Bottom ash of municipal solid wastes from incineration plant as mineral additions in concrete

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Abstract

The paper describes the results of a research aimed at studying the properties of concrete with the replacement of part of portland cement with bottom ash from municipal solid waste incinerators (MSWI). Concretes with bottom ash MSWI and traditional addition (coal fly ash and ground limestone), replacing up to 30% of cement, were manufactured. Fresh and hardened properties of the concretes were compared in order to study the advantages and the side effects of each type of addition. Results showed that MSWI bottom ash is potentially attractive as mineral addition for the production of concrete, provided that the risk of entrapment of hydrogen bubbles produced by corrosion of aluminium metallic particles in the fresh concrete is prevented. This could be achieved by wet grinding the bottom ash so that reactions leading to gas development could start within the slurry. However, by considering bottom ashes from different incinerators, a great variability was observed in the time required to exhaust the hydrogen gas production; a key factor for this variability was found in the pH of the slurry. A modest amount of cement (70-100 g/L) added in slurry could increase the pH of the slurries, reduce the reaction times and allow manufacturing of quality concrete suitable for aggressive environment.

Keywords: *MSWI ashes; Blended cement; Pozzolan; Waste management*

1 Introduction

Municipals Solid Waste Incineration (MSWI) bottom ashes have an average chemical composition that is not dissimilar from that of coal fly ashes traditionally used as pozzolanic additions able to improve the durability of concrete. In fact, MSWI bottom ashes are mainly composed of amorphous silica (usually more than 50%), alumina, iron oxide and calcium oxide [1-4]. This suggests that, once they are finely grounded, they can have pozzolanic or hydraulic behaviour and their addition to a concrete mix can have a beneficial role in the development of the microstructure of the hydrated cement paste. As a matter of facts, a great advantage in the sustainability of the concrete industry would be achieved if ground MSWI bottom ashes could actually be used as mineral additions. In fact, residues such as MSWI bottom ashes, which are available in great quantities throughout the world, could be converted into a resource able to produce quality concrete.

Some researches have actually shown the pozzolanic activity of ground MSWI bottom ashes showing their reactivity with lime or portland cement clinker [5,6]. Nevertheless, no successful use of MSWI bottom ashes as mineral addition in concrete has been reported, because of the side effects of this addition. The main side effect is related to the evolution of hydrogen gas after mixing due to the presence of metallic aluminium. In the alkaline environment produced by the hydration of portland cement (pH around 13), corrosion of some metals (mainly aluminium) produces a great amount of gaseous hydrogen. After placing and compaction of concrete, this gas is entrapped in the fresh material, producing a network of bubbles that leads to significant reduction in the strength and increase in the permeability of the hardened concrete.

This paper summarizes the results of a research aimed at developing suitable treatments to allow the use of MSWI bottom ashes as mineral additions for the production of structural concrete.

2 Experimental procedure

Bottom ashes from different municipal wastes incinerators in Northern Italy were considered. They were grounded both under dry conditions in a ball mill and under wet conditions in a micro-sphere mill (a slurry of solid/water ratio of 1/1 was obtained) [7]. pH of slurries was monitored in time by means of a glass electrode and a pH-meter. Concrete and mortar mixes were cast by using the dry and wet grounded ashes in replacement of 30% of cement. Concretes and mortars were made with 440 kg/m^3 of binder (70% portland cement type CEM I 52.5R plus 30% mineral addition), water cement ratio of 0.50 and 1700 kg/m^3 of crushed limestone aggregate. Three control mixes were also cast by using 100% cement or 30% replacement of traditional coal fly ash and grounded limestone.

Compressive strength was measured on 100 mm cubes for concretes and 40x40x160 mm prisms on mortars. The evolution in time of resistivity of wet cementitiuous materials was monitored. In order to study the resistance to chloride penetration, 150 mm cubes were exposed to drying-wetting cycles with a 3.5% by mass sodium chloride solution and chloride profiles were measured after different times of exposure. Chloride profiles were fitted with the solution of II Fick's law [8] in order to calculate the apparent diffusion coefficient.

