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Sustainable decision-making through stochastic simulation: Transporting vs. recycling aggregates for Portland cement concrete in underground mining projects

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A B S T R A C T

The procurement of high-quality aggregates is a global problem. In Chile, mining companies are in the process of developing massive underground projects that require the extensive use of Portland cement concrete (PCC), approximately 60%–75% of which is aggregate. Currently, mining projects transport all the required aggregate to the site from stockpiles that can be more than 100 km away, while mining excavations produce millions of cubic meters of waste rock (WR) that are disposed of in landfills. The use of WR in PCC seems to be a sustainable solution for the production of PCC, but decision-makers lack the tools to support a sustainable decision based on CO_2 emissions and operation costs.

This paper proposes a methodology that uses stochastic simulation tools to evaluate CO_2 emissions and operation costs to decide when it is sustainable to use WR in PCC for underground mining projects. The main objective of this paper is to provide a methodology to quantify CO_2 emissions and the cost of transporting natural aggregate versus recycling WR for PCC production in tunneling operations. A sensitivity analysis is also presented, which considers scenarios that include natural aggregate transportation distances of 50, 60, 70, 80, 90, and 100 km, and 0%, 25%, 50%, 75%, and 100% replacement of natural aggregate with recycled WR in PCC. The results indicate that the use of WR leads to reductions in CO_2 emissions only for natural aggregate transportation distances of greater than 70 km owing to the emissions produced when recycling WR. In addition, 100% replacement of natural aggregate with recycled WR leads to a greater reduction in CO_2 emissions than that obtained in scenarios in which a percentage of the required natural aggregate is obtained from WR. In terms of costs, 100% replacement of natural aggregate with recycled WR is the most economical alternative for most scenarios; however, the cost reduction varies with the required transportation distance of natural aggregate. It is concluded that using 100% recycled WR in PCC leads to lower CO_2 emissions and costs as compared to the traditional approach in which the natural aggregate is procured from a site located at a distance of 70 km or more from the construction site, under model assumptions.

1. Introduction

Portland cement concrete (PCC) is the most widely used construction material in the world. PCC is structurally safe, but new approaches are required to improve its sustainability and durability. To address this challenge, the PCC industry has proposed process improvements, product performance enhancements, improved energy efficiency, and technology transfers, among other strategies (Strategic Development Council, 2002). The PCC industry is one of the largest producers of CO_2 and is responsible for approximately 5% of global man-made emissions (Mahasenan et al., 2003). Efforts to reduce the equivalent CO_2 per t of PCC have focused on the incorporation of recycled PCC aggregate, recycled

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waste, and thermoelectric plants by-products, and on the use of supplementary cementitious materials and natural pozzolans to reduce the cement content (Aïtcin and Mindess, 2011).

Obtaining high-quality aggregates, which are granular materials that meet the American Society for Testing and materials (ASTM) standard (ASTM C33/C33M-16), is a growing problem in the global construction industry, mainly owing to their scarcity and increasing cost (Raigandhi et al., 2015). In particular, this problem affects PCC because its fabrication requires a considerable amount of coarse aggregate (CA) and fine aggregate (FA). According to Kosmatka et al. (2011), typically, 60%–75% of the PCC volume consists of aggregate, which means that 1 m^3 of PCC requires between 1600 kg and 2000 kg of aggregate.

Chile is the largest producer of copper in the world (International Copper Study Group, 2013). As a result, mining companies continue to invest in extensive natural reserves of copper, and to execute massive underground mining projects for this purpose (Codelco, 2015). Mining operations usually have a negative impact on the environment, both during ore extraction and after the mine is decommissioned (Adom-Asamoah and Afrifa, 2010). The two main waste streams produced by mining are WR and tailings. WR is obtained from tunnel excavations and contains no significant amount of precious minerals; however, it must be removed to gain access to the underground ore deposits. Tailings are obtained from materials that contain ore and are the result of a mineral separation process in the concentrator or processing plant (Fan et al., 2014). Due to the aforementioned separation process, tailings consist of both rock and residual chemical compounds. Therefore, they require a chemical compound removal process prior to being included in mining PCC. For this reason, the use of tailings is not considered in this study.

The availability of aggregate is crucial to the production of PCC for mining infrastructure. In mining applications, PCC is mainly used for shotcrete in tunnel fortifications and road pavements. In the case of Chile, the natural aggregates are generally transported over large distances, usually between 50 and 100 km, to the mining projects. Due to local geographic conditions, historically, it has been possible to obtain high-quality coarse and fine aggregates because the rivers running from the Andes Mountain range generate abundant fluvial deposits of sand and gravel. However, owing to over-exploitation, high-quality coarse and fine aggregates are now scarce (CDT, 2001).

