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

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ABSTRACT

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

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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

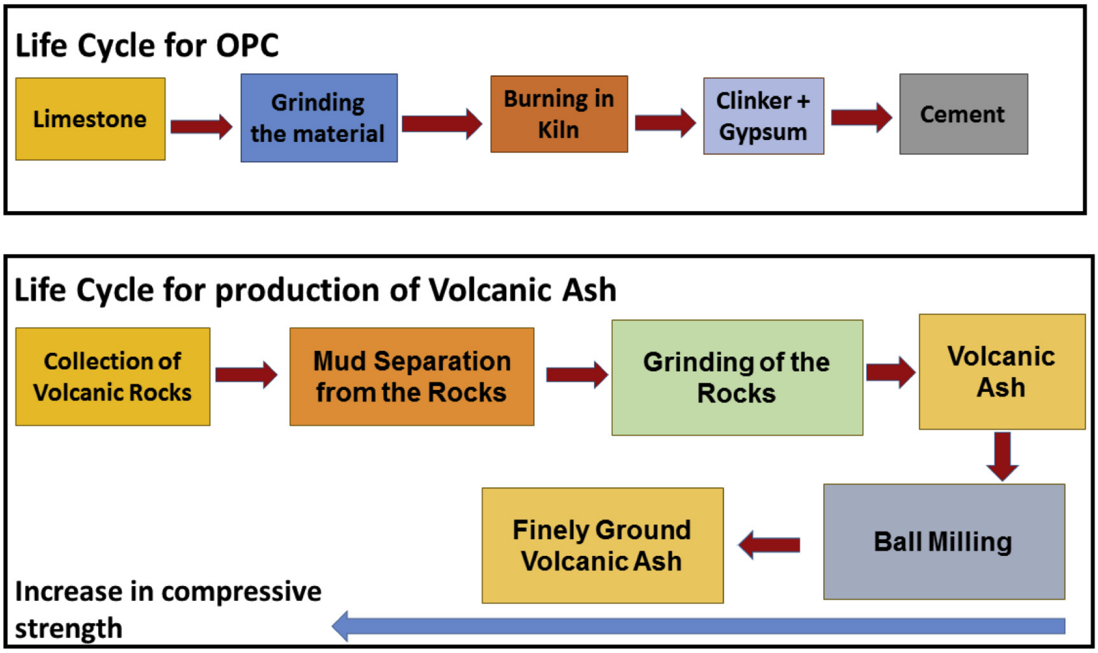

Fig. 1. Life cycle production of Ordinary Portland Cement and Volcanic Ash.

Table 1
Selected database of EEC from (Hammond et al., 2011; Harvey, 2010).

Material	EEC (MJ/kg)	Source
Limestone	0.85	ICE (Hammond et al., 2011)
Mortar	1.09–1.4	ICE (Hammond et al., 2011)
Concrete prepared with OPC	0.7–0.95	ICE (Hammond et al., 2011
Crushed Rock	0.083	ICE (Hammond et al., 2011)
(IP)Volcanic Ash (17 μm)	≤0.5	(Harvey, 2010)
(FA)Volcanic Ash (6 μm)	≤0.6	

also assumed that concrete was produced near the source of the raw materials and hence transportation distance was not considered for this case. The selection criterion for EE and carbon values for individual materials was based on four parameters (Hammond and Jones, 2008): compliance with approved methodology and standards, system boundaries for cradle-to-site embodiment, origin of country where the precursor material originated, and age of the data based on the historical changes in the mix. These parameters were used to estimate the fuel-related embodied carbon emission content related to the production of Portland cement and incorporation of VA as a substitute to Portland cement. It also highlights the importance of the amount of waste generated by volcanic rocks and the cost/energy involved to landfill these materials. This increases the EE for collecting and transporting the material to the waste accumulation area. By using VA in preparing concrete, we avoid landfilling of the rocks which reduces the GHG emissions, and thus saving the cost for transportation of volcanic rocks to the landfill area.

The approach for this study considers the effect of reduction in particle size of VA on compressive strength of OPC cements blended with VA. In order to apply the material data to obtain EE results at the building scale, the EEC of the engineered concrete with VA replacement was integrated across the entire building. Based on ranges of material quantities for various concrete buildings and structures that were estimated by (De Wolf et al., 2016b), a comparison was conducted for commercial and residential buildings with concrete as a main structural material using OPC and concrete with VA replacement. The material quantities were then multiplied with the respective EECs to obtain the EE at the building scale.

