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Case study

Influence of supplementary cementitious materials in sustainability performance of concrete industry: A case study in Hong Kong

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ABSTRACT

Although the use of a few industrial by-products as supplementary cementitious materials (SCMs) is one of the most recognized solutions to produce more durable and sustainable concrete, cost-competitive supply of such materials is of great concern, especially for a resource-scarce city like Hong Kong. In addition, several factors including the mechanical performance, transport distance and allocation of upstream impacts, can offset the environmental gain of concretes produced with such by-products. Other potential material such as volcanic ash, can be an effective alternative of industrial SCMs. However, there is a need to comprehensively demonstrate how this material can enhance the sustainability performance of the concrete industry. In this study, the greenhouse gases (GHG) emissions of using volcanic ash is evaluated and compared with its counterparts such as fly ash and ground granulated blast furnace slag in concrete production using a lifecycle assessment (LCA) technique. Based on the bottom-up approach, an industry level evaluation on GHG emission saving due to the use of different SCMs is conducted. The results show that more than 80 % lower GHG emissions are associated with volcanic ash compared to other SCMs. For the same grade of concrete, volcanic ash can reduce up to 25 % and 19 % of total GHG emissions compared to ordinary Portland cement and SCM concretes, respectively (at the product level). Considering the assumptions described in this study, the results reveal that by substituting 10–50 % industrial SCMs with volcanic ash, 11–37 % more GHG emissions can be reduced from the concrete industry in Hong Kong (at the industry level). The analysis conducted in this study would help source alternative SCMs for further promotion of sustainability in the construction industry of Hong Kong, where majority of SCMs are sourced from different countries.

1. Introduction

Concrete is one of the most commonly used construction materials globally, with an annual consumption rate of 25 giga tons (or

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around 3.5 tons per capita) [1]. While ordinary Portland cement (OPC) is extensively used for concrete manufacturing and the production of OPC itself is energy intensive [2], the construction industry is not only notorious for resource depletion but also contributing significantly to environmental impacts. Global production of cement ranges between 2.8 and 4.1 billion tons per annum [3], which is expected to double (about 216 %) by 2030 [4]. The cement sector alone contributes 8–10 % to the total anthropogenic GHG emissions [5], which could reach 10–15 % by 2020 [6]. Over the years, significant effort is devoted to producing more durable and sustainable concrete and construction products by replacing certain amount of OPC by SCMs [7–10].

Considering the cementitious properties, several industrial by-products including fly ash, ground granulated blast furnace slag (referring simply as 'slag' in this study) and silica fume are commonly used SCMs in the cement and concrete industry around the world [11–14]. The use of SCMs is also considered as one of the recognized and feasible strategies to reduce the environmental impacts for concrete [15–17]. It has been reported that SCMs not only can increase the strength of concrete through reactions between the siliceous and aluminous phase and the calcium phase, but it could also reduce porosity through the micro filler of SCMs [18].

Despite concrete with SCMs has been generally considered as green, recent studies have demonstrated that several factors, such as the exposure conditions, properties including the strength and workability, etc., are often ignored when evaluating their environmental impacts so that the results can be biased [19]. For example, by considering the three factors such as the compressive strength, effects of allocation on impact distribution (as those are by-products), and effects of transportation for concrete production with the use of slag and fly ash, Miller [20] concluded that the mentioned factors can outweigh the benefits of SCMs usage. The study also highlighted that using high amount of SCMs in lieu of OPC does not consistently reduce the GHG emissions when concrete strength is taken into consideration [19,20].

Due to the imbalanced source distribution of commonly used SCMs (e.g. fly ash and slag) [21], it is imperative to explore other potential alterative materials. The problem is aggravated when there is a transition coal fire to green electricity generation in many countries, which has resulted in a reduction in fly ash supply to satisfy the demand given rise by the surging construction activities globally. Several studies have indicated that SCMs (e.g. fly ash) being imported from long distance could outweigh their environmental benefits when used for concrete production [22]. The incorporation of fly ash in concrete may be limited by its quality, local availability and additional transportation cost [14]. On the other hand, some currently used SCMs are not geographically well distributed, e.g. blast furnace slag is rarely produced in the western states of the United States [23]. Therefore, the development of new types of SCMs is needed to mitigate the shortage of commonly used SCMs [24], and to provide more viable options for sustainable concrete production.

Natural pozzolana like volcanic ash has high potential to substitute ordinary cement in concrete production and also in blended cement production [25,26], and it has already been used as natural pozzolana in some countries [27]. Volcanic ash is also considered as an economically feasible and natural SCM used in cement paste, mortars and concrete production [28]. The use of volcanic ash for substituting OPC is significant due to its carbon reduction potential, regional availability, and pozzolanic properties [26]. This can not only improve concrete's compressive strength but also its durability against acid attack, sulphate attack, chloride permeability and sorptivity [29]. It can also be used in developing the alkali-activated binder systems with conventional by-products, such as fly ash, slag and silica fume with activators [30,31] and volcanic ash [32]. For example, the production of structural geopolymer with 50 % volcanic ash and 10 % slag can achieve up to a 85 MPa compressive strength at 28 days in room temperature while the initial setting time can also be significantly reduced [32].

In order to claim volcanic ash-based concrete as an environmentally sustainable product, it is imperative to evaluate its environmental performance when volcanic ash is used in concrete production comparatively to its conventional counterparts. Until now, only few studies on volcanic ash have been focusing on assessing its comparative environmental assessment. For example, Robayo-Salazar et al. [33] examined the alkali-activated binary concrete using volcanic ash (70 %) and slag (30 %), and found that the carbon footprint of the former is 45 % lower than that of the latter. However, the LCA of concrete with volcanic ash and other counterparts such as fly ash and slag is necessary. Moreover, such assessment is geographic dependent, and this has given rise to the need for a localized study to obtain the comparative results for the decision-making process. This paper, therefore, aims to comparatively evaluate the GHG emissions of concretes using volcanic ash as a natural SCM against its counterparts such as fly ash and slag. In addition, this study evaluates the GHG emissions at the industry level based on the bottom-up approach to help source alternative SCMs. The outcomes of this study can further enhance the sustainability of the construction industry in megacities like Hong Kong, where majority of SCMs are sourced from different regions and countries.

