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Cementitious characteristics and environmental behaviour of vitrified MSW incineration fly ash slag

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ABSTRACT

Although vitrification of municipal solid waste incineration fly ash (MSWIFA) is an energy-intensive process, it is a highly effective method to achieve detoxification and produce a vitrified MSWIFA slag (VFAS). This study presents cementitious characteristics and environmental behaviour of VFAS as a partial ordinary Portland cement (OPC) replacement in mortars. The hydration behaviour, mechanical properties, heavy metals leaching and environmental impacts of the produced mortars were evaluated. The experimental results showed that the leaching levels of lead (Pb) and chloride in VFAS were significantly lower than those of the original MSWIFA, and it can be considered as a non hazardous material. Regarding hydration behaviour, the replacement of 30% OPC by VFAS can accelerate early cement hydration, however obtaina relatively low cumulative heat of hydration. It took a long time to achieve a comparable OPC mortar strength at high VFAS replacement levels. Thus, VFAS can be regarded as a type of slowly reactive supplementary cementitious material (SCM). Moreover, using VFAS in mortars yielded a decrease in the global warming potential and non-renewable energy by an environmental impact assessment. This implies that using VFAS as SCM in cement based materials would be more sustainable for achieving carbon neutrality.

1. Introduction

With rapid urbanization, the amount of municipal solid waste (MSW) has been steadily ramping up in modern municipalities, particularly in developing countries (Xuan et al., 2018b). Due to the lack of landfill sites, increasing cost of waste disposal and related environmental pollution, there is an increasing trend on use of waste-to-energy technologies for managing MSW (Hossain et al., 2014). It has been acknowledged that MSW incineration (MSWI) technology has benefits of achieving a reduction in up to 90% waste volume as well as to provide an opportunity to recover energy from waste (Zhao et al., 2016).

However, MSWI still generates a relatively large amount of incinerated solid residues (approximately 20% by mass), including incineration bottom ash (MSWIBA), incineration fly ash (MSWIFA) and air pollution control residues (MSWAPC) (Stegemann et al., 1995; Tang et al., 2020a; Tang et al., 2020c; Tang et al., 2019; Van Gerven et al., 2005; Xuan et al., 2018a, 2019). Among them, MSWIFA contains high levels of leachable heavy metals and soluble salts, and it is usually classified as a hazardous waste. In compliance with legislative regulations, it is usually mandatory to first convert MSWIFA to a non-hazardous material prior to disposing it at landfills (Fedje et al., 2010; Zhang et al., 2020).

The common attempt to eliminate harmful impacts of MSWIFA is to physically and/or chemically stabilize or solidify it using specific additives or through high temperature treatment such as cementitious binders, chelating agents and vitrification (Chen et al., 2019; Zacco et al., 2014). As shown in Table 1, in particular, these methods are highlighted as: i) stabilization with chelating agents; 2) stabilization with cementitious binders and 3) vitrification. When compared with their practicality and limitations, these methods would cause an increase of treatment cost and no final value-added applications of the treated MSWIFA in practice. In light of economic view, industries would have to comply with local environmental regulations for disposal. This certainly yields economic burden for the MSWI industry.

Among these, noting that vitrification is a highly effective method to achieve detoxification and produce a MSWI fly ash slag (VFAS) (Carnogurska et al., 2015; Fan et al., 2018). The use of VFAS as secondary aggregates in concrete have been reported (Ecke et al., 2000), but this could cause expansive alkali-silica reaction (ASR) due to the increased glassy phase. There is a possibility to utilize it

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Table 1
Three typical treatment strategies of hazardous MSWIFA.

Techniques	Technical effects and advantages	Practicality and limitations
Stabilization with chelating agents (Ma et al., 2019)	• To form insoluble complexes or less toxic compounds; Chelating agents commonly applied for full-scale operations.	• Increase of treatment cost; Durability might be a concern; No application of the treated MSWIFA.
Stabilization with cementitious binders or alternative binders (Fan et al., 2018)	• To encapsulate a denser coating layer for trapping pollutants; It is commonly used to treat highly hazardous residues.	• Increase of treatment cost; Volume increase; Presence of metallic Al and salts could degrade the structure of hardened cement paste; Heavy metals leaching; No application of the treated MSWIFA.
Vitrification treatment of MSWIFA (Lindberg et al., 2015)	• To separate volatile metals and allow fixing of some metals in solids; To reduce the volume of MSWIFA; The vitrified slag has potential reactivity.	• Energy-intensive process; So far no good application of the vitrified MSWIFA slag.

in powdered form as a pozzolanic material (Wang et al., 2003). If VFAS developed and designed as a replacement of cement in concrete, it would become a value-added construction material and certainly it has a chance to compensate the vitrification cost of MSWIFA.

Some researchers have reported that VFAS had hydraulic behavior and could produce equal strengths if it was used in cement based materials (Lin et al., 2004). Analysis by X-ray Fluorescence Spectrometer (XRF) and X-ray Diffraction (XRD) had respectively showed that the majority of its oxide compositions were SiO_2, Al_2O_3 and CaO, and it was an amorphous material (Lee et al., 2009). It thus implies that VFAS has potential to be used as a supplementary cementitious material (SCM). In previous studies, it had been reported that replacement of cement by VFAS delayed the hydration and caused an increase in the initial and final setting time (Lin, 2005). It would then lower the early strength development, but had little effect on its long-term strength (Lin et al., 2003). Although the potential of cementitious activity of VFAS had been demonstrated, it is still not accepted in real applications due to the lack of systematic studies to evaluate the influence of VFAS on the early-age, long-term mechanical properties of cement-based materials as well as its environmental impacts in final products.