Two key variables are analyzed in the embodied carbon calculations for buildings: Structural Material Quantities (SMQ), expressed in kg of material ($kg_{material}$ or kg_m) per functional unit (often m^2 of Gross Floor Area); and EEC expressed in MJ/kg_m. Presently, there is no clear standard for accurate EEC values, and information on SMQ values for building structures is scarce. As illustrated in equation (1), the EE (MJ/m^2) was calculated by multiplying these two variables.

$$\textit{Embodied Energy } (EE)_{building} = \sum_{i=1}^{n} SMQ_i \times EEC_i \tag{1}$$

where i is a particular construction material i = 1, 2, 3, …, n.

A term “Sub-Raw Index” was introduced by Bontempi which quantifies environmental benefits of raw material substitution based on EEC and carbon footprint (CF) expressed in MJ/kg and $kgCO_2e/kg$, respectively. The Sub-Raw Index is defined as

$$Sub - Raw\ Index = \frac{[\log (EEC_{raw}) - \log(EEC_{sub}) + \log(CF_{raw}) - \log(CF_{sub})]}{2} \tag{2}$$

As per Bontempi the dimensionless values of Sub-Raw index can range from −9 to 9, where positive values suggest enhanced sustainability of newly proposed material when compared to the base material to be substituted (Bontempi, 2017a, 2017b). If the "Sub-Raw Index" values are negative this indicates higher sustainability of the base raw material when compared to the substituted material.

Many techniques were used to determine SMQ values typical to Kuwaiti architecture. Sources for direct information about the average material quantities were: floorplans of Kuwaiti villas publically available through the Public Authority for Housing Welfare (PAHW, 2016); site visits to Kuwaiti neighborhoods, construction sites, and demolition sites; the database of embodied Quantity outputs (deQo), which compiles typical SMQs for the Middle East; and bills of quantities provided by the municipality of the neighborhood. Building dimensions such as exterior wall length, wall thickness, and floor thickness were measured from the PAHW floorplans, and the thickness of the envelop material was measured at construction and demolition sites. In addition, drones captured detailed aerial photographs of entire blocks of the neighborhoods. Data from 13 residential and 13 commercial buildings were studied to estimate the SMQ. The EE results include structural concrete and reinforcement steel, which was assumed to have 59% recycled content. The EE results include structural concrete and assumed reinforcement steel with 59% recycled content.

2.2. Materials

Pozzolanic VA from the Kingdom of Saudi Arabia was obtained as a coarse powder from a manufacturer and then further ground using a high-speed vibratory ball mill. Particle size was analyzed using a laser-based particle size analyzer. The distribution of particle size calculated from cumulative intrusion was plotted (Fig. 2) and analyzed (Table 2), which showed that the sets of VA had mean diameters of 17 μm and 6 μm. These two sets of VA were denoted as IP and FA, respectively, and used as partial substitutes to OPC.

These two sizes of VA were mixed with OPC at various proportions to make the range of samples as shown in Table 3. The mixing was performed using a water to cement ratio of 0.35, since sufficient water is required to allow involvement of ash for forming hydration products. This work has investigated mixes by increment of 10% up to 50% by dry weight of OPC substituted by volcanic ash of 6 μm (FA) or 17 μm (IP). The samples are named based on both the particle size and the proportion of the VA; for example, a mix of 10% VA of size 17 μm and 90% OPC by dry weight was denoted IP-10, whereas a mix of 10% VA of size 6 μm and 90% OPC by dry weight was denoted FA-10. The samples were prepared as per the ASTM C305 standard and were lime cured for 28 days (ASTM, 2014). After 28 days of curing, the specimens were subjected to compression