2. Brief overview of cementitious materials in Hong Kong

Hong Kong is a resource scarce city, with almost all construction materials or raw materials imported from different regions of China and other countries (e.g. Japan, Philippines and Vietnam). Most importantly, the cementitious materials and products including OPC, SCMs, concrete (partly) are mainly imported from different regions of China and Japan [34]. Although around half of the demand of the total OPC is locally produced, the raw materials for clinker production are imported from China (34 %), Japan (60 %) and Philippines (7%), and manufactured clinkers are also imported from China (19 %), Japan (50 %) and Vietnam (30 %). For the fuel (coal) for burning clinker, it is mostly imported from Indonesia [34]. The production (including the long transportation distance of materials to Hong Kong) of cement and concrete is associated with high carbon emissions [35,36].

The demand of OPC in Hong Kong is about 3 million tons with an increase of 5% per year, of which more than half of them is imported from other regions (mainly from China, Japan and Taiwan) [34,35]. In addition, the total production of ready-mixed concrete in Hong Kong was 5.75 million m^3 in 2017 which is about 7% higher than the production in 2013 (Fig. 1). The production is expected to increase to 6.70 million m^3 in 2022 [37]. It has already been mentioned that the concrete industry in the globe has progressively adopted different SCMs as partial replacement of OPC to reduce its carbon footprint and sustainability concern. In Hong Kong, fly ash and slag are the predominant SCMs used materials for concrete production, and they were mainly from China (65 %) and Japan (35 %) in 2017 [34]. The demand for fly ash and slag has increased sharply in recent years, thanks to the greater awareness of environmental sustainability in the construction industry. For example, the imported total amount of fly ash and slag were 35 % higher in 2016 than that of 2013, although the imported volume was slight lower in 2017 (about 16 %) compared to that of 2016 (Fig. 2). Based on a case-specific study of SCMs in Hong Kong, Hossain et al. [16] has confirmed that SCMs are associated with considerably higher impacts, depending on the type of impact distribution methods and the longer transportation distances. To promote further sustainability of Hong Kong construction industry, it is important to source and use more environmentally friendly SCMs. Therefore, volcanic ash can be an attractive alternative SCM for substituting OPC in sustainable concrete production.

3. Methodology

This study aimed to evaluate the GHG emissions of concretes for using volcanic ash as a natural SCM using LCA technique comparatively to its counterparts, such as fly ash and slag. The scope of the study is to assess the potential GHG saving from the products to industry level based on the bottom-up approach.

3.1. Lifecycle inventory, functional unit and system boundary of different SCMs

The GHG emissions of commonly used industrial by-products (i.e. fly ash and slag) in Hong Kong and the potential natural SCM (i.e. volcanic ash) was evaluated based on mixed literature and first-hand data. The locally generated fly ash was considered in this study, whereas slag was imported from the nearest source location. The average transport distances from the raw material acquisition to the concrete batching plants (average of eight plants was considered) were estimated (details are given in Table S1). The energy consumption for further processing of fly ash and slag was collected from different literature, whereas the upstream data for the energy was collected from regional databases (Tables S1 and S2). Considering the globally adopting approach for industrial SCMs (e.g. [39,40]), economic allocation for slag and fly ash used in Hong Kong according to Hossain et al. [16], was adopted in this study.

For LCA of volcanic ash, first-hand data were collected from the respective manufacturer (in Indonesia) and suppliers (in Hong Kong) through a structured questionnaire survey (given in Tables S1 and S2). The key production and transport processes of volcanic ash is given in Fig. S1. The material is extracted from the generation sites using excavator as open pit mining. The material is handled by bulldozer, where impurities including large stone, gravel, soil, and tree are sorted and removed manually. The materials are then stored as open stockpile pending to shipment. The materials are transported to port using medium size truck, and then load to the hatch of vessel, and is sent to the destination (e.g., Hong Kong) by bulk. Again, loader and excavator are used to unload the vessel and load the truck for transport to further processing or use on sites (e.g. concrete batching plants). Although volcanic ash is a relatively soft material, additional grinding and sieving are required when used as a SCM in concrete. Moreover, drying is required due to the high moisture contents but usually air dried where space is available. Mostly, the processing such as grinding, sieving and drying is not carried out at source. In this study, ball mill was used to grind the materials, and then oven-dried after sieving. The cradle-to-site system boundary with 1 kg of functional unit was considered for the studied SCMs according to the ISO [41,42] guidelines.

3.2. Mix-design, LCI, functional unit and system boundary of concrete with different SCMs

For comparative GHG emission evaluation, a number of concrete batches were prepared such as a reference concrete (with OPC only), concrete with most commonly used percentage of slag (i.e. 30 % and 50 % ordinary cement replacement), concrete with most commonly used percentage of fly ash (i.e. 25 % ordinary cement replacement), and concrete with volcanic ash (i.e. 20 % and 30 % ordinary cement replacement) (Table 1). For industrial SCMs concrete, the most acceptable proportions of slag and fly ash were considered in this study [7,14,43,44]. The mixtures were also based on the guidelines provided by the Civil Engineering and

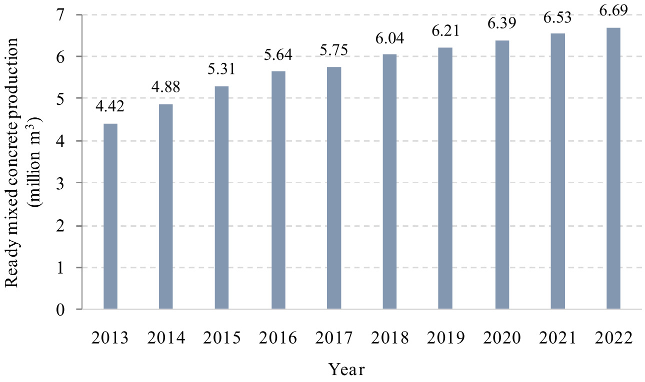

Fig. 1. Ready mixed concrete production in Hong Kong [37].

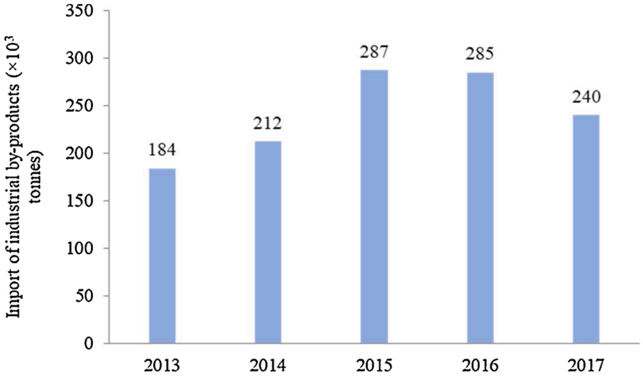

Fig. 2. Import statistics of slag and fly ash in Hong Kong [38].

