High Performance Shotcretes

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Synopsis: A combination of chemical and mineral admixtures was studied to manufacture new High Performance Shotcretes (*HPS*) by wet-mix process. Superplasticized low-slump-loss concretes (slump of 210 – 220 mm) with water-cement ratios in the range of 0.42 – 0.44 were treated by wet-mix guns. Silica fume (20 Kg/m^3) was used to reduce the rebound of aggregates and improve the bond to the substrate.
Pozzolanic or slag cements (450 Kg/m^3) were used to manufacture durable concretes, although these cements do not perform as well as portland cements in attaining high early strength.
Traditional accelerators based on sodium silicate and new alkali-free chemical admixtures were added at the nozzle and assessed through field tests for shotcrete applications in a tunnel.
Alkali silicate-based accelerators (12% by cement mass) performed slightly better than alkali-free chemical admixtures (7%) in terms of very early strength at 20-60 min. However, at 4 hours and later ages compressive strength of shotcretes with the alkali-free accelerator increased much more than in the corresponding mixtures with sodium silicate.
Compressive strength of cored cylinder specimens were 2-6 MPa at 4 hr, 12-15 MPa at 12 hr, 20-25 MPa at 1 day, 45-50 MPa at 7 days and 50-60 MPa at 28 days when the alkali-free accelerator was used. The compressive strength values of these *HPS* at 1-28 days were 5-10% less than the corresponding control concrete specimens, without accelerators, cast in forms. On the other hand, the 28-day compressive strength values of cored specimens for shotcretes treated with sodium silicate were, as usually, 50-60% less than the corresponding control concretes.

Keywords: Accelerating Admixture, Alkali-Free Accelerator, Shotcrete, Silica Fume, Superplasticizer.

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INTRODUCTION

According to the definition of American Concrete Institute (1) shotcrete is "mortar or concrete pneumatically projected at high velocity onto a surface". These are two different types of shotcrete: dry-mix and wet-mix. In the dry-mix procedure all ingredients except the water are mixed, and then the dry mixture is blown through the delivery hose in a stream of compressed air to the nozzle, where the water is added. In the wet-mix procedure, all ingredients including the water are combined in the mixer, and the resulting wet mixture is propelled to the nozzle where a blast of compressed air impels it on to the receiving surface (2).

Due to the difference in the water requirements between these two processes, the water-cement ratio (*w/c*) of the wet-mix shotcrete is in general higher than that of its corresponding dry-mix composition. This results in greater porosity, permeability, drying-shrinkage, lower strength, and durability of the wet-mix shotcrete with respect to that of properly applied dry-mix composition (2).

More recently, due to the combined use of superplasticizer and silica fume, wet-mix shotcretes have been developed with superior adhesive quality which makes them well suited for repair and rehabilitation of concrete structures by the wet-mix shotcreting process (3). Morgan (4) has reviewed new developments in shotcreting with several examples of shotcrete repair of infrastructures in North America. However, when for some reasons accelerating admixtures are used, the performance in service in terms of compressive strength is significantly reduced (by 50-60%) with respect to the control mixture without accelerator. Moreover, the traditional accelerators based on sodium silicate, aluminate and carbonate increase the causticity risk for the workers during the application of the shotcrete.

The purpose of the present work was to study the combined action of superplasticizer, silica fume, accelerator, and blended pozzolanic or slag-portland cement to produce high-performance shotcrete (*HPS*) by wet-mix process in terms of the following characteristics:

- low causticity risk during application
- high workability and low slump-loss
- low rebound
- high early and later strength
- high durability

MATERIALS

Cements: High-strength portland cements are in general preferred rather than blended cements for shotcrete process due to the faster cement hydration rate. Blended cements in form of pozzolanic or granulated blast furnace slag (*GBFS*) cements were used in the present work for their better performance in service in terms of higher durability, lower heat of hydration, and lower vulnerability to cracking from thermal, autogeneous, and drying shrinkage stresses (3). Pozzolanic cement (CEM IV/A 42,5 R according to the European Norm EN 197/1) with 35% of fly ash replacing portland cement was used. Granulated blast furnace slag cement (CEM III/A 42.5 according to the European EN 197/1) with 50% slag replacing portland cement was also used.

