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Accelerating Admixtures for Shotcrete

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Abstract

A variety of additives and admixtures are added to shotcrete to improve strength, adhesiveness, cohesiveness, freezing/thawing and abrasion resistance characteristics, and reduce rebound. Accelerators are being used increasingly in both dry- and wet-process applications. Accelerators are common in the dry process to increase early strength and reduce dust and rebound and in the wet process are used to achieve rapid set and early strength. The choice of a particular accelerator and its dosage is largely governed by the setting time required for the shotcrete application. Various watersoluble salts of the alkali metals can be used to accelerate the setting of cement. Most of the set accelerators used today are based on alkali aluminates in combination with carbonates and hydroxides and produced in both liquid and powder form. The performance of these accelerators depends on the cement chemical composition and fineness, and the presence of mineral additions such as flyash, and blastfurnace slag. This performance is generally evaluated using setting tests on cement/accelerator pastes despite the belief of some researchers that this procedure can produce misleading results. This paper describes the main accelerators used in shotcrete and presents some results of field tests performed on shocrete panels evaluating the behavior of different accelerators. Particular attention is given to a new liquid alkali-free shotcrete accelerator that showed a very interesting behavior at very early ages and no strength loss at later ages. The early strengths were evaluated using non-destructive tests (Constant Depth Penetrometer and Constant Energy Penetrometer). © 1998 Elsevier Science Ltd. All rights reserved

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INTRODUCTION

The use of shotcrete in underground works requires compliance with some basic requirements such as high early age strength and the possibility of being applied in thick layers without the risk of displacement. Compliance with these requirements, for both dry and wet mix shotcrete, is normally achieved by the use of accelerating admixtures. At present, there are several different accelerators available in the market. These accelerators are formulated from different chemical bases and act differently on the concrete setting and initial strength.

Despite its large application, there is not yet consensus on how to evaluate the efficiency of such admixtures. Paste tests have been proposed (Gillmore needle test and modified Vicat needle test) to study the compatibility of cement-accelerators. However, the efficiency of these tests has been questioned[1] and even criticised.[2]

The present paper aims to present the main types of shotcrete accelerators, describing briefly their chemical interaction with Portland cement and their performance at both early and later ages. It also presents the most recent developments in this field that attempt to overcome some of the main problems associated with the use of traditional accelerators.

USE OF ACCELERATORS IN SHOTCRETE: OBJECTIVES AND IMPLICATIONS

Accelerators are used in dry and wet mix shotcrete to facilitate the placing of thick linings particularly in overhead applications, and to promote early strength compatible to design performance requirements. Their performance, however, indirectly influences other shotcrete properties, which include the following:

(1) provision of a sudden change in consistency through a direct action on the setting of cement;
(2) direct reaction with the mix water promoting a stiffening of the mix;
(3) increase in mix thixotropy;
(4) no rheological action in the fresh paste but modifications in the hardening phase;
(5) changes in the amount of rebound and dust (dry mix) and ultimate strength.
(6) The choice of a particular type of accelerator indirectly influences the amount of rebound and dust generated by the dry-mix process. Accelerators that increase the thixotropy of the mixes, for instance, decrease the rebound by providing more plasticity to the shotcrete, increasing the capacity of fixing the sprayed particles.

The effect of accelerators on the early strength depends basically on their chemical base, dosage, chemical composition of the binder, presence of mineral additions and temperature. Since they are generally formulated to work within certain limits of a cement chemical composition, it is essential to determine in each case the compatibility between cement and accelerator in order to verify the suitability of its use and establish the correct dosage to be added.

A side effect of the traditional accelerators is a decrease of ultimate strength. Compared to plain concrete (without accelerators), the 28-day strength can be significantly reduced (values typically in the range 20–50%). This effect becomes more significant with increased dosage. However, this problem seems to be overcome with the introduction of a new generation of accelerators (alkalifree). The latter also reduces the hazards associated with handling alkalis.

