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 *w/cm* 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 tunnel applications.

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 sodium silicate mixtures.

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 to 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 American Concrete Institute definition, shotcrete is "mortar or concrete pneumatically projected at high velocity onto a surface" (1). 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 *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 shotcreting developments, with several examples of shotcrete infrastructures, repair in infrastructures in North America. However, for some reasons when accelerating admixtures are used, the service performance, 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: Portland cements are in general preferred rather than blended cements for shotcrete process due to the faster cement hydration rate and corresponding righer-early compressive strengths. 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 shotcrete rebound.

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 *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 limestones in form of fine sand (0-4 mm), coarse sand (4-6 mm) and gravel (6-8 mm) were used, with 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 used, (pozzolanic cement CEM IV/A 42.5 and slag cement CEM III/A 42.5).

Table 1 shows the mixture compositions 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 dosages 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 behavior 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 rebounds off the receiving surface and falls to the ground, with respect to the total amount of used shotcrete.
- **Bulk density** (g_o) of control concrete specimens (without accelerators) placed into forms and fully compacted, and bulk loose density (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 to 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 to 28 days of cored shotcretes (100 mm high, 50 mm in diameter) with accelerators added at the nozzle (1 to 28 days)

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

RESULTS

Because CAE type superplasticizer (5, 6) is used, the slump loss (within 30 min) is negligible, before the addition of the accelerators at the nozzle (Table 1).This means that the shotcrete production rate can be as high as 20 m^3/hr due to the increased workability of the pumped concrete, feeding the spraying equipment.

At a given superplasticizer dosage (1.2%), the *w/cm* 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 mixture cohesiveness related to the superplasticizer, silica fume, and accelerator combinations.

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 in terms of very early compressive strength, than the alkali-free accelerator. For example at 1 hour the compressive strength is 0.5 MPa for the silicate accelerator and 0.2 MPa with the alkali-free accelerator. However, at 4 hours the two accelerators have approximately the same compressive strength, and at 24 hours and later ages the mixture with alkali-free accelerator has higher strength than the accelerator 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 compressive strength results of the alkali-free accelerators at later ages were confirmed by using a little higher dosage of the accelerator (7%) in both the slag-cement concrete (Fig. 2) and in pozzolanic-cement mixture (Fig. 3). Again, the compressive 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 compressive strength loss at 28 days, with respect to the concrete control mixtures, were compared with their corresponding expected values. The comparison basis of the lower compaction degree was determined by the specific gravity ratio g/g_o. It is known (9) that, as a rule of thumb, for each 1% of lower bulk density 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 to 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 accelerator) 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, giving 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 gives high performance shotcretes (*HPS*) in terms of higher slump level, higher compressive strength, and better compaction. In addition, the *HPS* gives excellent durability, because of low *w/cm* and the use of pozzolanic or slag cements (30 and 50% respectively replacement of portland cement).

Low slump-loss, low rebound, and low causticity risk during shotcrete application are other important properties of this high performance shotcrete.

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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 Kg/m^3**	**1075 Kg/m^3**
Coarse sand (4-6 mm)	**495 Kg/m^3**	**495 Kg/m^3**
Gravel (6-8 mm)	**82 Kg/m^3**	**82 Kg/m^3**
Silica fume	**20 Kg/m^3**	**20 Kg/m^3**
Water	**198 Kg/m^3**	**190 Kg/m^3**
Superplasticizer (1-2% by cem.)	**5.4 Kg/m^3**	**5.4 Kg/m^3**
w/cm	**0.44**	**0.42**
Slump at		
5 min	**210 mm**	**220 mm**
30 min	**200 mm**	**215 mm**

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)	Bulk loose density, g (Kg/m^3)	Bulk density, 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

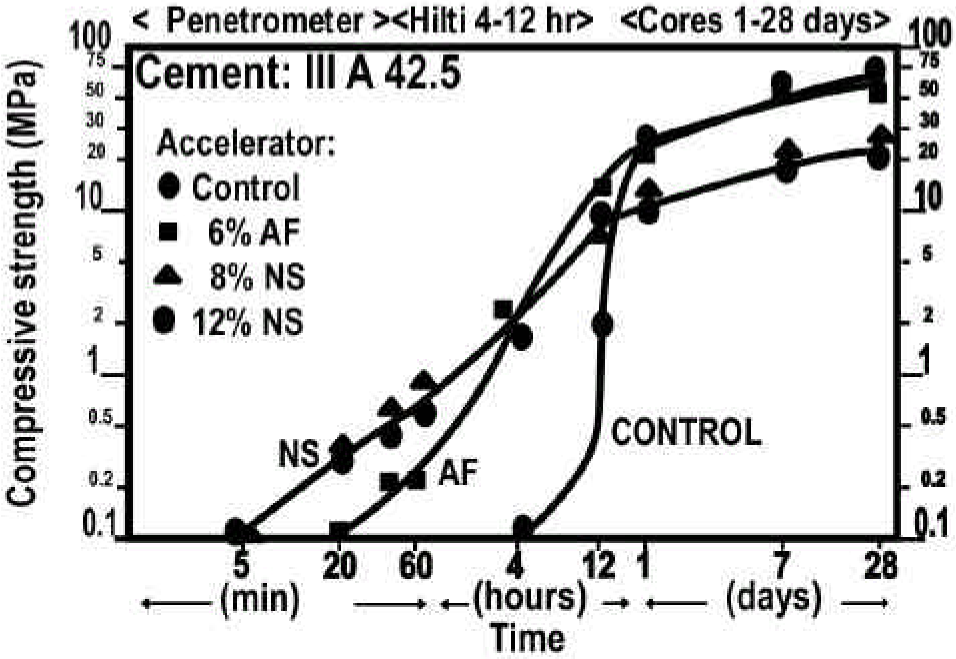

Fig. 1 - Influence of accelerators – sodium silicate (NS) or alkali-free (AF) – on the compressive strength of the shotcrete with slag cement III/A 42.5