In Chile, mining projects are primarily located in the Andes mountains and generate several Mt of WR per d during tunnel construction (Castro-Gomes et al., 2012); this WR is usually disposed of in landfills (Kore and Vyas, 2016). Landfills for WR are usually created near the location of mining projects for convenience, while natural aggregates are transported over large distances. Few cases of recycling WR in PCC have been reported, primarily due to the variability in the geology and physical characteristics, the lack of a reliable standard methodology to assess the material quality, and the uncertainty related to the PCC performance when WR is used as coarse and fine aggregates (Dincer et al., 2013). This uncertainty is related to the durability of the PCC, which is commonly defined as its ability to resist the effects of the environmental conditions, chemical attack, and abrasion, while performing its desired function (Hoff, 1991). In the case of conventional PCC, its durability will depend mainly on the exposure conditions: freezing and thawing, sulfate and chloride attack, and alkali-silica reaction (ASR) (Kosmatka et al., 2011). Sulfates react with the compounds in cement paste to cause weakening and cracking (Mohammed et al., 2004). An ASR can occur if reactive silica materials are present in the PCC, thus forming an expansive gel that can damage the PCC. Mining waste materials may release metals, acidic substances, and sulfates (National Research Council, 2002). As these discharges can be detrimental to PCC, the chemical reactions of WR in PCC require further investigation.

The durability of a given sample of PCC is significantly impacted by its aggregate's durability. Specifically, the aggregate's inherent strength and resistance to exposure conditions have a great impact on the durability of the PCC. The aggregate source should also not contain any foreign materials or substances that may cause a deterioration of the PCC (Gonilho Pereira et al., 2009). In addition, the physical characteristics and chemical composition of the aggregate may affect both the plastic and hardened states of the PCC (Beshr et al., 2003).

The inclusion of WR in PCC, in terms of both aggregate replacement percentage and its applications, is an important decision considering the uncertainty and variability involved in operations. According to the literature, several types of waste material have the potential for use in PCC. Aprianti (2015) found that several agricultural wastes and industrial wastes in PCC could provide technical and environmental benefits. Similarly, Paris et al. (2016) found that waste products used as supplements in PCC cause a significant reduction in economic and environmental impact, while Sharma and Khan (2017) identified copper slag combined with fly ash and silica fume as a potential candidate for incorporation into PCC. Although the use of waste materials in PCC is a promising alternative for sustainable and economical PCC mixtures, the extant literature does not provide advice or recommend a methodology to support a sustainable decision while considering the CO_2 emissions and operation costs as well as the uncertainty and variability of the operations.

Stochastic simulation modeling is a reliable decision-making tool used to estimate whether recycling WR is economical and sustainable, while considering the uncertainty and variability. Simulation modeling allows for the evaluation of the changes in projects before their actual implementation and, therefore, it is a convenient and an economical method for evaluating the potential impacts and benefits of using recycled WR as a PPC aggregate (Harrison et al., 2007). Discrete-event simulation (DES) has been a mainstay of operational research simulation for over 40 y (Siebers et al., 2010). Several authors have demonstrated that agent-based modeling (ABM) is one of the most promising simulation techniques. Majid et al. (2009) quantitatively compared the simulation output accuracy of the discrete-event and agent-based models. Paraunak et al. (1998) demonstrated that ABM is more appropriate than equation-based modeling for domains dominated by discrete decisions (such as aggregate production). There are a few main advantages of ABM over other modeling techniques: ABM captures emergent phenomena, provides a natural description of a system, and is a flexible, low cost, and time-saving approach (Bazghandi, 2012). Although ABM is still not widely used in construction, some papers have used it to study construction labor productivity on site (Watkins et al., 2009), estimate the productivity of bored piles (Marzouk and Ali, 2013), or even model earthmoving operations (Kooragamage et al., 2013). According to Zankoul et al. (2015), a simple problem can be simulated more easily in DES than in ABM, while in the case of a complex one (such as a methodology to support the decision of using WR in PCC), it might be more beneficial to simulate it in ABM.

The aim of this study was to develop an ABM model to stochastically quantify the differences in the cost and CO_2 emissions between the traditional production of PCC (i.e. using natural aggregate) and the production of PCC with total or partial replacement of natural aggregate with WR. The variables of the model were the percentage of replacement of natural aggregate with WR and the distance between the natural aggregate source and the mining project ($D_{NA\text{-}RMP}$). In addition, a sensitivity analysis of the main parameters that affect the costs and CO_2 emissions of