Silica fume: Densified silica fume was used to improve the bond to the substrate and reduce the rebound of aggregates. Table 1 shows the chemical composition of silica fume.

Superplasticizer: A commercial 30% aqueous solution of carboxylic acrylic ester (CAE) was used as superplasticizer to manufacture fluid concretes with a slump of 210-220 mm and a water-cement ratio (*w/c*) as low as 0.42-0.44. More details on the chemical composition of this superplasticizer were published in previous works (5, 6).

Accelerators: Two different types of commercial accelerating admixtures were used. A traditional shotcrete accelerator based on sodium silicate aqueous solution (36%) and a new alkali-free shotcrete accelerator based on a water emulsion of aluminium sulfate (60%) were used. Due to the absence of alkali there is a lower risk of causticity during application when the latter is used.

Aggregates: Three natural limestone in form of fine sand (0-4 mm), coarse sand (4-6 mm) and gravel (6-8 mm) were used by adopting the following percentages: 65, 30, and 5% respectively.

Concrete mixtures: Two basic control mixtures were manufactured, both without accelerators, the main difference being the cement type (pozzolanic cement CEM IV/A 42.5 and slag cement CEM III/A 42.5).

Table 1 shows the composition and the slump of the two fluid control mixtures before the addition of the accelerators.

For each basic concrete after 30 min of mixing, one or two different types of accelerator were added at the nozzle: sodium silicate admixture or alkali-free accelerator at a dosage of 8-12% or 6-7% by cement mass respectively.

METHODS

The following measurements were carried out:

- **Slump** at 5 and 30 minutes to assess the slump-loss bevahior before the addition of the accelerators.
- **Rebound** was determined, after tunnel lining operations in the absence of reinforcing, by measuring the percentage of shotcrete which ricochets off the receiving surface and falls to the ground with respect to the total amount of projected concrete.
- **Specific gravity** (g_o) of control concrete specimens (without accelerators) placed into forms and fully compacted, and specific gravity (g) of cored specimens from shotcretes with accelerating admixtures: g/g_o indicates the compaction degree of the shotcrete with respect to the corresponding concrete without accelerator, fully compacted according to the traditional methods.
- **Proctor penetrometer test** (needle of 9 mm in diameter) on placed shotcretes (5 min-60 min) and determination of the very early compressive strength (1.2 MPa) through calibration curves.
- **Piston tool Hilti method** developed by Kusterle (7) to determine the early compressive strength (2-15 MPa) of placed shotcretes (4-12 hr);
- **Compressive strength** at 1-28 days of cored shotcretes (100 mm high, 50 mm in diameter) with accelerators added at the nozzle (1-28 days)

- **Compressive strength** at 1-28 days of cored control concretes (100 mm high, 50 mm in diameter), without accelerators, placed and fully compacted into prismatic forms.

RESULTS

Due to the use of the CAE type superplasticizer (5, 6) the slump loss within 30 min is negligible before the addition of the accelerators at the nozzle (Table 1).This means that the productivity of the shotcrete can be as high as 20 m^3/hr due the workability of the pumped concrete feeding the spraying equipment in a reliable manner for the negligible slump-loss.

At a given superplasticizer dosage (1.2%), the *w/c* is a little lower (0.42 vs. 0.44) for the concrete with slag-cement than for that with pozzolanic cement, although the initial slump was slightly higher (220 vs. 210 mm) for the former.

In tunnel lining operations with no reinforcing the rebound of all shotcretes studied was as little as 2-3% due to the high cohesiveness of the mixture for the combined presence of superplasticizer, silica fume, and accelerators.

