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Impact of Embodied Energy on materials/buildings with partial replacement of ordinary Portland Cement (OPC) by natural Pozzolanic Volcanic Ash

Kunal Kupwade-Patil [a], Catherine De Wolf [b], Stephanie Chin [a], John Ochsendorf [a, b], Ali E. Hajiah [c], Adil Al-Mumin [d], Oral Büyüköztürk [a, *]

[a] Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[b] Building Technology Program in the Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[c] Energy and Building Research Center, Kuwait Institute for Scientific Research, Safat 13109, Kuwait
[d] Department of Architecture, Kuwait University, Safat, P.O. Box 5969, Safat, 13060, Kuwait

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This work studies the effect on Embodied Energy (EE) of concrete when Ordinary Portland Cement (OPC) is partially substituted with natural Pozzolanic Volcanic Ash (VA) at the material and the building scale. The work aims to demonstrate potential improvements to the EE of buildings by comparing the EE of the cement mix with VA replacement to that of baseline case of traditional concrete. Embodied Energy Coefficients (EEC) express the EE of each building product in Mega Joules (MJ) per kg of material. Hardened cement paste made with up to 50% of the OPC replaced by volcanic ash with a mean particle size of either 17 μm or 6 μm is considered. Replacement of OPC with volcanic ash decreases the EEC, however the mix design must be engineered considering the volcanic ash composition to maintain the optimum mechanical strength. Grinding the volcanic ash from 17 μm to 6 μm led to increased compressive strength when replacing up to 40% of OPC with 6 μm sized volcanic ash. An average of 16% decrease in EEC values can be achieved when 40% OPC was replaced with VA. On a building scale, the initial EE is the energy consumed related to the extraction, production, and transportation of materials. For buildings with an average Structural Material Quantities (SMQ, expressed in mass of material per area) value of approximately 2000 kg/m^2, a 16% decrease in EE value was observed among a sample set of 26 residential and commercial buildings when 50% of OPC is replaced with VA. The demonstrated reduction in EE values were calculated when natural supplementary cementitious materials (SCM) such as volcanic ash are used as a partial replacement to OPC, and it can be adapted to design and build energy-efficient systems tailored for structural and non-structural applications.

1. Introduction

Second to water, concrete is the most abundantly used material in the world (Aïtcin and Mindess, 2011). Excessive carbon dioxide (CO_2) emissions due to manufacturing of cement clinker has incentivized the industry to look for more sustainable alternatives to cement. Currently, Portland cement production accounts for approximately 5% of the world's CO_2 emissions (Nazari and Sanjayan, 2016; Tanaka and Stigson, 2009). One common strategy for reducing CO_2 emission is by replacing Portland cement with supplementary cementitious materials (SCM). Moreover, the reduction in CO_2 emission due to usage of SCM significantly contributes to the life cycle greenhouse gas (GHG) emissions and Embodied Energy (EE) of the concrete (Aïtcin and Mindess, 2011; Hodge et al., 2010; Schneider et al., 2011).

Hammond et al. (2011) defined cradle-to-gate EE as "the total primary energy consumed from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through fabrication processes until the product is ready to leave the final factory gate" (Hammond et al., 2011). Innovations in recent decades have focused on lowering the operational energy use of buildings, and as a result, EE has increased significance in the whole life cycle analysis of buildings (De Wolf et al., 2016b). The whole life EE would also include transport of the materials to the construction

* Corresponding author. 77 Massachusetts Ave, Department of Civil and Environmental Engineering, Cambridge, MA 02139.
E-mail address: obuyuk@mit.edu (O. Büyüköztürk).

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List of notations

C-A-S-H	Calcium Alumino Silicate Hydrate
C-S-H	Calcium Silicate Hydrate
CO_2	Carbon dioxide
deQo	Database for Embodied Quantity Outputs
ECC	Embodied Carbon Coefficient
EE	Embodied Energy
EEC	Embodied Energy Coefficient
FA	Volcanic Ash with a mean size of 6 μm
GGBS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GWP	Global Warning Potential
IP	Volcanic Ash with a mean size of 17 μm
M-S-H	Magnesium Silicate Hydrate
OPC	Ordinary Portland Cement
PSD	Particle Size Distribution
SCM	Supplementary Cementitious Materials
SF	Silica Fume
SMQ	Structural Material Quantities
VA	Volcanic Ash

site, construction, maintenance, and demolition of the building. For the purpose and scope of this study, the EE is related to the material extraction and manufacturing process (cradle-to-gate).

