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Fracture behavior of concrete containing MSWI vitrified bottom ash

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Abstract

The incorporation of waste materials into concrete allows responding to some of the most significant issues of our society: waste management and climate change. Experimental studies carried out in last decades have shown that municipal solid waste incineration (MSWI) ash, and particularly bottom ash, which constitutes the major solid by-product of incineration process, can be adopted to produce building materials. However, several issues are related to the safety and the environmental impact of MSWI ash utilization for concrete production, mainly linked with the leaching of heavy metals and toxic organic components. To solve these problems, several treatments for MSWI ash can be adopted and, among them, in this work the attention was focused on vitrification technology, which enables to convert the ash in a glassy inert solid material. The aim of the present paper is to study the feasibility of developing a "green concrete" that incorporates vitrified MSWI bottom ash as partial cement replacement, so reducing the cement content and consequently the carbon dioxide emissions as well as the raw materials consumption related to its production. The vitrified MSWI bottom ash, ground at micrometer size, was inserted into the admixtures by considering two percentages of cement substitution (10% and 20% by weight of cement). The flexural behavior of concrete containing vitrified MSWI ash was investigated through three-point bending tests under crack mouth opening displacement control. The crack path evolution was further explored by adopting the Digital Image Correlation technique. By analyzing the obtained results, it can be concluded that the use into concrete of vitrified MSWI bottom ash as cement replacement up to a percentage of 20% by weight of cement, allows reaching comparable flexural resistances with respect to the reference concrete. So, the proposed approach can represent a viable solution for the development of environmental-friendly concretes able to reduce the environmental impact of the concrete industry, which is mostly related to cement production, as known.

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1. Introduction

Waste management and climate change are among the most important social global issues. In recent decades, the generation of municipal solid waste (MSW) has increased significantly, and it is growing faster than the rate of urbanization. If the actual trend is maintained, by 2025 4.3 billion urban residents worldwide will generate about 2.2 billion tonnes of MSW per year, (Hoornweg and Bhada-Tata (2012)). Incineration, with or without energy recovery, is one of the strategies developed to treat this waste that cannot be recycled. The MSW percentage, sent to incineration plants, can be very different from one country to the other, depending on economic wealth, but also on how municipal waste is collected and managed. Limiting the attention to Europe, according to Eurostat – the Statistical Office of the EU – around 25% of the total MSW produced in 2019 was treated by incineration. Through this combustion treatment, the volume of waste can be reduced by 90% and the mass by 70% (Ginés et al. (2009)), but at the same time two main solid combustion residues are generated: bottom ash (BA, nearly the 80% of the total) and a finer fraction, referred to as fly ash (FA), usually characterized by a high content of heavy metal, toxic organic compounds and chlorides, (Ibañez et al. (2000)). Nowadays, the treatment, disposal and/or reuse of municipal solid waste incinerator (MSWI) ash represent one of the most relevant challenges to solve, due to the high amount produced and to the environmental issues related to their landfill.

MSWI fly ash is classified as hazardous waste, and nowadays it is still mainly treated for landfill disposal. Even if some strategy for its reuse as a secondary material has been proposed, there are still a lot of constraints related to the leaching behavior of the final products (Ferreira et al. (2003), Sun et al. (2016)).

MSWI bottom ash is not included in the list of hazardous materials established by the Council of the European Union and presently it can be disposed to landfills or can be reused (Saccani et al. (2005). However, in the perspective of circular economy, landfilling is not the optimal strategy, also for the environmental issues related to the leaching of contaminants (Xuan et al. (2018), so present and future research is focusing on their reuse. Several applications of MSWI bottom ash to produce building materials can be found (Lam et al. (2010), Verbinnen et al. (2017), Xuan et al. (2018), mainly concerning ceramic production, cement and concrete production (as raw materials for clinker, or as replacement for sand, gravel or cement (Juric et al. (2006)), or again as recycled aggregate in concrete, unbound granular materials (as recycled aggregates in unbound road bases and highway embankment) or the development of alkali-activated materials. Among these applications, their reuse in cement and concrete is of particular interest, since it can be seen also as a strategy to promote the reduction of the environmental impacts related to their production, because of the huge quantity of concrete produced worldwide every year. Anyway, the direct use of MSWI bottom ash without any treatment in engineering applications is generally not advisable, mainly because of the leaching of heavy metal and/or metalloids and the presence of soluble salts. To reduce these risks, allow a safe reuse and improve the quality of the final products, adequate pre-treatments have been developed, which can be grouped into three main categories. The first one aims at obtaining a restructuring of the chemical phases of MSWI bottom ash through high-temperature treatments (between 700 °C and 1500 °C), such as vitrification, melting or sintering. The other two groups of treatments are aimed at the removal or the immobilization of pollutants under ambient temperature and pressure.