This study aims to systematically evaluate the cementitious characteristics and environmental behaviour of VFAS as SCM in mortars, including hydraulic activity, relative strength indices and microstructural development at early and longer ages. The feasibility of utilizing VFAS as SCM was then explored and its environmental behaviour was assessed.

2. Materials and experimental program

2.1. MSWI fly ash and VFAS

During combustion processes of MSW at 800–900 °C, MSWIFA was collected by bag filer at a MSW incinerator in Hang Zhou, Mainland China. In order to further reduce its environmental risks, MSWIFA was treated by vitrification at 1400–1500 °C in a plasma reactor. The melted MSWIFA was cooled down by water quenching in order to form a glassy slag product. The VFAS was first crushed into fine particles and then ground into powders in the laboratory (as shown in Fig. 1) before it was used to partially replace cement in mortars. The appearance of VFAS was glassy and glazed in nature, and opaque with a black colour. The ground powder was grey in colour and homogenous, and its appearance was similar to ordinary Portland cement (OPC).

Table 2 lists physical properties and chemical compositions of the original MSWIFA, VFAS, cement, pulverized coal fly ash (PFA) and ground granulated blast-furnace slag (GGBS) used in the study. For comparison of cementitious behaviour, ordinary Portland cement, PFA and GGBS commercially available for the production of concrete were chosen as the reference binder and supplementary cementitious materials (SCMs), respectively. In accordance with ASTM C618, a good pozzolan shall have a sum of SiO_2, Al_2O_3 and Fe_2O_3 of more than 70% (Ali et al., 2020). Both MSWIFA and VFAS cannot be classified as good pozzolans, but the chemical composition of VFAS was similar to GGBS and it could be treated as a hydraulic material. Meanwhile, it was noticed that there was an obvious difference in the chloride (Cl) content between MSWIFA and VFAS, and it was only 16.8% in VFAS when compared to MSWIFA. This indicates that after vitrification, the Cl content in MSWIFA can be reduced considerably.

2.2. Mineralogy of MSWIFA and VFAS by XRD

Fig. 2 presents crystalline phases in MSWIFA and VFAS detected by X-ray Diffraction (XRD) analysis (Rigaku Smart-Lab apparatus with CuKα radiation ($\lambda = 1.54$ Å) conducting at 40 kV and 40 mA). It can be found that the crystalline chemical components in the original MSWIFA mainly consisted of NaCl, KCl, $Ca(OH)_2$, $CaCO_3$, $CaSO_4$ and Ca_2SiO_4. Their PDF reference numbers for analyzing the XRD spectra were listed. As shown in Table 2, the Cl content in MSWIFA was high, which was mainly associated with NaCl and KCl (Ma et al., 2017). It is known from the incinerator plant operator that air pollution control was used to spray of $Ca(OH)_2$. Therefore, $Ca(OH)_2$ and $CaSO_4$ were found in the collected MSWIFA, which was one of reasons that the original MSWIFA had a high CaO content in Table 2. For the XRD spectra of VFAS, it had no crystalline phases in the structure, and only had a diffraction hump ranging from 25° to 35°. This showed that VFAS was an amorphous material similar to that of GGBS (Ma et al., 2017; Oderji et al., 2019).

2.3. Mix design of cement mortars with VFAS

In the designed cement mortars as shown in Table 3, cement was replaced by PFA, GGBS or VFAS and their replacement rates were 10%, 30% and 60% by mass. A ratio of water to the cementitious binder (0.484) was fixed and the ratio of sand to the cementitious binder ratio was 2.75 by mass. A type of standard sand with a maximum size of 2.36 mm was used in this study.

The proportioned dry mixtures were first mixed for 1 min in a laboratory mixer. Then, the amount of water needed was added and the mixtures were mixed for another three minutes. The prepared fresh mixtures were cast into 40 mm cubic plastic moulds. In order to prevent the moisture loss, a polyethylene sheet was used to cover the surface of the mortar moulds. After 24 h, demoulding was carried out. All demoulded specimens were transferred into a water tank (27 °C) and cured for different ages in accordance with the Hong Kong's specification of CS1:2010 before the corresponding tests.

2.4. Experimental program

2.1.1. Reactivity of SCMs determined by Chapelle test

A modified Chapelle test in accordance with NF P18-513 was conducted to assess the activity of PFA, GGBS and VFAS (Tang et al., 2020b). Based on the amount of $Ca(OH)_2$ consumed by the materials,

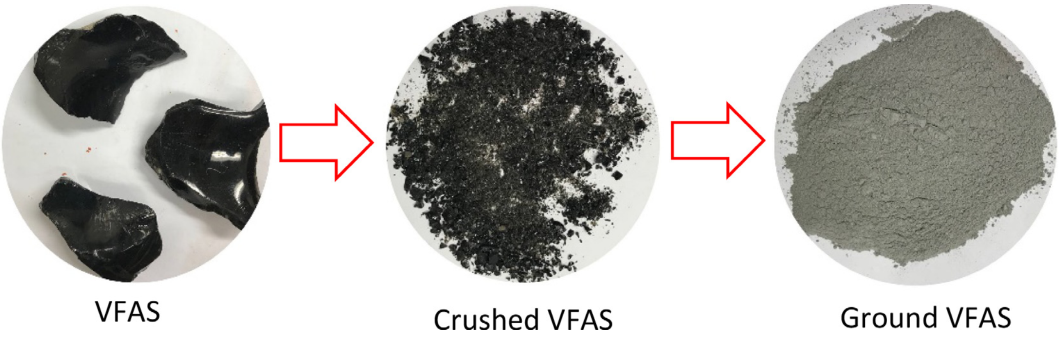


Fig. 1. Preparation of VFAS powder for testing.