3 Results and discussion

Table 1 shows the chemical composition of the MSWI ashes tested in this work. A first series of tests was carried out using MSWI bottom ash from the incineration plant of Udine.

After dry grinding these ashes reached a fineness such that the particle size corresponding to 50% of passing (d_{50}) was around 15 μm; after wet grinding it decreased to about 3 μm.

Figure 1 shows the compressive strength in time of the concretes cast with different mineral additions. The control concrete, with 440 kg/m^3 of cement and *w/c* ratio of 0.5 had a 28-day compressive strength on cube of about 64 MPa. The substitution of cement with 30% of limestone (i.e. an inert addition) led to an average 28-day cube strength of only 43.5 MPa, while the replacement of 30% of cement with FA (i.e. a traditional pozzolanic addition) led to 53.4 MPa. The concrete with the addition of dry ground MSWI bottom ash experienced a remarkable expansion during setting. Expansion was visible to the naked eye on the cube specimens after demoulding.

Table 1: Chemical composition of cementitiuos materials and MSWI ashes.

	Al_2O_3	Na_2O	K_2O	SO_3	CaO	Fe_2O_3	MgO	MnO_2	TiO_2	SiO_2
Cement CEM I 52.5R	4.71	0.2	0.84	3.48	62.7	1.93	1.99	0.07	0.19	23.74
Coal fly ash	6.15	0.19	0.19	0.79	6.53	4.49	1.7	0.05	0.39	78.45
Udine MSWI bottom ash	10.29	2.46	0.71	1.21	13.25	14.17	2.02	0.06	0.38	53.41
Desio MSWI bottom ash	6.36	1.72	0.4	3.43	15.89	6.53	1.99	0.16	0.85	61.9
Trezzo MSWI bottom ash	10.69	2.53	0.55	0.69	18.68	8.96	2.89	0.21	-	48.93
Bergamo MSWI bottom ash	10.27	1.92	0.56	0.70	15.59	4.21	1.83	0.09	-	62.75
Vercelli MSWI bottom ash	7.34	1.54	0.70	1.00	11.54	8.18	2.11	0.12	-	64.21

* The percentage of major elements, not including Cl^-, has been calculated in terms of oxides.

Expansion during setting was due to the development of hydrogen gas, after casting of concrete, in the form of bubbles (several mm in diameter). Hydrogen was produced by the cathodic reaction of the electrochemical process of corrosion of aluminium particles present in the slurry. In fact, when this metal comes in contact with the solution of pH 13 which is formed due to the hydration reaction of portland cement, it is indeed able to produce a remarkable volume of hydrogen, which is entrapped within the concrete before setting takes place. Details on this phenomenon have been described elsewhere [7].

Surprisingly, no expansion was observed in the concrete in which 30% of the cement was replaced with wet ground MSWI bottom ash. In this case, a slurry with a solid/liquid ratio of 1:1 was produced by the wet grinding and it was added to the mix (the water in the slurry was considered in the mixing water). Cube specimens did not expand and the 28-day compressive strength of concrete was similar to that of the concrete with 100% portland cement. It was even higher than that of the concrete with coal fly ash (FA). This shows that wet ground MSWI bottom ash has hydraulic properties. Even at longer curing, the concrete with wet ground MSWI bottom ash has strength fairly higher than that of the concrete made with 100% portland cement or with 30% coal fly ash. For instance, after 90 days of curing, the former showed a compressive strength slightly higher than 80 MPa, while the latter had a strength around 70 MPa

The wet grinding process played a primary role in preventing the expansion during setting. In fact, since the beginning of the grinding process the slurry showed a remarkable production of (hydrogen) gas bubbles. This can be attributed to the corrosion process on the newly formed surface of aluminium particles embedded in the bottom ash particles, which are broken by grinding. The pH of the slurry spontaneously reached a value around 11.5 which was enough to promote corrosion of aluminium, although at lower rate than that promoted by the liquid phase of the hydrated cement paste [7]. It was then assumed that, depending on the size of the aluminium particles after grinding, the actual corrosion rate of aluminium in the slurry and the time elapsed, the metallic aluminium particles can be depleted (or mostly depleted) before the slurry is added to the concrete mix. Indeed, if this occurs, no further expansion can take place in the fresh concrete.