Thus, it is very important to know the properties of the accelerators used in shotcrete, as well as the most suitable ways to evaluate their performance.

MAIN TYPES OF ACELERATORS

The most common types of accelerators traditionally used worldwide in underground works are sodium silicates (water glass, modified sodium silicates), aluminate-based set accelerators (both in liquid form), and earth metals carbonates/hydroxides (powder form)[3,4]. However, other new accelerators and accelerating systems are now available on the market. The main characteristics and properties of all these admixtures are described in the sections that follow.

Earth metals carbonates/hydroxides

The alkaline earth metals carbonates/hydroxides accelerators in powder form are used exclusively in dry-mix shotcrete. Until recently, they were the most used accelerators with this type of shotcrete. The normal dosages are between 2.5 and 6% by mass of cement. These admixtures act mainly by accelerating C_3S hydration. Normally, a small quantity of aluminates is added in their formulation in order to influence the cement setting time. The influence, however, is noticed only when large dosages are used. Figure 1 shows the early strength development obtained in shotcrete produced with two different dosages of this type of accelerator, in comparison to the performance of shotcrete accelerated by a potassium aluminate based admixture. The J1, J2 and J3 curves from the Austrian Concrete Society specification were used as a reference.

From this figure, it is possible to note that a large amount of carbonate based accelerator is necessary to provide some strength in the first 20 min after spraying.

The reactivity of this accelerator is highly influenced by the cement chemical composition, fineness and presence of mineral additions as well as ambient temperature. For example, during the construction of the Highway Cotapata-Santa Bárbara (Bolivia, 1996) some slopes were stabilised using a dry-mix shotcrete coating. Due to project requirements and costs, the shotcrete binder used was a pozzolanic cement, and the accelerator was a carbonate-based powder. The ambient temperature was between 5 and 13°C. In the first tests, no evidence of accelerated setting was detected, even when a high accelerator content was used (6%). The problem was solved by heating the water added to the mix. The suitable temperature (35°C) was determined by trial. Using this procedure it was possible to achieve the early age strength requirements (10 MPa at 24 h) and even provide a flash setting when the water temperature

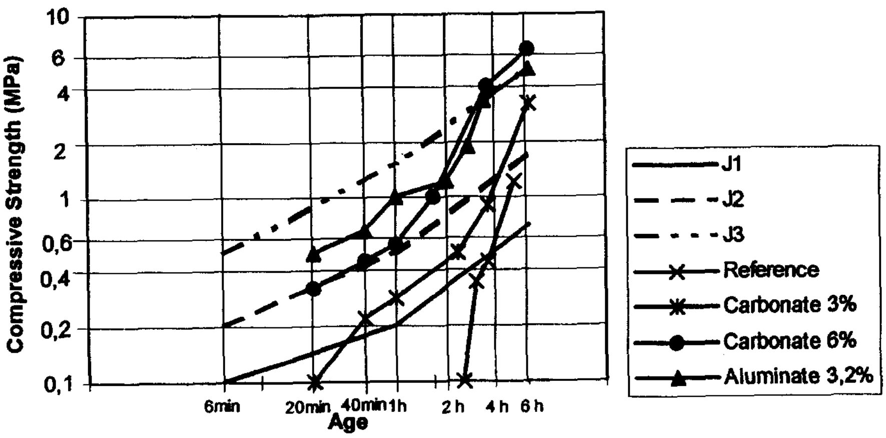

Fig. 1. Comparative performance of carbonate/hydroxide and aluminate-based accelerators.

was 70°C (this temperature led to a important loss of ultimate strengh more than 50%).

