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SCC with Ground Bottom Ash from Municipal Solid Wastes Incinerators

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Synopsis: Ground bottom ash (GBA) from Municipal Solid Wastes Incinerators (MSWI) does not perform as well as other mineral additions -such as 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 increase the porosity of concrete and reduce its strength.

Due to this drawback, a new process was developed to separate the aluminium metal particles through a mechanical removal of metals and a wet grinding of bottom ashes. At the end of the process, GBA was used as aqueous slurry to replace portland cement.

In the present work GBA with a maximum size of 1.7 μm (0.07 μin) was used to replace about 10% of portland cement in self-compacting concretes (SCC). Mixtures with shrinkage-reducing admixture (SRA) and a CaO-based expansive agent were also manufactured to reduce the drying shrinkage and the related cracks. Moreover, an alternative way to reduce both number and length of cracks was adopted by using SRA combined with polyvinyl alcohol (PVA) macrosynthetic fibres. Corresponding mixtures with silica fume or fly ash were also manufactured. GBA performed as well as silica fume in terms of mechanical properties, durability and crack behavior, and much better than fly ash.

Keywords: Durability. Fly ash. Ground bottom ash. Municipal Solid Wastes Incinerators. Self-compacting concrete. Shrinkage-reducing admixture. Silica fume. Superplasticizer.

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INTRODUCTION

Ground bottom ash (GBA) from Municipal Solid Wastes Incinerators (MSWI) could be used as mineral addition to partially replace portland cement in a sustainable concrete mixture.

In some researches[1,2] the pozzolanic activity of ground bottom ashes from MSWI was found due to their reactivity with lime or portland cement clinker. However, no successful use of this bottom ash as mineral addition in concrete has been reported, because of the side effects of this addition. The main drawback is related to the evolution of hydrogen gas in the fresh mixture due to the presence of metallic aluminium.[3] In the alkaline environment produced by the hydration of portland cement (with 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 mixture, producing a network of bubbles that leads to significant strength loss and increase in the permeability of the hardened concrete.

EXPERIMENTAL PROCEDURE

The present paper shows the results of a research work aimed at developing suitable treatments of MSWI bottom ashes to allow their use as mineral additions for the production of structural concrete without the evolution of hydrogen gas due to the presence of metallic aluminium particles.

Materials

Bottom ash from MSWI appears as a mixture of inorganic particles mixed with metallic pieces. The new patented process, based on a wet grinding of bottom ash, enabled to

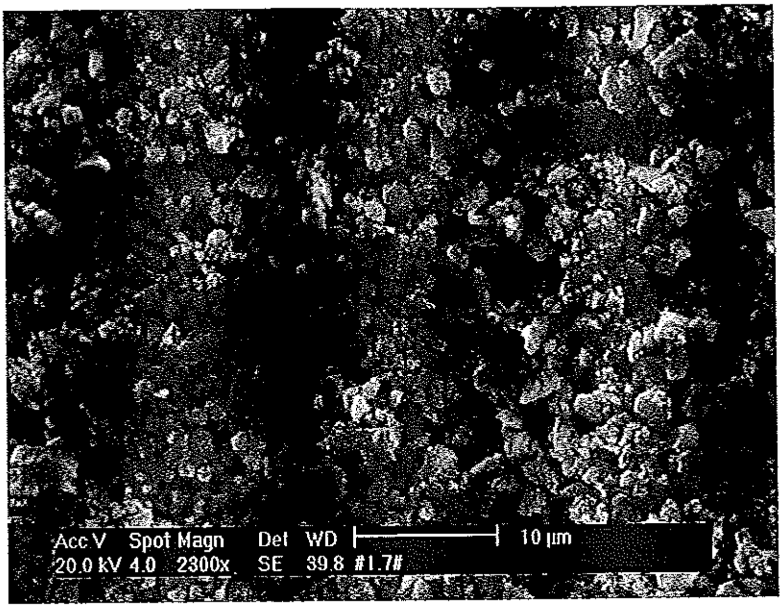

Fig. 1 – Scanning electron microscope of irregular crushed particles of ground bottom ash (GBA)