Focusing the attention on vitrification treatment, which is particularly promising since it converts the ash into a material inert towards most chemical or biological agents, and on concrete production, some experimental works have shown the feasibility of using vitrified MSWI bottom ash as cement or sand replacement in mortar and concrete (Ferraris et al. (2009), Sharifikolouei at al. (2020)). However, the research on this use in concrete is still very limited and, as regards mechanical characterization, it focuses mainly on compressive strength.

In the present work an experimental campaign aimed at developing a "green concrete" that incorporates vitrified MSWI bottom ash was conceived. The use of the vitrified material as partial cement replacement was pursued, so contributing to the reduction of CO2 emissions related to cement production. Two different percentages of substitution (10% and 20% by weight of cement) were considered, and the obtained flexural and fracture behavior was compared to that of a reference concrete in order to identify the influence of vitrified MSWI ash. The flexural behavior of concrete containing vitrified MSWI ash was investigated through three-point bending tests under crack mouth opening displacement (CMOD) control and the crack path evolution was further explored by adopting the Digital Image

Correlation (DIC) technique. The obtained performances show that the use of vitrified MSWI ash as cement replacement up to 20% by weight can represent a viable solution for the development of sustainable concrete.

2. Specimen preparation

2.1. Materials and mix design

Three different mix designs were analyzed to assess the influence of the vitrified MSWI ash use on the mechanical properties of concrete: two admixtures contained MSWI vitrified ash in different percentages as partial cement replacement, while a third mix referred to a standard plain concrete, which was considered as control.

The bottom ashes used in this work derived from a municipal solid waste incinerator located in the North of Italy. They were thermally treated through vitrification, which consists of subjecting MSWI ash to temperatures above 1300 °C, thus converting the waste into a stable and homogeneous glassy solid material by melt quenching (Colombo et al. (2003)). It also enables to combust toxic organic components, such as dioxins, and incorporate heavy metals in a stable and inert form inside the glass matrix. The considered MSWI bottom ash was vitrified at 1450 °C without adding any additive (Ferraris et al. (2009)) and later, in order to be used as cement replacement, the glassy material was ground to obtain a maximum grain size lower than 70 μm.

Concrete specimens were prepared by using II A-LL 42.5 R Ordinary Portland Cement, fine aggregates (calcareous sand - 0/4 mm), coarse aggregates (siliceous gravel - 2/8mm), water, and superplasticizer (Mapei Dynamon Xtend W202R). For reference concrete (denoted as P in the following), cement, sand, gravel and water were used in the proportion of 1:2.75:1.375:0.5 by weight, while the two other mixes (in the following denoted as V10 and V20, respectively) were prepared by substituting 10% and 20% by weight of cement with MSWI vitrified ash.

2.2. Casting and curing of specimens

The materials were mixed in a drum-type mixer through the following procedure. After pouring all the dry aggregates into the drum, half of the required water was added, and they were mixed for about 3 minutes. Then, the binders (cement and the vitrified ash when present) and the quarter of total water were added and mixed for about 2 minutes. Finally, the remaining water, which contained the superplasticizer, was added and the mixing continued for about 3 minutes. All concrete mixes, even those containing MSWI vitrified ash, were homogenous and did not present any problem of segregation or bleeding.

It is worth noticing that the superplasticizer dosage was opportunely chosen to obtain the same workability for all the mixes, i.e. a consistence class S4 that represents a slump in the range 160 – 210 mm (Fig. 1a), according to Standard EN 206–1:2013. Reduced contents of superplasticizer were needed for increasing amounts of vitrified MSWI ash. More in detail, 10% and 20% less of superplasticizer contents was used with respect to control concrete (P), to prepare V10 and V20, respectively. This means that the incorporation of vitrified MSWI in the admixture of concrete leads to higher flowability with obvious advantages for in-situ applications.