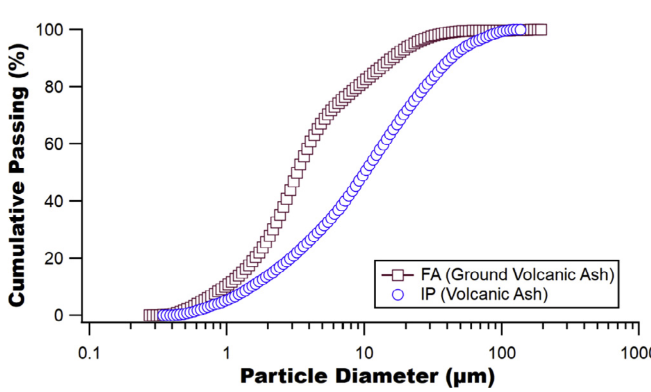

Fig. 2. Particle Size Distribution analysis for the volcanic ash as determined using laser-based particle size analyzer.

testing as per ASTM C 39 (ASTM-C39, 2016).

3. Results and discussion

3.1. Strength and EE analysis on a material scale

On a material level, the base VA was ground into two mean sizes, and the VA was used as a partial replacement to Portland cement. The compressive strength and EEC values for IP and FA samples are shown in Figs. 3 and 4, respectively. Excluding FA-30 (63.34 MPa), all the samples showed lesser compressive strength than the OPC specimen (62.63 MPa). By only comparing IP samples prepared with 17 μm VA, a strength increase was observed up to 30% substitution of OPC with VA, followed by a decrease in strength at 40% and 50% substitution of VA (Fig. 3). For IP samples, a strength increase of 32% was observed as the concentration of VA increased from 10% to 30% followed by a decrease in 4% at 50% substitution of OPC with VA (IP-50) when compared with the IP-30 sample. A similar trend in strength increase was observed for the FA samples prepared with 6 μm VA. FA samples made with 6 μm VA had 15% higher compressive strength than IP samples made with 17 μm VA.

The increase in strength of the FA samples has been attributed to the increased surface area and more uniform mix, which together lead to better utilization of VA in the pozolanic reactions (Kupwade-Patil et al., 2018a). Microstructure and pore structure studies were performed on hardened cement paste prepared with VA (Kupwade-Patil et al., 2018c). These studies show that a finer size of VA reacts more effectively with the base Portland cement, thus forming higher amounts of Calcium-Silicate-Hydrate (C-S-H) along with C-A-S-H gel phases, which are responsible for strength initiation in the cement paste. Also, increasing the proportion of VA increases the CaO and MgO content leading to the formation of Magnesium Silicate Hydrates (M-S-H), thus attributing to lower strength as compared to C-S-H gel (Kupwade-Patil et al., 2016a, 2018b). Furthermore, early age studies on hydrating OPC with VA was examined by Quasielastic Neutron Scattering (QENS), in situ electrochemical impedance spectroscopy (EIS) and Raman spectroscopy (Husain et al., 2017; Kupwade-Patil et al., 2016b; Masmoudi et al., 2017). These studies examined the role of free and chemically bound water during hydration of OPC-VA mixes with varying particle size and concentration of VA. Recently, Johnston used accelerated electrokinetic treatment to ingress sodium and magnesium sulfate into hardened cement pastes prepared with VA and OPC combinations (Johnston, 2017). Micro-pore and mechanical analysis determined that 10–30% partial substitution of VA was optimal for sulfate resistance. Previous studies corroborate the findings that using more than 30% VA results in the domination of M-S-H related phases over C-S-H and C-A-S-H gel phases (Kupwade-Patil et al., 2016a, 2016b). Thus, unless the VA is engineered, above 30% VA replacement of OPC may lead to decrease in strength and increase in porosity, forming less dense cement pastes.

OPC samples showed the highest EEC values when compared with OPC/VA combination of samples as shown in Fig. 4. For example, the EEC value for IP-10 was calculated by adding the 90% value of EEC for OPC (0.9 MJ/kg), 10% value of the EEC of the 17 μm VA, which is the regular VA obtained from the manufacturer (0.5) and 35% of the EEC value for the water (0.01) as the water to cement ratio of 0.35 was used for mixing. For FA samples, the EEC value was 0.6, while values of OPC and water remained same for all samples. A linear decrease in EEC values was observed with the increase in the VA content. These calculations show that IP-10, IP-50, FA-10, and FA-50 had a 4%, 22%, 3%, and 16% lower EEC, respectively, than that of the baseline OPC. On average, the FA samples had a 4% increase in EEC values than the IP samples. This increase in EEC values accounts

Table 2
Particle size distribution analysis of the volcanic ashes.

