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Concrete with Bottom Ash from Municipal Solid Wastes Incinerators

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ABSTRACT

Mineral solids in form of fly ash and bottom ash are produced by burning municipal solid wastes in incinerators (MSWI). Fly ash is negligible and it is so chloride-rich that it cannot be used as mineral addition in cement-based mixtures for reinforced concrete structures.

On the other hand, bottom ash is about 25% with respect to MSWI and its chloride content is negligible, so that it could be potentially used as mineral addition for manufacturing concrete mixtures. However, ground bottom ash (GBA) from MSWI does not perform as well as other mineral additions (silica fume or fly ash produced by coal burning) due to the presence of aluminium metal particles which react with the lime formed by the hydration of Portland cement and produce significant volume of hydrogen in form of gas bubbles which strongly increase the porosity of concrete and reduce its strength.

INTRODUCTION

Municipal 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, alumina, iron oxide and calcium oxide [Pera et al 1997; Kikuchi 2001.; Pecqueur et al.2001; Alkemade et al. 1994]. This suggests that, once they are finely ground, 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.

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 [Paine et al. 2000; Macias et al. 2001]. 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 [Bertolini et al. (2004)]. 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 shows 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 without the evolution of hydrogen gas due to the presence of metallic aluminium particles.

ENVIRONMENTAL ASPECTS

All concretes with ground bottom ashes were submitted to leaching tests in form of monolithic specimens, of broken pieces or finely ground particles thus simulating the situation of a concrete structure at the end of its life if any. The results, which will not shown in the present paper for the sake of brevity, were absolutely positive and all the concretes respected the limit values for wastes according to the European Norm. In particular these results confirmed that the GBA has good environmental properties, that the separation of heavy metals is really effective, and that the ground bottom ash can be compared, from an environmental point of view and life cycle, to the usual mineral admixtures (coal fly ash, silica fume, blast furnace slag) and cement.

EXPERIMENTAL PROCEDURE

Bottom ash from MSWI appears as a mixture of inorganic particles mixed with metallic pieces. The new process through a very effective separation of metals (including heavy metals) and a special wet grinding, enabled to produce a fluid aqueous slurry from which aluminium-based metallic particles were completely separated.

Table 1 shows the characteristics of the three GBA slurries with a mean particle size (D_{50}) of about 5, 3 and 1.7 μm manufactured by increasing the grinding time. Due to the higher specific surface area, the slurry with the 1.7 μm mean size contains less dry GBA (41.2%) with respect to the coarser ones (about 55%) in order to keep the same fluidity. Figure 1 shows the scanning electron microscopy (SEM) of the three GBA.

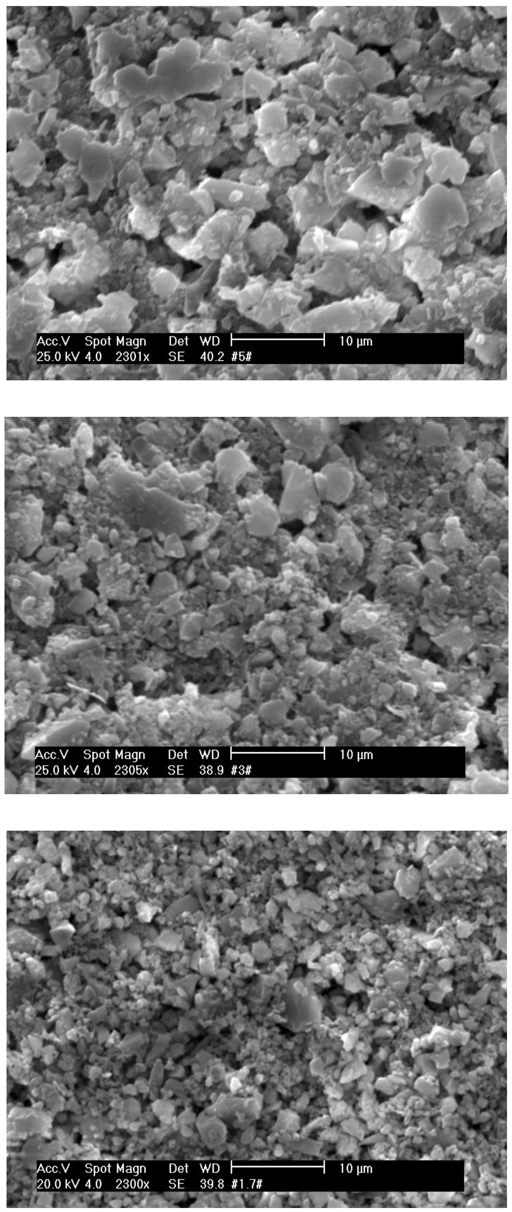
Table 2 shows the chemical composition of the water-free bottom ash (GBA), coal fly ash (FA), silica fume (SF) and Portland cement CEM I 52.5 R used to manufacture concrete mixtures.