Development Department of the Hong Kong SAR Government [45], and then 28-day compressive strengths were evaluated as examples of mechanical properties according to BS Standard Methods.

According to ASTM C618, a good pozzolan should contain materials with the amount of SiO_2 $+Al_2O_3$ $+$ Fe_2O_3 not less than 70 % [47], and it is 86.88 % for volcanic ash (Table S3). This implies that volcanic ash would be a good replacement of cement in concrete, although other parameters of natural pozzolana such as strength activity index, fineness and alkali content are needed to be critically considered in the technical studies.

The system boundary was set as ‘cradle-to-gate’ with the functional units (FUs) of: (i) per 1 m^3 concrete production (for comparing and calculating the industry level impact saving due to the use of different SCMs as a partial substitution of OPC), and (ii) per strength by considering the 28 days compressive strength of the designed concretes (for comparing the concrete produced with different SCMs effectively, as the compressive strength is a common functional requirement for concrete applications). Both approaches were widely adopted in the LCA of concrete or concrete products (e.g. [4,8,13,43,48–50]. The lifecycle inventory (LCI) data of all materials for the concrete production including their sources, transportation, energy consumption, and upstream databases / references for such transportation and processes is given in Supplementary information (Tables S1 and S2). Aggregates used in Hong Kong were mostly sourced from China in 2017 [34], and thus, the LCI data for aggregates production was collected from natural aggregate manufacturers and suppliers (for both fine and coarse aggregates) at Guangdong province of China [51]. The data (both energy and transportation) for OPC production in Hong Kong was based on Hossain et al. [36], as locally manufactured OPC was used in this study. The average transport distances from the generation sites to the concrete batching plants were estimated for all materials (as the concrete batching plants are located at different places). The energy consumption for concrete batching in Hong Kong was collected from Zhang et al. [35]. Regional but representative database such as Chinese Lifecycle Database (CLCD) was used for collecting the upstream data for electricity and fuel consumption (Table S2). However, other database and literature were also used for some materials and processing where those were not available in regional database and local studies (Table S2). Finally, the considered concrete production was modeled using the SimaPro 9 software, and the total GHG emissions (in terms of kg CO_2 eq) was evaluated by the IMPACT 2002+ impact assessment method [52].

3.3. Industry level GHG emission saving for using SCMs

It is established that SCMs can reduce the GHG emissions considerably. In this section, the industry level GHG emission saving for the concrete production due to the use of SCMs as a partial replacement of OPC was evaluated. At first, the savings were calculated for the use of industrial by-products (e.g., FA and slag) annually in the construction industry of Hong Kong based on the mixtures

Table 1
Mixtures of concretes produced with different alternatives [46].

Materials (kg/m^3)	M1 (*OPC only*)	M2 (*30% slag*)	M3 (*50% slag*)	M4 (*25% fly ash*)	M5 (*20% volcanic ash*)	M6 (*30% volcanic ash*)
Ordinary Portland cement	445	333	225	350	356	311
Ground granulated blast furnace slag	0	142	225	0	0	0
Fly ash	0	0	0	120	0	0
Volcanic ash	0	0	0	0	89	134
Coarse aggregates	905	935	925	940	1,005	1,002
Fine aggregates	745	680	720	720	730	730
Water	208	221	204	172	140	140
Superplasticizer	1.69	1.81	1.93	1.80	4.36	5.27
Total weight (kg)	2,304.69	2,312.81	2,300.93	2,303.8	2,362.36	2,360.27
Average 28 days compressive strength (MPa)	59.23	63.0	64.37	68.5	70.70	64.80

mentioned in Table 1. After that the additional savings were calculated for the substitution of FA and slag by unconventional SCM (e.g., volcanic ash) (based on the mixtures highlighted in Table 1). Based on the interview with the construction industry (through the personal communication), it was assumed that 30 % fly ash and 70 % slag were used in Hong Kong. On the basis of the last 5 years import statistics (Fig. 2), an average of 2.42×10^5 tons of total fly ash and slag are used annually in the construction industry in Hong Kong [38], which included 7.25×10^4 tons of fly ash and 1.69×10^5 tons of slag according to the above assumption. The industry level GHG emission reduction was quantified according to the use of industrial by-products with respect to the reference concrete (shown in Table 1). As a counter product of fly ash and slag, the potential GHG emission reduction due to the use natural pozzolana can be estimated based on the scenario analysis under two strategies:

*Strategy 1:*GHG emission reduction due to the replacement of 10–50 % imported fly ash by volcanic ash;

*Strategy 2:*GHG emission reduction due to the substitution of 10–50 % imported slag by volcanic ash.

In this study, GHG emissions due to the use of entire amount of SCMs for replacing certain amount of OPC were estimated first based on the savings for the mentioned concrete production (Table 1). Then the industry level GHG emission saving for the use of entire amount of imported industrial SCMs can be estimated using Eqs. (1) and (2). It is assumed that all SCMs are used in concrete production.

$$S_{FA(p)} = FA_{TA} \times \left[C_{OPC} - C_{(OPC(P)+FA(p))}\right] \tag{1}$$

In the case of 25 % fly ash, Eq. (1) can be written as:

$$S_{FA(25\%)} = FA_{TA} \times \left[C_{OPC} - C_{(75\%OPC+25\%FA)}\right]$$

where S_{FA} is the total potential CO_2 eq saving per year for the use of total amount of fly ash, p is the percentage of fly ash being used, FA_{TA} is the total amount of fly ash being used, C_{OPC} is the total CO_2 eq emissions for a unit of OPC concrete, and $C_{(}75\ \%_{OPC+}25\ \%_{FA)}$ is the GHG emissions of concrete produced with 25 % of fly ash and 75 % of OPC. Similar explanation is applicable for slag (Eq. (2)).

$$S_{GBFS(30\%)} = GBFS_{TA} \times \left[C_{OPC} - C_{(70\%OPC+30GBFS\%)}\right] \tag{2}$$

On top of the saving for the use of fly ash and slag, further reduction due to the use of volcanic ash instead of these two industrial by-products was estimated with 5 scenarios such as replacing 0% (Scenario 1: base case), 10 % (Scenario 2), 20 % (Scenario 3), 30 % (Scenario 4), 40 % (Scenario 5), and 50 % (Scenario 6) for the concrete production using Eq. (3).

$$S_{VA} = \left[(C_{USCMs} \times SCMs_{TA}) + \ (C_{UVA} \times \%\ VA_i)\right] \tag{3}$$

where S_{VA} is the net saving of GHG emissions due to the use of volcanic ash, $SCMs_{TA}$ is the total amount of SCMs, and %VA is the percentage of volcanic ash that substituted SCMs ($i = 10\%–50\%$). The saving of GHG emissions for the corresponding substitution was calculated using Eq. (3), where C_{USCMs} is the saving of GHG emissions for the use of per unit SCMs (e.g. 1 kg for substituting certain amount of OPC considering the equivalent strength), and C_{UVA} is the GHG emission saving due to the use of per unit volcanic ash (e.g. 1 kg for substituting certain amount of OPC considering the equivalent strength).