Binder type	Nomenclature	Mean (μm)	Median (μm)	Model (μm)	Diameter for selected percentiles by volume		
					D 90 (μm)	D50 (μm)	D 10 (μm)
Volcanic Ash	IP	17.14	10.00	13.27	42.46	10.00	1.50
Volcanic Ash	FA	6.00	3.25	2.97	15.79	3.25	0.97

Table 3
Mix design composition of Ordinary Portland Cement and Volcanic Ash.

Nomenclature	Composition by weight (%)										
	OPC	IP-10	IP-20	IP-30	IP-40	IP-50	FA-10	FA-20	FA-30	FA-40	FA-50
OPC (%)	100	90	80	70	60	50	90	80	70	60	50
IP (%)	0	10	20	30	40	50	0	0	0	0	0
FA (%)	0	0	0	0	0	0	10	20	30	40	50

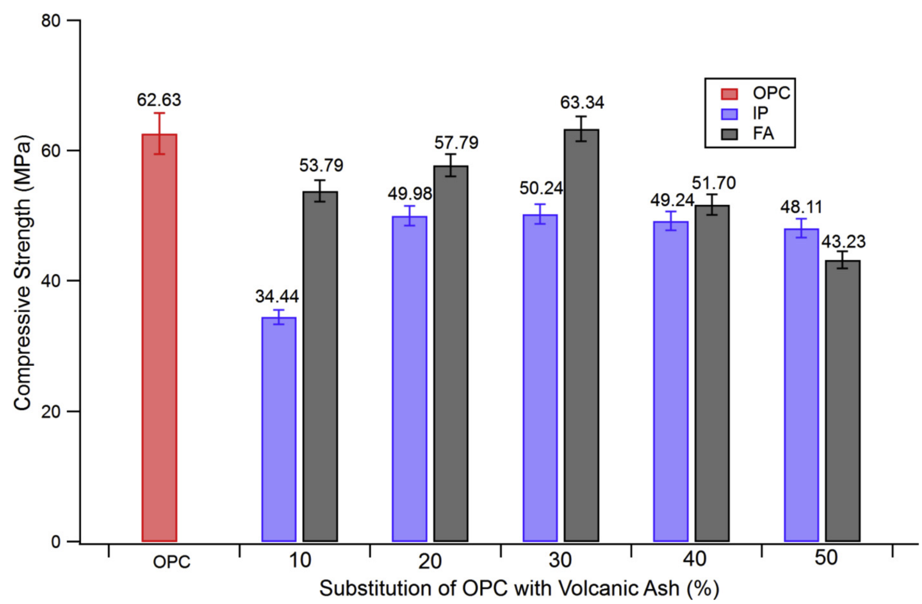

Fig. 3. Compressive strength of cement paste at 28 days prepared with 17 μm and 6 μm volcanic ash and OPC.

for the additional energy used to grind the VA from 17 μm to 6 μm, although this grinding also led to an average of 15% increase in compressive strength for FA samples.

Contour plots of EEC versus compressive strength prepared with 17 μm and 6 μm of VA are shown in Fig. 5A and B, respectively. These plots are useful in selecting the mix-design range in terms of replacement of OPC with VA while considering the effect of compressive strength and EEC. For IP samples prepared with 17 μm VA, a decrease in EEC was observed with an increase in compressive strength. In contrast, an increase in EEC was detected with the increase in compressive strength for FA samples prepared with 6 μm of VA.

Sub-Raw indices for all OPC-VA combinations are shown in Fig. 6. OPC had least Sub-Raw index value of 0.161 and the value increases from 0.162 to 0.205 when OPC is replaced by IP from 10% to 50%. The positive sub-index values show that the proposed mix designs are more sustainable than the baseline of OPC. Furthermore, the increase in sub-raw index indicates that increasing the proportion of volcanic ash additive increases the sustainability of the material even further. However, the sub-raw index values were lower for FA than the corresponding IP samples, which suggests that the energy used in grinding the ash from mean size of 17 to 6 μm could have an impact on overall sustainability of the raw material substitution.

