In the case of OPC manufacture, NG is added to OPC in the grinding process to control the rate of hardening or the setting time: generally around 2–10% of ground-up Portland cement is comprised of gypsum (Imbabi et al., 2012).

Previous studies have examined the technical feasibility of using RG instead of NG in the production of OPC, by evaluating the mechanical and chemical properties of the resulting product. The results demonstrated that the properties were similar for both types of cements, and confirmed that RG can be used as an alternative to NG in the production of OPC (Chandara et al., 2009; Morales Martinez, 2010; Ahmed et al., 2011).

Notably, concrete is the most heavily consumed material in the construction industry, and the second most consumed material on earth after water. It is also the largest fraction of CDW. Thus, recycling of concrete is considered an important option to avoid landfill and reduce consumption of the virgin resources used in construction industry (Srubar, 2015).

The recycled concrete aggregates (RCA) derived from CDW that can be used in both structural and non-structural concrete could help reduce depletion of natural mineral resources and the amount of CDW being put in landfill (Behera et al., 2014; Tošić et al., 2015).

Several researchers have studied the durability of recycled aggregate concrete (Medina et al., 2012; Anastasiou et al., 2014; de Bravo et al., 2015; Faella et al., 2016), as well as its water absorption by immersion and capillarity (De Bravo et al., 2015), resistance to penetration of chloride ions in the concrete (Corinaldesi and Moriconi, 2009; Evangelista and De Brito, 2010; De Bravo et al., 2015) and compressive strength (Sánchez de Juan, 2004; Alaejos, 2008; Lima et al., 2013; González-Corominas et al., 2014; Pepe et al., 2014).

Marinković et al. (2010) and Tošić et al. (2015) in Serbia performed a comparative LCA for different types of used aggregate and transport scenarios in concrete production. In addition, they used a multi-criteria optimization method for natural aggregate concrete (NAC) and recycled concrete aggregate (RCA), based on their local life cycle inventory (LCI), and taking into account technical, economic and environmental criteria. The results showed that concrete with a 50% replacement ratio of coarse aggregate with RCA could be an optimal solution. The analysis identified taxes on river aggregate, taxes on landfill, and subsidies for using RCA as feasible measures to establish similar costs in natural aggregate and recycled aggregate. In addition, they found that energy savings in recycling projects are only possible if recycling plants are located close to building sites. Others author such us Dong et al. (2015) and Hossain et al. (2016) in Hong Kong or Turk et al. (2015) in Slovenia conducted LCA studies to evaluate the environmental consequences of NAC and RCA application. They also found that closeness of recycling plants to building sites is a key factor to ensure environmental benefits.

Moreover, the economic viability of recycling plants for CDW has been shown. Coelho and De Brito (2013a) and Coelho and De Brito (2013b) found that, even in the absence of government intervention, there was a clear alignment between economic viability and environmental benefits of the operation of a CDW recycling plant.

In addition, Tam (2008) compared the costs and benefits of the current practice of obtaining aggregates and concrete recycling methods. The results of this study showed negative net profit for the current practice of obtaining aggregates, but positive net profit for the concrete recycling method.

Various studies have evaluated the production of concrete made with RA. However, they generally examined the physical, chemical and mechanical properties of the material; the environmental and economic performance of using CDW in the production of concrete was not evaluated in depth. Suárez et al. (2016) found that the environmental