4. Results and discussion

4.1. GHG emissions of cementitious materials and concretes

Considering the system boundary, the GHG emissions per kg of SCMs used in Hong Kong are shown in Fig. 3. It has already been

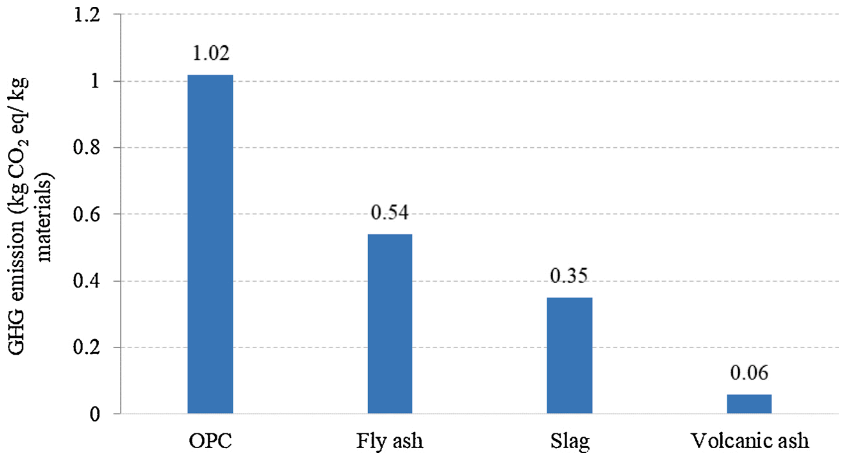

Fig. 3. GHG emissions for per kg of cementitious materials.

mentioned that an economic allocation approach was adopted for industrial by-products. The results show that about 0.54 and 0.35 kg CO_2 eq are associated with fly ash and slag, respectively. These are significantly lower than the OPC produced in Hong Kong. The production, transport and processing of volcanic ash (for using in concrete production) are associated with 94 %, 89 % and 83 % lower GHG emissions compared to OPC, fly ash and slag, respectively (Fig. 3). Although it is not absolutely fare to compare GHG emissions of different cementitious materials (OPC, fly ash, slag and volcanic ash) due to the different strengths of concretes produced, an overall indication of the environmental impacts can be evaluated. As the addition of SCMs can significantly influence both the mechanical performance and environmental impacts, it is necessary to compare different proportions of SCMs when these materials are used in concrete with equivalent compressive strength, since it is an important parameter for concrete LCA [53].

4.2. GHG emissions of concretes based on per m^3 FU

Based on the designed mixtures of the SCMs concrete (Table 1), the LCA results on the GHG emissions for per m^3 functional unit are shown in Fig. 4. The results reveal that CO_2 eq emissions for M1 concrete are considerably high in Hong Kong, due to the higher GHG emission factor of OPC as compared with other SCMs. Therefore, the total GHG emissions are 511 kg CO_2 eq for M1 concrete (Table 1). For M1 concrete, OPC and aggregates contributes to about 99 % of total GHG emissions, whereas less than 1 % is contributed by others (such as admixture and the production process) (Fig. 5). The addition of slag can considerably reduce the GHG emissions for the similar grade of concrete production, as the emissions for M2 and M3 are 446 kg CO_2 eq and 366 kg CO_2 eq, respectively. The figures are 13 % and 28 % lower than that of M1 concrete (Fig. 4). For M2, OPC has contributed to 76 % of total emissions, whereas 5 %, 7 %, 11 % and less than 1 % by the fine aggregates, coarse aggregates, slag and others, and only 63 %, 6 %, 8 %, 22 % and 1 % by the OPC, fine aggregates, coarse aggregates, slag and others for M3, correspondingly (Fig. 5). Comparatively, the addition of fly ash does not significantly reduce the GHG emissions for the same grade of concrete production when economic allocation is considered, as the reduction is only 6% for M4 compared to M1. Although only 25 % of fly ash was used, the contribution to the total GHG emissions is high (about 14 % due to its upstream burden induced by the economic allocation) (Fig. 5). The results are also consistent with other studies (e.g. [14,19].

The addition of natural pozzolana can considerably reduce the emissions for the same strength concrete compared to OPC as well as other SCMs concretes (Fig. 4). For substituting 20 % OPC by volcanic ash, about 16 % lower GHG emissions are found (compared to M1), as the emissions are 429 kg CO_2 eq per m^3 for the same grade concrete (M5). However, the saving is even higher (about 25 %) when 30 % OPC is replaced by volcanic ash (M6), as the emissions are 385 kg CO_2 eq as compared to 511 kg CO_2 eq for M1 production. About 85 %, 6 %, 7 %, 1 % and 1 % GHG are emitted by OPC, fine aggregates, coarse aggregates, volcanic ash and admixture and processing, respectively, for M5, whereas they are 82 %, 6 %, 8 %, 2 % and 1 %, correspondingly for M6 (Fig. 5). The overall results indicate that concrete with volcanic ash was associated with significantly lower GHG emissions compared to concrete produced with OPC, slag and fly ash. This is mainly due to less processing requirements of volcanic ash, and no upstream emissions is associated with volcanic ash unlikely to industrial by-products (e.g. fly ash and slag). Therefore, M5 and M6 concretes are associated with about 16–25 % lower GHG emissions compared to the OPC concrete (M1), i.e. about 10–19 % lower than that of fly ash concrete (M4). The emissions for M6 is also lower than the concrete containing similar replacement of slag (e.g. 30 % slag in M2), but slightly higher when compared to that of concrete containing 50 % slag (M3).

