Potential Applications of Vitrified Slag as a Product of Plasma Arc Melting

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Abstract

The present article presents the potential of vitrified slag, one of the products of plasma arc melting, for further industrial applications based on previous experiments. The existing publications on the investigation into this field is hence supplemented with our series of experiments conducted using vitrified slag from plasma arc gasification and melting of fly ash from municipal waste, as well as a mixture consisting of fly ash produced by fluidised-bed boilers in a heat power plant and recovered asbestos cement roofing sheets. It should be noted that the process of plasma arc gasification and melting facilitates not only a significant reduction of the quantity of processed hazardous wastes, but also a possibility of transforming such wastes into an inert product, which may be used as an input raw material in certain industrial processes.

Keywords: vitrified slag; plasma arc melting; concrete; foam glass

1. Introduction

Due to a growing demand for reducing the quantity of the produced waste all over the world and with regard to an increasing intensity of global changes, or even a climate crisis, our attention should be paid primarily to the recovery of industrial wastes because the production of such wastes cannot be yet fully eliminated by implementing new green technologies. Furthermore, it is necessary to ensure that wastes containing hazardous substances are disposed of and processed without imposing danger to human life and the environment. Based on multiple investigations carried out in this field, it seems that plasma arc gasification and melting is an optimal waste processing technology. A product of hazardous waste processing may still be classified as inert waste, unless recovered. Moreover, the plasma arc gasification and melting technology represents a waste processing technology that is more environment-friendly than the conventional waste combustion.

2. Plasma arc gasification and melting of wastes in the world

The development of plasma arc gasification and melting in metallurgy gradually resulted in extending this technology to the field of waste disposal. Extensive research into this technology dates back to 1980s [1], when multiple experiments were carried out with various plasma technologies, such as PLASMADUST Process (Sweden), Westinghouse Plasma (USA), RCL´S Plasma arc gasification Process (Canada), Linde Plasma Arc Furnace (Austria), RAPID (Korea) etc. [1–4]

Figure 1. A laboratory plasma reactor; input and output materials [5].

The use of plasma technology in waste processing should be addressed in a comprehensive manner; it means that it is necessary to search for potential applications of the products of this plasma process, i.e. syngas and vitrified slag. Vitrified slag is a solid material with a glassy structure. Such a glassy structure ensures that some heavy metals, their compounds and other hazardous materials bind in a stable glassy matrix. The produced inert slag is literally predetermined for further recovery and production of secondary raw materials. [1]

3. Potential applications of vitrified slag

The glassy structure and the chemical composition of this product (Table 1) of plasma arc gasification and melting indicate its further potential use in the production of:

- Composite building materials (concrete),
- Insulation building materials, such as mineral wool, foam glass etc.

Table 1. Proposed design of a metal hydride tank.

Chemical composition	Mineral wool fibres (wt. %) *	Vitrified slag from MSWI (wt%)
SiO_2	34 – 45	39.93
Al_2O_3	15 – 24	17.54
Fe_2O_3	2 – 11	2.79
CaO	20 – 35	32.93
MgO		2.80
K_2O	1 – 7	0.16
Na_2O		0.65

* *Source: ROCKWOOL [6]*

3.1 Vitrified slag and its applications in composite building materials

Several scientific papers [7, 8, 9], as well as our own experimental research (Fig. 2), indicate a promising use of vitrified slag, a product of plasma arc gasification and melting primarily of fly ash from the combustion of municipal waste, in the production of cement and concrete.

a ***b*** ***c***

Figure. 2 Production of concrete in laboratory conditions using vitrified slag (a, b) and verification of the suitability of its use by strength tests (c)

The suitability of the use of vitrified slag as a replacement filling for concrete was subsequently thoroughly verified by strength tests conducted by a testing laboratory (Table 2).

Table 2. Test samples of concrete and their strength characteristics.