Table 3 shows the composition of the following concrete mixtures:
- *Control mix* without any mineral addition;
- *FA mix* with 20 % of coal fly ash replacing Portland cement;
- *SF mix* with 10 % of silica fume replacing Portland cement;
- *5 GBA mix* with 20 % of 5-μm ground bottom ash replacing Portland cement;
- *3 GBA mix* with 20 % of 3-μm ground bottom ash replacing Portland cement;
- *1.7 GBA mix* with 20 % of 1.7-μm ground bottom ash replacing Portland cement.

Table 1. Characteristics of the GBA slurries determined by laser granulometry

Type of slurry	D_{50}* (μm)	Specific surface area (m^2/kg)	Dry Content (%)
5 GBA	4.88	2440	55.7
3 GBA	2.85	3430	56.7
1.7 GBA	1.67	4724	41.0

* Size corresponding to 50% of GBA with particles smaller than this value



5 GBA

3 GBA

1.7 GBA

Fig. 1. SEM of the ground bottom ashes in the aqueous slurries

Table 2. Chemical composition of ground bottom ash (GBA), coal fly ash (FA), silica fume (SF) and Portland cement (PC)

Oxide	GBA	FA	SF	PC
SiO_2	40.07	55.11	95.12	23.15
CaO	20.43	2.12	0.79	63.12
Al_2O_3	11.08	27.91	0.21	5.20
Fe_2O_3	10.60	3.75	0.70	1.05
MgO	3.37	0.51	0.58	0.15
Na_2O	3.52	0.41	0.19	0.35
K_2O	0.90	0.71	0.31	0.41
P.O.I.	5.2	6.8	2.01	2.2

In all the concrete mixtures the amount of the cementitious material including Portland cement and mineral additions was about 340 kg/m^3. The amount of mixing water, including the water of the GBA slurries, was about 167 kg/m^3, so that the water/cementitious material ratio (*w/cm)* of all the concrete mixtures was 0.49. An adequate amount of a polycarboxylic superplasticizer (about 1% by weight of the cementitious material) was used to manufacture all the concrete mixtures at the same slump level of about 210 mm).

The following measurements were carried out on the above concrete mixtures:

- compressive strength at 20 °C from 1 to 60 days;
- water penetration in 28-day cured concrete under according to the EN 12390/8;
- chloride diffusion in 28-day cured concrete fully immersed in a 3.5 % NaCl water solution for 120 days;
- CO_2 penetration in 28-day cured concrete exposed to air for 120 days.

RESULTS

Compressive strength

Figure 2 shows the compressive strength of the *Control mix* in comparison with those of the *FA mix* and *SF mix*. The 20% replacement of Portland cement by coal fly ash reduces the concrete strength particularly at early ages. When Portland cement is replaced by 10% of silica fume there is a small decrease of strength at early ages (1-7 days) and an increase at later ages (28-90 days).

Figures 3, 4 and 5 show the compressive strength of concrete when 20 % of Portland cement is replaced by 5 GBA, 3 GBA and 1.7 GBA respectively. The smaller is the particle size of the ground bottom ash, the higher is the compressive strength. The finest ground bottom ash (1.7-μm GBA) performs as well as silica fume and both produce concretes stronger than the control mix after 7 days of curing (Fig.5). The replacement of 20% of Portland cement by 3-μm GBA slightly reduces the early strength and does not modify the 90-day compressive strength (Fig.4). The replacement of 20 % of Portland cement by the coarsest ground bottom ash (5-mm GBA) performs better than the same replacement by coal fly ash at early ages (Fig. 5). Therefore, depending on its fineness, the ground bottom ash performs between the coal fly ash and the silica fume.