Table 2
Physical properties and chemical compositions (%) of MSWIFA, VFAS, cement, PFA and GGBS.

Oxides	MSWIFA	VFAS	Cement	PFA	GGBS
Na_2O	11.55	1.62	–	1.29	1.01
MgO	0.52	1.49	1.48	4.07	4.69
Al_2O_3	0.72	3.53	3.81	19.10	13.16
SiO_2	3.33	52.8	19.57	43.16	44.84
P_2O_5	0.32	0.31	–	–	–
SO_3	5.64	1.58	5.43	1.95	1.32
K_2O	7.00	0.38	0.69	1.68	–
CaO	42.10	32.4	64.51	11.88	33.76
TiO_2	–	1.17	0.27	1.09	–
Fe_2O_3	0.74	1.16	3.12	11.71	0.90
MnO	0.05	0.05	0.06	0.17	–
PbO	0.214	–	–	–	–
SnO2	0.045	–	–	–	–
ZnO	0.655	0.02	–	–	–
Cl	20.0	3.36	–	–	–
Loss on ignition	6.86	0.45	1.08	3.91	0.32
$SiO_2 + Al_2O_3 + Fe_2O_3$	4.79	57.49	26.50	73.97	58.90
Physical properties					
Density (kg/m^3)	2589	2952	3150	2315	2985
Characteristics of particle sizes					
Dv(10) (μm)	4.92	11.31	3.11	0.8	1.73
Dv(50) (μm)	37.54	39.04	18.86	9.07	16.81
Dv(90) (μm)	138.30	102.89	62.36	32.36	57.05

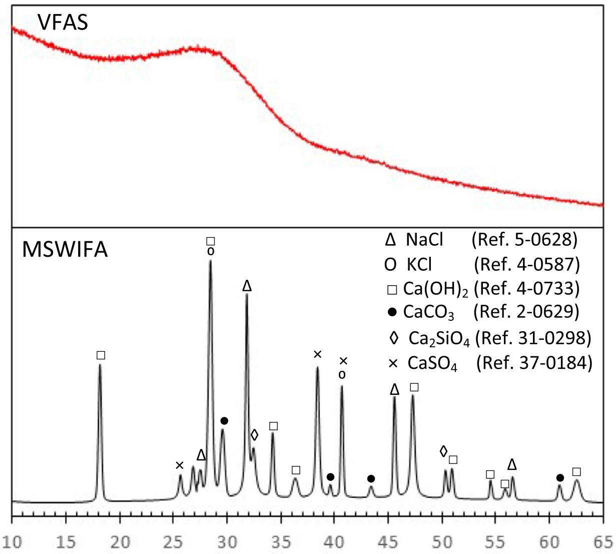


Fig. 2. XRD spectra of MSWIFA and VFAS.

the quantitative values can be used for assessing the activities of the materials.

2.2.1.2. Hydration heat evolution of early-age blended cement. The hydration heat evolution in the first 3 days was determined and analysed by an isothermal calorimeter (Calmetrix I-CAL). In the test, 30% wt. replacement of cement by PFA, GGBS and VFAS was chosen. The total amount of binder was 100 g and 48.4 g of water was added. The fresh binder paste was hand mixed for two minutes in a container, and the container was transferred into the calorimeter. The testing temperature was kept constant at 20 °C.

2.2.1.3. Compressive strength development of mortars. For the tested cement mortars produced with SCMs, their compressive strengths were tested after curing at 2 day, 28 days and 90 days.

The ratio of compressive strength of the tested mortar to the control prepared without SCMs was then calculated and defined as:

$$R_{SCM} = \frac{F_{SCM,t}}{F_{Cement,t}} \times 100\% \quad (1)$$

Where, $R_{SCM,t}$is the strength ratio at a specific curing day, t; F_{SCM} is the strength of the mortar prepared with SCMs at a specific curing day, t; and F_{Cement} is the strength of the control without SCMs at a specific curing day, t.

2.2.1.4. Thermogravimetric analysis. The influence of VFAS on hydration products was evaluated by a thermogravimetric analysis (TGA), in particular the content of portlandite (CH) after different curing

Table 3
Mix design of cement mortars prepared with different PFA, GGBS and VFAS contents.

Item	Cement	PFA	GGBS	VFAS	Sand (g)	Water/Binder
Control	1	–	–	–	2.75	0.484
PFA-10	0.9	0.10	–	–	2.75	0.484
PFA-30	0.7	0.30	–		2.75	0.484
PFA-60	0.4	0.60	–		2.75	0.484
GGBS-10	0.9	–	0.10	–	2.75	0.484
GGBS-30	0.7	–	0.30	–	2.75	0.484
GGBS-60	0.4	–	0.60	–	2.75	0.484
VFAS-10	0.9	–	–	0.10	2.75	0.484
VFAS-30	0.7	–	–	0.30	2.75	0.484
VFAS-60	0.4	–	–	0.60	2.75	0.484

days. The size of the tested sample was less than 75 μm and 10 mg of it was put in a corundum crucible. Its heating speed was at 10 ˚C/min from 20 ˚C up to 1000 ˚C in an argon gas condition. The CH content in the hydrated sample can be determined through its decomposition which causes a mass loss due to the emission of H_2O. In addition, the percentage of ettringite, C-S-H gel and calcium carbonate can be also estimated.