Sample designation	**Binder**	**Filling**				**Water**	**Strength characteristics**			
	Cement CEM I	**Natural aggregate**		**Vitrified slag**			**Tensile and flexural strength**		**Compressive strength**	
		0/4	**4/8**	**0/4**	**4/8**		***F* (kN)**	**σ (MPa)**	***F* (kN)**	**σ (MPa)**
L_0 (reference)	■	■	■	-	-	■	2.18	5.11	42.60	26.62
L_1	■	■	-	-	■	■	1.35	3.16	43.13	26.96
L_2	■	-	■	■	-	■	0.44	1.04	28.68	17.93

3.2 Vitrified slag and its use in insulation building materials

Depending on the slag production method, it is possible to produce porous slag products with good insulation properties, i.e. low a thermal conductivity coefficient. The types of slag are as follows [10]:

a) Expanded of foamed slag

If the molten slag is cooled and subsequently solidifies due to the addition of a controlled quantity of water, air or steam, the cooling and solidification processes may be accelerated; as a result, the cellularity of the slag increases and a final product acquires a light, expanded or foamed form.

b) Pelletised slag

If the molten slag is cooled and subsequently solidifies due to the addition of water and air, which is cooled in a fiberisation drum, a resulting product is in form of pellets, not a solid material. By controlling this process, it is possible to achieve higher crystallinity of pellets, which is optimal for the use of the pellets in aggregates, or higher glassiness, which is desirable in cement applications.

c) Granulated slag

If the molten slag is cooled and subsequently solidifies due to rapid water cooling and acquires a glassy form, the crystallisation does not occur, or it only occurs to a small extent. This process leads to the formation of fragments of a sand-grain size. A physical structure and gradation of the granulated slag depend on the slag's chemical composition and temperature during the water-cooling process, as well as on the method of production.

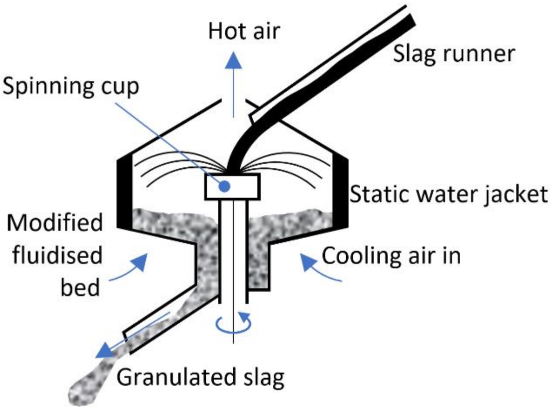

Figure 3. Granulation unit [11].

d) Foam glass [12]

Commercially produced foam glass is produced by crushing glass into glass powder and mixing the powder with glass-making dust, a mineral activator and coal in a precisely specified ratio. The mixture is heated in aggregates with regulated heating in order to achieve an evenly foamed resulting product. The porous structure is achieved by thermal decomposition of the mineral activator to form CO and CO_2.

The glass materials described above are well-known for their properties, such as being non-absorptive and incombustible, as well as their low volumetric mass density, safety for human health, high resistance to external effects, compressive strength, multiple use and, obviously, high insulation capacity.

4. Production of foam glass from vitrified slag in laboratory conditions

Production of foam glass from vitrified slag obtained from the plasma processing of fly ash from municipal waste in company Kosit, a.s., company in laboratory conditions consists of several key phases:
Phase 1 − selection of a mineral activator; Phase 2 − preparation of samples; Phase 3 − heating the samples; Phase 4 − an analysis of the performed experiments; and Phase 5 − methodology modification.
In the industrial production of foam glass, a mixture containing glass waste must be heated to a temperature above the glass softening point, i.e. the temperature at which the glass viscosity η exceeds the value of 106.6 Pa·s. When heated, the mixture of crushed glass and an activator transforms into a liquid melt, while its volume decreases by approximately 44% due to sintering.
A focus of the initial investigation was a selection of an appropriate mineral activator (Table 3) which would facilitate formation of a porous structure of a resulting product. In addition to choosing a proper activator, it is also important to ensure optimal dosage and a temperature for heating a mixture of slag and an activator on order to ensure the chemical decomposition of the activator into gaseous components.