Table 3. Composition of concrete mixtures

Mix	Portland cement (kg/m^3)	Mineral addition			Sand 0-4 mm (kg/m^3)	Gravel 4-32 mm (kg/m^3)	Water* (kg/m^3)	Super-plasticizer (% by c.m.)	w/c	w/cm	Slump (mm)
		Type	Dry	Water							
Control Mix	340	—	—	—	976	970	167	0.90	0.49	0.49	220
FA Mix	272	FA	68	—	976	970	167	0.90	0.62	0.49	220
SF Mix	304	SF	34	—	968	962	166	1.10	0.54	0.49	210
5 GBA Mix	273	5 GBA	68	54	980	974	167	0.90	0.60	0.49	220
3 GBA Mix	273	3 GBA	68	54	980	974	168	0.90	0.61	0.49	210
1.7 GBA Mix	273	1.7 GBA	68	48	980	974	168	0.90	0.61	0.49	210

* It includes the water of the GBA slurries

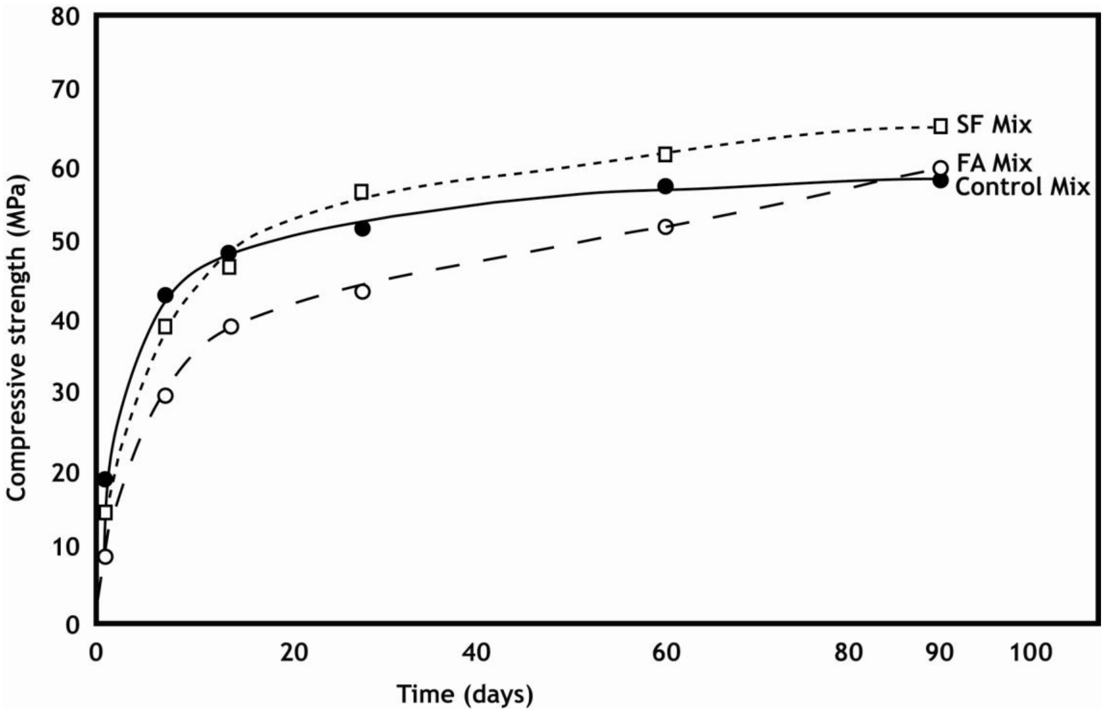


Fig. 2. Compressive strength of concrete with and without replacement of Portland Cement by 20% of fly ash (FA) or 10% of silica fume (SF).

