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The Effect of Sodium Silicate on the Behaviour of Shotcretes for Tunnel Lining

Luigi Coppola[1], Alessandra Buoso[1], Denny Coffetti[1], Patricia Kara[2*], Sergio Lorenzi[1] and Franco D'Alessandro[3]

[1]DISA, University of Bergamo, Dalmine (BG), Italy.
[2]EMIB, Faculty of Applied Engineering, University of Antwerp, Belgium.
[3]BASF C.C. Underground Construction, Treviso (TV), Italy.

Authors' contributions

This work was carried out in collaboration between all authors. Author LC designed the study. Authors AB, DC and FDA performed the statistical analysis and wrote the protocol. Authors PK and SL managed the analyses of the study, the literature searches, wrote the first draft of the manuscript. All authors read and approved the final manuscript.

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Case Study

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ABSTRACT

Present case study investigates the rheological, mechanical and in-placing performances of fiber-reinforced shotcrete manufactured with different fibers (steel, glass and polypropylene) and with sodium silicate based set-accelerating admixture for tunnel linings. The study compares the performances of concretes manufactured and fully compacted with those shotcretes which are manufactured directly on the job-site. The influence of sodium silicate accelerator on mechanical and rheological properties of fiber-reinforced shotcretes with respect to reference concrete were evaluated. It was observed that: The addition of fibers does not influence slump and workability retention with respect to reference concrete, independent of type and dosage of fibers; Spraying and set accelerator dosage determined a decrease about of 10-30% in compressive strength compared to that of concrete placed and vibrated without sodium silicate accelerator; The set-accelerating admixture has negative effect on compressive strength of fiber-reinforced shotcrete (15%).

**Corresponding author: E-mail: patricija.kara@uantwerpen.be;*

Keywords: Sodium silicate based set-accelerating admixture; mechanical and rheological properties.

1. INTRODUCTION

Sprayed concrete, or shotcrete, is used world-wide to construct tunnels or underground structures. The poured mix must set quickly in order to stabilize the structure [1-2]. The important basic requirements of shotcrete are good adhesiveness, a low amount of rebounding, good shooting, and the quick formation of initial strength [3-4]. To meet these requirements, accelerators have become a fundamental additive in shotcrete to achieve appropriate initial strength, reduce rebound, and suppress early ground relaxation. This affects not only the early strength of the shotcrete but also the development of long-term strength, durability and thickness. Traditionally, shotcrete's quick-setting properties have been achieved by the injection of high-alkaline additives at the spraying nozzle. Accelerating admixtures are composed of chemicals that influence the rate of cement hydration, thereby shortening the setting time and, in some cases, increasing the rate of early strength development [3]. Set accelerators affect both the C_3A hydration (by interfering with the C_3A – gypsum reaction) and the C_3S hydration (aiding the dissolution of lime) [5-6]. However, this method resulted in concrete with high porosity and density, low strength and durability, and environmental concerns.

Nowadays, shotcrete accelerators are classified as silicate-, aluminate-, or alkali-free, cement-based minerals, depending on the main material that is present. The sodium silicate accelerator gives a rapid initial set and a slow final set, while the aluminate accelerator provides a slow initial set and a fast final set. Both types suffer the same deficiency of loss in strength and durability over the long term. Furthermore, their strong alkalinity may endanger workers and lead to environmental contamination. Increasing the accelerator amount adds to the cost and also increases the rebound ratio [1,7]. To mitigate these issues, alkali-free and cement-based mineral accelerators (CMs) that are environmentally friendly and provide good long-term strength are now frequently used in construction sites. Sodium silicate based admixtures are more effective – in terms of set acceleration - and cheaper than alkali-free products. For these reasons, sodium silicate accelerators are widely used in tunnel linings. However, a very fast increase of early strength development in sodium-accelerated shotcretes is followed by a sharp reduction of mechanical properties of concrete at later ages.