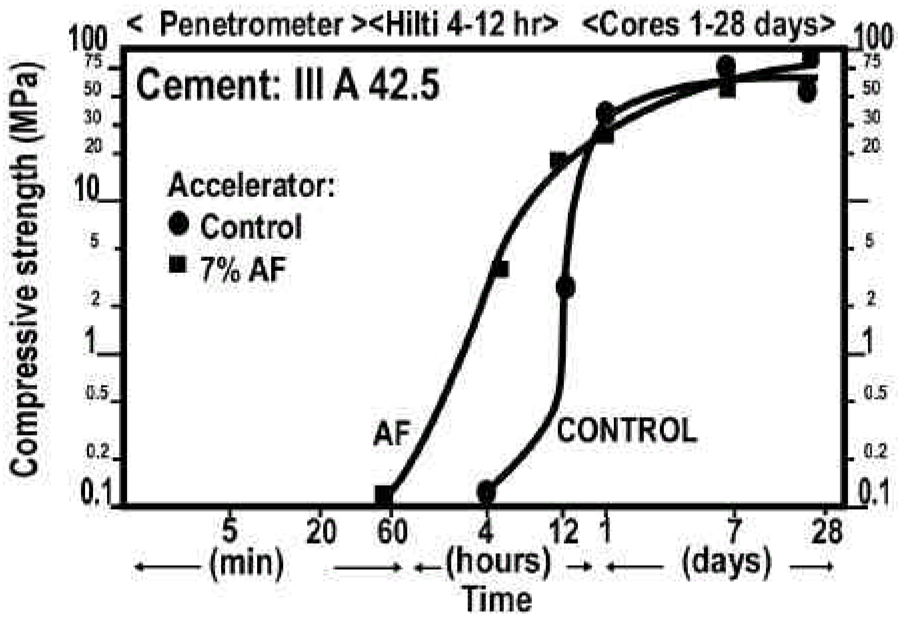

Fig. 2 - Influence of the alkali-free (AF) accelerator on the compressive strength of the shotcrete with slag cement III/A 42.5.

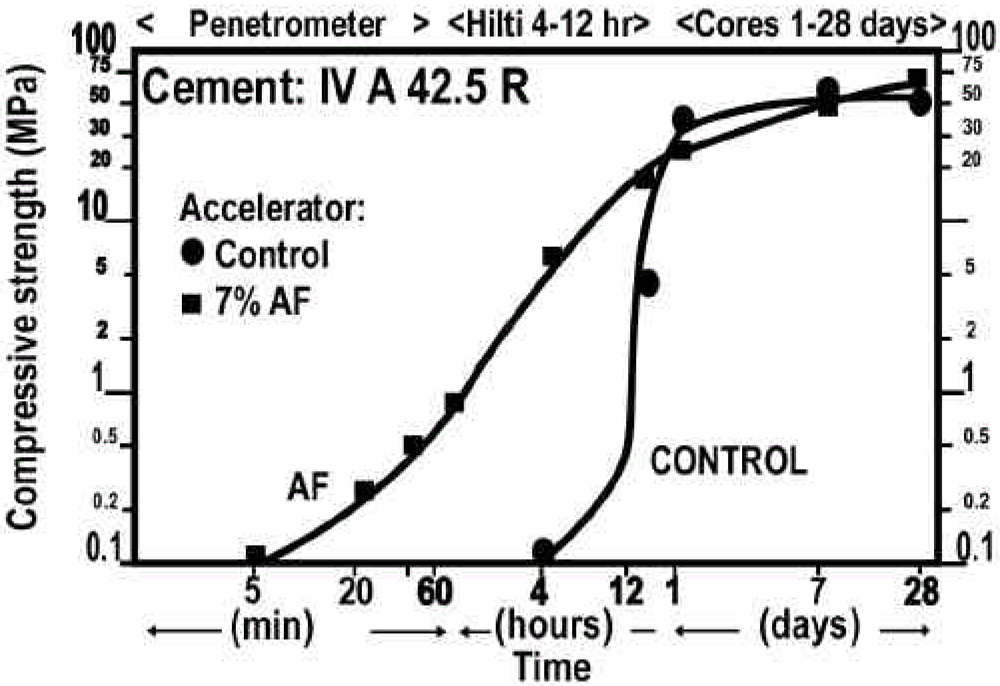

Fig. 3 - Influence of the alkali-free (AF) accelerator on the compressive strength of the shotcrete with pozzolanic cement IV/A 42.5 R.