Fig. 1. (a) Slump test (class S4); casting of prismatic specimens; (b).

The concrete mixes were cast into 100 mm × 100 mm × 400 mm prisms by using a poker vibrator, (Fig. 1b). Polythene sheets were put on the molds, which were placed in a moist air room for the next 24 hours until demolding. The obtained specimens (three for each batch) were then wet cured until the day of testing, i.e. 28 days after casting.

2.3. Experimental set-up

The flexural behavior of the produced specimens was investigated through three-point bending tests. Once the water curing was finished, a U-shaped cut was made in the middle of the prismatic specimens by using a saw with a rotating blade, according to the dimensional prescriptions of the Japan Concrete Institute Standard JCI-S-001-2003. In particular, the notch height was set equal to $0.3D$, where D denotes the height of the beam (equal to 100 mm), while the notch thickness was less than 5 mm. The tests were performed on a net span S equal to $3D$, under Crack Mouth Opening Displacement (CMOD) control by using a INSTRON 8862 testing equipment having a 100 kN load capacity. The load was measured through a load cell, while a clip-on strain gauge was installed at the two sides of the notch to measure the CMOD. During testing, an initial displacement rate of 0.6 mm/hour was used, while over the peak load the test speed was gradually increased until CMOD of 1 mm was reached.

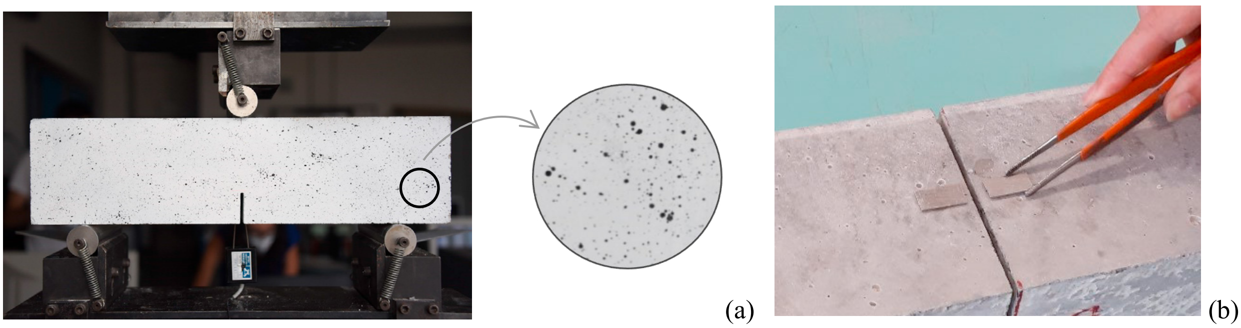


Fig. 2. (a) Specimen prepared for three-point bending test (3PBT) and DIC with related detail of speckle pattern; (b) steel plates needed for mounting the clip-on strain gauge on the specimen.

During three-point bending tests, Digital Image Correlation (DIC) technique was also applied to obtain more information concerning the displacement field and crack pattern evolution. To this aim, before testing, a random, high-contrast speckle pattern was produced on one lateral surface of each beam (Fig. 2a), while stable lighting conditions were guaranteed during the tests. The evaluation of displacement and strain field was obtained by comparing the digital images of the deformed specimen during the test execution with the initial undeformed state. The images obtained from the camera NIKON D750 were processed by means of software Ncorr (Blaber et al. (2016)), developed in MATLAB environment.