2.2.1.5. Microstructure of the tested samples. Morphological observations of the hydrated mortars prepared with VFAS was conducted by scanning electron microscopy (SEM, TESCAN VEGA3), which was equipped with an energy-dispersive x-ray spectrometer (EDS) for elemental analysis. The microstructural and chemical features were then identified for the mortars with and without VFAS. The fractured surface of the specimen was carbon coated by using a SPI Module™ Carbon Coater.

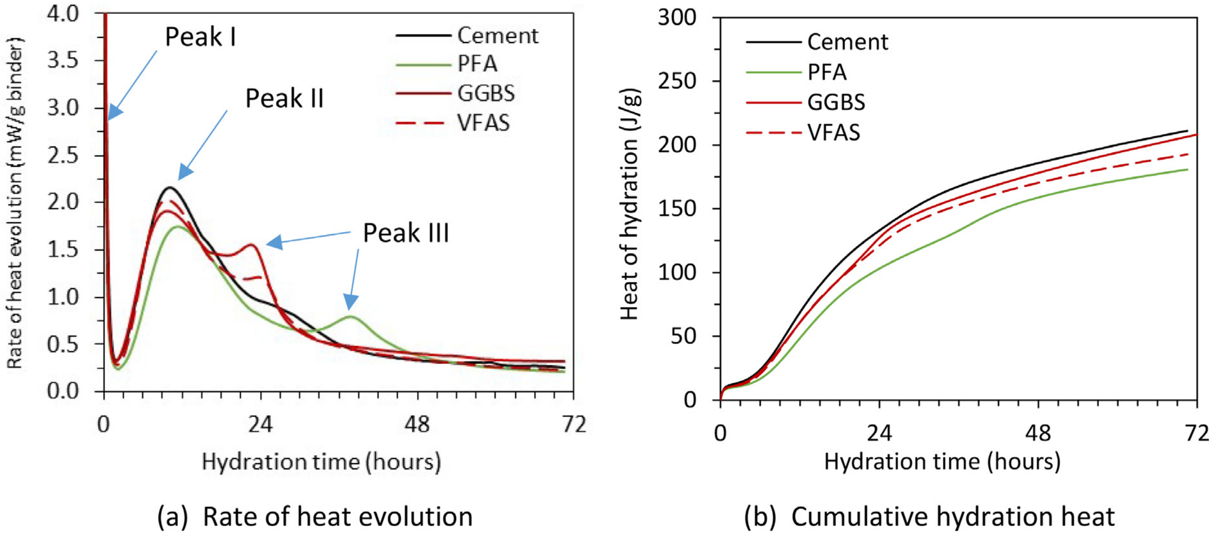
2.2.1.6. Leaching test of the raw materials and the tested mortars. The leaching levels of heavy metals coming from the raw material and the tested mortars were determined in accordance with the toxicity characterization leaching procedure (Xuan and Poon, 2018). The leaching solution chosen was 0.1 M acetic acid with a pH of 2.88 ± 0.55, and the ratio of leaching solution to solid was 20 L/kg. The sample mixed with the leaching solution in a rotator was tumbled for 18 h at a speed of 30 rpm. The leachate was then filtrated through a fibre filter. The inductively coupled plasma-mass spectrometer (ICP) equipment was used to detect the concentrations of heavy metals in the extracted leachate after a filtration step.

3. Results and discussion

3.1. Hydration heat evolution of early-age blended cement with SCMs

Fig. 3 shows the rate of hydration heat evolution and the cumulative hydration heat of cement pastes incorporating PFA, GGBS and VFAS. GGBS and PFA as commercial SCMs have been commonly used in the production of concrete and their influence on hydration heat development has been already acknowledged (Ballim and Graham, 2009; Tang et al., 2020b). In this study, the influence of VFAS on the hydration heat was compared with these two commercial SCMs. As shown in Fig. 3**(a)**, three typical heat evolution peaks in the isothermal calorimeter curves can be identified, where the first one was due to the wetting of the powder (i.e., the quick initial hydration of aluminate species in cement happened and the initial heat was released). For the second peak associated with the hydration of tricalcium silicate in cement at around 9th hours, the incorporation of PFA resulted in the lowest heat release rate, followed by GGBS and VFAS. This indicated all the SCMs reduced the heat evolution rate due to the dilution effect. But VFAS provided the highest contribution to the second hydration peak. This might be due to the relatively high chloride content in VFAS. The Cl-based salts are normally regarded as hydration accelerators. For the third peak, where ettringite changes to monosulphate, both GGBS and VFAS facilitated the earlier formation of monosulphate than PFA, which might be due to the quicker depletion of sulphate ion in early hours.

For the cumulative heat of hydration in Fig. 3**(b),** the trend is cement > GGBS, > VFAS > PFA. In early 72 h, GGBS can contribute



(a) Rate of heat evolution (b) Cumulative hydration heat

Fig. 3. Isothermal calorimetric curves of cement pastes containing PFA, GGBS and VFAS: (a) rate of heat evolution; (b) cumulative hydration heat.

more hydration heat than that of VFAS and PFA. The cumulative hydration heat of VFAS was between GGBS and PFA, indicating that VFAS can accelerate the initial hydration and involve the partial reaction. Compared to the rate of heat evolution, VFAS can speed up the hydration in 12 h, however still obtain a relatively low cumulative hydration heat.