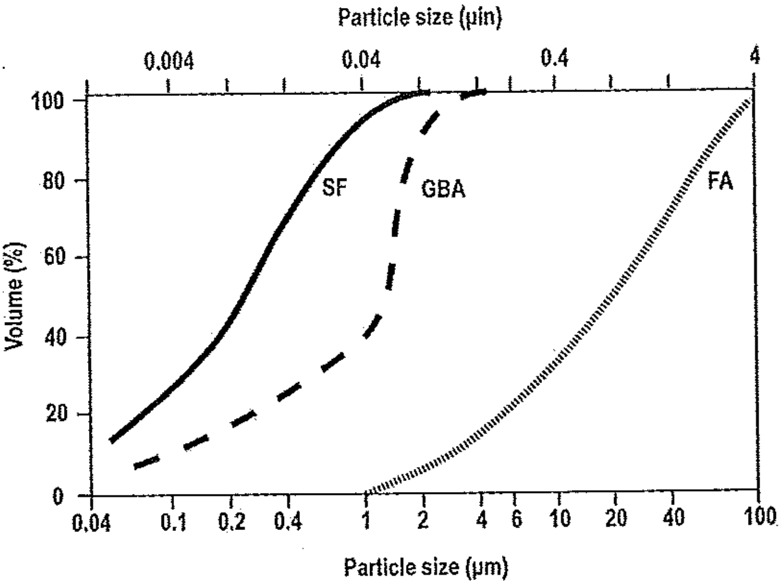

Fig. 2 – Laser-granulometry of silica fume (SF), ground bottom ash (GBA) and fly ash (FA)

produce a fluid aqueous slurry with 60% of water from which the aluminium-based metallic particles were completely separated.

Figure 1 shows the SEM of the GBA particles with a specific surface area of 470 m^2/kg (256.4 yd^2/lb). Figure 2 shows the laser-granulometry of GBA in comparison with those of silica fume and coal fly ash with a mean particle size (D_{50}) of about 1.5 µm (0.06 µin), 0.3 µm (0.01 µin), and 30 µm (1.17 µin) respectively.

Table 1– Chemical composition of ground bottom ash (GBA), coal fly ash (FA), silica fume (SF) and ground limestone (LS)

Oxide	GBA	FA	SF	LS
SiO_2	40.07	55.11	95.12	-
CaO	20.43	2.12	0.79	54.92
Al_2O_3	11.08	27.91	0.21	-
Fe_2O_3	10.60	3.75	0.70	-
MgO	3.37	0.51	0.58	-
Na_2O	3.52	0.41	0.19	-
K_2O	0.90	0.71	0.31	-
Loss of ignition	5.2	6.8	2.01	44.02

Table 1 shows the chemical composition of the cementitious materials including the water-free bottom ash (GBA), coal fly ash, silica fume and that of the ground limestone (LS) used as filler to manufacture self-compacting concrete (SCC) with portland cement (type CEM I 52.5 R according to European Standard EN 197-1.

Table 2 shows the composition of the SCCs all with a water/(cement + cementitious material) ratio, *w/(c+cm)*, of 0.42. The amount of portland cement was about 400 kg/m^3 (675 lb/yd^3) combined with about 100 kg/m^3 (170 lb/yd^3) of LS in order to attain a sufficient amount of fine material to avoid segregation and bleeding.

The amount of SF or GBA was about 50 kg/m^3 (85 lb/yd^3) replacing the same weight of portland cement, whereas about a double amount of FA (100 kg/m^3 or 170 lb/yd^3) was used to replace the same amount of portland cement.

The amount of a polycarboxylate superplasticizer (PCS) was adjusted in order to keep the same slump-flow at 720 mm in all the concrete mixtures: the amount of PCS was higher in the presence of silica fume (15 kg/m^3 → 25 lb/yd^3) than in the presence of GBA (12 kg/m^3 → 20 lb/yd^3) or FA (11 kg/m^3 → 18.5 lb/yd^3) and this difference seems to be related with the particle size of these mineral additions (Fig.2).

