Shrinkage and durability of shotcrete

B. Lagerblad
Division of Concrete Structures, Royal Institute of Technology (KTH), Stockholm, Sweden

L. Fjällberg & C. Vogt
Swedish Cement and Concrete Research Institute, Sweden

ABSTRACT: Cracking of shotcrete in tunnels has in recent years become a problem in Sweden. Thus an investigation was initiated. The results show that shotcrete differs from of ordinary cast concrete in many ways. Basically, wet shotcrete is ordinary concrete but is mixed with a set accelerator at the nozzle and as a result the major cement reactions will take place in a stiff (but not hardened) material. Cement hydration results in shrinkage that in ordinary concrete will be compensated for due to settlement, but in the stiffened shotcrete it will change the properties of the concrete. It will give a different structure and mode of porosity, which in turn will increase shrinkage. Especially with an alkali free set accelerator the shotcrete develops a larger amount and coarser porosity, which in turn will generate significantly larger drying shrinkage than in cast concrete. Moreover, the shotcrete is very sensitive to early shrinkage if not properly water cured. Water must be added to compensate for the chemical shrinkage in the stiff but not hard structure of the young shotcrete.

1 INTRODUCTION

In Sweden, especially in recent years, there has been problem with cracking of shotcrete in tunnels most of which has been constructed using wet-process shotcrete. This is especially the case where the shotcrete is covering drainage systems, where the bonding to the substrate is weak. The purpose of this investigation was to determine if shotcrete exhibits a greater tendency to shrink and crack than ordinary cast concrete. Basically the shotcrete is based on ordinary concrete but there are differences.

A shotcrete mix normally has a smaller maximum aggregate diameter D_{max} and contains more cement that will increase shrinkage but the major difference relative to ordinary cast concrete is that shotcrete is mixed with a set accelerator at the nozzle and is stiffened very quickly. Moreover, in later years water glass has been replaced with an alkali-free (aluminum sulphate salt) type set accelerator, another variable that will change the properties.

In shotcrete the early cement hydration reactions will take place in a stiff structure produced by the set accelerator. Thus the shotcrete can not adjust to early volume changes in the way that normal cast concrete can. Moreover, the set accelerator will interact with cement hydration. This will generate an altered structure within the binder and thus one can not assume that shrinkage will be the same as in cast concrete. It will also depend on the type of set accelerator as the different types

will interact with the cement hydration in different ways and result in different internal hydration structures. This paper will include a theoretical discussion and some laboratory tests to examine the relationship between shotcrete, binder reactions, binder structure, and shrinkage.

1.1 *Shrinkage*

All concretes shrink but this is a complex process that is influenced by several factors, see Figure 1. Basically there are two types of shrinkage: autoge-
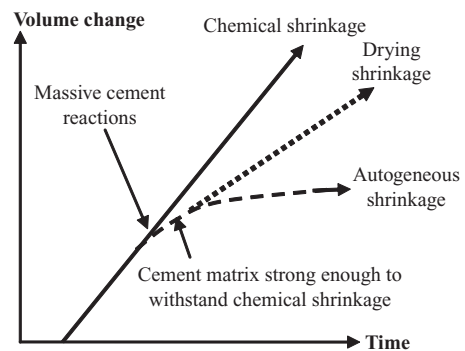

Figure 1.   Sketch illustrating the different types of shrinkage. Chemical shrinkage is a theoretical value, autogeneous free shrinkage is the measured value and drying shrinkage occurs when the matrix is stiff.

neous shrinkage and drying shrinkage. These occur as a result of chemical reactions, development of the cement paste, and evaporation of water. Different causes will affect the concrete at different stages. Thermal volume changes that also can result in cracks are not considered in this paper.