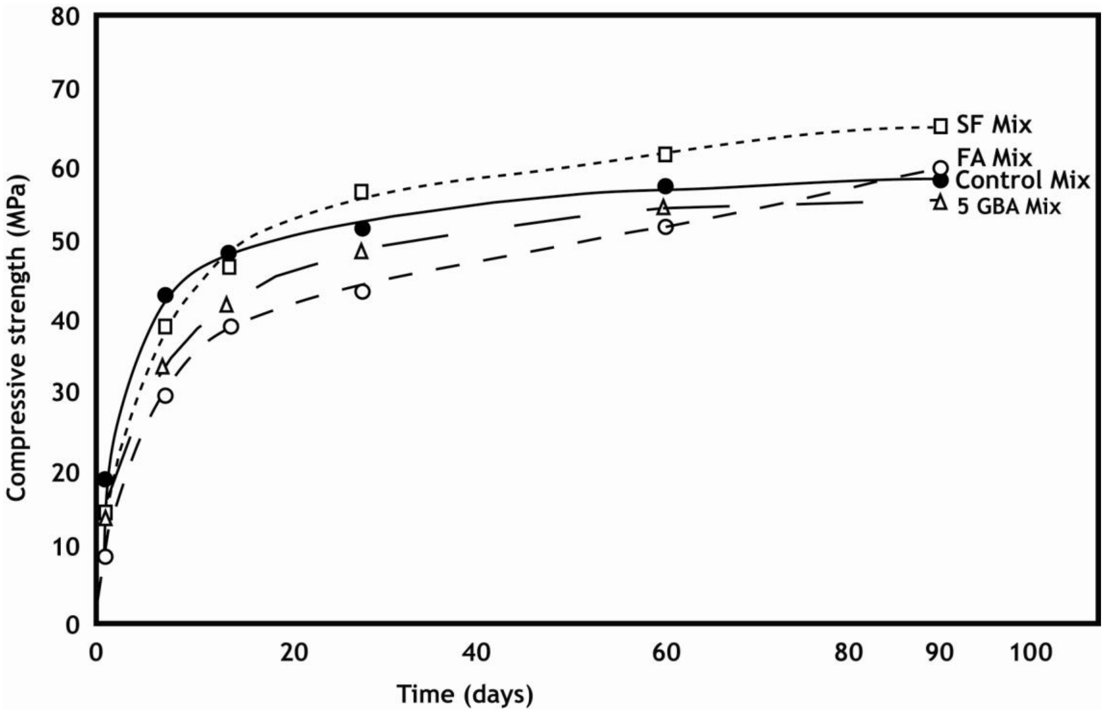


Fig. 3. Compressive strength of concrete with 5-μm ground bottom ash (5 GBA), fly ash (FA) and silica fume (SF).