3.2. Consumed $Ca(OH)_2$ content of VFAS compared to commercial SCMs

Fig. 4 shows the amount of $Ca(OH)_2$ consumption by VFAS compared to the commercial PFA and GGBS. The $Ca(OH)_2$ consumption per gram PFA, VFAS and GGBS was 548 mg, 314 mg and 268 mg, respectively. It is known that PFA is a typical pozzolanic material and GGBS is a typical hydraulic material in the system of SCMs (Ali et al., 2020). On the basis of the results presented in Fig. 4 and the CaO content in Table 2, it implied that the VFAS may be considered as a hydraulic material similar to GGBS, however can consume a certain amount of $Ca(OH)_2$ through its reactive amorphous phases.

3.3. Hydration products of the blended cement prepared with VFAS

The hydration products of the blended cement prepared with VFAS at 28 days were determined using TGA and the experimental results are shown in Fig. 5. From the DTG curves in Fig. 5**(b)**, the four typical zones related to the decomposition of main hydration products upon heating can be classified (Zhan et al., 2020). Zone I: decomposition of AFt /AFm between 50 °C and 150 °C; Zone II: decomposition of C-S-H between 150 °C and 380 °C; Zone III: dehydroxylation of $Ca(OH)_2$ from 380 °C to 500 °C; and, Zone IV: decarbonation of calcium carbonates in the temperature range of 500 °C and 900 °C (Fang et al., 2017). It can be observed that the $Ca(OH)_2$ content in the hydration products in Zone III was decreased when the VFAS replacement content in the blended cement paste increased. Due to the natural carbonation, the presence of calcium carbonate was detected after 500 °C.

According to the TG curves in Fig. 5**(a)**, the mass loss fractions in the four identified temperature zones are further listed in Table 4. When there was 30% replacement of cement by VFAS, it slightly influenced the mass loss in zone I, zone II and Zone IV. For zone III, there was a decrease in $Ca(OH)_2$ content in the 28-day hydrated pastes. This would imply that using 30% VFAS slightly affected the formation of hydration products, and the decease of Ca $(OH)_2$ should be attributed to the decrease of cement as well as the $Ca(OH)_2$ consumption by VFAS as confirmed in Fig. 4. For the paste prepared with 60% VFAS, except zone IV, all mass loss fractions in zone I, zone II and zone III were decreased. This demonstrated that the amount of hydration products in VFAS-60 was less than those in cement and VFAS-30. It had been reported that VFAS was a type of slowly reactive materials and it would take a long time to obtain a comparable OPC strength (Wang et al., 2003).

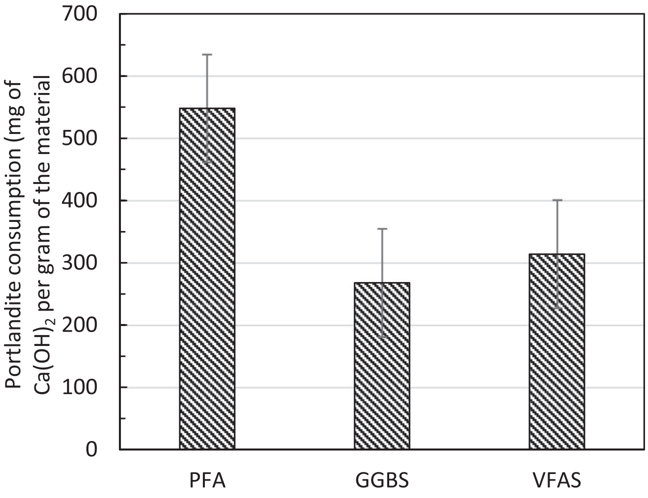
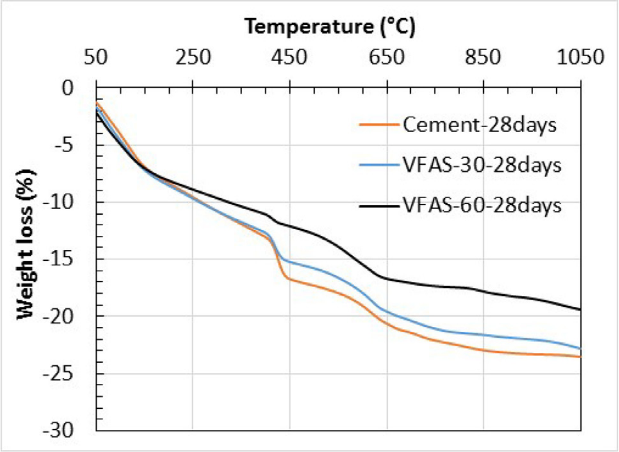
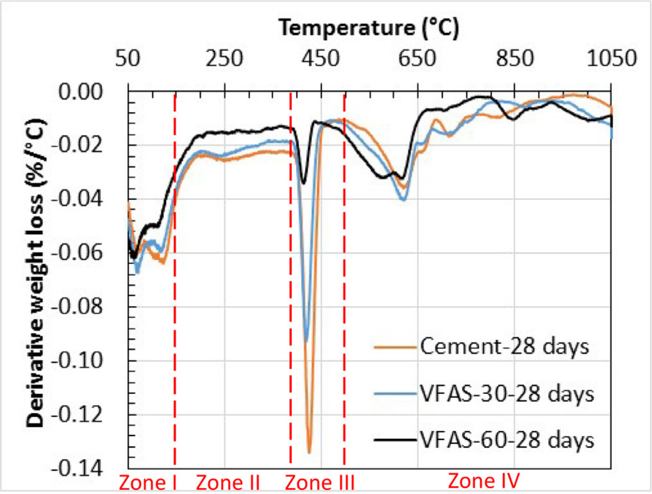


Fig. 4. $Ca(OH)_2$ consumption of VFAS compared to commercial PFA and GGBS.



（a）**TG curves of the hydrated pastes with VFAS**



（b）**DTG curves of the hydrated pastes with VFAS**

Fig. 5. TG and DTG curves of the hydrated paste incorporated with VFAS at 28 days.