In the young fresh concrete shrinkage is mainly linked to cement hydration. The volume of water and cement is larger than that of the cement hydrates, which will create shrinkage forces as long as cement is hydrating. This is called chemical shrinkage and is the force behind autogeneous shrinkage. In a fully hydrated paste with a w/c of 0.4 the volume change is around 7–8 volume % depending on type of cement. The fluid and plastic concrete will contract but this will change when the concrete hardens. Moreover, the stiff but not hardened shotcrete will have a large open surface and will thus be sensitive to water movements. When the concrete is strong enough to withstand stresses due to chemical shrinkage, this will first result in an internal under pressure and later in an increased porosity. Thus the autogeneous shrinkage is smaller than the chemical shrinkage. With cement paste and a water/cement ratio of 0.4 and CEM I cement the autogeneous shrinkage will be around 0.5 vol. % (Justnes et al. 1999, Hammer 1999). This is equivalent to a one dimensional free shrinkage strain of around 1.6‰. The bulk of the concrete is made up of aggregate and if we assume 75 vol. percent aggregate this would result in a shrinkage strain of 0.4‰.

In ordinary fluid concrete this is of subordinate importance but it will affect the shotcrete as at this stage the early hydration will take part in a stiff structure. Added water will compensate for the chemical shrinkage. Thus one can presume a larger shrinkage of shotcrete if water is not added. If the concrete loses water during the plastic stage one can get plastic shrinkage that results in wide and deep cracks.

In a properly hardened concrete one will mainly get drying shrinkage that is a result of evaporation of water from the capillary system. When the capillary pores are drying out they will contract and the concrete will shrink. Changes of the pore structure will affect the amount of drying shrinkage and one can not presume that shotcrete has the same porosity as ordinary cast concrete, both due to the application technique that gives a more inhomogeneous product and chemical shrinkage in a stiff structure.

The consequences of shrinkage depend on several parameters. The shrinking forces may result in increased porosity, micro cracks, internal cracks or free shrinkage. In the laboratory free shrinkage can be measured. In most standard tests free shrinkage of hardened concrete is measured over time. As the shrinkage is not restrained, large cracks do not normally form but a part of the shrinkage may result in micro-cracks. When the shrinkage results in internal cracks the free shrinkage will be less. Formation of cracks instead of free shrinkage will in most cases be the result of internal restraint due to reinforcement, aggregates, fibres etc. External restraint leads to wide cracks. Measurements on fresh cast concrete with a w/c ratio of 0.4 gave an autogeneous shrinkage of 0.25‰ (Holt & Leivo 1999) which is less than predicted from paste experiments. This is due to the internal restraint provided mainly by the larger aggregate particles.

2 CHEMISTRY AND FUNCTION OF SET ACCELERATORS

Wet shotcrete is ordinary concrete that is mixed with a set accelerator in the nozzle. In the normal case ordinary Portland cement and local aggregates are used. It must ordinarily display good pumpability and be formulated so that the rebound is small. To get this the D_{max} is smaller than in ordinary cast concrete and the amount of cement is higher. In Sweden the concrete mix will often contains 5 wt. % silica fume (by weight of cement) to make the concrete more cohesive. Silica fume is known to increase autogeneous shrinkage.

Set accelerators are chemicals that react with the early cement hydrates and alter the pore solution. The reaction forms either a network of solid products or, in the case of water glass, a viscous gel that stiffens the concrete and keeps it in place. The reaction must be fast and starts already in the air before the concrete reaches the intended surface. If it is too fast there will be rebound and if too slow the concrete will slough or fall out. Thus the amount needed for a certain thickness must be carefully adjusted.

2.1 *Background to cement chemistry*

When in contact with water, cement reacts exothermically and forms cement hydrates. The cement hydrates are in equilibrium with the water, called the pore solution. The reactions are slow in the beginning (during the dormant period) but after a certain time rapid cement reactions start (acceleration period) followed by slower reactions that increases the strength. During the dormant period the concrete can be cast and during the acceleration period the concrete first stiffens and then hardens. The different periods can be identified by isothermal calorimetry that measures the heat generated by the exothermic cement hydration reactions.