This again demonstrates how grinding the VA to a finer size not only increases the compressive strength, but also increases the EEC values. These contour plots (Fig. 5A and B) demonstrate that the greatest compressive strength is developed between 20% and 30% replacement of OPC with VA for both sizes. Hence, VA-cement mixes can be engineered depending on the required compressive strength to obtain benefits in terms of EEC of materials. This study therefore recommends considering each mix design and tailoring the VA-cement paste based on the applications related to structural concrete. In what follows are the results of VA-concrete mixes that can be used for calculating the EE values for residential and commercial buildings predominantly for the Gulf region.

3.2. EE analysis on a building scale

SMQ's for different structural types by main material used in the building structure are shown in Fig. 7. As shown in Fig. 7, structures using concrete (and steel) as main structural material have higher

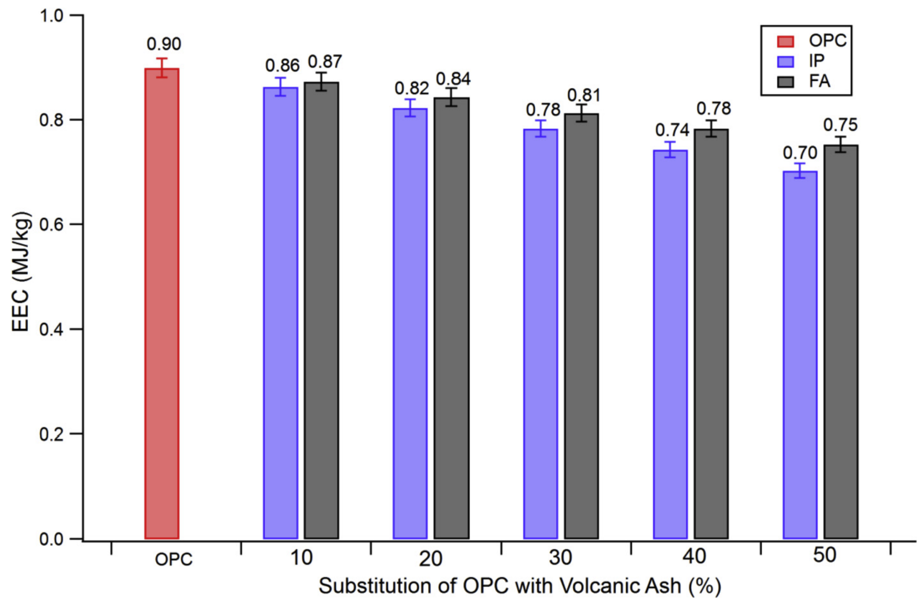

Fig. 4. Embodied Energy Coefficient (EEC) values for OPC and cement paste prepared with 17 and 6 μm volcanic ash.

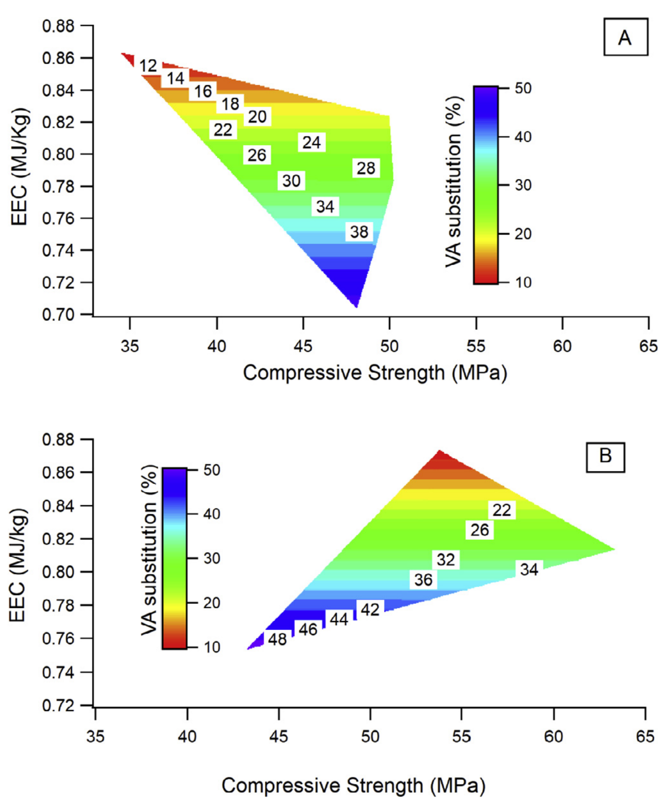

Fig. 5. Embodied energy vs compressive strength for hardened cement paste prepared with 17 μm (A) and (B) 6 μm mean size of volcanic ash from 10% to 50% replacement of OPC.