Table 4
Mass loss fractions in the identified zones estimated by TGA.

Sample	Mass loss fractions, %			
	Zone I	Zone II	Zone III	Zone IV
Cement	5.60	5.67	4.68	5.86
VFAS-30	5.51	5.10	3.46	5.99
VFAS-60	4.81	3.72	2.01	5.40

Fig. 6 shows the XRD spectra of the mixtures with and without VFAS. It can be found that for normal cement, ettringite can be detected, while it was not found in the mix prepared with 30% of VFAS. But, another new reaction product, Friedel's salt ($Ca_2Al(OH)_6$-$Cl{\cdot}2H_2O$), was found. Furthermore, from the peak intensity of Ca $(OH)_2$ that is one of major hydration products, it can be noticed that after incorporating VFAS, its intensity was decreased, implying its reaction with VFAS and its reactivity.

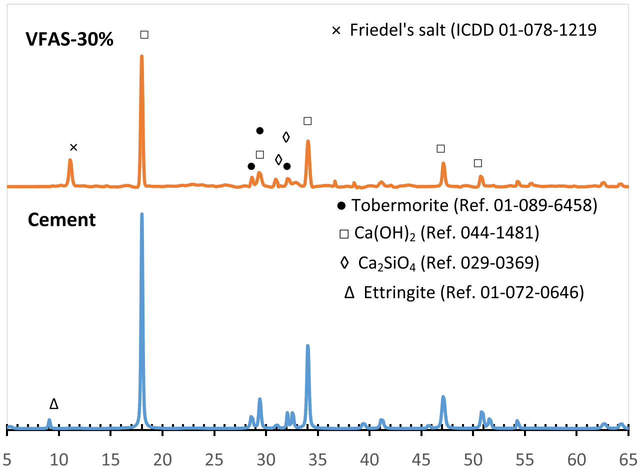


Fig. 6. XRD spectra of the mixtures with and without VFAS.

3.4. Development of compressive strength of mortars with curing times

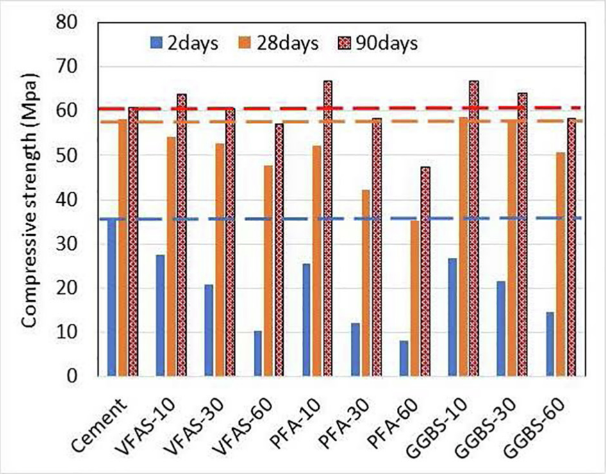
Fig. 7 shows the ratio of compressive strength of the tested mortars (prepared with VFAS, GGGBS and PFA) to the reference without SCMs. As shown in Fig. 7**(a)**, the 2-day compressive strengths of all the specimens prepared with SCMs were lower than that of the reference. Incorporating SCMs reduced the early strength of the mortars. The more SCMs used, the more the strength reduction at the early ages. When cured for 28 days, only the mortars prepared with 10% and 30% GGBS reached the same strength of the reference. However, continuously cured for 90 days, the mortars prepared with 10% VFAS, 30% VFAS, 10% PFA, 10% GGBS and 30% GGBS also obtained the strength comparable or even higher than that of the reference. These results demonstrated that VFAS as SCMs contributed the long-term strength development.

Referring to the compressive strength ratios in Fig. 7 **(b),** it can be found that at the early curing age (2 days), the mortars prepared with 30% PFA, 30% VFAS and 30% GGBS were 34%, 59% and 61% of that of the reference, respectively. This demonstrated that the level of contribution of VFAS to strength was between FA and GGBS. For the 90-day long-term age, the relative compressive strength ratio of the mortars prepared with 60% of VFAS was comparable to that of the one incorporated with 60% of GGBS. This further implies that VFAS has potential of long-term activity.

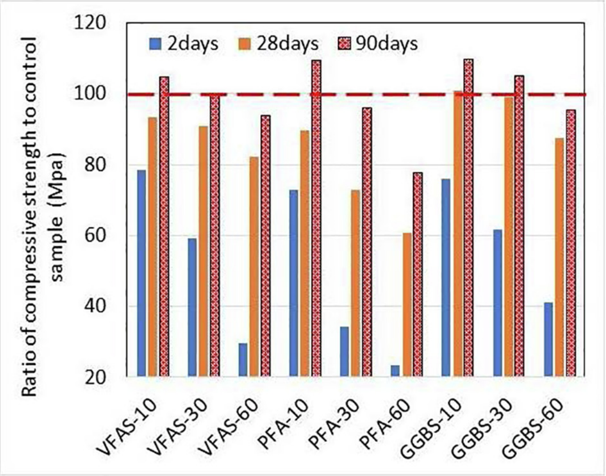
3.5. Microstructure of the tested samples by SEM

Fig. 8 shows the morphologies of the hydrated pastes prepared with 30% replacement of cement by VFAS at 2 days and 90 days. For the 2-day cured sample, the hydration products seemed foils or flakes present on the surface of unreacted cement particles, and the thin plate-shaped $Ca(OH)_2$ was precipitated in the microstructure (Taylor, 1990). By comparison, the 2-day 30% VFAS sample was filled with flakes and fibrous products on the surface of VFAS. From Fig. 3, the presence of residual Cl salts could be the reason to influence the rate of heat evolution of the paste prepared with VFAS, which caused the formation of Friedel's salt $Ca_2Al(OH)_6Cl{\cdot}2H_2O$ (Suryavanshi and Swamy, 1996) and the acceleration of the change from ettringite to monosulphate. Fig. 8 (c) and (d) further illustrates the formation of $Ca(OH)_2$ and a type of chloride product like Friedel's salt by the elemental analysis of EDS. As a consequence, the morphology of the paste prepared with VFAS was obviously different from that of the pure cement paste at early ages.