Table 3. Overview of mineral activators for the foam glass production.

Mineral activator	Properties
Li_2CO_3	t_d = 733 °C; ρ = 2,110 kg·m^{-3}
Na_2CO_3	t_d = 850 °C; ρ = 2,530 kg·m^{-3}
K_2CO_3	t_d = 891 °C; ρ = 2,430 kg·m^{-3}
$CaSO_4$	t_d = 800–1,000 °C; ρ = 2,990 kg·m^{-3}
ZnO	t_d = 950 °C*); ρ = 5,700 kg·m^{-3}
C	t_d = > 700 °C**); ρ = 2,250 kg·m^{-3}

t_d – decomposition temperature, ρ – density, *) $\mathrm{ZnO + C} \xrightarrow{950°\mathrm{C}} \mathrm{Zn}$ [Chemistry of the Elements]; **) reactions between carbon and mineral phases

The preparation of samples is summarised in the following flowchart (Fig. 4):

- Crushing the slag in a wolfram-carbid crusher into a fraction < 10 mm.
- Subsequent slag milling in a Retsch PM 100 ball mill into a fraction of 71 µm in Isopropyl Alcohol ($((CH_3)_2CHOH)$).

- Evapouration of $(CH_3)_2CHOH$ from the milled vitrified slag in a vacuum vaporiser.

- Sieving of the crushed slag into a fraction < 71 µm using the Retsch AS 200 analytical sieve.

- Weighing the slag and a corresponding expansive agent to achieve a predefined *slag : expansive agent* ratio.

- Mixing the crushed slag with an expansive agent in a predefined ratio in an agate bowl in Isopropyl Alcohol.
- Drying the mixture under a UV lamp.

- Dosing the mixture into moulds.
- Presing the mixture (100 MPa, 2 minutes).

- Weighing and measuring the weight and height of the prepared sample (m_0, h_0), i.e. the parametres of samples prior to sintering.

Figure 4. Sample preparation methodology.

The heating phase was followed by an analysis of samples (Fig. 5), after which it was concluded that the amount and the sizes of pores in the experimental samples were not sufficient when compared to the samples of industrially produced foam glass. Potential reasons of this failure in the process of heating the tablet-shaped samples may consist in the fact that during the heating (t_{heating} = 1,050 – 1,200 °C; heating time τ = 15, 40 and 120 min.), the activating agents:

a) Did not completely decompose; or
b) Overreacted and the sample melted.
c)

Figure 5. Results of the foaming process in laboratory conditions.

The applied research methodology was subsequently reassessed, but the standard boundary condition, i.e. a sample heating temperature, as well as the sample preparation procedure remained unchanged. Changes in the conducted experiment included the use of a tube furnace for a simulation of the industrial production of foam glass in tunnel furnaces.

$CaSO_4$, was selected as a mineral activator and a ratio of glassy slag to $CaSO_4$ was 99 : 1. A DSC analysis revealed that the phase transitions began in the sample of the prepared mixture at a temperature of 875 °C (Fig. 6); therefore, in the investigation into changes that occurred in the examined samples due to changed temperatures was carried out with a predefined sample-heating temperature of 1,000 °C. At this temperature, it may be expected that a foaming agent will decompose and the sample viscosity will reach optimal values for a successful foaming process. [13]