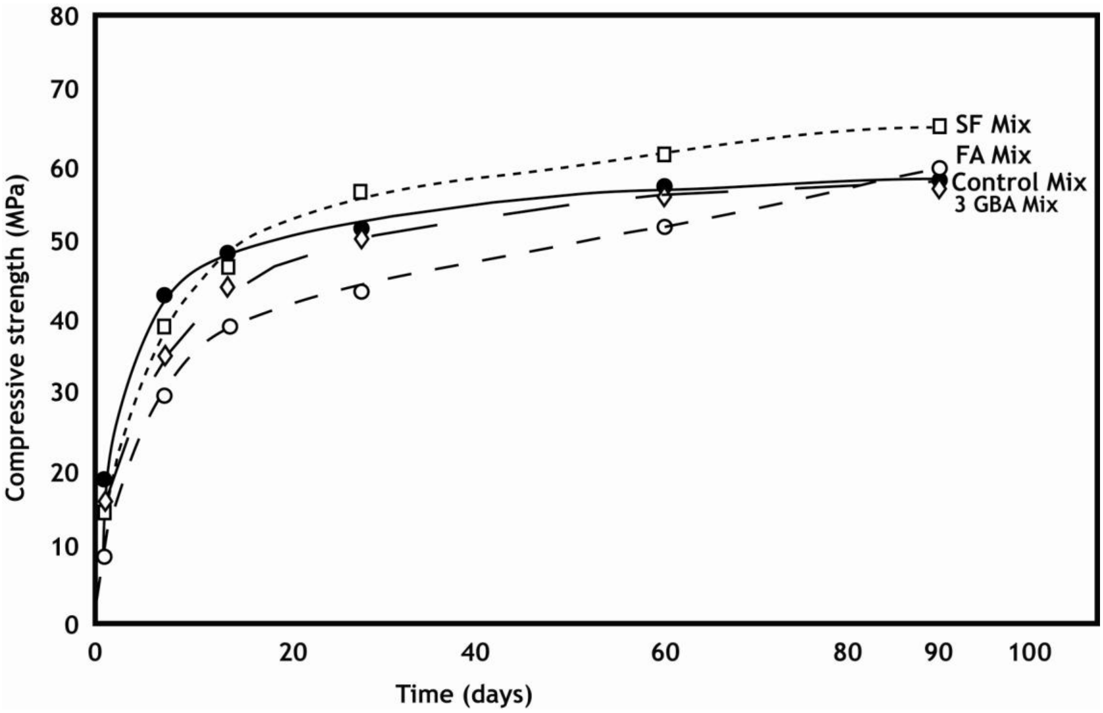


Fig. 4. Compressive strength of concrete with 3-μm ground bottom ash (5 GBA), fly ash (FA) and silica fume (SF).

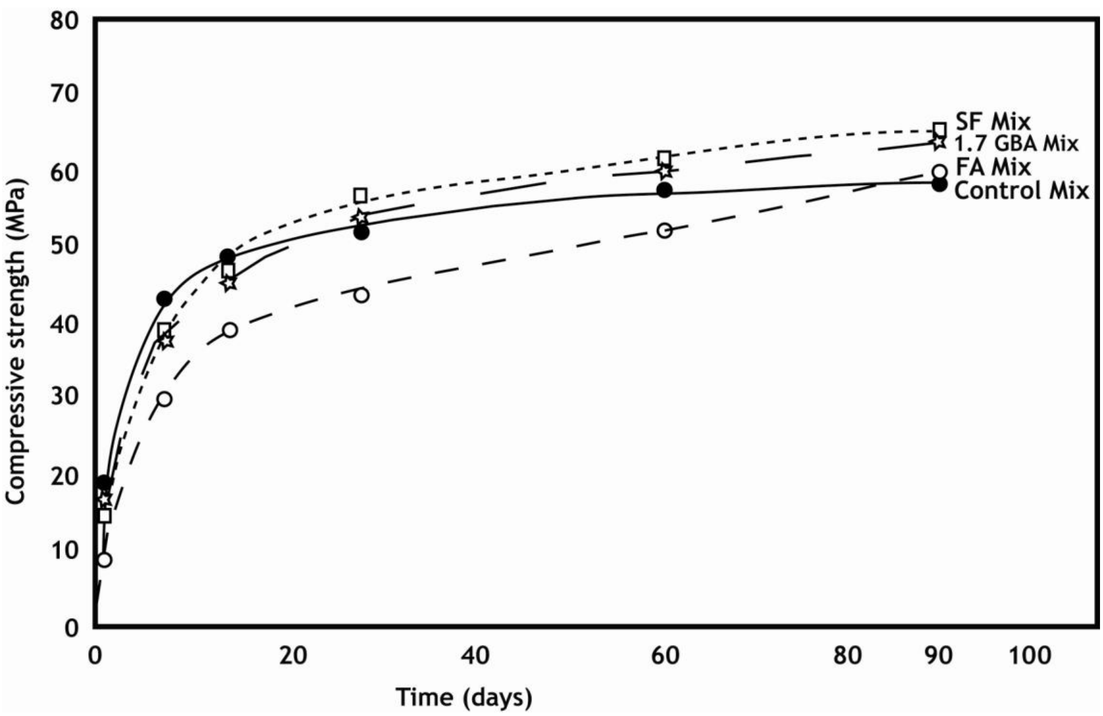


Fig. 5. Compressive strength of concrete with 1.7-μm ground bottom ash (5 GBA), fly ash (FA) and silica fume (SF).