After curing for 90 days as shown in Fig. 8 **(e) and (f),** the morphologies of both the pastes prepared with and without VFAS were densified. The difference would be that the morphology of the 90-day cured pure cement paste was rougher than that of the paste prepared with 30% of VFAS. This should be because the paste prepared with 30% of VFAS contained less CH that would have randomly precipitated in the microstructure and more C-S-H gel were formed from the long-term reaction of the incorporated VFAS.



(a) Development of the compressive strength of the mortar with SCMs



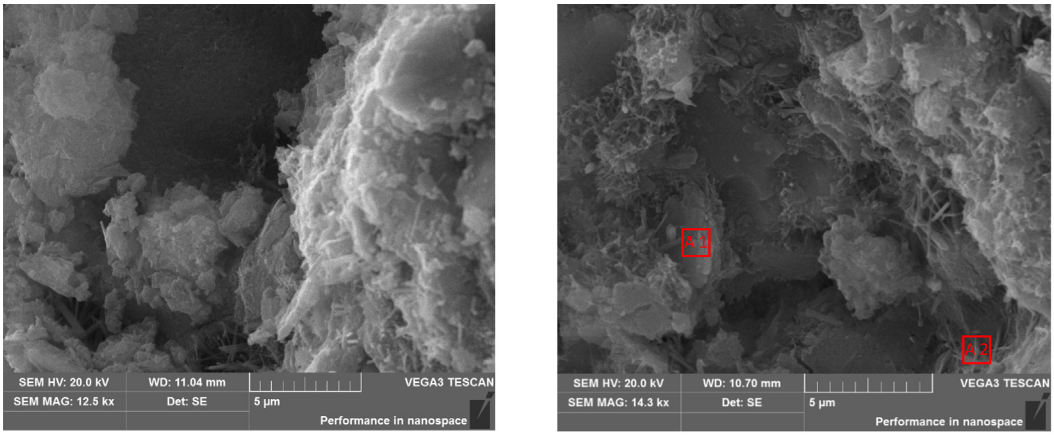
(b) Ratio of compressive strength to the control sample without SCMs

Fig. 7. Influence of VFAS on the compressive strength of the mortar.

3.6. Heavy metal leaching of the tested mortars by TCLP

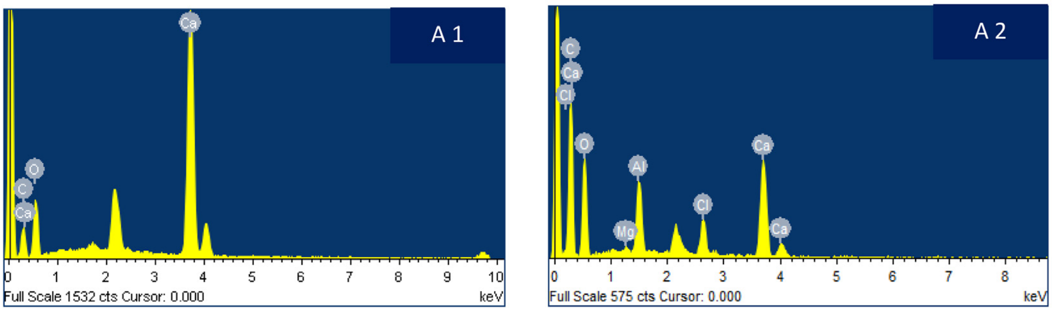
Table 5 lists the TCLP leachate concentrations from original MSWIFA, VFAS and the hydrated mortars prepared with 30% and 60% of VFAS. The US EPA regulatory leaching limits of As, Ba, Cd, Cr, Pb and Se are listed in Table 5. It can be found that except Pb associated with the original MSWIFA, the leaching levels of other heavy metals met USEPA requirements. The leaching level of Pb in the original MSWIFA (18.27 mg/L) was over three times higher than that of the limit. After vitrification, the leaching levels of all heavy metals were lower than that of the original MSWIFA. Moreover, the Pb leaching was considerably reduced to 0.06 mg/L, and this indicated that VFAS can be classified as a non-hazardous material.