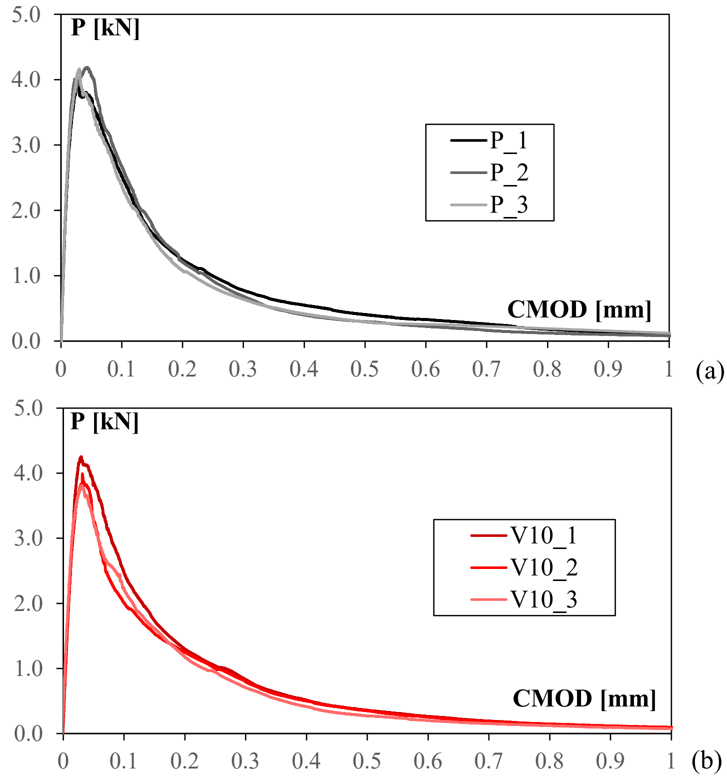
3. Results and discussion

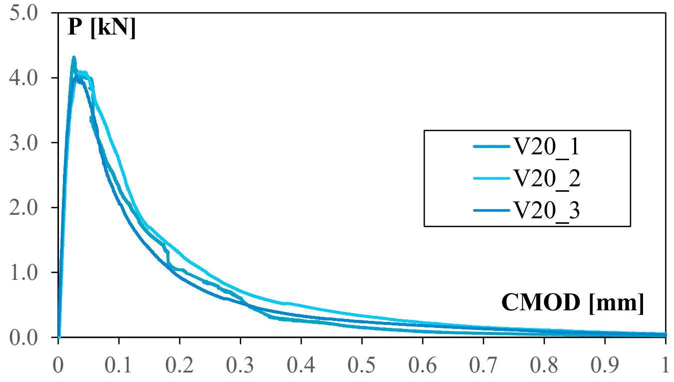
The performed 3PB tests allowed obtaining the load (P) - CMOD curves (Fig. 3), so as to evaluate both flexural strength σ_f and fracture energy G_f.

By adopting the symbols previously defined in Section 2.3, the flexural strength σ_f was determined as:

$$\sigma_f = P_{\max} \frac{3S}{2b\left(D-0.3D\right)^2}, \tag{1}$$

where P_{max} represents the peak load of P - CMOD curve and b is the width of the cross section (equal to 100 mm).





(c)

Fig. 3. Load – CMOD curves for concrete: (a) control (P), (b) with 10% vitrified ash (V10) and (c) with 20% vitrified ash (V20).

Fracture energy G_f was computed according to the Japan Concrete Institute Standard JCI-S-001-2003 as:

$$G_f = \frac{0.75W_0 + W_1}{A_{lig}} \quad (2)$$

This code evaluates G_f as the ratio between the area W_0 under the P - CMOD curve and the area of the nominal ligament, i.e. $A_{lig} = b\ (D - 0.3D)$, by also taking into account the work done W_1 by the deadweight of specimen and experimental equipment. W_1 was determined as:

$$W_1 = 0.75\left(\frac{S}{L}m_1 + 2m_2\right)g \cdot CMOD_C$$

where L is the total length of the specimen (equal to 400 mm), g is the gravitation acceleration (equal to 9.81 m/s^2), while m_1 and m_2 are the mass of the notched beam and of the experimental arrangement directly attached on it (i.e clip-gauge and steel plates, as can be seen in Fig. 2b). $CMOD_C$ represents the crack mouth opening displacement at rupture and it was taken as 1 mm, which corresponded to a residual load of about 0.05 kN.

By analyzing the P - CMOD curves reported in Fig. 3, it can be seen that the same flexural behavior can be recognized for all the admixtures, so implying that the replacement of cement up to 20% by weight with vitrified ash does not lead to a significant difference with respect to control. This can be obtained since the vitrified compounds of bottom ash are able to provide a pozzolanic reaction in combination with Portland cement, as also pointed out in the literature, Pera et al. (1996), Saccani et al. (2005), Ferraris et al. (2009), Sharifikolouei et al. (2020).

