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Alkali-Free Accelerators for Sprayed Concrete

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Abstract. The application of wet sprayed concrete requires the accelerating component to achieve setting of the concrete and strength development. Common accelerators are highly alkaline and contain substantial amounts of alkali. Corrosive aerosols produced during addition of the accelerator at the nozzle can cause serious problems to skin and eyes of workers. Other disadvantages of the traditional accelerators are damage due to alkali-silicate reaction and a reduction of the mechanical strength of up to 50% over time.

A goal of the worldwide operating R&D division of the Underground Construction Group of MBT was the development of an alkali-free accelerator to overcome some problems of sprayed concrete applications and contamination by leaching water. This paper will show some results with these types of accelerators from laboratory tests and practical applications at interesting job sites world-wide.

1. What is Sprayed Concrete?

The application of sprayed concrete has been known for more than 80 years. The first applications were done by the *Cement-Gun Company* at the beginning of the 20th century. The first device was developed by *Carl Ethan Akeley*, who needed a system to spray a mortar onto mesh to make model dinosaurs. The name 'Guniting', a registered trade-mark for this special mortar, is still used widely for these applications.

For more than 20 years, sprayed concrete has been used in tunnels and other underground constructions. It is a key factor for rock support in tunnelling, mining and hydroelectric power projects for the protection of workers and equipment.

For this application, a concrete mix is conveyed to a nozzle, where an accelerator is added. Air is used to increase the velocity of the concrete and to enable

spraying onto the rock surface. The use of an accelerator enables the buildup of a shotcrete layer, reduces the setting time, improves the strength development for a safe working environment and gives shorter cycle times.

Traditional accelerators for sprayed concrete are based on alkali aluminates and alkali silicates. Both contain high amounts of alkali and have a pH in the range of 11–14.

2. Ecological and Application Problems

For the application of sprayed concrete, two different methods are known. The 'dry mix' procedure is the use of a mix of aggregate and cement which is transported to the nozzle by compressed air. There the required water and the accelerator for the chemical reaction of the cement are added. Dust formation is considerable, and working conditions are normally not in compliance with safety requirements.

In the 'wet mix' process, concrete produced in a concrete plant is transported by a special pumping system through a hose to the nozzle. There, the accelerator and the compressed air are added to 'spray' the material to the substrate.

The use of compressed air is mandatory to apply the material in both methods. But this air causes also the formation of dust by handling and applying the material and aerosols of the accelerators when mix-

ing into the concrete-air mixture. The accelerating chemicals can cause corrosion to skin and eyes due to the high alkalinity. Handling and storage of the accelerators require special precautions and safety regulations.

The material that will not stick to the substrate, the rebound, has to be dumped into the environment. Leaching of soluble calcium salts eventually close drainage systems in the construction when they are precipitated by carbon dioxide from air. Another dangerous side effect of alkaline additives for concrete is the alkali aggregate reaction. A chemical reaction with the aggregates leads to an expansion and finally to the disintegration of the concrete structure.

3. The Chemistry of Cement

The chemical reactions of individual phases of Portland cement are known. The interactions and kinetics of the different chemical reactions in real concrete are not fully understood.

The slurry of the pure clinker reacts rapidly with the mixing water. Considerable heat is developed, and the material becomes stiff and develops significant strength within minutes. Normally, ca. 3–5% of gypsum is added to the clinker to increase the open time of the mixture. In the initial phase after addition of water, a fast reaction starts, but within some minutes, this reactivity is slowed down.

The gypsum is dissolved and produces ettringite ($3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 3\text{CaSO}_4\cdot 32\text{H}_2\text{O}$) around the clinker particles, without causing any stiffening of the mix, as opposed to the formation of plates of calcium-aluminum hydrates, which causes setting when no gypsum was added.

The addition of the accelerators changes the reaction of the cement quite drastically. The dormant phase is shortened from hours to minutes, and immediately after addition, the setting of the concrete starts.

Alkali aluminates consume the formed ettringite to build up monosulfate and this forms additional calcium-aluminum hydrate in the paste. The change of the sulfate source is also a way to influence the reactivity of the concrete system. Silicates react in a different way. The high pH combined with available calcium ions causes the precipitation of an independent silicate network in the concrete. This stabilises the structure, and so, the visible initial stiffening effect can be explained. The added alkali later increases the reaction rate of the normal cement reactions.