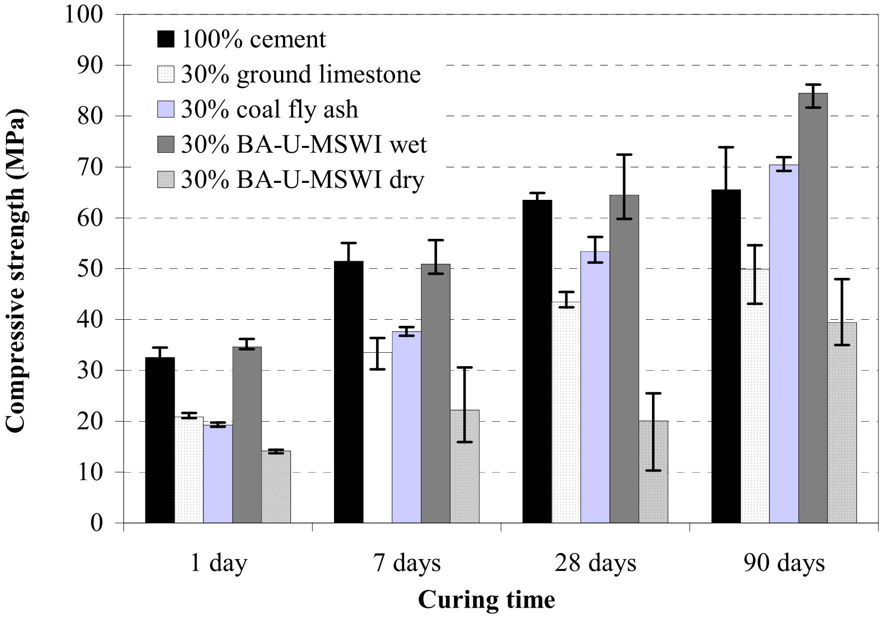

Figure 1: Compressive strength as a function of time of reference concretes (with 100% cement, 30% ground limestone and 30% coal fly ash) and concretes with Udine MSWI bottom ash (wet and dry grinding).

Results obtained with Udine MSWI bottom ashes showed that a few days of rest after wet grinding were enough to exhaust the chemical reactions leading to gas evolution. In fact, the results previously described were obtained with a slurry used for concreting only 48 hours after grinding.

The progressive hydration of cement pastes with addition of wet ground MSWI bottom ash could also be indirectly detected by means of electrical resistivity measurements. Figure 2*a* shows the concrete resistivity after 28 days curing for different mixes, measured on wet specimens (exposed in the curing room at 23°C). The concrete with addition of wet ground MSWI bottom ash had a higher resistivity (about 200 Ω·m), even higher than that of the concrete made with addition of coal fly ash (about 150 Ω·m); this supports the hypothesis that a pozzolanic reaction also occurred in the former and lead to the refinement of capillary pores in the cement paste, which is typical of that reaction.

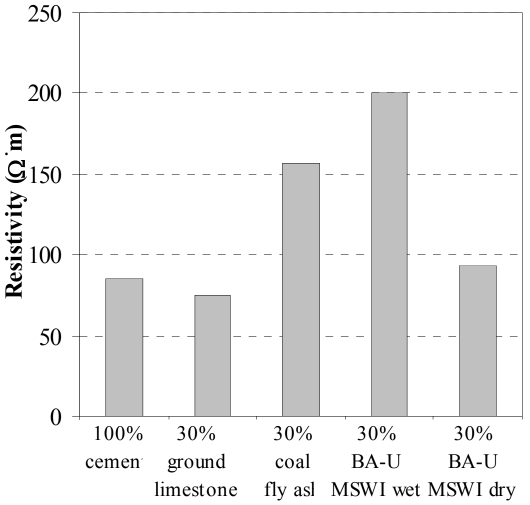

Figure 2: Electrical resistivity of concretes with different types of mineral addition after 28 days curing.