The main results of all the experimental tests are compared in Fig. 4 in terms of flexural strength σ_f and fracture energy G_f. Each batch was composed of three specimens and the value reported in the histogram corresponds to the mean ± standard deviation. It can be stated that the use of vitrified ash does not negatively influence flexural strength σ_f and fracture energy G_f, since there is not a statistically significant variation between the three batches analyzed.

The statistical test ANOVA (one-factor variance analysis) was performed by choosing a significance level of 95% (α=0.05). The F test results were analyzed; in particular, since $F_{calculated}$ (equal to 0.92 and 0.36 for σ_f and G_f, respectively) was less than $F_{critical}$ (equal to 9.55) the null hypothesis was accepted, which means that there is no statistically significant effect at the 5% level among the averages of the considered batches.

The responses in terms of load P – midspan deflection δ were obtained by using the displacement field from DIC. Fig. 5 reports the mean of the results obtained for batches P and V10.

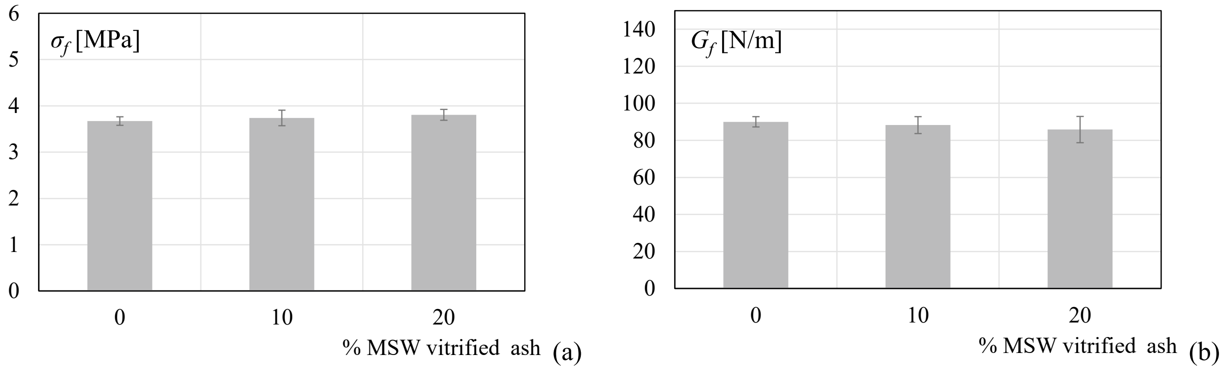


Fig. 4. Mean values of (a) flexural strength σ_f and (b) fracture energy G_f for concretes with different MSWI ash percentage (0%, 10%, 20%) of cement replacement by weight.

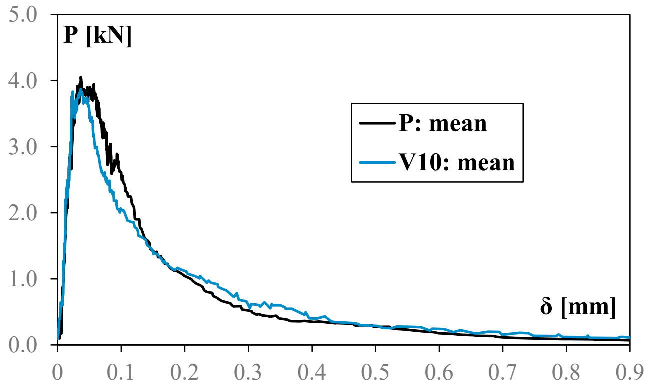


Fig. 5. Load-midspan deflection δ curves obtained from DIC, for reference concrete (P) and concrete with 10% vitrified ash (V10).

These P - δ curves enable to control if the procedure used in this work for the measuring of G_f, based on P – CMOD curve and suggested by Standard JCI-S-001:2003, is consistent with the most common method of computing G_f of concretes, proposed by RILEM TC 50-FMC. By analyzing, for example, the results reported in Fig. 5 for batches P and V10, it can be observed that the mean values of G_f computed by following the JCI approach (equal to 90.02 and 88.25 N/m, for P and V10, respectively) are comparable to that computed according to RILEM (94.46 and 91.91 N/m, for P and V10, respectively). This allows to check the reliability of the reduction factor (equal to 0.75) of the JCI relation for using the area under P – CMOD curves instead of that under the P - δ curves of RILEM, obtaining a reduction factor of 0.78 and 0.77 for P and V10, respectively, to equal these areas.