In some mixtures 30 kg/m^3 (50.7 lb/yd^3) of a lime-based expansive agent or 4 kg/m^3 (6.8 lb/yd^3) of PVA-based macrosynthetic fibers -30 mm (1.17 in) long and 1 mm (0.039 in) thick- were used by replacing the same amount of limestone filler to reduce the number and the width of the cracks caused by the drying shrinkage in restrained slabs exposed to drying shrinkage. Due to the presence of CaO in the expansive agent the amount of superplasticizer must be increase by 1 kg/m^3 (1.69 lb/yd^3) to keep the same workability.

TEST

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

- Compressive strength at different ages (1-180 days);
- Water penetration in 28-day cured concretes;
- Chloride diffusion in 28-day cured concretes kept under 3.5% NaCl water solution;
- CO_2 penetration in 28-day cured concrete exposed to air;
- Drying shrinkage of un-restrained specimens with and without PVA macrofibers;

Table 2– Composition of self-compacting concretes with a slump-flow of 720 mm (28.1 in) and w/(c+cm) of 0.42

Mix	Portland cement: kg/m^3 (lb/yd^3)	Mineral additions: kg/m^3 (lb/yd^3)				Aggregate* kg/m^3 (lb/yd^3)	Water** kg/m^3 (lb/yd^3)	Superplasticizer kg/m^3 (lb/yd^3)	SRA kg/m^3 (lb/yd^3)	Expansive agent kg/m^3 (lb/yd^3)	PVA kg/m^3 (lb/yd^3)
		LS	GBA	SF	FA						
Control	398 (673)	99 (167)	-	-	-	697 (1178)	166 (281)	12 (20)	4 (7)	-	-
GBA-1	350 (592)	97 (164)	48 (81)	-	-	700 (1183)	167 (282)	12 (20)	4 (7)	-	-
GBA-2	349 (590)	70 (118)	49 (83)	-	-	698 (1180)	168 (284)	13 (22)	4 (7)	30 (51)	-
GBA-3	351 (593)	93 (157)	49 (83)	-	-	695 (1175)	167 (282)	12 (20)	4 (7)	-	4 (7)
SF-1	349 (590)	98 (166)	-	47 (79)	-	700 (1183)	167 (282)	15 (25)	4 (7)	-	-
SF-2	348 (588)	69 (117)	-	48 (81)	-	698 (1180)	167 (282)	16 (27)	4 (7)	30 (51)	-
SF-3	348 (588)	94 (159)	-	47 (79)	-	698 (1180)	167 (282)	15 (25)	4 (7)	-	4 (7)
FA-1	302 (510)	99 (167)		-	95 (161)	698 (1180)	168 (284)	11 (19)	4 (7)	-	-
FA-2	305 (515)	70 (118)	-	-	94 (159)	698 (1180)	167 (282)	12 (20)	4 (7)	30 (51)	-
FA-3	301 (509)	96 (162)	-	-	94 (159)	697 (1178)	167 (282)	11 (19)	4 (7)	-	4 (7)

* Sand 0-4 mm (0-0.16 in) = 40% by weight; gravel 4-16 mm (0.16-0.62 in) = 60% by weight

** It includes the water of the GBA slurry

- Restrained length change of reinforced specimens with or without expansive agent;
- Field tests on restrained slabs 8-m long to visually monitor the cracks.

RESULTS

The following results were obtained on the compressive strength, water penetration, chloride diffusion, CO_2 penetration, drying shrinkage, restrained expansion and field tests.:

Compressive strength

Figure 3 shows the compressive strength at 20°C and RH of 95% of cube (150 mm → 5.85 in) specimens cured from 1 to 180 days for the *Control Mix* in comparison with the *GBA-1 Mix*, *SF-1 Mix* and *FA-1 Mix* shown in Table 2. The compressive strength of the *FA-1 Mix* was much lower than the *Control Mix* at early ages and was approximately the same at longer ages (60-180 days). On the other hand, silica fume and ground bottom ash perform much better particularly at early ages. These results agree with those obtained in a work[4] where GBA of different particle size were studied and where it was found that only