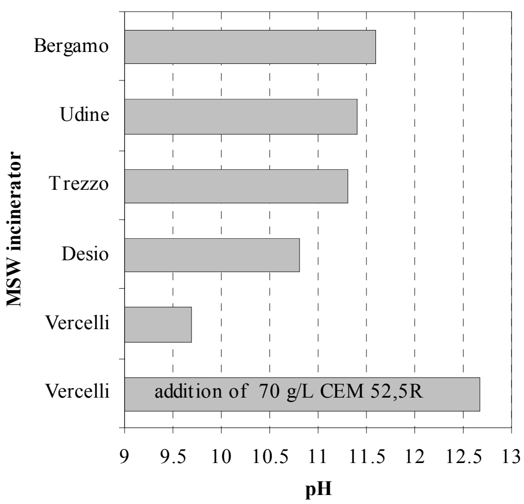

Figure 3: pH values of slurries made with bottom ashes from different incinerators of Northern Italy.

Table 2 Values of chlorides apparent diffusion coefficient (D_{app}) and surface chloride content (C_{s}) calculated by fitting the chloride profiles measured after 6 and 15 months of exposure to chloride wetting and drying cycles with the relationship:

$$C(x) = C_s \cdot \left(1 - erf \frac{x}{2\sqrt{D_{app} \cdot t}}\right)$$

Time	6 months		15 months	
	C_{s}	D_{app}	C_{s}	D_{app}
100% cement	0.63	1.93	1.06	0.86
30% ground limestone	0.52	11.58	0.48	7.20
30% coal fly ash	0.46	1.80	1.27	0.77
30% BA-U MSWI wet	0.9	0.58	1.37	0.58
30% BA-U MSWI dry	0.47	4.23	1.26	2.06

The beneficial effect of hydration of MSWI bottom ashes could also be observed in relation to chloride penetration. Table 2 shows the apparent diffusion coefficient obtained by fitting the chloride profiles measured on cube specimens after 6 and 15 months of exposure to chloride wetting and drying cycles. The concrete with addition of wet ground MSWI bottom ash showed the lowest value of apparent diffusion coefficient ($0.58 \cdot 10^{-12}$ m^2/s). This behaviour can again be related to the well-know pore refinement and decrease in permeability produced by pozzolanic reaction, although some filler effect of finer particles cannot be excluded.

To confirm the results discussed above, several further tests were carried out using ashes from other incinerators located in Northen Italy (Table 1). Remarkable changes in behaviour were observed among different types of MSWI bottom ashes, as far as the effect of hydrogen evolution is concerned. In fact, the time required to deplete aluminium (and possibly other metals responsible of hydrogen evolution) contained in the slurry ranged from less than 1 day to several months.

Consequently, the effect of possible factors that can influence the time for the exhaustion of the hydrogen evolution reaction within the slurry was studied, in order to define possible treatments that can reduce this time to acceptable values (e.g. few days) regardless of the provenience and the batch of the bottom ashes. Influence of the following variables was investigated: *a*) the fineness of MSWI bottom ash particles in the slurry produced by wet-grinding; *b*) the temperature of the slurry during grinding and the subsequent rest period (i.e., from the end of grinding to the time it is added to the concrete mix); *c*) the stirring conditions of the slurry during the rest period; *d*) the possible acceleration of the hydrogen evolution reaction in the slurry by increasing its pH; *e*) the reduction of non-ferrous metals in the bottom ash before wet grinding.

pH was found to play a major role. For instance, ashes from Vercelli incinerator, where hydrogen evolution continued for several weeks in the slurry, showed a lower pH (about 9.6) compared to the other ashes (Figure 3). Nevertheless it was shown that a minimal addition of cement to the slurry (70 g/L) could increase its pH to about 12.6. This was enough to avoid any expansion when the slurry was added to mortar mixes.