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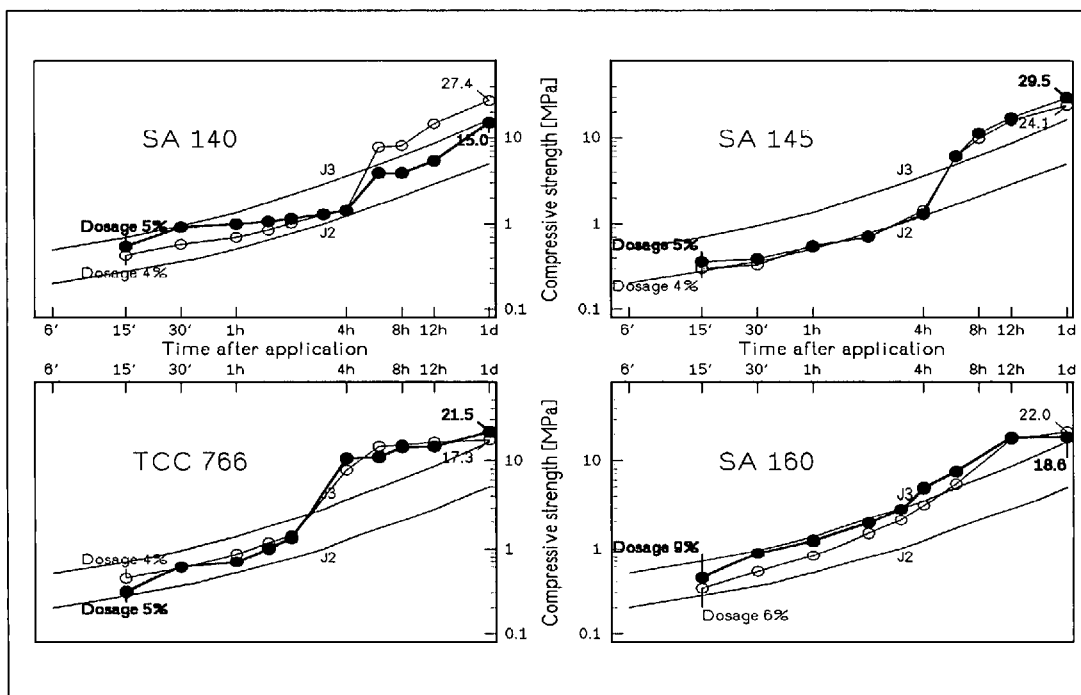


Fig. Strength development of sprayed concrete (20°). Mix design: cement: 425 kg CEM I 42.5 Siggenthal; aggregate: 1720 kg, 0–8 mm; 1.5% RHEOBUILD 1000, 0.9% DELVO stabiliser; air: 4%; density: 2.35; flow: 50–55 cm; w/c: 0.47; MEYCO SA 140, SA 145, SA 160: Alkali-free accelerators; MEYCO TCC 766: silicate-based accelerator

4. Alkali-Free Accelerator Approach

Some of the existing problems of sprayed concrete applications are caused by the high alkaline content of traditional accelerators. Unfortunately, a simple replacement of the alkali metal in the raw materials of aluminates and silicates is not possible. The ‘products’ are not stable under these pH conditions. The precipitation of aluminum hydroxide or silicate will start immediately. Furthermore, one of the influences on the chemical reactivity of the cement is the increasing free alkali content in the mix.

To get a similar overall performance, more than just the elimination of the alkali is needed. The design of a successful alkali-free accelerator was possible by using slightly soluble aluminum salts. The lack of alkali and thus the reduced solubility in the first period after addition to the concrete was one of the major problems in the development of these additives.

In order to avoid skin and eye burns, a lower pH was strongly recommended. By using various aluminum salts, a wide range of pH levels could be achieved. The optimum from a hygienic point of view is the range of the pH of the skin, 5–6. This was the solution for the first generation of liquid alkali-free accelerators from MBT. These products performed quite well, but showed a significant sensitivity to the type of cement, and the range of the dosage was limited to 4–6% of the cement content. A higher dosage significantly reduces the final strength.