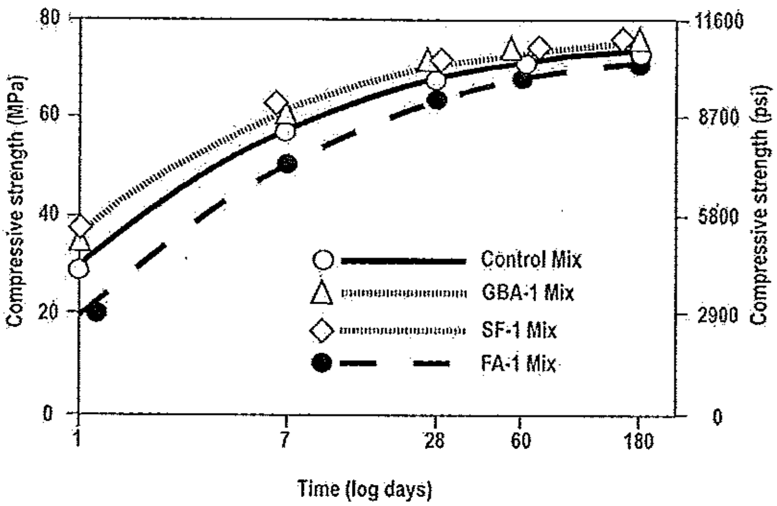

Fig. 3 – Comparison of compressive strength at different ages of Control Mix, GBA-1 Mix, SF-1 Mix and FA-1 Mix

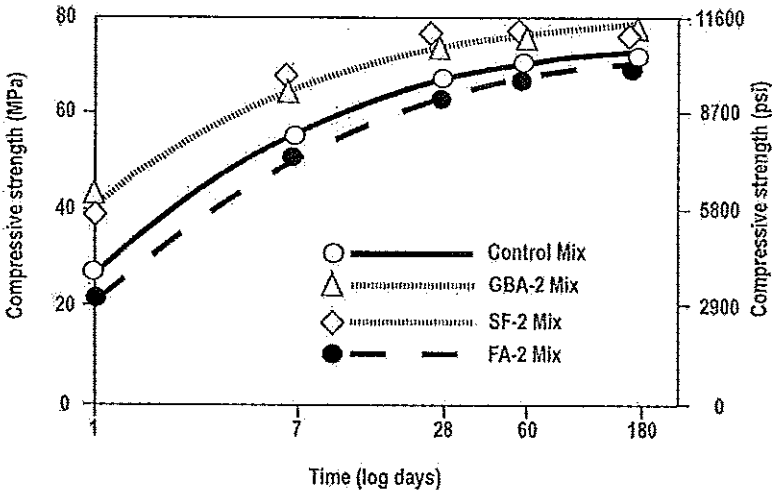

Fig. 4 – Comparison of compressive strength at different ages of Control Mix, GBA-2 Mix, SF-2 Mix and FA-2 Mix

concrete with very fine GBA (about 1.7 μm), as that used in the present work, performed as well as the concrete with silica fume

Similar results were obtained in the presence of the expansive agent (Fig. 4) with a little higher compressive strength in the *GBA-2 Mix*, *SF-2 Mix* and *FA-2 Mix* due to the presence of CaO which reacts with water and then reduces the actual amount of mixing water with respect to that of the *Control Mix* without the expansive agent.

In the presence of the PVA macrofibres (Fig. 5) the compressive strength of *GBA-3Mix*, *SF-3 Mix* and *FA-3 Mix* were similar to those obtained in the absence of fibres (Fig. 3).

Water penetration

Table 3 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 European Norm, concrete is considered