Cement clinker includes four main minerals: alite (C_3S), belite (C_2S), calcium aluminate (C_3A) and ferrite (C_4AF), where $C = CaO$, $S = SiO_2$, $A = Al_2O_3$ $F = Fe_2O_3$ and $H = H_2O$. In addition the cement contains calcium sulphate (gypsum) to regulate the properties of the fresh concrete. Alite and belite are

the main clinker minerals that form the cement gel, the calcium silicate hydrate (C-S-H) and the portlandite (CH). The calcium aluminate is a very reactive clinker mineral that promote the onset of hydration. Without gypsum it would lead to "flash setting" by forming calcium aluminate hydrates. Gypsum (calcium sulphate) reacts with aluminates and forms ettringite. The same mineral is formed with the introduction of aluminum sulphate set accelerators (see Section 2.2.2). Gypsum-free cement leading to flash setting is sometimes used in dry shotcrete.

The set accelerators react during the dormant period with the components of the pore solution. During the dormant period the normal cement reactions are stifled by the early cement hydrates. The pore solution is dominated by Ca^{2+}, Na^+, K^+, OH^- and SO_4^{2-} ions (Taylor 1997) and the set accelerator must react with one or several of these ions. During the acceleration period, massive cement reactions starts. In the hardened concrete the contents of calcium and sulphate ions are low and the pore solution is dominated by alkali hydroxides. The length of the dormant period depends on the type of cement and the temperature. The speed of setting and hardening depends on cement fineness and temperature. The rock walls in tunnels are normally relatively cool and thus the onset of the acceleration period is often late.

In Sweden, a low alkali, sulphate-resistant and slow reacting cement (Anläggningcement from Cementa AB, CEM I, MH, SR, LA) is demanded by several authorities and is thus commonly used and was thus used in this investigation. It is rather coarse grained, high in C_2S and low in C_3A. With this type of cement and commonly cold tunnel walls it can take several days until the massive cement hydration and proper hardening starts. This will probably result in higher dosages of set accelerator and thus increase the shrinkage problems.

Ordinary accelerators used in cast concrete regulate the dormant period and/or the speed of reactions during the acceleration period. They are not effective enough to be used in shotcrete. Thus, in shotcrete another group of accelerators called set accelerators have been developed and used. The set accelerators are not supposed to interfere with the major cement reactions. They will react with the pore solutions of the young cement paste during the dormant period. This is basically a false or flash set generating a structure within which the rapid hydration of the acceleration period takes place, resulting in proper hardening.

2.2 *Set accelerators and their reactions with Portland cement*

The intension with the set accelerator is to make the concrete stiffen very quickly. To do this the set accelerator must react with components of the pore solution and form a product that is stiff enough to keep the shotcrete in place. The set accelerator will interact with the cement hydration during the dormant period. Thus, it must react with the pore fluids formed during the dormant period. During this period the pore solutions are dominated by calcium and sulphate ions. In cement paste there are two major chemical systems, the silicate and aluminum systems. The set accelerator will interfere in this system and forms either calcium-silicate-hydrate or ettringite that are products of normal cement hydration. Sometimes the set accelerators also contain some alkali carbonate that precipitates calcite, which also leads to a stiffening action.

There are three principal types of set accelerators available:

1. Water glass (alkali silicate),
2. Alkali accelerators,
3. Alkali-free accelerators.

Of these three, the alkali-free accelerator type currently dominates the market. A cheaper product, called 'water glass', was more common earlier, but it leads to an alkaline fog that may harm workers. The alkali free accelerator allows thicker concrete layers to be sprayed and is thus more cost effective in production.