A characteristic of this accelerator is the drastic decrease of ultimate strength. Compared to plain concrete (without accelerators), the 28-day strength can be reduced significantly (values typically 30–40%). Values of up to a 50% reduction in the 28-day strength were observed in certain cases.[2]

Alkaline silicates (water glass)

Sodium and potassium silicate-based accelerators are mainly used in wet-mix shotcrete. They are added to the mix in liquid form and used normally in high dosages (> 10% per binder weight). The soluble silicates provide quick set by precipitating as calcium silicates. When used in great amounts, these accelerators produce a decrease in adherence to the substrate and, later, a decrease in strength of the shotcrete, as well as producing a high degree of drying shrinkage.[5] The authors report that these problems were also taken into account in the 'Guideline on Shotcrete' published by the Austrian Concrete Society, which recommends a maximum dosage of 15% and limiting the decrease in ultimate strength to 30%.

Melbye[6] states that when modified sodium silicates are used in dosages between 4 and 6%, they only momentarily (< 10 s) induce a gluing effect of the sprayed concrete mix (probably due to a loss of slump) and take no part in the early hydration process as aluminate-based accelerators do. They allow application of a thickness of between 80 and 150 mm. The same author reports other advantages of these admixtures: compatibility with all types of cements; less decrease in ultimate strengths than with aluminate based accelerators when used in normal dosages (4–6%); they are not so aggressive for the skin (pH < 12); and they have much lower alkali content than aluminate-based products. However, these admixtures do not provide good initial strengths and are not usually specified for applications with this kind of requirement.

Sodium and potassium aluminates

Aluminate-based accelerators in liquid form are the most used for both dry and wet mix shotcrete. The most common dosages are between 2.5 and 5.5%. The potassium aluminate-based accelerators generally perform better than the sodium aluminate-based ones. However, they are also more expensive. Their main characteristic is to promote rather quick setting by acting directly on the Portland cement hydration, through combination with gypsum, thus preventing etringite formation around the cement grains. This allows an almost instantaneous reaction of the C_3A, conferring the initial stiffness desired in most shotcrete applications (Figs 1 and 2).

Their efficiency is also influenced by the cement chemical composition, fineness and the presence of mineral additions, although this influence is less then that observed in carbonate-based admixtures. They produce a ultimate strength decrease of 20–25% in relation to plain shotcrete.

The aluminate-based accelerators undoubtedly provide the best wet mix shotcrete, making it possible to project thick linings even in overhead works. Their high alkali content, with

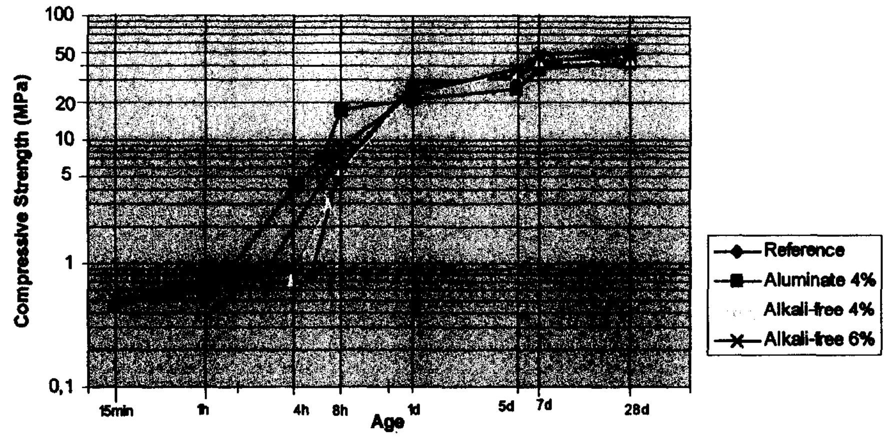

Fig. 2. Comparison between the performance of shotcrete with alkali-free and sodium aluminate-based accelerators.

consequent health hazard underground conditions, is the main restriction to their application[7]. Furthermore, the use has been questioned of such admixtures in massive works containing sulphate or in works where reactive aggregates are used because of a possible alkali–aggregate reaction.