Water permeability

Table 4 shows the penetration depth of water in concretes exposed to a 3 bar pressure of water for 5 days. According to the EN 12390/8 test, concrete is considered to be impermeable if the average profile of water penetration is lower than 20 mm and the maximum penetration is not higher than 50 mm. The results shown in Table 4 indicate that all the concretes according to this test are impermeable and this is due to the relatively low *w/cm* ratio of 0.49 (Table 3). However, the penetration of water in the *1.7 GBA mix* is very similar to that of the *SF mix* which appears to be the less permeable. The penetration of water in the other two GBA mixes is lower than that of the coal fly ash mix.

Table 4. Penetration of water according to EN 12390/8 test in 28-day cured concretes

Type of mix	Penetration depth of water into concretes	
	Maximum	Average
Control Mix	7 mm	3 mm
FA Mix	11 mm	6 mm
SF Mix	5 mm	2 mm
5 GBA Mix	10 mm	5 mm
3 GBA Mix	11 mm	4 mm
1.7 GBA Mix	6 mm	3 mm

Chloride diffusion

Table 5 shows the diffusion depth of Cl^- ions through the concrete specimens. The results indicate that the performance of concretes with 5-µm and 3-µm GBA is higher than that of coal fly ash and lower than silica fume, whereas 1.7-µm GBA performs as well as silica fume.

Table 5. Diffusion of chloride ions (Cl^-) in 28-day cured concretes

Type of mix	Diffusion depth of Cl^- into concrete at:		
	28 days	45 days	120 days
Control Mix	5.0 mm	6.0 mm	15.0 mm
FA Mix	8.0 mm	11.5 mm	18.0 mm
SF Mix	5.0 mm	6.0 mm	12.0 mm
5 GBA Mix	7.0 mm	9.0 mm	19.0 mm
3 GBA Mix	6.0 mm	8.0 mm	18.0 mm
1.7 GBA Mix	5.0 mm	6.0 mm	12.0 mm

CO_2 penetration

The results shown in Table 6 indicate that the concrete with 20 % of the finest ground bottom ash (1.7-µm GBA) performs as well as that containing 10 % silica fume and both resist the CO_2 penetration better than the *Control mix*. The concrete with 3-µm GBA performs better than the *Control mix*, whereas the penetration of CO_2 in the concrete with the coarsest ground bottom ash (5-µm GBA) occurs to a lower extent than that in the concrete with coal fly ash.

Table 6. Penetration depth of CO_2 in 28-day cured concretes

Type of mix	Penetration of CO_2 into concrete at:		
	28 days	**45 days**	**120 days**
Control Mix	1.0 mm	2.0 mm	3.5 mm
FA Mix	2.0 mm	3.0 mm	5.5 mm
SF Mix	1.0 mm	1.0 mm	2.0 mm
5 GBA Mix	2.0 mm	3.0 mm	4.5 mm
3 GBA Mix	1.0 mm	2.0 mm	2.5 mm
1.7 GBA Mix	1.0 mm	1.0 mm	2.0 mm

CONCLUSIONS

Ground bottom ashes (GBA) from municipal solid waste incinerators (MSWI) were manufactured according to a new technology based on a high degree of separation of metals including the heavy ones, the wet grinding process, and other specific technical solution to completely remove the aluminium metallic particles. At the end of the process, a fluid slurry was obtained with particle size in the range of 1-5 μm. By changing the wet grinding time three GBA were produced with a mean particle size of 5 μm, 3 μm and 1.7 μm.

Compressive strength and durability measurements were carried out in concretes where Portland cement was replaced by 20% of ground bottom ashes from MSWI in comparison with concretes containing 20% of coal fly ash or 10% of silica fume.

The finest ground bottom ash (with a mean size of 1.7 μm) performs as well as silica fume in terms of compressive strength, water permeability, chloride diffusion and CO_2 penetration. The performances of GBA with mean sizes of 3 and 5 μm were higher than that of the coal fly ash particularly at 1-60 days.

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