For many years, fibers of different nature have been used to reinforce shotcrete in tunneling applications. Several research investigations have ascertained the significant effect of fiber addition on ductility and punching resistance of tunnel segments and shotcrete panels [8]. Currently, concrete is reinforced by using steel, glass, polypropylene or acryl-nitrile fibers and carbon nanotubes in order to assess the stress level in reinforced concrete elements [9-13]. To improve durability in severe conditions and to favor replacement of temporary solutions requiring subsequent cuttings glass fibers and glass fabric solutions are used [8,14-16]. To increase fire resistance and prevent explosive spalling of concrete cover polypropylene fibers are used [17]. Compared with traditional steel mesh, fibers arrange themselves in three-dimensional directions inside the cement matrix and they are able to absorb the tensile stress induced by shrinkage and thermal gradients. Therefore, fibers could limit crack width and increase the energy absorption capacity (toughness) of the material [18]. In particular, fibers determine a considerable improvement in the post-cracking behavior of concrete [19]. Reference concrete fails suddenly once the deflection corresponding to the ultimate flexural strength is exceeded; On the other hand, fiber-reinforced concrete continues to sustain considerable loads even at deflections considerably in excess of that of the reference concrete. So, compared to reference concrete, fiber-reinforced concrete is tougher and more resistant to impact [18], permitting control of the local detachment of tunnel linings [7,20-21].

The paper presents research results on rheological and mechanical properties of reference and fiber - reinforced shotcretes manufactured with sodium silicate accelerator and glass, steel and polypropylene fibers.

2. EXPERIMENTAL INVESTIGATION

2.1 Materials

Limestone Portland cement (CEM II/A-LL 42.5R) according to EN 197-1 was used. The chemical composition of cement is shown in Table 1. Coarse-grained sand (40% of the total mass of the aggregates) and crushed sand (25%) were used as fine aggregates. In addition, crushed stone (max size 8 mm) was used as coarse aggregate (35%). A sieve analysis of fine and coarse aggregates is shown in Table 2.

Table 1. Chemical composition (% by mass) of the cement (CEM II/A-LL 42.5R)

	CEM II/A-LL 42.5R
Loss of ignition, %	0.88
SiO_2, %	19.31
Al_2O_3, %	4.31
CaO, %	61.08
MgO, %	2.38
SO_3, %	2.96
Na_2O, %	0.29
K_2O, %	0.86
TiO_2, %	0.14
Fe_2O_3, %	2.28

Combined aggregate grading is presented in Fig. 1. A polycarboxylate-based superplasticizer with dosage 1.4% vs. cement mass was used [6,22]. Sodium silicate accelerator was used as a set-accelerating admixture. The dosage of sodium silicate accelerator was in the range of 13% - 17% vs. cement mass and it was added in the nozzle during spraying. The w/c was equal to 0.44. Workability of reference concrete was measured by slump test according to EN 12350-2 and the consistency class required for the mix was S5 (slump ≥ 220 mm). The composition of reference concrete without fibers and set-accelerating admixture is shown in Table 3.

In order to compare the influence of different types and dosages of fiber reinforcement on rheological and mechanical properties of shotcrete with respect to reference concrete (without fibers: PL), steel fibers (SF), glass fibers (GF) and polypropylene fibers (PF) were added to the mix. The main properties of fibers are listed in Table 4. The amount of fibers added to the concrete mixes is shown in Table 5. The dosage by volume of steel and glass fibers is very similar; Consequently, rheological and mechanical properties are directly comparable establishing the efficiency of the two types of fibers. The dosage of polypropylene fibers is lower than that used for the steel and glass fibers (about 37% and 39% lower, respectively). During casting (at 1/5 and 4/5 of the placing), before the addition of set-accelerating admixture, the workability and the density were evaluated in order to investigate the fiber influence on rheological properties of the concrete. The fiber content and the shotcrete rebound were measured according to EN 14488-7.

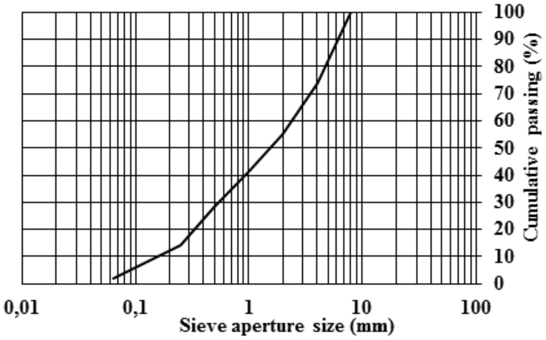


Fig. 1. Aggregates grading

2.2 SPECIMENS

Test panels with and without the addition of set-accelerating admixture were manufactured to evaluate hardened concrete properties according to EN 14488. The panels were manufactured by spraying the set-accelerated admixture in order