Non-alkaline powder accelerators

The non-alkaline powder accelerators were first used in shotcrete at the beginning of the 1990s.[8] Generally, these are calcium aluminate-based admixtures used in dosages from 6 to 12%. Their chemical function differs from that observed in alkali-based admixtures[9]. The setting acceleration is provided by the reaction of the accelerators with water, without any direct interference with the cement compound hydration.[10]

Early strength resistance is not normally achieved with amounts below 7%. High dosages are required in thick linings for the coating of tunnels overhead. They result in a decrease of ultimate strength when compared to plain shotcrete, though smaller than the decrease observed in alkali-based accelerators.

A disadvantage with their use is their susceptibility to humidity, a disadvantage that requires the installation of a dryer together with the dosing device.[11]

Totally alkali-free accelerators are beginning to be used in shotcrete. The new products are aluminum hydroxide-based or in combination with aluminum sulphate. They develop enough early age strength, even in low amounts (4%). There is no decrease in strength at later ages with amounts of up to 8%. However, a significant loss of later age strength has been observed with amounts above 10%.[8]

In spite of the advantages mentioned above, there is some restriction in the use of non-alkaline accelerators in powder form. The dosage and homogenisation of these admixtures require special adaptations of the equipment available. Furthermore, Melbye[6] mentions that rebound is 10–15% greater with this type of admixture than with non-alkaline admixtures in liquid form.

Non-alkaline liquid accelerators

The use of non-alkaline liquid accelerators has been introduced quite recently in the international market, and therefore, the literature on their use is still scarce. They were conceived to solve some classical problems stemming from the use of alkaline accelerators, such as: hazardous conditions of the underground ambient where shotcrete was used, the risk of alkali-aggregate reaction, the risk of handling conventional accelerators with extremely high pH level, and reduction of shotcrete later ages strength.

The chemical composition of these accelerators is neither described in the pertinent literature nor divulged by their producers. However, studies on shotcrete microstructure conducted by an English laboratory in January 1996 did not reveal any alterations in the morphology of cement hydration products used in samples of shotcrete with this type of accelerator[12].

These products have a pH between 3 and 5.5 and an alkali content of less than 0.3%. They are used in amounts between 3 and 10% in relation to the binder's mass. When used in adequate amounts, they produce early age strength compatible with J2 and J3 curves of the Austrian shotcrete guideline[13] and allow overhead projections in linings up to 300 mm thick. An important characteristic of these accelerators is that ultimate strengths are not reduced when compared with a reference material (without accelerator).[14]

In the construction of the tunnels of the south freeway (Via Expressa Sul) in Florianópolis, comparative tests were made with an alkali-free liquid accelerator and the currently used sodium aluminate-based accelerator. The aluminate-based accelerator was added at a concentration of 4%, while 4 and 6% of alkali-free accelerator were added. The results obtained are summarised in Table 1 and Fig. 2.

The data in Table 1 show that the aluminate-based accelerator performed better at early ages than the alkali-free accelerator. However, as far as initial strength up to 30 min is concerned, the 6% alkali-free accelerator showed a slightly better performance.

Whereas a dosage of 4% of alkali-free accelerator gave an unsatisfactory performance at early ages, a 6% dosage amply satisfied the work design requirements (8 h: 4.7 MPa; 24 h: 11.8 MPa; 7 days: 17.6 MPa and 28 days: 21.2 MPa).

The shotcrete with 6% alkali-free accelerator after 28 days showed a markedly better performance to that of the shotcrete with aluminate-based accelerator and even the performance of plain concrete.