When VFAS was used to replace cement in the cement mortar, leaching of some heavy metals (As, Cd and Se) was higher than that of VFAS, while leaching of other heavy metals (Ba, Cr and Pb) was lower than that of VFAS. This could be due to the encapsulation and



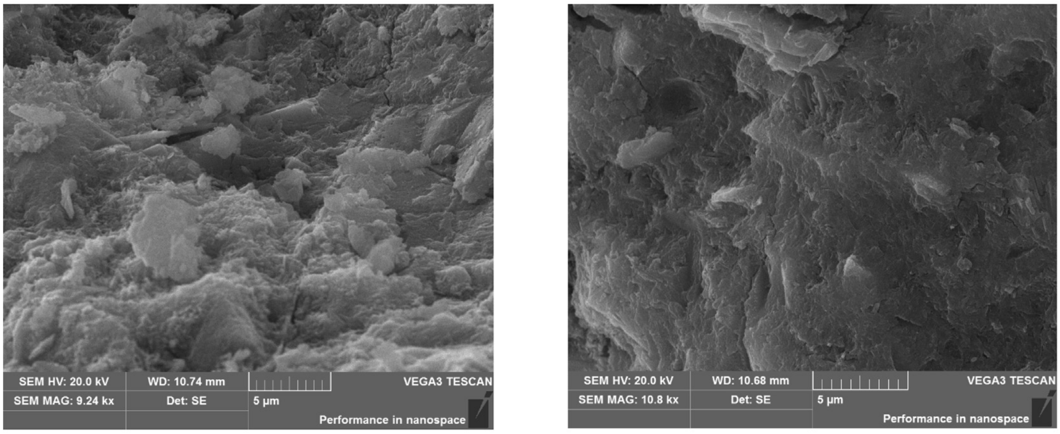
(a) Cement paste at 2days

(b) Cement paste with 30% VFAS at 2days



(c) EDS of the product at the area of A1

(d) EDS of the product at the area of A2



(e) Cement paste at 90 days

(f) Cement paste with 30% VFAS at 90 days

Fig. 8. Microstructures of the tested samples with and without VFAS.

Table 5
Leaching of heavy metals of raw materials and mortars by TCLP test.

Items	Concentrations of heavy metals by TCLP (mg/L)					
	As	Ba	Cd	Cr	Pb	Se
Original MSWIFA	0.06	6.89	0.02	0.14	18.27	0.20
VFAS	–	1.33	0.02	0.05	0.06	0.10
VFAS-30-Mortar	0.04	0.88	0.05	–	0.05	0.11
VFAS-60-Mortar	0.02	1.12	0.05	–	0.05	0.12
TCLP regulatory level	5	100	1	5	5	1

Table 6
Comparison of environmental impacts of the cement mortars prepared with VFAS.

Items		Impact category (per ton)	
		Global warming potential (kg CO_2 eq)	Non-renewable energy (MJ primary)
Materials	Cement(Hossain et al., 2017)	980	5732
	Sand(Hossain et al., 2016a)	23	341
	VFAS(Hossain et al., 2016b)	0.05	0.76
Mortars	Cement mortar	246 (100%)	1575 (100%)
	VFAS-30	177(72.0%)	1169 (74.2%)
	VFAS-60	108(43.9%)	763(48.4%)

immobilization effects of the cement hydration products, while the alkaline environment worsened the leaching of some heavy metals (Li et al., 2016). Nonetheless the leaching of all heavy metals were minimal. All the mortars prepared with VFAS would induce little environmental risks.

3.7. Environmental impact of the mortars with VFAS

The experimental results obtained above indicated that VFAS can be considered as a potential supplementary cementitious material to be used in cement based materials. Hong Kong is a resource-scarce city, where most of the construction materials are imported from other regions or countries. Using the VFAS would bring beneficial environmental impacts for achieving carbon neutrality.

To assess the environmental impacts of the mortars prepared with VFAS, the cradle-to-gate system boundary was used for assessment (Hossain et al., 2016a, b, 2017). The data of global warming potential (kg CO_2 eq) and non-renewable energy (MJ primary) for cement and sand are listed in Table 6**.** For the production of VFAS powder, the local collection, grinding and crushing process were considered referring to the production of the waste glass powder (Hossain et al., 2016b).

Table 6 lists the levels of two environmental impact categories of raw materials and the mortars prepared in this study. The functional unit of the produced mortar was 1 ton. For per ton traditional cement mortar, the global warming potential (kg CO_2 eq) and non-renewable energy (MJ primary) were 246 and 1575, respectively. When VFAS was used to replace cement by 30% and 60% in the mortar, it caused an approximate 25% and 55% reduction in the global warming potential and non-renewable energy, respectively. This implies that if more VFAS used to produce the cement mortar, it is beneficial to migrate the environmental impacts in its construction industry.

4. Conclusion

In this study, the vitrified MSWIFA slag (VFAS) was used as a potential SCM and accordingly was evaluated in terms of its hydration behaviour, mechanical properties, heavy metals leaching and environmental impacts in mortars. The major findings are given below:

- After vitrification, the leaching level of lead (Pb) of VFAS by TCLP was considerably lower than that of the original MSWIFA. Moreover, the chloride content in VFAS was only 16.8% of that of the original MSWIFA.
- Compared to the influence of GGBS and PFA on the heat evolution of cement hydration, VFAS can speed up the hydration in the initial 12 h and accelerate the change of ettringite to monosulphate, however obtain a relatively low cumulative hydration heat. The cumulative hydration heat of VFAS was between GGBS and FA, indicating that VFAS can accelerate the initial hydration.
- The strength of the mortar prepared with 60% of VFAS at 2 days and 90 days was 30% and 94% of the control, respectively. This demonstrates that VFAS is a type of slowly reactive material that takes a long time to achieve a comparable OPC mortar strength at high replacement levels.
- Using 30% of VFAS reduced the content of Ca $(OH)_2$ in the resulting binder due to the decrease of cement as well as the $Ca(OH)_2$ consumption by VFAS to form the additional C-S-H gel. The long-term reaction of VFAS consequently caused smoother microstructure compared to the control without VFAS.
- If VFAS used to replace cement by 30% and 60% in the mortar, it would cause an approximate 25% and 55% reduction in the global warming potential and non-renewable energy, respectively. This implies that replacing cement by VFAS in a cement based material would be more sustainable towards achieving carbon neutrality.

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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