4.3. GHG emissions of concretes based on per strength FU

Considering the compressive strength as FU, the 28-day per strength (MPa) GHG emissions for different concrete mixtures is given in Fig. 6. As higher amount of OPC was used in M1 concrete, GHG emissions was significantly higher than all other concretes. When 30

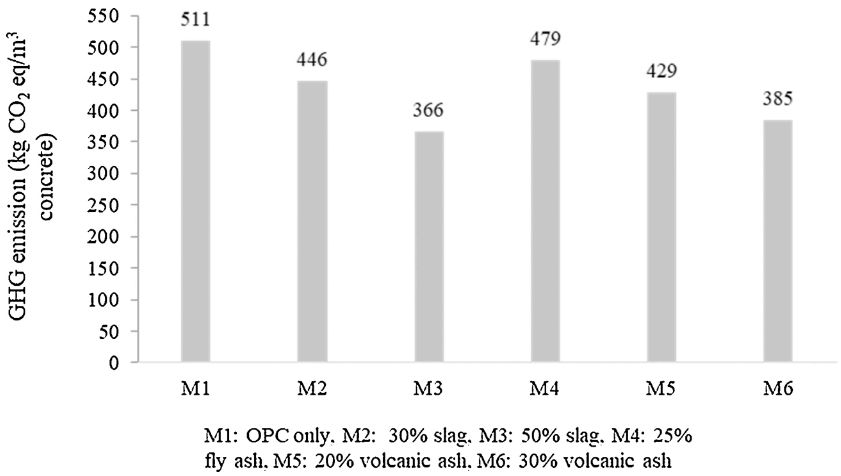

Fig. 4. GHG emissions of the studied concrete mixtures.

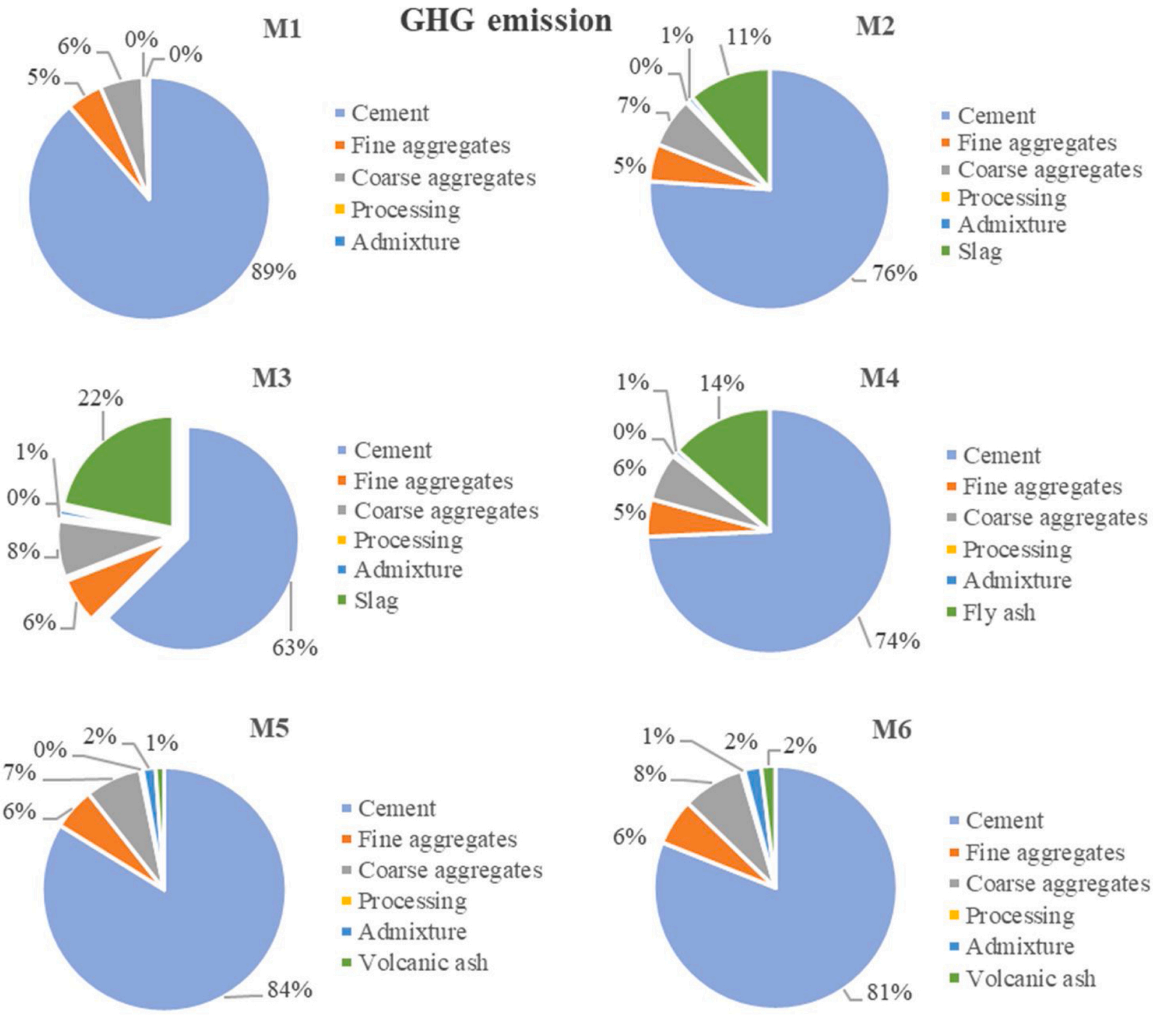

Fig. 5. Contribution analysis of GHG emissions for different mix-designs of concrete.

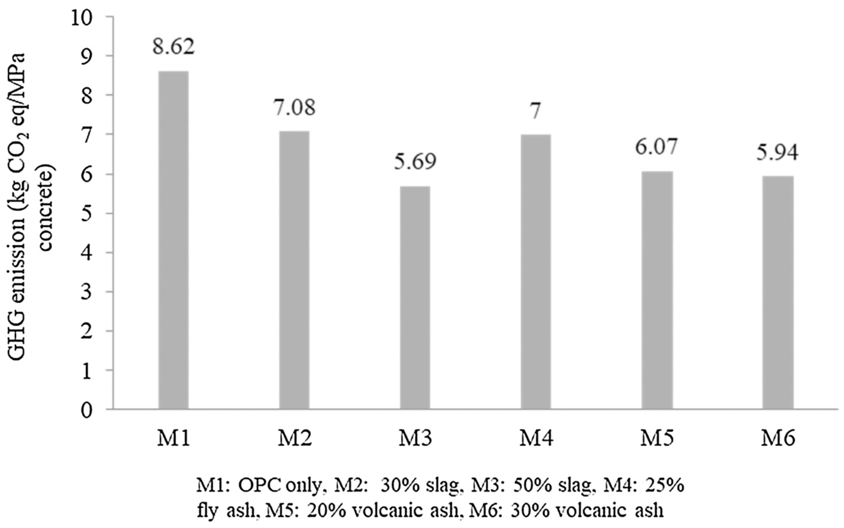

Fig. 6. GHG emissions of different concrete mixtures of 28 days per strength (MPa).