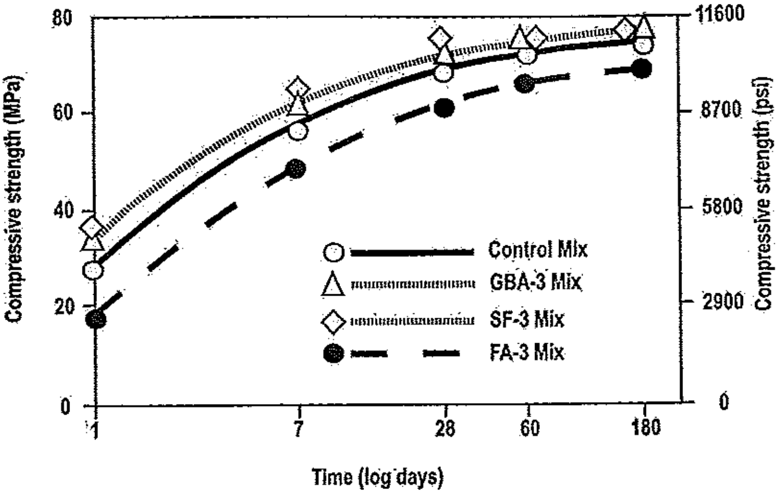

Fig. 5 – Comparison of compressive strength at different ages of Control Mix, GBA-3 Mix, SF-3 Mix and FA-3 Mix

Table 3– Penetration of water in 28-day cured concretes

Type of SCC	Penetration depth of water into concretes	
	Maximum	Average
Control Mix	5 mm (0.20 in)	2 mm (0.08 in)
GBA-1 Mix	5 mm (0.20 in)	1 mm (0.04 in)
SF-1 Mix	5 mm (0.20 in)	1 mm (0.04 in)
FA-1 Mix	8 mm (0.31in)	4 mm (0.16 in)

Table 4– Diffusion of chloride ions in 28-day cured concretes

Type of mix	Diffusion depth of Cl^- into concrete at:		
	28 days	45 days	120 days
Control Mix	1.3 mm (0.051 in)	6.0 mm (0.234 in)	6.6 mm (0.257 in)
GBA-1 Mix	1.1 mm (0.043 in)	4.0 mm (0.156 in)	4.4 mm (0.172 in)
SF-1 Mix	1.0 mm (0.039 in)	3.9 mm (0.152 in)	4.3 mm (0.168 in)
FA-1 Mix	2.3 mm (0.090 in)	5.8 mm (0.226 in)	5.9 mm (0.230 in)

to be impermeable if the average profile of water penetration is lower than 20 mm (0.78 in) and the maximum penetration is not higher than 50 mm (1.95 in). The results shown in Table 4 indicate that all the concretes according to this test are impermeable and this is due to the low *w/(c+cm)* ratio of 0.42 (Table 2). The penetration of water in the *GBA-1 Mix* is very similar to that of the *SF-1 Mix* and much lower than the *FA-1 Mix*.

Table 5– 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	0.9 mm (0.035 in)	1.8 mm (0.070 in)	3.0 mm (0.117 in)
GBA-1 Mix	0.7 mm (0.027 in)	1.0 mm (0.039 in)	2.0 mm (0.078 in)
SF-1 Mix	0.6 mm (0.023 in)	1.0 mm (0.039 in)	2.0 mm (0.078 in)
FA-1Mix	1.8 mm (0.070 in)	2.6 mm (0.101 in)	4.5 mm (0.176 in)

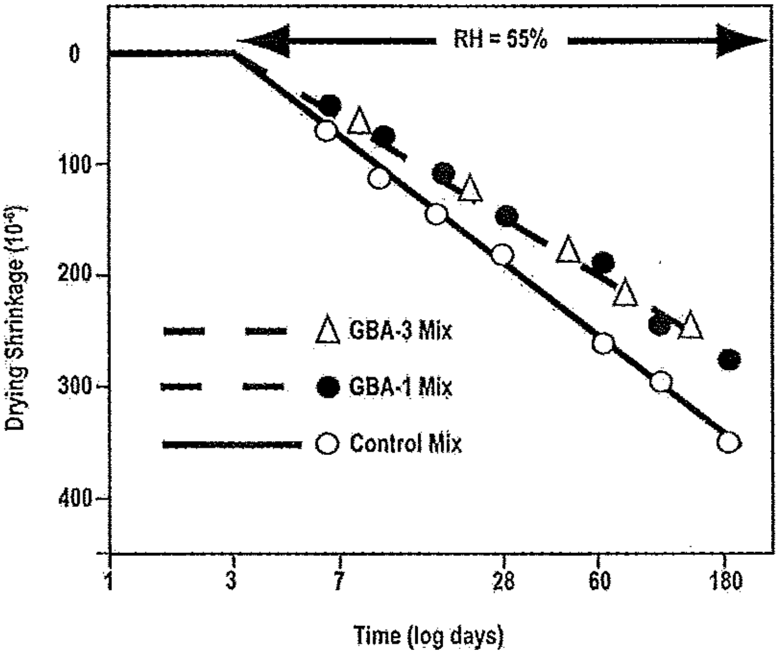

Fig. 6 – Influence of GBA (GBA-1 Mix) or GBA+PVA fibers (GBA-3 Mix) on the concrete drying shrinkage

