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Optimizing recycled concrete containing high volume of fly ash in terms of the embodied energy and chloride ion resistance

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CDW
construction and demolition waste
CIPR
chloride ion penetration resistance
dnssm
non-steady state chloride migration coefficient of diffusion
EE
embodied energy
EI
environmental impacts
FA
fly ash
LCA
life cycle assessment
NA
natural aggregate
OPC
ordinary portland cement
RCA
recycled concrete aggregates
SP
superplasticizer
W/b
water to binder ratio
WA
water absorption

ABSTRACT

The objective of this research is to enhance concrete produced with high content of fly ash (FA) and recycled concrete aggregates (RCA), individually and jointly, with low (with superplasticizer) and high (without superplasticizer) water to binder ratio (w/b), according to their chloride ion penetration resistance (CIPR)-related service life and embodied energy (EE). For that purpose, the EE was determined for the production of 1 m^3 (declared unit) of concrete considering the primary energy, non-renewable (PE-NRe) of the “Cumulative Energy Demand” environmental impact assessment method, and the CIPR of concrete are considered the conditioning factors. The environmental assessment of the mixes was evaluated by considering the Life Cycle Assessment (LCA) standardized methodology. In addition, the assessment was mostly made either according to the local Life cycle inventory (LCI) data or environmental product declaration (EPD) report and selected according to NativeLCA methodology on typical conditions in Portugal. Generally, the CIPR of concrete decreases when the RCA content increases, and the opposite occurs by replacing cement with FA. After 28 days, the rate of CIPR development of the concrete made with incorporating both FA and RCA is higher than that of concrete containing either FA or RCA. Therefore, it is positive to use simultaneously RCA and FA in concrete. This rate increased even more when SP was used. Furthermore, the EE significantly reduced with increasing replacement level of cement and coarse natural aggregates (NA) with FA and coarse RCA, respectively. Nonetheless, the changes in EE caused by the incorporation of SP and fine RCA are small. In term of the influence of combining FA and RCA in low and high w/b concrete, the EE linearly changed with each individual effect. Nevertheless, the optimal solution of mixes by means of both EE and CIPR (measured by the yearly EE of the mixes relative to the reference concrete) does not necessarily consider the one that requires less EE or that has higher CIPR. According to this parameter, the best-case scenario is always the low w/b mixes with high volumes of RCA and FA, followed by the corresponding high w/b mixes.

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YEE
yearly embodied energy of the concrete mixes relative to the reference concrete

1. Introduction

The construction sector had a significant development throughout the last century because of the exponential population growth. According to data obtained by the United Nations, in 2015 the world population was about 7.3×10^3 millions, and this figure is expected to reach 9.7×10^3 millions by the year 2050 (UN-DESA-PD, 2015). However, this development caused critical damage to the environment, such as an unsustainable use of natural materials and uncontrolled CO_2 emissions to the atmosphere.

The construction sector is one of the major contributors to environmental impacts (EI), regarding energy consumption, emissions released and extracted natural resources into the atmosphere. Thus, it is essential that sustainability in construction is promoted, to reduce the ecological footprint during the construction, service, maintenance and end-of-life stages of a structure. Since concrete is the most widely used construction material in the world, the annual demand of aggregates (major components of concrete) increased up to an expected value of 52×10^9 tonnes in 2019 (Freedonia, 2016).

Cement is one of the components of concrete and a major contributor to the high EI values of concrete production (Marinković et al., 2008) with more than 5% of yearly CO_2 emissions worldwide (CSI, 2017), and other EI categories (Kurda, 2017), e.g. energy consumption (Paris et al., 2016). Furthermore, the demand of cement is expected to be 6.0×10^9 tonnes in the years 2025 (Fig. 1).

Additionally, as detailed in the study of (Kurad et al., 2017), there are significant amounts of construction demolition wastes (CDW)