Table 1. Shotcrete strength obtained at different ages

Age	*Compressive strength (MPa)*			
	Reference	*Aluminate 4%*	*Alkali-free 4%*	*Alkali-free 6%*
15 min		0.44		0.51
30 min		0.54		0.55
1 h		0.75		0.58
1 h 30 min		0.93		0.72
2 h 30 min				0.84
3 h 40 min			0.74	
4 h		4.15		
5 h	0.76			
6 h		7.03		4.38
6 h 40 min			3.05	
8 h	5.97	17.12	5.80	8.52
1 day	28.3	20.9	24.8	23.9
5 days	31.8	25.2	34.2	36.4
7 days	40.3	36.5	42.7	48.02
8 days	50.1	41.7	43.5	53.8

Similar results were found in other studies with this type of accelerator,[6,14] but from another producer. The high cost of these materials has been a hindrance to their more frequent use.

METHODS OF EVALUATING ACCELERATORS PERFORMANCE

One of the main difficulties in the study of the accelerating admixtures performance is the definition of a methodology capable of yielding reliable results for the shotcrete initial stiffness and early ages strength evolution. Until recently, the paste tests (Gillmore needles and modified Vicat test) were normally used for this purpose. Melbye[6] for instance, proposes and describes a procedure for the assessment of the aluminate-based liquid accelerators performance based on a paste test.

However, this kind of test has been criticised for providing results distinct from those observed in the field.[1,2]

More recently, penetrometers have been used.[15] These apparatus are designed to measure the force necessary to drive a patterned needle into the concrete. This force is related to the concrete compressive strength. The Proctor and Meynadier needles are examples of this type of equipment. However, this equipment can only monitor strength in ranges of 0.1–1 MPa. The use of other procedures and equipment has been proposed in the 1–8-MPa range, where the concrete does not yet exhibit enough mechanical strength for core extraction. The Constant Energy Penetrometer is a piece of equipment that has produced good results. It measures the depth reached by a patterned needle when driven into the concrete by a patterned force (constant energy).[15]

Another method involves shooting beams and testing portions of these beams in compression using the ASTM C 116 test method. However, this test requires a large amount of beams to monitor the early strength development.

RECENT DEVELOPMENTS AND NEW TRENDS

Some innovations have recently been introduced in the area of shotcrete accelerators, aiming at improving the performances of the dry and wet mix processes. Cement hydration controlling admixtures, which prolong the initial setting time, have been introduced to make possible the use of industrial concrete in the case of long distance transportation. Accelerators that break the action of plasticisers, thus suddenly increasing the stiffness in wet mixtures[6,14], are innovations in the market.

The development of special binders for shotcrete — sulphate-low content binder, quick stiffness binder and controlled setting with medium-sulphate content and controlled setting binders with additions that decrease or even do without the use of accelerators — is a new trend in the area.

Other specially formulated types of binders have been recently developed for shotcrete. Schmidt[16] describes a special binder based on activated blast furnace slag with low dosages of Portland clinker and hemihydrated calcium sulphate, and another one based on pozzolanic cement free from C_3A, highly resistant to pure or sulphate water.

Finally, although it cannot be classified as an admixture, silica fume has been widely used in shotcrete world-wide. It is a very reactive pozzolan that provides both cohesiveness for increased thickness of buildup and early strength gain. In most cases, its use leads to a decrease in the required accelerator dosage. In some applications, where there is no requirement for high early strengths (e.g. at 8 h), silica fume makes possible the use shotcrete without any accelerator, even in overhead jobs.

CONCLUDING REMARKS

Shotcrete, which was previously limited in its use to special applications, is today widely used in ground support and repair. Consequently, it is receiving significant attention both in research and in product development. The search for better performances for early ages shotcrete and environmental concerns has led researchers and formulators of accelerators to the development of new products and new methodologies to evaluate their efficacy. Nowadays, a great variety of products are available in the market, the behavior and efficiency of which have been succinctly described in this article. However, much research is still necessary to develop products that satisfy all the characteristics required by shotcrete, at a cost comparable to that of conventional accelerators. Research success will undoubtedly intensify the application of both dry and wet mix shotcrete, contributing especially to enhanced safety and economy in the construction of underground works.

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