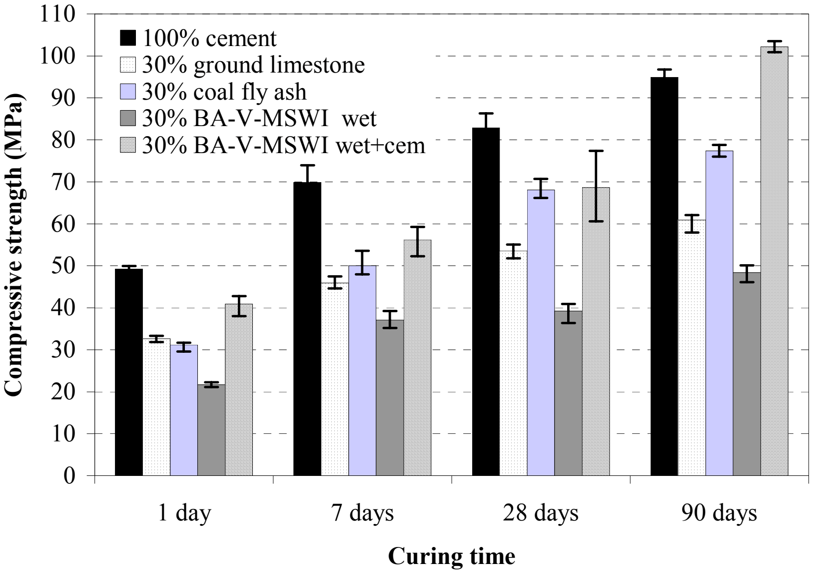

Figure 4: Compressive strength as a function of time of reference mortars (with 100% cement, 30% ground limestone and 30% coal fly ash) and mortars with 30% wet-grounded bottom form Vercelli MSW Incinerator (with and without addition of cement to increase the pH of the slurry).

For instance, Figure 4 shows that the mortar made with cement-treated Vercelli slurry had a compressive strength even higher than the reference concrete with 30% coal fly ash. After 90 days of curing the strength was even higher than the mortar with 100% cement.

4 Conclusions

MSWI bottom ashes treated with a wet grinding process could be used as mineral additions for the production of concrete and they acted as a true cementitious material able to increase strength and durability of concrete.

When MSWI bottom ashes were added to the concrete mix after being dry ground, strength and durability of concrete were negatively affected by entrapment of gas bubbles. This was the consequence of hydrogen produced by the cathodic reaction of corrosion of particles of aluminium (and possibly other non-ferrous metals) that were contained in the bottom ashes. Conversely, wet grinding could avoid problems related to the evolution of hydrogen in the fresh concrete. In this case, the reactions leading to the development of gas began in the slurry produced by wet grinding and they continued afterwards until, after a certain time, they exhausted, so that the slurry could be safely added to the concrete mix. Nevertheless, a remarkable variability was observed for the time required to terminate these reactions. For some ashes a couple of days was enough, while in same cases a much longer time, of the order of months, was not sufficient to end the gas development. Further tests showed that the pH of the slurry can play a major role. It was shown that a small addition of cement to the slurry can be suitable to increase the pH and prevent any expansion in the mix.

When the negative effects of hydrogen evolution in the fresh concrete could be avoided, the wet ground MSWI bottom ashes showed to behave as pozzolanic additions. Replacement of 30% of portland cement with these ashes led to a remarkable improvement in the strength and to a significant reduction in permeability of concrete, even more than that obtained when the same quantity of coal fly ash was used.

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