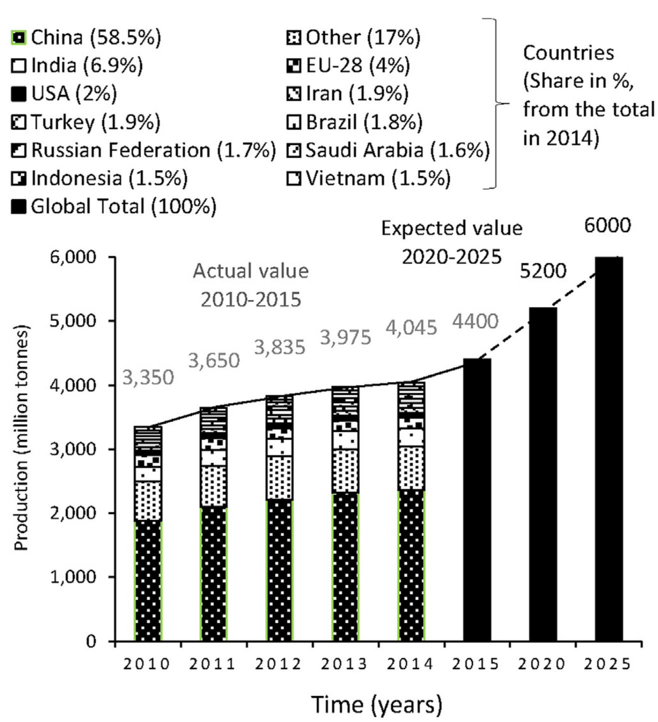

Fig. 1. Global cement production in the top 10 countries, in EU-28, and in the other countries (adapted from (Duve, 2015; NBS, 2015; USGS, 2015)).

e.g., recycled concrete aggregates (RCA), and supplementary cementitious materials (SCM), e.g. fly ash (FA) which results from electrical thermal power generation plants and considered a toxic substance to soil (Rodrigues et al., 2017). Thus, to overcome the mentioned issues, several alternatives have been proposed by researchers to decrease the EI related with the production of concrete mixes, e.g. replacing cement with SCM like FA (Chen et al., 2010; O'Brien et al., 2009), or/and replacing natural aggregates (NA) with RCA (Evangelista and de Brito, 2010; Estanqueiro et al., 2016). For that purpose, there are various standards or recommendations worldwide that focus on the use of RCA as construction materials, namely to produce concrete (Fig. 2), and standards for FA use (ASTM C618-02; 2005; CSA A23.1, 2004; EN 450-1, 2012). However, they only consider the technical performance. For example, all the standards shown in Fig. 2 are specified to the quality of the aggregates, namely their density, water absorption (WA), components and maximum incorporation ratio in construction materials, but none of them (ACI 555R-01, 2001, BRE Digest 433, 1998, BRV, 2007, BS 6543, 1985, BS 8500-2, 2002, CUR 125, 1986, CUR-VB 4, 1984, CUR-VB 5, 1994, DCA-N.34, 1995, DIN 4226-100, 2002, DREIF, 2003, EEPL, 2012, JSA - JIS A 5021, 2016, JSA - JIS A 5022, 2016, JSA - JIS A 5023, 2016, E471, 2006, NBR 15.116, 2005, Nordtest BUILD, 1999, RILEM TC 121-DRG N. 27, 1994, TV 70085, 2006, WBTC-N, 2002) have a specific limitation in terms of Life Cycle Assessment (LCA). This is due to lack of studies in terms of in technical and EI simultaneously. Furthermore, the simultaneous replacement of alternatives components (e.g. RCA and FA) to traditional materials (e.g. NA and cement) is still scantily studied, in technical and environmental terms.

There are many studies on the single effects of FA or RCA on the chloride ion penetration resistance (CIPR) of concrete, and they generally report that it decreases as the RCA content increases (Cartuxo et al., 2016; Cong, 2006; Evangelista and de Brito, 2010; Kou and Poon, 2013), and the opposite occurs with the incorporation ratio of FA (Balakrishnan and Awal, 2014; Shaikh and Supit, 2015; Simčič et al., 2015; Zhao et al., 2015a). Concerning the effects of combining RCA and FA, there are a few studies on the total charge passed (Cong, 2006; Huda, 2014; Kou and Poon, 2013) and the non-steady state chloride migration coefficient of diffusion (D_{nssm}) (Corinaldesi and Moriconi, 2009; Kim et al., 2013). Moreover, there are but a few studies on the influence of RCA (Marinkovic' et al., 2010; Tošić et al., 2015; Wijayasundara et al., 2017) and FA (NRMCA, 2014; Tait and Cheung, 2016) on the embodied energy (EE) of concrete. However, studies regarding the simultaneous effects of FA and RCA are very scarce (Marinković et al., 2016). Broadly speaking, the results of the previous works confirm that the EE of FA concrete depends on the transportation distance and on the allocation procedure, although it seems the EE decreases by replacing cement with FA. Nevertheless, the EE of RCA concrete mainly relies on the transportation scenario. In addition, there are a few studies comparing the quality of concrete with their EI. For example, Tošić, et al. (2015) used the VIKOR method (multi-criteria optimization method, Opricovic, 1998) to complement the Marinkovic' et al. (2010) study and select the optimal solution in concrete production by using different transport scenarios and aggregate types.

In this study EE, namely non-renewable primary energy resources (PE-NRe) was considered as the main relevant indicator