Journal of Cleaner Production xxx (2014) 1–11

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Multicriteria optimization of natural and recycled aggregate concrete for structural use

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ARTICLE INFO

Article history:
Received 22 January 2014
Received in revised form
13 October 2014
Accepted 27 October 2014
Available online xxx

Keywords:
Recycled aggregate concrete
Transport scenario
Life Cycle Assessment
Multicriteria optimization
VIKOR method
Compromise solution

ABSTRACT

Recycling of concrete waste to produce recycled concrete aggregates (RCA) and its use in the production of structural concrete is the way towards reducing the depletion of natural mineral resources and the amount of construction and demolition waste being land-filled. The goal of this study was to determine the optimal choice of aggregate type and transport scenario in concrete production, employing a multicriteria optimization method taking into account technical, economical and environmental limits and constraints. Several concrete types with different type of used aggregate (river aggregate, crushed stone and recycled concrete aggregate) and different transport scenarios were analyzed. The environmental system evaluation criteria were chosen according to the Life Cycle Assessment methodology and the economical system evaluation criteria were determined in accordance with the current state of the ready-mixed concrete market in Serbia. The normative multicriteria optimization method (VIKOR method) was employed to determine the optimal solution. Analysis was performed for different decision making scenarios that gave emphasis to different criteria. Results have shown that concrete with a 50% replacement ratio of coarse aggregate with RCA can be presented as an optimal solution. Since natural aggregate concrete made with river aggregate was shown to have the lowest price, a further analysis was conducted to determine what economical measures should be undertaken in order to achieve cost equality of recycled and natural aggregate concrete. The analysis identified taxes on river aggregate, taxes on land-filling and subsidies for using RCA as viable measures.

1. Introduction

Concrete is the most widely used construction material in the world. The data for the annual world production of concrete vary depending on the source between 6 billion (6×10^9) (ISO, 2005) and 21 billion t (WBCSD, 2009). Among all human activities, the building industry has one of the largest environmental impacts: 40% of the raw stone, gravel and sand consumption; 25% of virgin wood; 40% of total energy and 16% of annual water consumption in the world (Dixit et al., 2010). Global annual consumption of aggregates is around 15 billion t (AGI, 2004). The question is raised then about the availability of natural aggregates (NA) and the effect of their production on the environment.

On the other hand, construction and demolition (C&D) waste poses an increasing threat to the environment. In the EU alone, 850 million t of C&D waste is generated annually, which accounts for about 31% of the total waste generated (Fisher and Werge, 2011). The most common method of dealing with this waste is still land-filling. Recycling of C&D waste represents one way to convert waste into a resource. Waste concrete cannot be recycled back into its original constituent materials or original whole form. Rather, concrete is crushed into aggregate called recycled concrete aggregate (RCA) for use in new applications.

The production of RCA usually includes a two-stage crushing and sieving process and a removal of any impurities such as steel, wood, gypsum, masonry, glass etc. During the crushing of concrete waste a certain quantity of cement paste remains attached to the aggregate. This residual cement paste is the main cause of the lower quality of RCA compared to NA. Compared to natural aggregate, recycled concrete aggregates have on average a 10% lower density (Poon and Lam, 2008). Water absorption ranges from 3.5% (Rahal, 2007) to 10% (Xiao et al., 2005) in the case of coarse RCA and from 5.5% (Yang et al., 2008) to 13% (Evangelista and Brito, 2007) in the case of fine RCA.

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http://dx.doi.org/10.1016/j.jclepro.2014.10.070
0959-6526/

Concrete made with recycled concrete aggregates is called recycled aggregate concrete (RAC). The replacement of NA with RCA can be total (100%) or partial (<100%). Despite the results of all the research in this field, RCA is still considered to be inferior to NA and mainly used for applications such as road sub-base and non-structural concretes. However, the positive effects of concrete waste recycling can be fully utilized only if recycled concrete aggregates find their use in all types of concrete, especially structural concrete. Currently only 1% of aggregates used worldwide in structural concrete production are recycled concrete aggregates (FIB TG 3.3, 2004). The applicability of RCA in structural concrete has been investigated for several decades – Nixon (1978) published the first literature review of RCA use. Numerous investigations have been carried out into the short-term and long-term mechanical properties of RAC. The investigated short-term properties are mainly compressive and tensile strength, modulus of elasticity, bond stress (Ajdukiewicz and Kliszczewicz, 2002) while the long term properties, creep and shrinkage, have been investigated for different aggregate replacement ratios (Domingo et al., 2010) or for different aggregate sources and mixing procedures (Fathifazl et al., 2011). More recently there has been an increasing number of experimental testing of structural elements made from RAC – seismic performance of frame structures (Xiao et al., 2006); shear capacity (Fathifazl et al., 2009) and flexural capacity of reinforced RAC beams (Ignjatović et al., 2013). These investigations have shown that recycled aggregate concrete has somewhat inferior mechanical and durability related properties compared to natural aggregate concrete. This difference depends mostly on the investigated concrete property, quality of the recycled concrete aggregates and the replacement ratio of natural aggregates with RCA.