Figure 1 shows in a double-logaritmic scale the concrete compressive strength, measured at 5 min to 28 days after shotcreting, on the slag-cement concrete (Table 1) manufactured without accelerator, with sodium silicate (8 and 12%), and with alkali-free accelerator 6%. The sodium silicate accelerator is a little better than the alkali-free admixture in terms of very early compressive strength: for instance at 1 hr the compressive strength is 0.5 MPa with the silicate admixture and 0.2 MPa with the alkali-free accelerator. However, at 4 hr the two accelerators perform the same, and at 23 hr and later ages the alkali-free accelerator perform much better than the silicate admixture. For instance, the 28 day compressive strength of the shotcrete with the alkali-free accelerator is as high as 60 MPa (only 10% less than the control mixture), whereas the corresponding strength loss of the shotcrete with silicate is 60% less than that of the control concrete.

The excellent results of the alkali-free accelerators in terms of the strength at later ages were confirmed by using a little higher dosage of the admixture (7%) both in the slag-cement concrete (Fig. 2) and in pozzolanic-cement mixture (Fig. 3). Again, the strength loss at later ages is negligible (only 10%) with respect to the usual strength reduction caused by the traditional accelerators based on sodium siliconate, aluminate or carbonate (8).

In order to explain the different role played by sodium silicate accelerators and alkali-free admixtures, the strength loss at 28 days with respect to the control mixtures were compared with the corresponding expected values on the basis of the lower compaction degree determined by the specific gravity ratio g/g_o. It is known (9) that for each 1% of lower specific gravity there is a compressive strength reduction of about 5-6% for the voids caused by the lower compaction. Therefore a compaction degree of 0.94 in terms of g/g_o in the 12% silicate shotcrete (Table 2) should correspond to an expected strength loss of 30-36%. This is much lower than that (55%) measured at 28 days on the silicate shotcrete in service with respect to the control concrete without admixture placed in forms and completely compacted. This means that, in addition to an uncomplete compaction, something else must be taken into account to explain the measured strength loss. This could be related to the lower degree of hydration caused by the sodium silicate admixture on the C_3S and C_2S hydration of the clinker phase (10).

On the other hand, in the presence of the alkali-free accelerator the degree of compaction (0.97-0.98) is higher for the better workability at the time of spraying. Moreover, the measured strength loss at 28 days is equal or a little lower with respect to the expected value (10-18%) on the basis of the lower degree of compaction. This means that alkali-free accelerators do not produce any reduction in the degree of hydration at later ages. On the contrary, the lower strength loss at 28 days with respect to the expected value based on the reduction of the compaction degree (Table 2) would indicate that this effect is partly compensated by a higher degree of hydration.

CONCLUSIONS

The combined use of an acrylic superplasticizer, silica fume and an alkali-free accelerator allows to manufacture high performance shotcretes (*HPS*) in terms of high slump level, high compressive strength, good compaction, and excellent durability for the low *w/c* and the use of pozzolanic or slag cements with 30 or 50% replacement of portland cement respectively.

Low slump-loss, low rebound, and low causticity risk during application are other important properties of this *HPS*.

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Table 1 - Composition and slump of the control mixtures before the addition of the accelerators at the nozzle.

Ingredient	Concrete P with pozzolanic cement (IV/A 42.5)	Concrete S with GBFS cement (III/A 42.5)
Cement	**450 Kg/m^3**	**450 Kg/m^3**
Fine sand (0-4 mm)	**1075**	**1075**
Coarse sand (4-6 mm)	**495**	**495**
Gravel (6-8 mm)	**82**	**82**
Silica fume	**20**	**20**
Water	**198**	**190**
Superplasticizer (1-2% by cem.)	**5.4**	**5.4**
w/c	**0.44**	**0.42**
Slump at		
5 min	**210**	**220**
30 min	**200**	**215**

Table 2 - Influence of the sodium silicate (NS) or alkali-free (AF) accelerator on the specific gravity of the shotcrete (*g*) with respect to that (g_o) of the control concrete without admixture fully compacted.