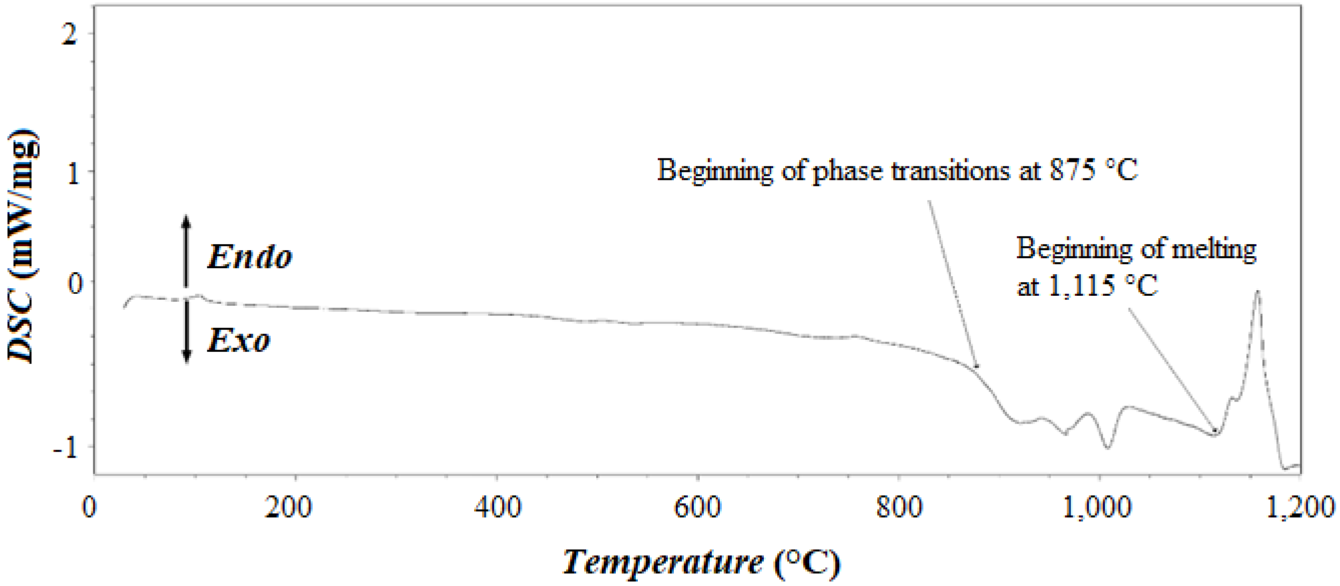

Figure 6. DSC analysis of samples.

In the sample with a diameter of 1.2 cm and a height of 0.67 cm, the content of $CaSO_4$ was as little as 1%. The sample was heated to 1,000 °C in a Clasic 0213 T (Clasic CZ) tube furnace with an endurance time of up to 3 minutes (**Error! Reference source not found.**).

Figure 7. The process of heating the prepared sample.

After several dozens of experimental test runs of the production of foam glass within the initial investigation, a desired effect was achieved when the prepared sample was heated for ca 3 minutes. A comparison of the porosities of the industrially produced foam glass and of the sample of foam glass produced in a laboratory from vitrified slag and an activating agent $CaSO_4$ (1 wt%) revealed the following:

- Porosity of the industrially produced insulation material was 77.2%; and

- Porosity of the sample produced in a laboratory was 65.5%.

A microscopic analysis of the structure of the experimentally produced sample and the industrially produced insulation material indicated that the industrially produced insulation material exhibited a more homogeneous structure of pores. In order to achieve regular pores and homogenous pore sizes in the foam glass produced from vitrified slag, it is still necessary to make minor adjustments to the boundary conditions for the foaming process.

The differences in the homogeneity of the structure of the experimentally produced foam glass and of the industrially produced foam glass are probably attributable to:

- Insufficient homogenisation of the experimental sample prior to the heating phase; or
- The heating process to which the sample was exposed.

It was observed that the resulting experimental sample of foam glass exhibited a weight loss of 1.19 wt%; this observation confirms the hypothesis that the selected foaming agent $CaSO_4$ fully decomposed.

5. Conclusion

Based on the available technical literature and on our investigation into processing of vitrified slag, it is possible to confirm very good results in the investigated field.

Processing municipal and hazardous wastes by an environment-friendly method with a subsequent option of further applications of a product of the plasma processing of wastes (for example, in the building industry) would mean a significant diversion from the waste dumping practices. Unfortunately, waste dumping (associated with occupying the arable land) and combustion of municipal waste are still the preferred practices in the waste management. Research into these issues and early implementation of the respective findings would contribute to the mitigation of the overall impact of anthropogenic activities on all the components of the environment, and hence also on the reversion of the ongoing climate crisis.

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