Chloride diffusion

Table 4 shows the diffusion of Cl⁻ ions through the concrete specimens. The results indicate that the chloride diffusion depth in the *GBA-1 Mix* and *SF-1 Mix* is lower than in the *Control Mix* and in the *FA-1 Mix.*

CO_2 penetration

The results shown in Table 5 indicate that the *GBA-1 Mix* performs as well as the *SF-1 Mix* and both resist the CO_2 penetration better than the *Control mix* and the *FA-1 Mix.*

Drying shrinkage

Figures 6-8 show the influence of PVA macrofibres (4 kg/m^3 → 7 lb/yd^3) on the free drying shrinkage of concrete specimens (100x100x500 mm → 3.9x3.9x19.5 in) demolded at 3 days and exposed to a dry air with a RH of 55% for 3 months. In the presence of the mineral additions (*GBA-1 Mix, SF-1 Mix, FA-1 Mix*) the drying shrinkage is lower than that

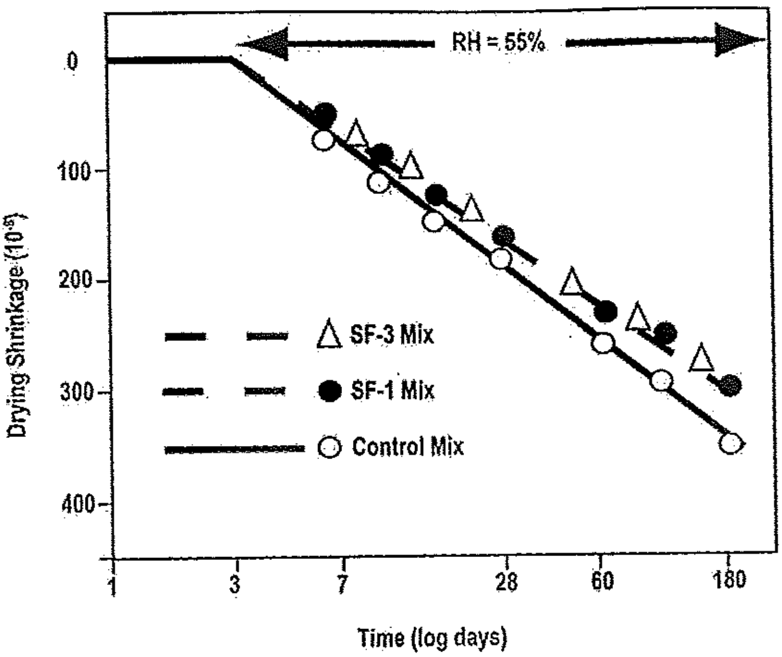

Fig. 7 – Influence of SF (SF-1 Mix) or SF+PVA fibers (SF-3 Mix) on the concrete drying shrinkage

of the *Control-Mix*, whereas the influence of the macrofibres in *GBA-3 Mix*, *SF-3 Mix* and *FA-3 Mix* on the drying shrinkage is negligible.

Restrained expansion

Restrained expansion was measured on concrete specimens reinforced with a 240-mm long steel bar of 6 mm in diameter (corresponding to 9.36-in and 0.23 in respectively) and two metallic plates at the ends to help the specimens to be demolded immediately after the setting time at 4-8 hours. On the demolded concrete specimens the initial length of the steel bar was measured and then the specimens were immediately wrapped by an impermeable plastic sheet to avoid water loss as in a concrete structure in a formwork. The subsequent length change of the steel bar was measured in the wrapped specimens up to 1 day and then the drying shrinkage occurred due to the exposure to dry air with a RH of 50%.