The initial EE of a building is defined as the energy used to obtain raw materials to extract, manufacture, transport and install products for the initial construction of buildings (Cole and Kernan, 1996). It must be noted that the EE considered in this paper is related to the energy to initially construct a building and does not include maintenance, repair and replacement of construction materials/components over the life time of the building. Also, EE for transportation from extraction to concrete production site is not accounted due to the uncertainty in the distance and the method of transportation. EE of materials directly affects the EE of buildings, thus any modifications to the material affects the EE of buildings (Jong-Jin and Rigdon, 1998). One way to reduce the EE of buildings is by using low energy materials instead of conventional materials. For example, volcanic ash is a naturally available material and has a lower EE than Portland cement. Findings from one case study in Hong Kong demonstrated that use of recycled materials can lead to more than 50% of savings in EE of buildings (Chen et al., 2001). The readers are referred to the following references for detailed review on EE measurements for buildings (De Wolf et al., 2016a; Dixit et al., 2010; Dixit et al., 2012; Pearlmutter et al., 2007). Usage of natural materials instead of man-made materials for construction significantly lowers the EE of buildings along with less toxicity and several environmental benefits thus lowering the overall carbon foot print in the eco-system (De Wolf et al., 2017; Diaz-Loya et al., 2017). Another way to lower the EE of buildings is to use less materials. Therefore, the low energy materials need to perform as well as conventional materials. This paper analyses both EE and strength of concrete using volcanic ash replacement of Portland cement.

Despite a growing interest among practitioners, for building materials no appropriate standards have been developed yet for the Embodied Energy Coefficient (EEC) expressed in $MJ/kg_{material}$. EEC expresses the EE of each building product in MJ per kg of material. One of the strategies to reduce the embodied carbon of concrete buildings is altering the concrete mixes. Indeed, most carbon emissions associated with buildings are due to the Portland cement that is traditionally used for concrete. Typically, the inventory of carbon and energy (Hammond et al., 2011) gives ECC values of 0.74 kg_{CO2e}/kg for cement, 0.1 kg_{CO2e}/kg for 16/20 MPa concrete, and 0.113 kg_{CO2e}/kg for 25/30 MPa concrete. Here, 16/20 and 25/30 indicates the ratio of characteristic cylinder strengths (16 and 25 MPa) to characteristic cube strength (20 and 30 MPa) after 28 days of curing. These numbers are mainly for cement and concrete in the United Kingdom. The Athena Sustainable Materials Institute gives ECC values for North America: 0.776 kg_{CO2e}/kg for cement and 0.091 kg_{CO2e}/kg for 16/20 MPa concrete and 0.128 kg_{CO2e}/kg for 25/30 MPa concrete (Athena, 2015).

Another way of reducing embodied carbon content is to use more recycled materials in construction. Use of fly ash and ground granulated blast furnace slag (GGBS) has helped significantly to reduce the embodied carbon content. Recently, Bontempi has proposed a formula to calculate the effectiveness of raw material substitution using a term “Sub-Raw” Index. This index is considered as a parameter to compare the base raw material and the substituted material. Moreover, this index takes in consideration the EE and CO_2 footprint to evaluate the environmental performance on the usage of the materials. In this paper partial substitution of Portland cement with natural pozzolanic VA is seen as a potential alternative to effectively substitute Portland cement using naturally- and locally-available waste stream by-products. The key impact of this study would be to reduce the GHG emissions by substituting OPC with VA in concrete products. This paper investigates the effect on EE at a material and building scale when volcanic ash (VA) is used as a partial replacement to Portland cement. To date, several studies have analyzed the EE content for the use of fly ash, GGBS, and silica fume (SF) as an admixture, partial substitute, or full substitute to OPC (De Wolf, 2014; De Wolf et al., 2014; Jamieson et al., 2015; McLellan et al., 2011). However, limited studies on EE efficiency are available on the use of naturally available materials particularly VA as a replacement to Portland cement. This study examines the effect of EE emissions when various compositions of natural pozzolanic VA is used as a partial substitute to OPC. Furthermore, effect of reduction in particle size of VA and increase in concentration of VA have been evaluated for EE values on a material and a building scale.

2. Methods and materials

2.1. Methodology

The current study utilizes our recent experimental data that was obtained by substituting OPC with VA to provide an insight into EE consumption from a material to building scale (Kupwade-Patil et al., 2018c). EEC values were calculated based on the initial material inputs to the mix and were related to the compressive strength values after 28 days of curing. In addition to the effect of reduction in particle size of VA concentration effect was examined when VA was used as a partial replacement to OPC from 10 to 50%.

EE for Portland cement based concretes has been well analyzed (Hammond et al., 2011; Hammond and Jones, 2008; Tanaka and Stigson, 2009; Venkatarama Reddy and Jagadish, 2003). However, no studies have been reported for calculating the EE of VA with OPC. Material input and life cycle processes needed for OPC and VA production are shown in Fig. 1. The assumed values used for calculating the EE are shown in Table 1, illustrating the selected values and ranges that are reported for EE of construction materials. For this study, standard EEC values for base materials were obtained from ICE database (Hammond et al., 2011; Hammond and Jones, 2008) and from the World Business Council report applied to the Middle East (WBCSD, 2015).

Several assumptions were made for calculating the EE such as mixing, laying, and curing of OPC and OPC/VA combinations. It was