Table 2. Sieve analysis of aggregates in shotcrete

Square mesh - mm	Cumulative per cent passing [%]			
	Crushed sand (25%)	Coarse-grained sand (40%)	Crushed stone (35%)	Total (100%)
16.0	100.0	100.0	100.0	100.0
12.5	100.0	100.0	100.0	100.0
8.0	100.0	100.0	100.0	100.0
4.0	100.0	99.0	26.0	73.7
2.0	78.0	87.0	1.7	54.9
1.0	54.0	69.0	0.5	41.3
0.5	38.0	47.0	0.2	28.4
0.25	25.0	20.0	0.2	14.3
0.063	4.9	1.2	0.2	1.8

Table 3. Composition and principal characteristics of reference concrete

Cement CEM II/A-LL 42.5R	kg/m^3	450
Water	kg/m^3	200
Aggregates:		
Crushed sand	kg/m^3	410
Coarse-grained sand	kg/m^3	650
Crushed stone (max size 8mm)	kg/m^3	575
Superplasticizer	% vs c.m.	1.4
	l/m^3	6.3
Entrapped air	%	2.5
	l/m^3	25
Water/Cement		0.44
Specific mass	kg/m^3	2344

Table 4. Principal characteristics of fibers

Abbreviation	Material	Length – mm	Diameter – mm	l/d
SF	Steel	33	0.55	60
GF	Glass	40	1.6	25
PF	Polypropylene	40	0.9	44

Table 5. Type and dosage of fiber added to reference mix

Mix	Fiber type	Specific mass	Fiber dosage	
		kg/m^3	kg/m^3	l/m^3
PL	-	2341	-	-
SF	Steel	2394	38.2	4.4
GF	Glass	2342	11.2	4.7
PF	Polypropylene	2324	3.5	2.9

to evaluate the energy absorption capacity after 1, 7 and 28 days. For reference mix (without fibers), a steel mesh (diameter: 6 mm; Spacing: 150 mm) was used as reinforcement. In order to avoid water evaporation the panels were immediately wet cured after casting. Afterward, the specimens were cured on site conditions until they were cored according to EN 14488-1:2005. Three cylindrical specimens (d=100mm, h=100mm, h/d=1) for each panel were obtained. The density and compressive strength of the hardened concrete at 1, 7, 14 and 28 days were measured in accordance with EN 12390-2.

3. RESULTS AND DISCUSSION

Fig. 2 shows the average values of density of fresh concrete which were measured after 1/5 and 4/5 of the dumping, before the set-accelerating admixture was added.

The values are similar for all the mixes, independent of the type of fiber used. It can be noted that fibers do not determine any anomalous air entrapment. The target workability (S5 according to EN 206-1) was attained without any increase in water demand with respect to the reference concrete for all the fiber-reinforced mixes, independent of the type of fiber. Moreover, no slump loss was noticed at 1/5 of the dumping (see Fig. 3).

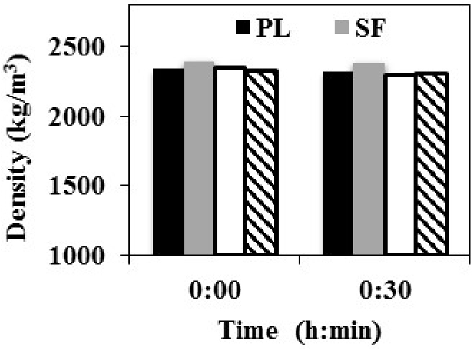


Fig. 2. Density of fresh concrete vs. time

Fig. 4 shows the shotcrete rebound index and the set-accelerating admixture dosage. The lower dosage of sodium silicate accelerator was used for the steel fiber-reinforced shotcrete and the higher one for glass fiber-reinforced shotcrete. The reference and the polypropylene fiber-reinforced shotcretes required a similar set-accelerating admixture dosage (about 15%). The shotcrete rebound varied between 18 and 35% for the mixes.