For the next generation of alkali-free accelerators, the pH range was lowered.

The product MEYCO® SA 160 is a liquid alkali-free accelerator that performs very well with most cement types and concrete mixes.

In addition, the risk of an alkali aggregate reaction can be minimised. The total amount of alkali available in the concrete can be easily increased over the acceptable limit of ca. 3 kg of Na₂O/m³ by using an alkali-containing accelerator. In combination with water, the destructive reaction can be initiated, or to increase the durability and lifetime of the structure, can be prevented by using alkali-free accelerators.

5. Technical Aspects

The requirements for an accelerator can be divided in three different areas of performance:

- 1) Improving the spraying conditions; less dust production and reduced rebound
- 2) Setting behaviour and the possibility of spraying thick layers of concrete
- 3) Strength development and low strength loss caused by the cement reactions.

We have seen in multiple spraying tests that dust formation is very low and rebound is significantly reduced, by using alkali-free accelerators, down to 5%. The lower reactivity within the first seconds helps to prevent significant dust formation and reduces the rebound. The sprayed concrete layer on the substrate does not become hard and rigid within these initial seconds. As a result, the next layer of material can be much better embedded into this plastic substrate. The compaction

of the sprayed structure, important for the final strength, is improved and so are many properties of the mature concrete.

After this first step, setting takes place. The material becomes stiffer and can withstand small loads, certainly enough to stabilise more than 20 cm of sprayed concrete overhead (1 m² of a 20 cm thick concrete has a weight of nearly 500 kg). With an optimised mix design, significantly thicker layers can be applied in one application.

Within the first 15–30 min, the hardening of the concrete starts with measurable strength development. The Fig. shows the strength development of a sprayed concrete mix using different accelerators. The curves J2 and J3 are defined by the NATM (New Austrian Tunnelling Method). They indicate an area of shotcrete strength requirements for specific rock conditions.

A similar strength development may be observed for all four shown accelerators. A very fast reaction within the first 15 minutes gives up to 0.1–0.3 MPa, then a period of 2–3 hours with a very slow increase of the compressive strength, finalised with a jump up to 3–5 MPa. The strength development following this period is similar to that of a normal concrete.

Additionally, a reduced strength of mature sprayed concrete compared to a non-accelerated version is common. Depending on the type of accelerator, this loss can be up to 50% of the total strength.

The accelerators for the wet mix process are normally liquids. They can be added more easily to the concrete mix at the correct dosage, and the formation of dust is less problematic. As explained before, accelerators are highly reactive chem-

Table 1. Strength Development of the Sprayed Concrete

6 min 0.24 MPa	12 min 0.45 MPa	30 min 0.67 MPa
6 h 10.7 MPa	9 h 14.5 MPa	12 h 17.5 MPa
1 d -	3 d 21.4 MPa	7 d 27.4 MPa

Mix design and some properties from the Sieberg tunnel:

cement: 425 kg (Gmundner PZ 275 (K)); aggregate: 0-8 mm; 1.2% RHEOBUILD T3, 9% MEYCO SA 160; w/c: 0.44, density: 2.38; flow 62 cm (0 min), 62 cm (30 min), 59 cm (105 min).

Table 2. Strength Results and Requirements of the Sprayed Concrete

Time [days]	Requirement [MPa]	Performance [MPa]
1	>18	>26 (Ø 35)
28	>40	>55 (Ø 59)
120	-	>61 (Ø 70)

Mix design and properties from Heathrow Express: (Ø = average value)

cement: 355 kg CEM I 42.5 N (Blue Circle); aggregate: 1780 kg, 0-8 mm; additions: micro silica slurry 50 kg, steel fibres 50 kg; 2% RHEOBUILD 2000 PF, 0.9% DELVO stabiliser; 3.5-4% MEYCO SA 145; w/c: 0.40-0.42.

Table 3. Mix Design of the Concrete for FATI-MA (Northcape)

cement:	500 kg CEM I 52.5 R
aggregate:	1700 kg, 0-8 mm
additions:	micro silica slurry 25 kg
	2% RHEOBUILD 716, 0.5% DELVO stabiliser
	1% MEYCO TCC 735, 8% MEYCO SA 160
w/c:	0.45

icals and inhalation should be prevented under all circumstances.