When the concrete is fluid, during the dormant period, the bulk of the cement is still unhydrated. The set accelerator will change the composition of the pore fluid but in general the hydration of the cement will occur independently of the set accelerator. This means that during the initial period the early strength is wholly dependent on the structure of set accelerator products (Figure 2). The basic prerequisite for the stiffening of water glass and alkali-free accelerators is enough of Ca in the pore solution (see later). The release of Ca ions will be somewhat slower with the Swedish cement compared to normal "standard" cement but the reactions will take place. The later strength will be due to
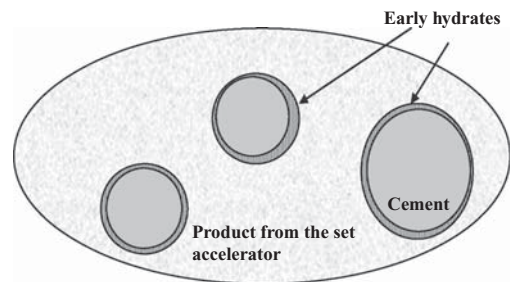

Figure 2. The set accelerator will form a lose structure between the cement grains. In this structure the proper hydration will eventually occur.

the cement hydrating in a structure affected by the set accelerator. Thus the composite structure will not be the same as in an ordinary cast concrete.
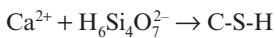
2.2.1 *Water glass*

Water glass is an alkali silicate in solution. Earlier it was made from quartz that was dissolved in warm concentrated alkali hydroxide. Water glass has a high pH, between 11 and 12 depending on composition. The solubility of silica increases with the pH. Stepwise the silica complex loses its protons with increasing pH.

$$4H_3SiO_4^- + 4OH \rightarrow SiO_4^{2-} + 4H_2O$$
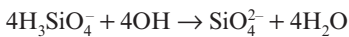
This will lead to a successively higher negative charge on the surfaces. In an aqueous solution in equilibrium with silica at high pH, ionized polymers like $H_6Si_4O_7^{2-}$ can also be found (Dove & Rimstedt, 1994).

With the presence of monovalent cations (alkali) ions in water glass, the silica ions and silica-ion-complexes stay in solution. In the case of divalent ions like calcium, the silica ions will, due to the strong negative surface charge, bond to calcium and cause precipitation of calcium silicate hydrate (C-S-H). This is the same process that takes place during hydration of ordinary Portland cement forming C-S-H. The Ca ions are a product of the early cement reactions.

$$Ca^{2+} + H_6Si_4O_7^{2-} \rightarrow C\text{-}S\text{-}H$$

The difference is that in the case of cement, the C-S-H will precipitate on the cement grain surface, while with water glass the C-S-H will precipitate and gelate the pore water. This will produce the stiffening effect. The end product will be similar to that of cement paste without water glass. The differences include: the amount of calcium hydroxide will be somewhat lower, the amount of C-S-H higher and the amount of alkalis in the pore solutions higher.

2.2.2 *Aluminum salt set accelerators*

There are two types of aluminum set accelerator: alkali aluminum and aluminum sulphate salts. Both act in a similar way reacting with components in the pore solution forming ettringite. The function is based on the fact that the ettringite crystals form a network of needle-like crystals that stiffen the concrete. The composition of the ettringite mineral is:

$$3CaO \times Al_2O_3 \times \cdot 3CaSO_4 \times 32H_2O \text{ (Ettringite)}$$

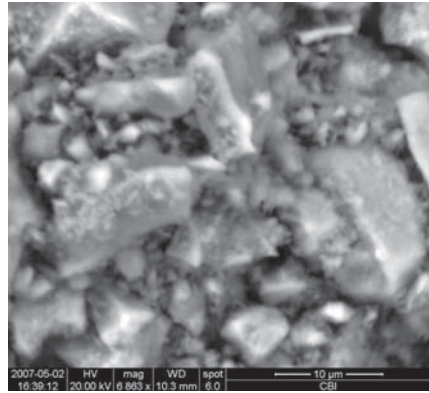The aluminate (Al_2O_3) can also come from other components. Ettringite needs sulphate ions

Figure 3. SEM photo taken 1 hour after mixing with alkali free set accelerator. It shows cement grains and a matrix of ettringite needles. The photo is taken in a vacuum on a broken surface. In a wet shotcrete the ettringite crystals would be evenly distributed.

in its structure. The major difference between the two aluminum salts is that the alkali accelerator consumes sulphate and releases alkali ions to the pore solution while the alkali-free accelerator only consumes calcium and hydroxide ions.