Cement type	Accelerator (%-type)	Specific gravity, g (Kg/m^3)	Specific gravity, g_o (Kg/m^3)	g/g_o	Strength loss (%) Expect.	Measur.
III	**12 NS**	**2239**	**2384**	**0.94**	**30-36**	**55**
III	**8-NS**	**2247**	**2359**	**0.95**	**25-30**	**54**
III	**7-AF**	**2300**	**2359**	**0.97**	**15-18**	**10**
IV	**7-AF**	**2296**	**2336**	**0.98**	**10-12**	**8**

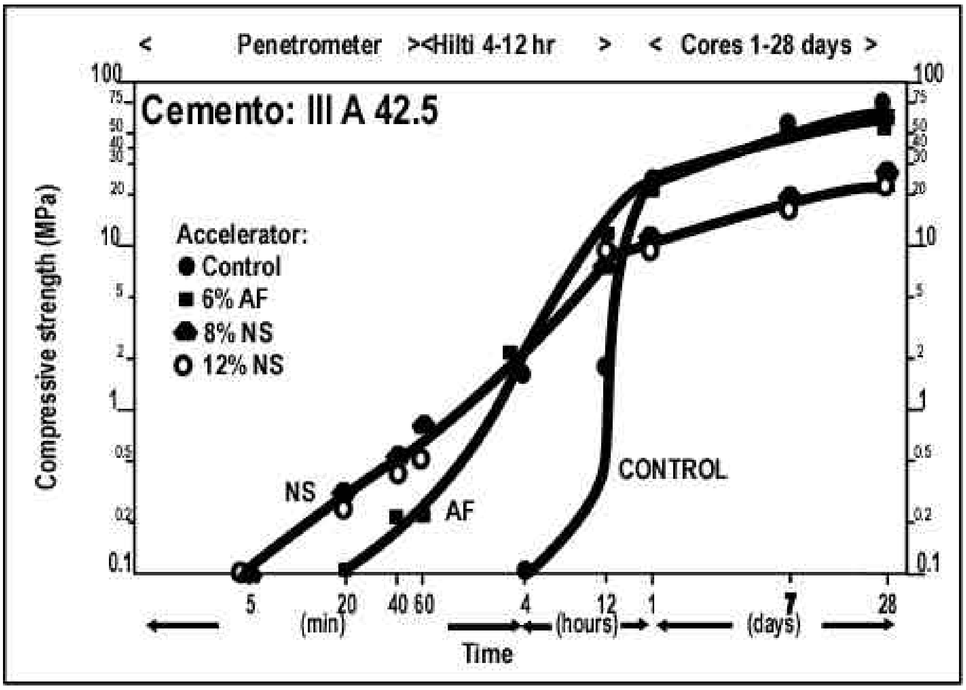

Fig. 1 - Influence of accelerators – sodium silicate (NS) or alkali-free (AF) – on the compressive strength of the shotcrete with slag cement III/A 42.5