6. International Construction Sites

Alkali-free accelerators have been used worldwide. Some very interesting construction projects will now be described briefly, to give an overview of the usability for different requirements.

A: Melbourne City Link, Melbourne, Australia

An important and exciting feature of the City Link project is the inclusion of

two tunnels that will run under the Yarra River and King's Domain. The tunnels are one vital part, and they will enable traffic to be diverted from congested streets and to flow freely under industrial and residential areas.

Both tunnels will carry three lanes of traffic in one direction only. They will finally have a size of 11.5 m width and 4.9 m height. The total length of the tunnels will be 5000 m.

The tunnels are constructed partly using a tunnel boring machine (TBM) and by the use of road headers. The tunnels are supported by preshaped steel arches and steel bolts. All is then covered with a temporary lining of sprayed concrete with the addition of alkali-free accelerators, because of the excellent working conditions and superior concrete quality permitted by their use. Finally they will be lined with a layer of concrete of thickness between 350 and 400 mm.

B: Sieberg Tunnel, Scheibbs, Austria

This is a twin-track high-speed railway tunnel near Linz with a length of 6500 m. The terrain is mostly marls, with very little overburden, in some sections of only a few meters. The cross section is built for two tracks, maximum speed of trains will be 200 km/h.

There are two intermediate access points, which allows six faces to be excavated. The tunnel is supported with 30-40 cm sprayed concrete as a primary lining and non-reinforced cast concrete lining as a permanent lining. Several sections are built by cut and cover methods because of the lack of overburden.

The tunnel was started with six dry shotcrete units, using a ready mix of over-dry aggregates and quick-setting cements blown with compressed air. The system is very simple, but the site could not get dust, rebound and cost under control.

The use of liquid alkali-free accelerators gave significant reduced dust, low rebound and fast application, and this convinced the contractor. For results and mix see Table 1.

C: Heathrow Express, London, Great Britain

The Heathrow express tunnel received worldwide publicity when it started to collapse while still under construction. After this accident, the quality control of the construction building materials used for the tunnel system was enhanced. The contractor had to follow the guidelines of the NATM system to achieve improved safety conditions for the workers and the tunnel structure. The use of alkali-free

accelerator allowed the achievement of a much better concrete quality. For results and mix see Table 2.

D: Northcape, Honingsvag, Norway

A road tunnel running under the sea, 6820 m long, in the far north of Norway. The excavation method is drill and blast, and one two-lane tunnel with a cross section of ca. 62 m² is prepared. The tunnel is being excavated from Vesterpollen (on the mainland) and from Veidnes (on the Mageröya island). Eight months after the originally planned breakthrough, the length remaining to excavate is still ca. 1400 m (end of Sept. 1997). From Vesterpollen, the first 3.4 km were excavated in good rock conditions. Then very poor sandstone and shale formations were encountered, as it has been the case from the very beginning from Veidnes. Round lengths between 2.5 and 5 m and *in situ* concrete poured per round were used until August 1997, with advance rates of 10-15 m per week and face. The change to shotcrete, using MEYCO® SA 160 and a shotcrete layer of ca. 25 cm (7 m³/m) directly at face, increased the weekly advance to ca. 35 m per face.

They achieved with their special mix (Table 3) more than 2 MPa after 1 h and up to 10 MPa after 4 h. After one day, they had a concrete strength of >30 MPa. For mix design of the concrete see Table 3.

E: NEAT Access Tunnel, Sedrun, Switzerland

The intermediate access point of the NEAT in Sedrun combines some very interesting tunnelling projects.

Firstly, there is a 990 m long access tunnel to the shaft heading. Then, there is a 450 m long ventilation shaft for better air exchange to the planned railway lines, and finally, there is a 800 m long vertical shaft to the level of the railway.

For rock support, sprayed concrete is used. For this project, the excavated material from the tunnel is collected and reused as aggregate for the production concrete. This requires a very tolerant mix design from all the components. Cement, grading curve, additions, concrete admixtures and the accelerator have to be optimised.

The obvious benefits such as better working hygiene (less rebound and dust, no corrosion to skin and eyes) and improved concrete quality (higher compressive strength) made the decision to use alkali-free accelerators easy.

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