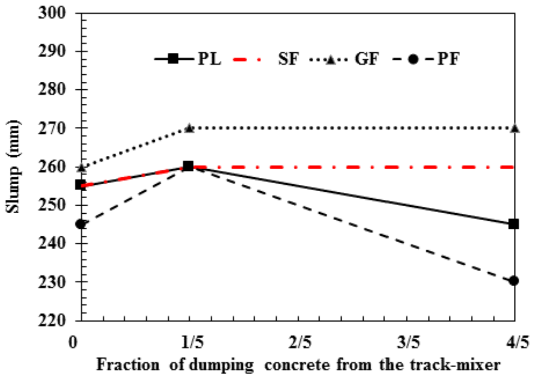


Fig. 3. Slump vs. time

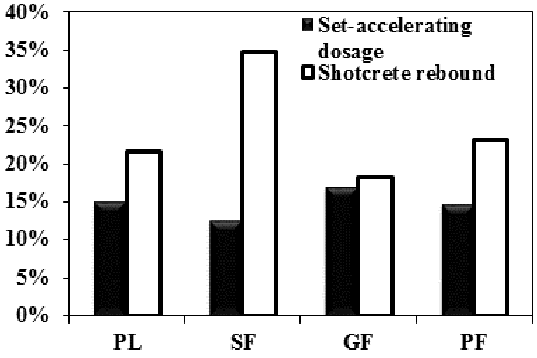


Fig. 4. Set-accelerating admixture dosage and shotcrete rebound

Set-accelerating admixture and the spraying operation determines a reduction of density in the range 2-6% with respect to the mixes without sodium silicate accelerator, which were poured and vibrated independent of curing time and type of fibers (see Fig. 5). It can be noticed that the density of hardened mix is substantially equal or higher than that of the reference shotcrete without fibers.

Fig. 6 summarizes the compressive strength values as a function of time for concretes (placed and vibrated) and shotcretes (sprayed) without and with the set-accelerating admixture, respectively. After 1 day, the compressive strength of shotcrete with the addition of set-accelerating admixture is higher (50 to 85%) than that of poured and vibrated concrete mixes without the sodium silicate accelerator, independent of the fiber reinforcement. The compressive strength at the age of 2 days is very similar for all the mixes.

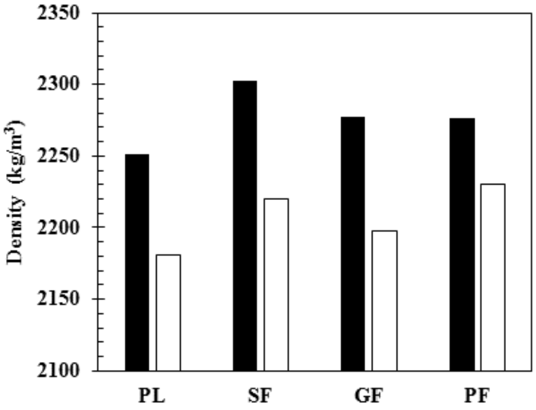
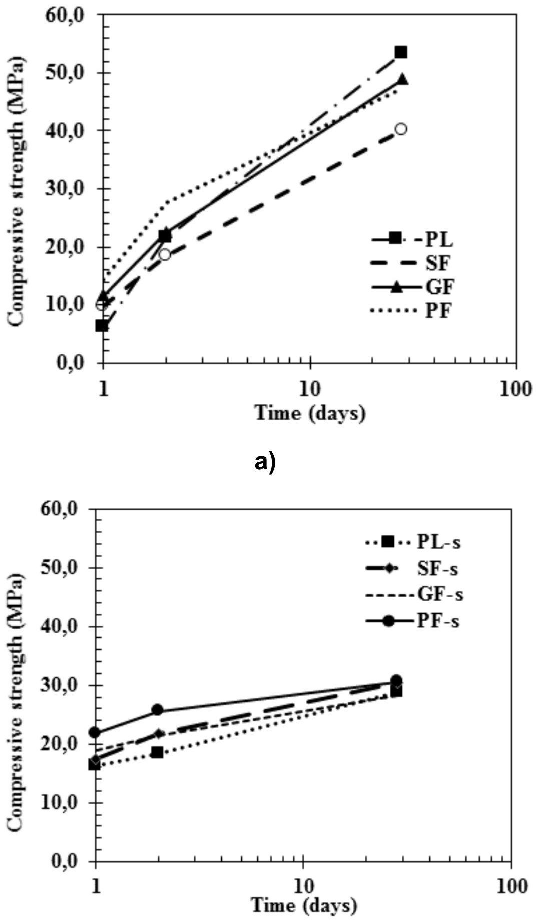