Aluminum salts that can be used as set accelerators include:

- Sodium aluminium salt $Na[Al(OH)_4]$
- Aluminum sulphate salt $Al_2(SO_4)_3$
- Amorphous aluminum hydroxide $Al(OH)_3$
- Aluminum chloride $AlCl_3$

In earlier times an alkali accelerator was more common while the alkali-free type dominates today's market. The difference between them is that the alkali-free accelerators do not contain alkalis. Instead they contain an aluminum sulphate salt. The major advantage of the alkali-free accelerator compared to water glass is that the shotcrete becomes stiffer faster and thus it is possible to shoot thicker layers, Figure 3.

3 INVESTIGATION/TEST SERIES

Wet shotcrete is basically ordinary concrete that is mixed with a set accelerator. Most tests are developed to investigate ordinary concrete. Commonly used shrinkage tests measure length changes of cast prisms. Shotcrete, however, can not be cast to prisms thus the major problem is the experimental set up. Shotcrete has to be produced and the length change has to be measured. Moreover, the effect of the set accelerator on the cement hydration must be examined.

To produce a realistic result the concrete must be mixed with the set accelerator in the nozzle. Hand mixing gives an inhomogeneous product. To get a proper result the shotcrete has to be measured as early as possible after mixing. The autogenous shrinkage is normally measured in flexible tubes filled with fluid concrete but it is impossible to get stiff shotcrete into these tubes. Thus fresh shotcrete has to be cut into prisms that are measured. Tests and measurements have been done on cement paste, mortar and concrete. The complete investigation is published in Swedish (Lagerblad et al. 2006, 2007). In this article the results from the cement paste experiments in the above mentioned publications are presented.

The effect of the accelerator on the exothermic hydration reaction has been studied in an isothermic calorimeter. In this instrument temperature is kept constant (20°C) and the amount of energy needed to keep the temperature constant is measured. In the experiments a cement paste is mixed with a set accelerator and immediately put into a cup in the instrument.

Two types of experiments have been performed with pure cement paste. The autogeneous shrinkage is measured on cement paste put in elastic rubber containers (condoms) that are put in a water bath. Weight changes are measured. The shrinkage will result in a change in buoyancy leading to a higher weight (as the container is in water). The change in weight can be used to calculate volume change. The method is described in Justnes et al. (1999).

To determine the free shrinkage, cement paste was mixed with the set accelerator and shot into a 250 mm steel mould. The cement paste contained 1 kg of cement, 50 grams of silica fume and 400 grams of water. This gave a w/c ratio of 0.4 and a w/b of 0.38. Gauge studs were installed in the steel mould. Paint spraying equipment driven by compressed air was used. The set accelerator was introduced in the air stream. After spraying steel plates were pushed into the stiff, but still plastic, grout. The steel mould was placed in a humid room at 20°C and was dismantled the next day, resulting in three $250 \times 250 \times 25$ mm^3 prisms with gauge studs. The prisms were kept in the humid room for 7 days and then put in a climate chamber with 65% RH.

The mortar was sprayed onto wooden surfaces in the laboratory. It was sprayed with a modified putty sprayer. The shotcrete contained 1540 kg (0–4 mm) aggregate, 500 kg cement, 25 kg silica fume, 236 kg water and 1.5 kg polycarboxylate superplasticizer per m^3 concrete. An alkali-free accelerator was introduced in the air stream during spraying. The cake of stiffened grout was cut into prisms and measurement devices were put on them. The first measurement was done within an hour. The prisms were put in a humid room and kept

there for a week. After this first week the prisms were put in a climate chamber with 65% RH.

Shotcrete was also studied in field experiments. It was sprayed onto wooden panel forms. From these panels prisms were cut and gauge studs were glued either on the sides or, as in the normal procedure, to the short surfaces.