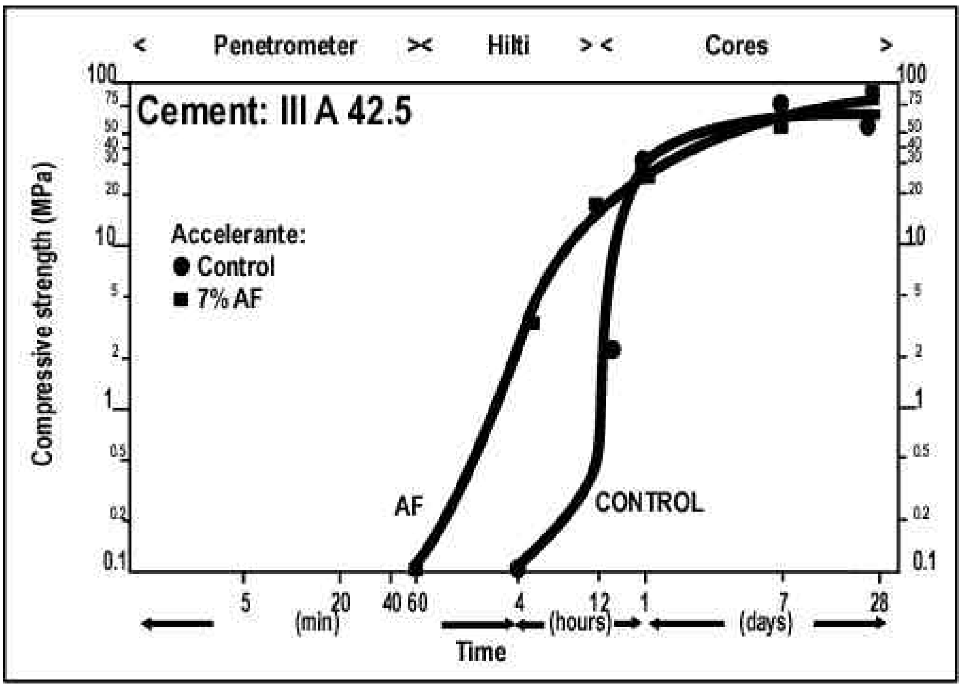

Fig. 2 - Influence of the alkali-free (AF) accelerator on the compressive strength of the shotcrete with slag cement III/A 42.5.

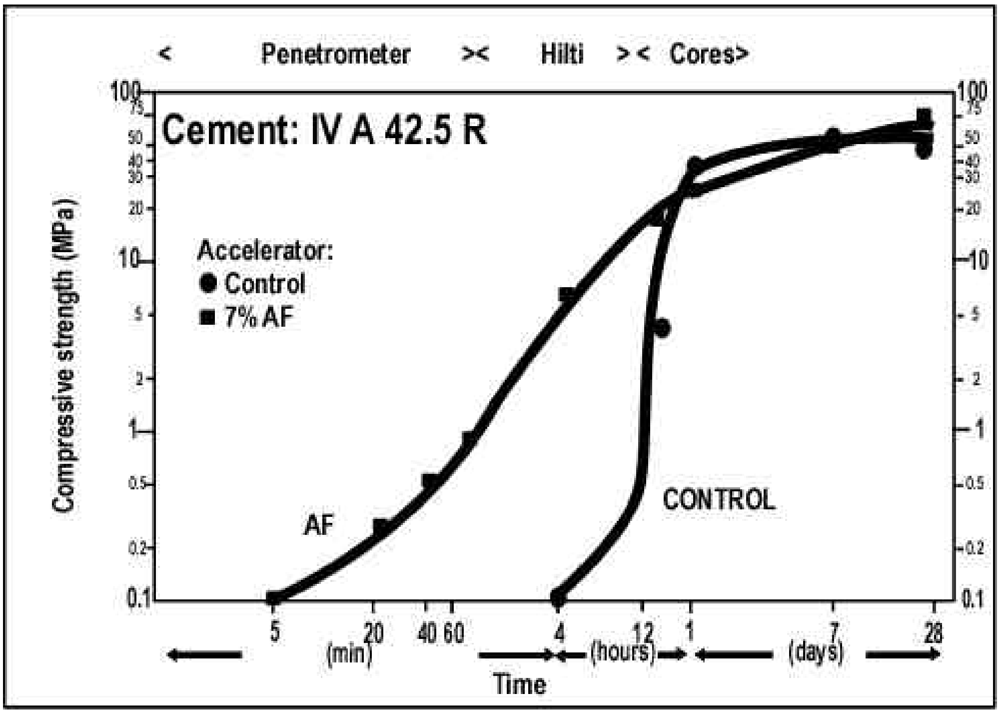

Fig. 3 - Influence of the alkali-free (AF) accelerator on the compressive strength of the shotcrete with pozzolanic cement IV/A 42.5 R.