material quantities than masonry buildings in the Middle Eastern context. The average SMQs of over 600 existing buildings were collected in the database for embodied Quantity outputs (deQo), developed at MIT (De Wolf, 2017). The methodology for collecting data through deQo is illustrated in (De Wolf et al., 2016b). The database collects structural material quantities from structural engineers worldwide through an interactive web interface.

The EE of concrete structures in residential and commercial buildings for the baseline case (OPC) and for the VA replacement scenarios (IP-10, IP-50, FA-10, and FA-50) are shown in Fig. 8. At higher SMQs (expressed in kg of material per functional unit) value of 1955 kg/m^2 a 16% decrease in EE value is observed when 50% OPC is replaced with VA. The results demonstrate two strategies that can lower the EE impacts on the building scale: using less material (lower SMQ) and using low energy materials (lower EEC). In general, the most efficient strategy for lowering the net EEC is to replace as much of the higher EEC-OPC with the lower EEC-VA. Therefore, combinations with the most OPC replacement, IP-50 and FA-50 had the lowest net EE values on the building scale, in addition to the material scale, with up to 50% reduction in EE (MJ/m^2) compared to the material scale, whereas settings with a low amount of OPC replacement showed limited EE reductions from the EE of traditional concrete with OPC.

This work provides new insight into the usage of natural supplementary cementitious materials (VA) for preparing Portland cement pastes with an emphasis on EE analysis. The current study has been tailored to examine the effect of successful substitution of Portland cement with natural pozzolanic VA. Although, there is a 4% increase in EEC values due to grinding but this allows higher substitution of VA along with higher strengths due to the usage of fine ground VA.

Depending on the variation of the compressive strength of concrete, the VA can be tailored into structural concrete for which further analysis is required to examine the long term durability of VA blended Portland cement concretes. Thus, this work shows that naturally available VA that is regionally available in the Gulf region (Saudi Arabia) can be a viable partial substitute to Portland cement thus facilitating low carbon emission for developing sustainable concretes.

4. Conclusions

This work demonstrated potential improvements to the EE of buildings by comparing the EE of cement-VA mix to that of the baseline traditional OPC. A laboratory-scale study was performed to optimize the EE and compressive strength of concrete building

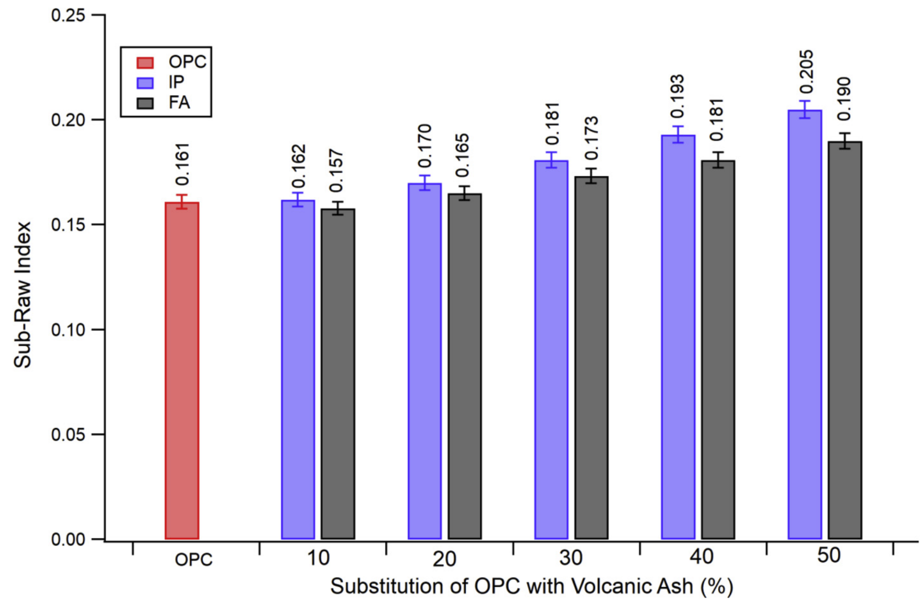

Fig. 6. Sub-Raw indices calculated for different substitution of Portland cement with volcanic ash.