Research done so far in the area of the environmental assessment of concrete has shown that cement production is by far the largest contributor to all impacts. Since the contribution of the aggregate production phase is small compared to the contribution of other phases in the concrete's life cycle, different energy consumptions in production of various aggregate types do not affect the environmental impacts significantly. However, the lower quality of RCA can lead to an increased amount of cement being used and consequently, to an increase of RAC impacts compared to corresponding NAC impacts.

Braunschweig et al. (2011) have found that environmental impacts of high quality NAC and RAC with 25% of recycled concrete aggregate are similar, as long as the increase of cement amount in RAC is up to a few percent. They compared the following impacts: energy use, climate change (global warming), acidification, respiratory effects, land use and gravel use and showed that the contribution of natural and recycled aggregate production is below 10%. Weil et al. (2006) compared NAC to RAC with 35% and 50% of recycled concrete aggregate and different cement contents. Their conclusion is similar to that of Braunschweig et al.: for the same cement content, the energy use and global warming potential of NAC and RAC are similar. According to these authors the contribution of NA and RCA production in global warming potential is only 3%. Marinković et al. (2010) have reported that the same environmental impacts for NAC and RAC with 100% of recycled coarse aggregate and 3% additional cement can be obtained only if the transport distances of recycled aggregates are smaller than the transport distances of natural aggregates; otherwise, the RAC impacts are slightly larger than NAC impacts. Knoeri et al. (2013) concluded that if the additional amount of cement used for RAC is below 10%, the impacts from NAC and RAC will be comparable. Unlike the other authors, they have included the benefits from recovered steel scrap and avoided impacts of waste disposal into the Life Cycle Assessment (LCA) which makes their results more beneficial for RAC.

The economical viability of RAC use is broadly studied and debated. Duran et al. (2006) analyzed the case of Ireland and proposed a model to assess the economic viability of creating markets for C&D waste. Nunes et al. (2007) investigated the potential for operating C&D waste recycling centers in Brazil. Coelho and de Brito (2013) carried out a study on the viability of a C&D waste recycling plant in Portugal. For an economical viability of RCA use, all of these studies highlight the importance of legislative and economical measures such as taxing natural aggregates, taxing recyclable materials that are land-filled, subsidizing C&D waste recycling businesses, lowering taxes on construction products with recycled content etc.

All of the above stated means that when analyzing concretes made with different types of aggregates some will be better from an economical viewpoint, others from an environmental or from a technological viewpoint. The problem in that case is a multicriteria decision making problem. Choosing the best solution in such cases can be a difficult task. However, there are analytical models that can successfully aid in the multicriteria optimization process. One such method – the VIKOR method is used in this work to determine the optimal choice of structural concrete type and transport scenario, taking into account technical, economical and environmental criteria.

In recent years multicriteria optimization has become popular in the assessment of various industrial processes involving conflicting environmental and economical criteria. Herva and Roca (2013) present a thorough review of different multicriteria analyses of industry and energy-related cases, waste treatment and management and wastewater treatment. The authors also point out the wide use of LCA in environmental evaluation and the wide application of so-called outranking methods.

Besides traditional multicriteria optimization methods there is also research into potentially different approaches. One of the cited setbacks of traditional methods is the necessity for decision makers to assign weights to criteria leading to implicit subjectivity in the system. A potential by-pass of this problem was investigated in (Lim et al., 2013) where a bi-objective problem was converted to a single-objective problem using monetization and trade-off of environmental effects into economic cost.

2. Goal and scope of the work

The goal of this study is to determine the optimal choice of structural concrete type and transport scenario, employing a multicriteria optimization method taking into account technical, economical and environmental limits and constraints. The production of ready-mixed concrete studied in this work is located in Serbia. Several concrete types with different type of used aggregate (river aggregate, crushed stone or recycled concrete aggregate) were analyzed. The transport scenarios were chosen regarding the real industry and transport infrastructure situation in Serbia. The environmental system evaluation criteria were chosen according to the Life Cycle Assessment methodology (ISO, 2006). The economical system evaluation criteria were determined in accordance with the current state of the ready-mixed concrete market in Serbia. Finally, a normative multicriteria optimization method (VIKOR method) was employed to determine the optimal solution.

3. Methodology

Multicriteria optimization is the process of determining the best feasible solution for a given problem according to established criteria (Opricovic and Tzeng, 2004). In practical multicriteria optimization problems, the criteria are often noncommensurable, conflicting or competing. Hence, there may be no solution that