Fig. 5. Density of hardened concretes and shotcretes after 28 days

The positive effect of set-accelerating admixture is equal to the negative effect due to the increase in porosity as a consequence of spraying. After 28 days, shotcretes with sodium silicate accelerator show lower compressive strength, between 25 and 45% less than that of vibrated concrete without set-accelerating admixture. In particular, a minor decrease (about 25%) is observed for steel fiber shotcrete, manufactured using the lowest set-accelerating admixture dosage. The greatest gap in the compressive strength was detected for glass fiber shotcrete, containing the highest set-accelerating admixture dosage. It can be seen that the compressive strength values depend on set-accelerating admixture dosage rather than on type and dosage of fibers. However, widespread experience in the industry has shown that different fiber types display very different levels of rebound, commonly fibers are added to improve tensile/flexural strength and post-cracking behavior. Bond strength was not measured in this study. In general terms, considering that the reduction of compressive strength due to spraying is about 5% for each percent decrease in density and taking into account that the density reduction is about 2-6%, the reduction of compressive strength due to spraying should be about 10-30%. So, if the compressive strength decrease is between 25 and 45%, the set-accelerating admixture effect on reduction of mechanical properties is about 15%.



a)

b)

Fig. 6. Compressive strength vs. time for poured and vibrated specimens (a) and for set accelerated and sprayed (b)

The results of punching tests (see Fig. 7) are shown in terms of deformation energy of the panels manufactured: with set-accelerated admixture shotcretes containing fibers and with the set-accelerated admixture reference concrete reinforced by a steel wire mesh (diameter: 6 mm; spacing: 150 mm). Results indicate that fibers do not guarantee the same performance as steel mesh. In fact, after 1 day, the shotcrete reinforced by steel mesh exceeds the minimum value of 500 Joules required by the standard. By contrast, this value is attained using steel, glass and polypropylene fibers only at the age of 28 days. It is important to underline that the polypropylene fibers shotcrete mix was manufactured with a fiber dosage (2.9 l/m^3) lower than that used for steel fiber and glass fiber shotcretes (respectively 4.4 and 4.7 l/m^3). In conclusion, results pointed out that the better punching behavior is for steel reinforced shotcrete than for fiber-reinforced shotcrete. This could be explained by the fact that the shotcrete behavior in punching tests depends not only on the fiber type and dosage, but also on the matrix quality, a continuous steel mesh or short fibers. In this research, a hypothesis, that the addition of set-accelerating admixture has caused a worsening of matrix quality and consequently a reduction of the bonding between fibers and shotcrete, could be investigated in further research. The toughness behavior and the energy absorption of fiber-reinforced mixes have decreased. The difference between fiber-reinforced and steel mesh reinforced shotcretes increased.

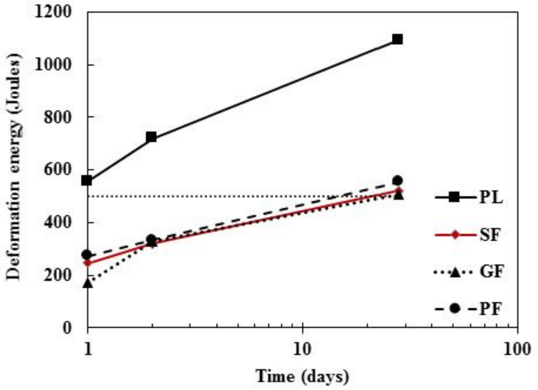


Fig. 7. Deformation energy vs. time

4. CONCLUSION

This paper presents research results regarding the use of different fibers (steel, glass and polypropylene) in reinforced shotcretes manufactured with a sodium silicate based set-accelerating admixture for tunnel linings. The influence of sodium silicate accelerator on mechanical and rheological properties of fiber-reinforced shotcretes with respect to reference concrete were evaluated. Based on the results of this experimental investigation, the conclusions are as follows:

1. The addition of fibers does not influence slump and workability retention with respect to reference concrete (PL), independent of type and dosage of fibers.
2. The density of hardened shotcrete and compressive strength at the age of 28 days decreases when adding set-accelerating admixture. After 28 days, shotcretes with sodium silicate accelerator show

compressive strength lower (in the range of 25-45%) compared to fully compacted concrete without set-accelerating admixture. In particular, compressive strength decreases by 10-30% as a consequence of spraying. The set-accelerating admixture has negative effect on compressive strength of fiber-reinforced shotcrete (decrease is about 15%).

3. The toughness behavior and the energy absorption of fiber-reinforced shotcrete are lower than that of steel reinforced mix. However, as the recommendation, it could be improved if the dosage rate of fibers and the depth of mesh in the shotcrete cross-section which strongly influences the apparent performance, would be considered in the further investigation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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