Moreover, DIC analysis enables obtaining the horizontal strain ε_x field, as reported in Fig. 6 for the zone around the notch for specimens P_3 and V10_3, as an example. The strain values at different post-peak loading stages, as the tortuosity of the crack paths, are the same for all the specimens of the experimental campaign, hence, it can be stated that the substitution of cement with vitrified ash up to 20% by weight does not compromise the fracture behavior.

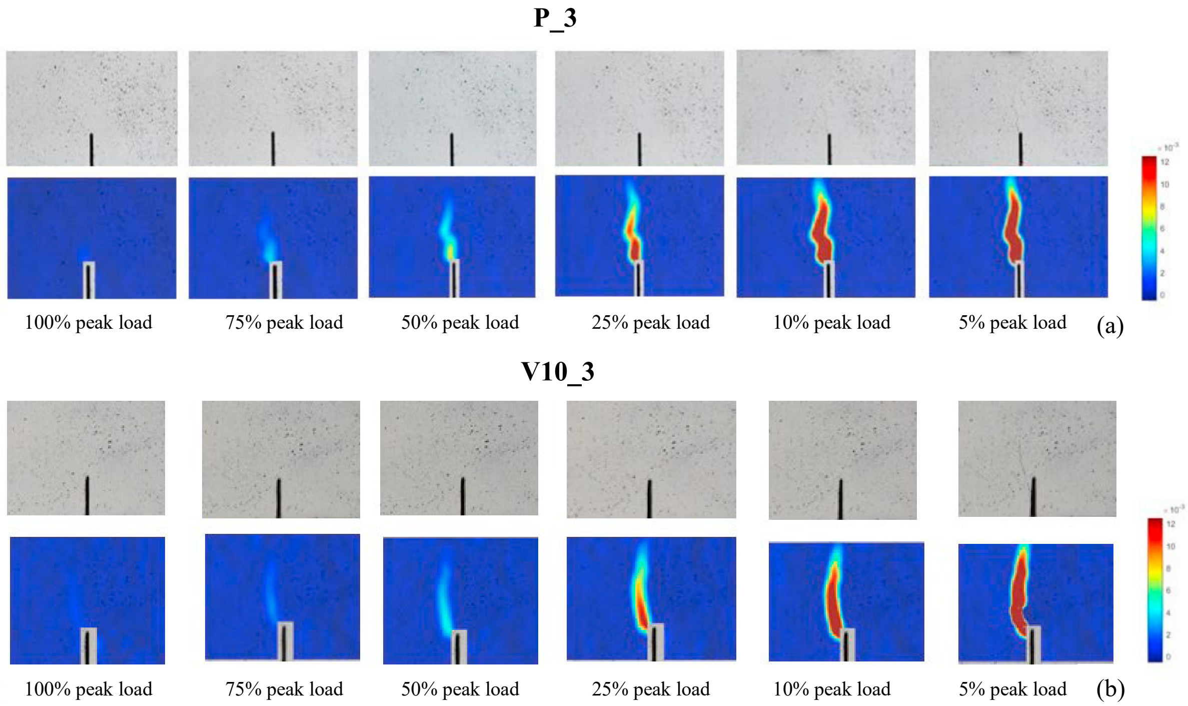


Fig. 6. Crack development around the notch obtained from DIC, for different post-peak loading stages for specimens (a) P_3 and (b) V10_3

4. Conclusions

MSWI bottom ash subjected to a vitrification process can be successfully used as partial cement replacement to develop “green concretes”. This process allows increasing the recycling rate of this by-product and at the same time reducing the environmental impacts of the concrete industry, mainly related to the carbon dioxide emissions during cement production but also to raw materials consumptions.

The performed experimental program shows that the vitrified material, ground at micrometers size, can be used in concrete admixture as cement replacement up to 20% by weight of cement, since it does not compromise the final mechanical performances, in particular in terms of flexural and fracture behavior of concrete.

The vitrification process is surely a promising technology, since it allows eliminating toxic and dangerous compounds for humans and environmental health, preventing at the same time the durability problems related to the detrimental reactions that the MSWI ash tends to develop with cement.

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