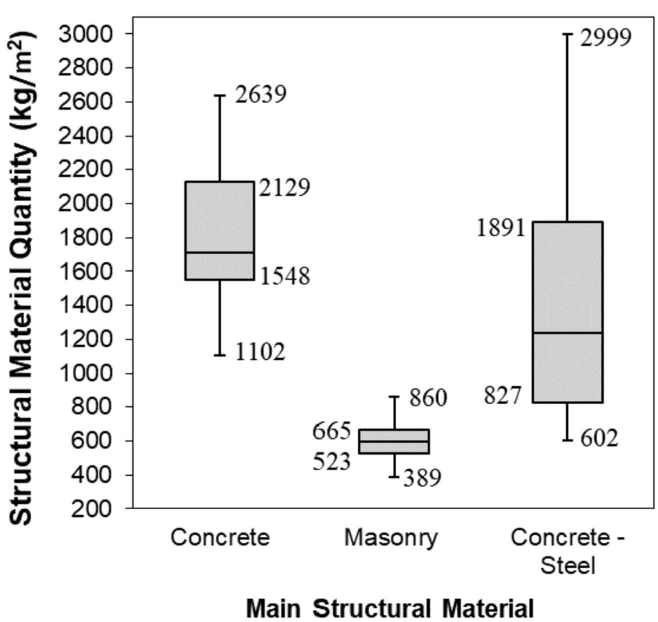

Fig. 7. Structural Material Quantities (SMQ) in different structural systems for projects in the Middle East (De Wolf, 2017).

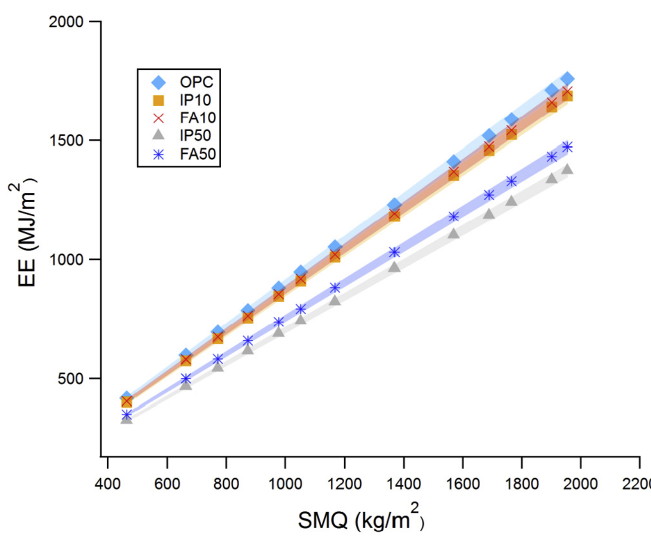

Fig. 8. EE results for residential and commercial case studies with different concrete mixes (shading represents the error).

materials by partially replacing Portland cement with two different sizes (17 μm and 6 μm) of VA. Increasing the proportion of VA reduced the EEC values. Grinding the volcanic ash from 17 μm to 6 μm was beneficial for increasing the compressive strength at the cost of a 4% increase in EEC values; FA-40 had 40% higher compressive strength than IP-40. The greatest compressive strength is developed between 20% and 30% replacement of OPC with VA for both sizes.

EEC values for the cement mixes were calculated based on laboratory study and then integrated to estimate the EE on the building scale. This study suggested that maximizing replacement of OPC with VA would optimize for low EE. Thus, two strategies for decreasing the EE of buildings and building structures were illustrated: reducing the material quantities and increasing the percentage of cement replacement. Using recycled, locally-sourced, and naturally-available construction materials could achieve significant embodied-carbon emission reductions on a building scale. For a building with an SMQ value of 2000 kg/m^2, a 16% decrease in EE value is observed when 50% OPC is replaced with VA. Cement mixes with VA need to be engineered depending on the required compressive strength and environmental conditions of the resulting built structure. These results showed that replacing OPC with volcanic ash, a natural SCM, can reduce EE values, and they can be adapted to design and build energy-efficient systems tailored for specific structural applications.

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