Figure 9 shows the length change of the steel bar of the three SCCs with the lime-based expansive agent: *GB-2 Mix*, *SF-2 Mix* and *FA-2 Mix*. The expansion during the initial 2-3 days of the SCCs in the presence of SF or GBA is much higher than that of the corresponding concrete with FA. This is due to the fact that the early expansion of the steel bar is related to the steel-concrete bond which in its turn depends on the early compressive strength of the concrete (Fig.4): therefore, the higher the compressive strength of the concrete, the higher is the restrained expansion of the reinforced specimen.

Field tests on restrained slab concretes

Field tests were carried out to check the appearance of cracks in restrained concrete slabs -8 m (8.8 yd) long, 400 mm (15.6 in) wide and 60 mm (2.3 in) thick- kept in the open air in the same exposure conditions of temperature, relative humidity and wind speed.

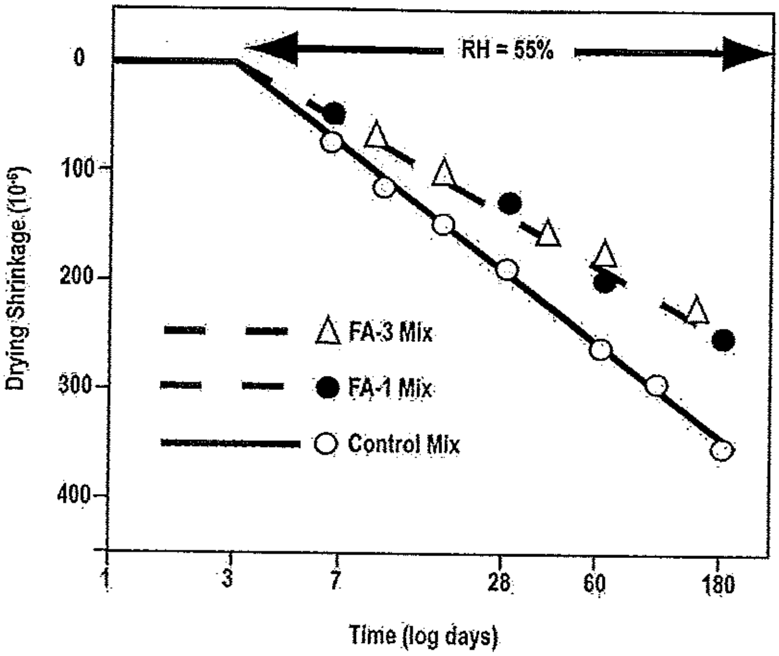

Fig. 8 – Influence of FA (FA-1 Mix) or FA+PVA fibers (FA-3 Mix) on the concrete drying shrinkage

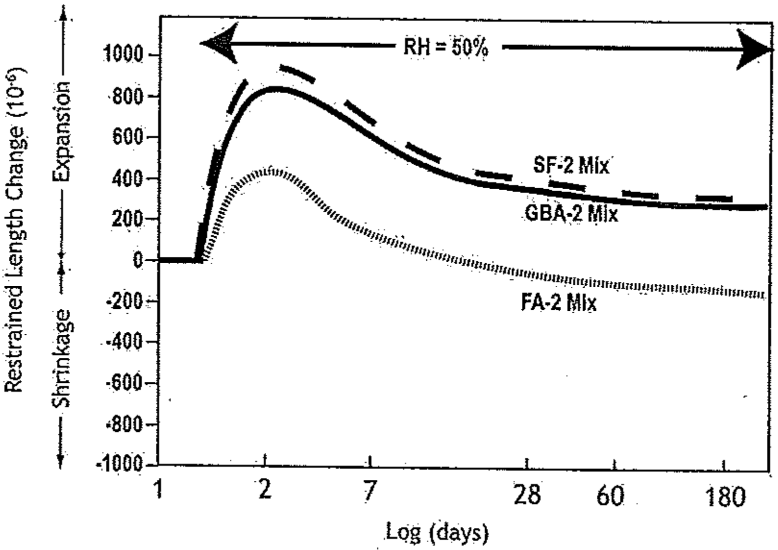

Fig. 9 – Restrained length change of SCCs in the presence of lime-based expansive agent and GBA, or SF or FA

The slabs were fixed on the foundation at the two ends (Figure 10), so that the restrained drying shrinkage occurring in the open air would produce cracks, if any, on the surface of the concrete. The number and the maximum width of the cracks measured after 14 days of exposure to air by a hand-held equipment with magnifying lens were recorded to assess the behavior of the SCCs.