% and 50 % slag in M2 and M3 concrete were applied, about 18 % and 34 % lower GHG emissions was found than that of M1. Similarly, the use of 25 % FA can also reduce about 19 % total the GHG emissions compared to that of M1. Volcanic ash could reduce about 30 % and 31 % of the total GHG emissions compared the OPC concrete, as the emissions were 6.07 kg CO_2 eq and 5.94 kg CO_2 eq per MPa for C5 and C6 concrete, respectively, whereas it was about 8.62 kg CO_2 eq for M1 concrete.

Considering the different FUs, the comparative GHG emissions for the designed concretes is shown in Fig. 7. The differences are 5 %, 6 %, 13 %, 14 % and 6 % for M2, M3, M4, M5 and M6, respectively. The results have demonstrated a 5–14 % higher savings for the strength as FU compared to the volume as FU for the designed concretes. This is because all mixtures designed with SCMs had considerably higher strengths as compared to OPC concrete.

4.4. Industry level GHG emission reduction for using supplementary materials in different scenarios

According to the compressive strengths of concrete of different alternatives (Table 1), 30 % OPC replacement by slag (M2), 25 % OPC substitution by fly ash (M4) and 30 % by volcanic ash (M6) have similar strengths. Moreover, their replacement ratios are also consistent in concrete applications. Previous studies have also demonstrated that 10–30 % replacement of OPC by volcanic ash can obtain the maximum benefits in cement paste according to the mechanical and microstructural properties [54]. Similarly, 20–30 % replacement is ideal with an increased compressive strength of concrete, but higher percentage (up to 40 %) is possible if finer volcanic ash is used [25,26]. Therefore, the GHG emission saving for using volcanic ash can be estimated based on the two strategies (Section 3.3) by considering the M2, M4 and M6 concrete production. The savings of total GHG emissions for the use of industrial SCMs can be estimated by using Eqs. (1) and (2). It is about 26,122 tons for fly ash, while 77,881 tons for slag (the calculation is given in Appendix 1). It is noted that the industry level GHG emission savings for both the industrial by-products and volcanic ash were evaluated according to the savings calculated by using volume as FU of the studied concretes although 5–14 % higher savings were observed when strength is considered as FU. Because it is not practically feasible to evaluate the industry level GHG emission savings by considering the strength as FU.

The results show that in total 1.04×10^5 tons (25 % for fly ash and 75 % for slag) of GHG emissions can be reduced due to the use of 2.42×10^5 tons of fly ash and slag (30 % and 70 %, respectively) in the construction industry of Hong Kong annually. Using slag can reduce higher GHG emissions than fly ash due to the lower GHG emissions for the upstream burden.

Based on the scenario analysis (Section 3.3), the saving of GHG emissions for the corresponding substitution was calculated using Eq. (3). For example, about 30,330 tons of GHG emissions can be reduced with Scenario 2 (e.g. 10 % substitution of fly ash by volcanic ash), whereas it is 86,008 tons for using 90 % slag and 10 % volcanic ash (the calculation is given in Appendix 2).

The results of all scenarios for both fly ash and slag are given in Tables 2 and 3. It can be seen that, by replacing 10 % fly ash (Scenario 2) with volcanic ash, about 14 % higher GHG can be saved from the concrete production, which is about 9% for the replacement of slag. Similarly, about 45 % higher GHG emissions can potentially be saved by replacing about 50 % of the total fly ash used in Hong Kong annually (Table 2). For substituting 50 % of total slag used in Hong Kong with volcanic ash, about 34 % more GHG emissions can be saved in the construction industry of Hong Kong (Table 3).

Similarly, the potential GHG emission reduction due to the replacement of different percentages of both fly ash and slag by volcanic ash can be estimated by the integrated scenario (IS) analysis based on the considered strategies mentioned in Section 3.3, as below:

IS-1: The first integrated scenario refers to the reduction of GHG emissions (compared to OPC concrete) when 100 % of both fly ash and slag are used in the concrete industry in Hong Kong (currently used every year).

IS-2: The second integrated scenario implying that when 90 % of both fly ash and slag are used and the remaining 10 % is replaced by volcanic ash for each.

IS-3: The third integrated scenario indicating that when 80 % of both fly ash and slag are used and the remaining 20 % is replaced

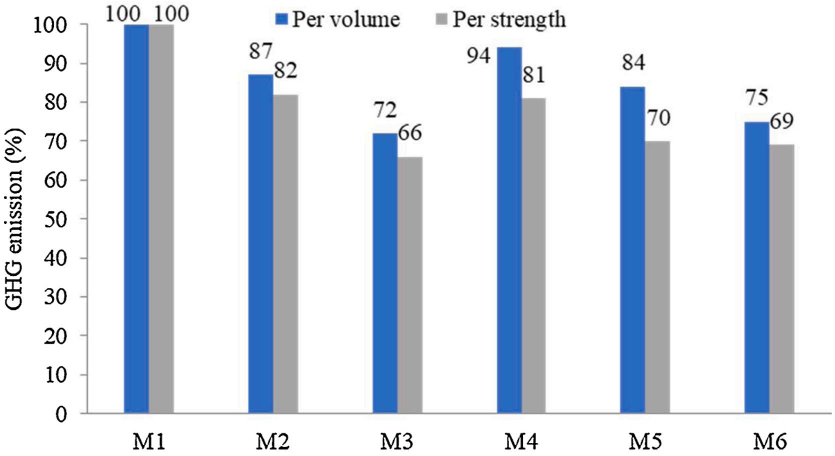

Fig. 7. Comparative GHG emissions of different concretes for different functional units.

Table 2
Scenario analysis for GHG emission (in tons of CO_2 eq) reduction for substituting fly ash by natural pozzolana.

Strategy 1	Fly ash		Natural pozzolana						
	(%)	*Values*	*0 %*	10 %	20 %	30 %	40 %	50 %	*Values (in total)*
Scenario 1	100 %	26,122							26,122
Scenario 2	90 %	23,510		6,821					30,331
Scenario 3	80 %	20,897			13,641				34,538
Scenario 4	70 %	18,285				20,462			38,747
Scenario 5	60 %	15,673					27,283		42,956
Scenario 6	50 %	13,061						34,103	47,164

Table 3
Scenario analysis for GHG emission (in tons of CO_2 eq) reduction for replacing slag by natural pozzolana.

Strategy 2	Slag		Natural pozzolana						
	(%)	*Values*	*0 %*	10 %	20 %	30 %	40 %	50 %	*Values (in total)*
Scenario 1	100 %	77,881							77,881
Scenario 2	90 %	70,093		15,915					86,008
Scenario 3	80 %	62,305			31,830				94,135
Scenario 4	70 %	54,517				47,745			102,262
Scenario 5	60 %	46,729					63,660		110,389
Scenario 6	50 %	38,941						79,574	118,515

by volcanic ash for each.

IS-4: When 70 % of both fly ash and slag are used and the remaining 30 % is replaced by volcanic ash for each.

IS-5: When 60 % of both fly ash and slag are used and the remaining 40 % is replaced by volcanic ash for each.

IS-6: The sixth integrated scenario indicating that when 50 % of both fly ash and slag are used and the remaining 50 % is replaced by volcanic ash for each in the concrete industry in Hong Kong.

The results of integrated scenario are shown in Table 4 and Fig. 8. The results show that about 11 % more GHG emissions can be saved by replacing 10 % both fly ash and slag using volcanic ash (IS-2), and the savings are increasing consistently with the increase in percentage of replacement (Table 4 and Fig. 8). For instance, the saving is significantly higher when 30 % of both fly ash and slag are replaced by 30 % volcanic ash (IS-4), which is about 26 %, while the potential GHG emission reduction would be 37 % for IS-6 (Table 4 and Fig. 8).

This study has comprehensively analyzed the benefits in the of GHG emissions when using natural pozzolana as a substitute of OPC and industrial by-products by considering the compressive strength of concrete production. For evaluating the GHG estimation of concrete industry in Hong Kong due to the use of different materials, concrete with volcanic ash has shown higher GHG reduction compared to other SCMs. For volcanic ash concretes (M5 and M6), higher aggregate contents, lower water-to-binder ratio and higher dosages of superplasticizer were used. Thus, further investigation is needed for designing the optimum use of materials for volcanic ash concrete, particularly the use of optimal dosage of superplasticizer as higher dosage can increase the total costs. In addition to the compressive strength, more tests on durability such as carbonation resistance, creep, cracking resistance, chloride and sulfate resistance, etc. are necessary for comprehensive evaluation of volcanic ash concrete. In addition to mineral content, other parameters such as strength activity index, fineness and alkali content of natural pozzolana have to be considered in future, as the strength and durability of concrete are also influenced by those parameters. Although the technical benefits such as controlling the alkali-silica reaction and reducing shrinkage were reported by previous studies (e.g. [29,55]), the properties of volcanic ash are heavily dependent on its origin, chemical composition, etc. [56,57]. Therefore, other mechanical performance and durability of concrete produced with volcanic ash should be conducted comprehensively in future studies. Similar to GHG emission evaluation conducted in this study, the economic evaluation of using various alternative materials in the concrete industry would be valuable in the decision-making process in the concrete industry. Based on the most important concern in the concrete industry globally due to the use of GHG emission intensive materials, this study only considered GHG reduction strategies to enhance the sustainability performance of the industry by evaluating the potential reduction of industry level GHG emissions. However, future study should consider the comprehensive environmental assessment with wide range of impacts including the GHG emissions, human toxicity, particulate matter, ecotoxicity, resource depletion (particularly for the depletion of natural resources associated with natural pozzolana), etc. due to the integral designs associated with volcanic ash and industrial by-products in concrete production. In addition, the use of alternative cementitious materials, including both industrial SCMs and natural pozzolana in designing sustainable concretes should be comprehensively evaluated using LCA by considering the extended system boundary (e.g. cradle-to-grave) for the inclusion of the potential impacts of disposal and recycling scenarios. The consideration of end-of-life scenarios of concretes with different alternatives, particularly fly ash and slag is also important for the potential leaching of metals to the environments [58].

Table 4
Integrated scenario analysis for saving GHG emissions for replacing fly ash and slag by volcanic ash.

Integrated scenario	GHG emission reduction (ton CO_2 eq)				Reduction compared to IS-1 (%)
	Fly ash	Slag	Volcanic ash (VA)	Total	
IS-1 *(100% fly ash and slag)*	26,122	77,881	0	104,003	–
IS-2 *(90% fly ash and slag + 10% VA)*	23,510	70,093	22,736	116,339	11
IS-3 *(80% fly ash and slag + 20% VA)*	20,897	62,305	45,471	128,673	19
IS-4 *(70% fly ash and slag + 30% VA)*	18,285	54,517	68,207	141,009	26
IS-5 *(60% fly ash and slag + 40% VA)*	15,673	46,729	90,943	153,345	32
IS-6 *(50% fly ash and slag + 50% VA)*	13,061	38,941	113,677	165,679	37

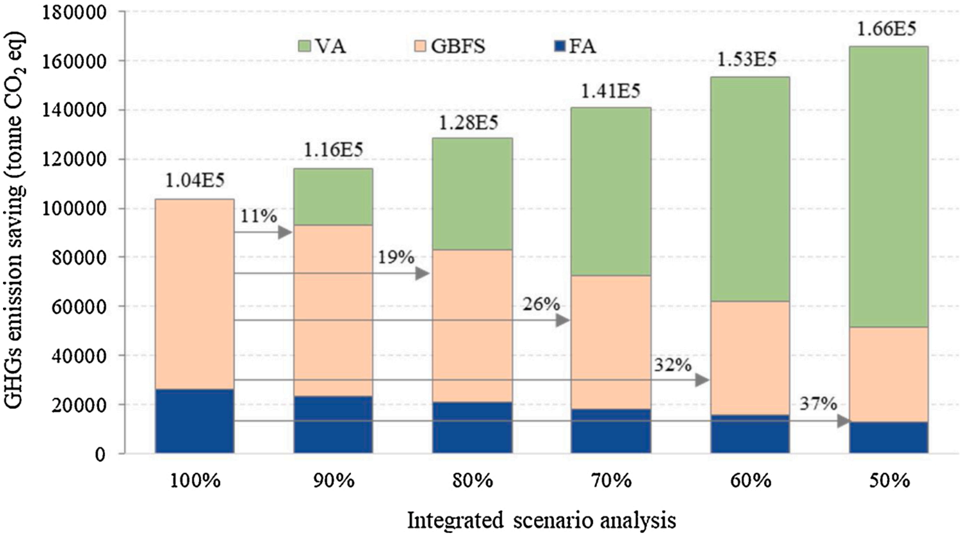

Fig. 8. Net GHG reduction for integrated scenario analysis.