Table 6 shows the results of the field tests and indicate that:

Table 6– Crack distribution in the restrained concrete slabs shown in Figure 10

Type of mix	Number of cracks	Maximum crack width
Control Mix	3	1.5 mm (0.059 in)
GBA-1 Mix	2	1.2 mm (0.047 in)
SF-1 Mix	2	1.3 mm (0.051 in)
FA-1 Mix	1	1.0 mm (0.039 in)
GBA-2 Mix	—	—
SF-2 Mix	—	—
FA-2 Mix	—	—
GBA-3 Mix	—	—
SF-3 Mix	—	—
FA-3 Mix	—	—

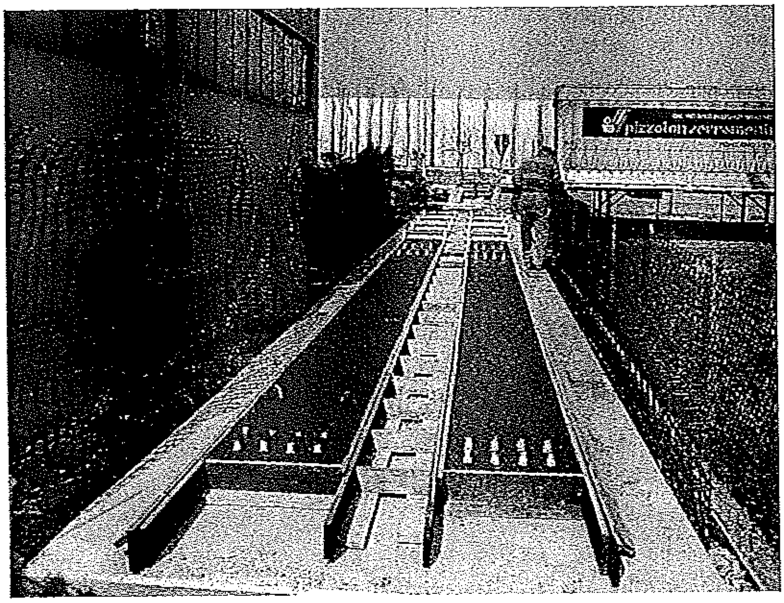

Fig. 10 – Restrained concrete slabs -8 m (8.8 yd) long, 400 mm (15.6 in) wide and 60 mm (2.3 in) thick- fixed on the foundation at the two ends.

- In the presence of GBA, SF or FA the number and the width of the cracks were lower than in the *Control Mix*, particularly when FA was used;
- In the presence of the expansive agent all the SCCs were crack-free due to the restrained expansion which counteracted the drying shrinkage;
- In the presence of the PVA macrofibers no crack was observed although no change in the drying shrinkage was recorded (Fig. 6-8) and this behavior could be ascribed to the increase in the toughness of the fiber-reinforced SCCs.

CONCLUSIONS

Bottom ash from Municipal Solid Wastes Incinerators (MSWI) was wet ground under water and an aqueous slurry (about 40% of solid material) with a maximum size of 1.7 μm was used to replace about 12.5% of portland cement in self-compacting concretes (SCC).

Mixtures with shrinkage-reducing admixture (SRA) and a CaO-based expansive agent were also manufactured to reduce the drying shrinkage and the related cracks.

Moreover, an alternative way to reduce both number and length of cracks was adopted by using SRA combined with polyvinyl alcohol (PVA) macrosynthetic fibres.

Corresponding mixtures with silica fume or coal fly ash were also manufactured. Measurements of compressive strength and durability in terms of water permeability, chloride diffusion and CO_2 penetration were carried out. Ground bottom ash from MSWI performed as well as silica fume in terms of mechanical properties, durability and crack behavior, and much better than fly ash.

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