5. Conclusions

Considering the raw materials used to produce concrete and its global applications, the use of SCMs as a partial substitution of ordinary Portland cement is the most recognized and sustainable options for concrete production. In addition to conventional SCMs, this study evaluates how natural SCM can enhance the environmental sustainability performance from product to industry level. The analysis showed that natural pozzolana can be used as an alternative to industrial SCMs, as it potentially reduces substantial GHG emissions from the concrete industry. By considering the consistent replacement ratios and comparable compressive strength, the results show that concrete with volcanic ash is associated significantly lower GHG emissions compared to that of concrete produced with only OPC and other industrial SCMs. At the industry level, the results have also demonstrated that about 26 % additional GHG emissions can be reduced from the concrete industry for replacing 30 % fly ash and slag (currently used by the industry) with volcanic ash. However, further investigation is needed for evaluating several other properties of volcanic ash such as strength activity index, fineness and alkali content, and the design of the optimum use of materials in volcanic ash-based concrete and its mechanical performance and durability comprehensively in future study. In addition, comprehensive environmental assessment using LCA approach and the cost-benefit analysis is needed to promote the application of volcanic ash in the concrete industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Appendix 1 Calculation of total GHG emission saving for the use of industrial SCMs

$$S_{FA} = FA_{TA} \times [C_{OPC} - C_{(75\%OPC+25\%FA)}]$$

$$= 72,560,286 \times \left[\left(511\ kg\ CO_2\ eq/m^3 - 479\ kg\ CO_2\ eq/m^3\right) \div 89\ kg/m^3\right]$$

$$= 26,121,703\ kg$$

$$= 26,122\ tonnes$$

$$S_{GBFS} = GBFS_{TA} \times [C_{OPC} - C_{(70\%OPC+30GBFS\%)}]$$

$$= 169,307,333\ kg \times \left[\left(511\ kg\ CO_2\ eq/m^3 - 446\ kg\ CO_2\ eq/m^3\right) \div 142\ kg/m^3\right]$$

$$= 77,881,373\ kg$$

$$= 77,881\ tonnes$$

where S_{FA} is the total GHG saving due to the use of fly ash, FA_{TA} is the total amount of imported fly ash used in Hong Kong annually, S_{GBFS} is the total GHG saving due to the use of slag, $GBFS_{TA}$ is the total amount of imported slag used in Hong Kong annually, C_{OPC} is the total GHG emissions for M1 concrete, where $C_{(72\ \%_{OPC}+25\ \%_{FA})}$ is the carbon emissions for M4 concrete, and $C_{(72\ \%_{OPC}+30\ \%_{GBFS})}$ is the GHG emissions for M2 concrete. It is already mentioned that about 30 % fly ash and 70 % slag of the total industrial SCMs were assumed in this study (from the last five years average import statistics mentioned in Fig. 2).

Appendix 2 Calculation of total GHG emission saving for the use of volcanic ash and industrial SCMs for Scenario 2 using Eq. (3) (e.g. 10 % substitution of both fly ash and slag separately by volcanic ash)

$$S_{VA} = [(C_{USCMs} \times SCMs_{TA}) + (C_{UVA} \times \%\ VA_i)]$$

In addition, the saving for unit amount was calculated according to the saving of GHG emissions based on Fig. 3 (using the mixed-design presented in Table 1). For instance, GHG emissions associated with M1 minus GHG emissions for M6 divided by the amount of volcanic ash is used in M6 concrete.

$$C_{UVA} = \left[\left(\frac{511\ \text{kg CO}_2\ \text{eq}}{\text{m}^3} - \frac{385\ \text{kg CO}_2\text{eq}}{\text{m}^3}\right) \div \frac{134\ \text{kg}}{\text{m}^3}\right] = \frac{0.94\ \text{kg CO}_2\ \text{eq}}{\text{kg}}$$

About 0.94 kg CO_2 eq GHG emissions can be saved for per kg of volcanic ash. Similarly, the unit saving for fly ash and slag are calculated using the same Equation, and it is 0.36 (C_{UFA}) and 0.46 (C_{UGBFS}) for per kg of fly ash and slag, respectively.

An example of GHG emission saving due to the use of volcanic ash as a substitute of fly ash and slag under Scenario 2 is given below:

Fly ash replacement

Scenario 2 of Strategy 1 (10 % fly ash replacement by volcanic ash in concrete production).

$$\begin{gathered} S_{FA} = [(C_{UFA} \times FA_{90\%}) + (C_{UVA} \times VA_{10\%})] \\ = [(0.36\ kg\ CO_2\ eq\ \times 65,304,257\ kg) + (0.94\ kg\ CO_2\ eq \times 7,256,029\ kg)] \\ = 23,509,533\ kg\ CO_2\ eq\ + 6,820,667\ kg\ CO_2\ eq \\ = 30,330,200\ kg\ CO_2\ eq \\ = 30,330\ tonnes\ CO_2\ eq \end{gathered}$$

The *FA*90 % represents the 90 % of the total amount of fly ash mentioned in Appendix 1 (FA_{TA}), and *VA*10 % represents the 10 % of the total amount of fly ash replacement by volcanic ash.

Slag replacement

Scenario 2 of Strategy 2 (10 % slag replacement by volcanic ash in concrete production).

$$\begin{gathered} S_{GBFS} = [(C_{UGBFS} \times GBFS_{90\%}) + (C_{UVA} \times VA_{10\%})] \\ = [(0.46\ kg\ CO_2\ eq\ \times 152,376,600\ kg) + (0.94\ kg\ CO_2\ eq \times 16,930,733\ kg)] \\ = 70,093,236\ kg\ CO_2\ eq\ +\ 15,914,889\ kg\ CO_2\ eq \\ = 86,008,125\ kg\ CO_2\ eq \\ = 86,008\ tonnes\ CO_2\ eq \end{gathered}$$

The *GBFS*90 % represents the 90 % of the total amount of slag mentioned in Appendix 1 ($GBFS_{TA}$), and *VA*10 % represents the 10 %

of the total amount of slag replacement by volcanic ash.

Appendix 3 Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cscm.2021.e00659.

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