In all the experiments fairly coarse grained and slow reacting low alkali sulphate resistant cement (CEM I MH, LA, SR) was used typical of underground shotcrete in Sweden. This type of cement must be used due to relevant Swedish standards. In Sweden it is also common to use mixtures with 5% silica fume (by weight of cement).

4 RESULTS

4.1 Effect of set accelerators on cement hydration

The paste was hand mixed and immediately put in the calorimeter. The results show that one of the alkali free set accelerators (Af-1) led to a distinct retardation while the other (Af-2), like water glass, does not effect the onset of the acceleration period (Figure 4). A third type (Af3) leads to a slight retardation.

The differences in effect on retardation are related to the amount added and are thus a result of energy release from the set accelerator reactions. The result show that there is a difference between different brands of alkali free set accelerators where some can lead to distinct retardation. This shows that different alkali free accelerators lead to different effects presumably due to different formulations. Water glass, on the other hand, produces a slight acceleration even at high dosages. The conclusions from this investigation are that there are variations in the composition of alkali-free set accelerators and that some of them lead to retardation with this type of cement. The water glass seems to accelerate the reactions.

A difference can also be found in relation to strength where the reference mix and water glass give a distinctly higher strength after 1 day compared to the mixes with alkali-free accelerator, Figure 5. The 28 day strength is lower than that of the reference paste. Water glass leads to less retardation and thus confirms the results from the calorimeter. These tests were performed at 20°C and one can presume that with lower temperature the retardation will be stronger.

4.2 Shrinkage of cement paste

4.2.1 Autogeneous shrinkage
Autogeneous shrinkage is a result of chemical shrinkage within the hydrating cement paste. The
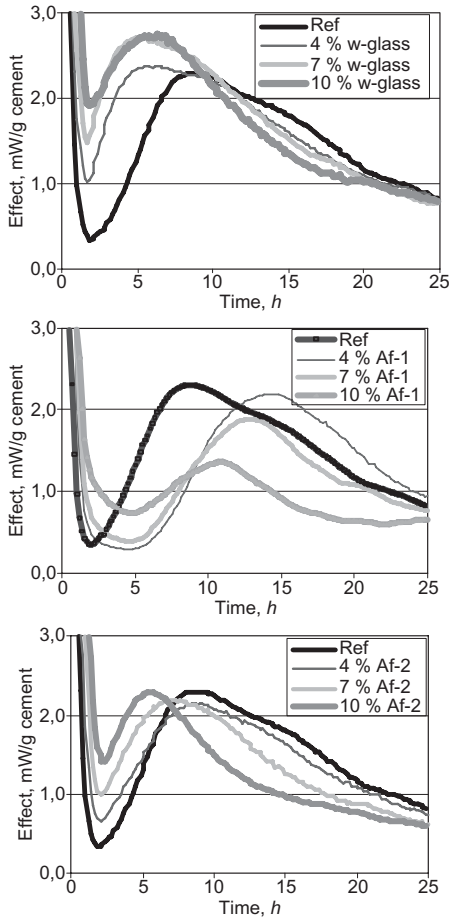
Figure 4. Results from isothermal calorimetry. Two different types of alkali free (Af) and one type of waterglass (Wg) at different dosages.
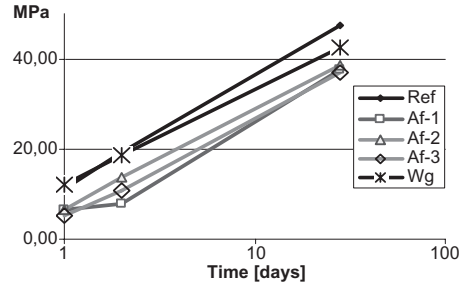

Figure 5. Compressive strength for 1, 2 and 28 days for sprayed cement paste. This was measured on prisms ($40 \times 40 \times 160$ mm). Af = alkali free accelerator, Wg = Water glass.
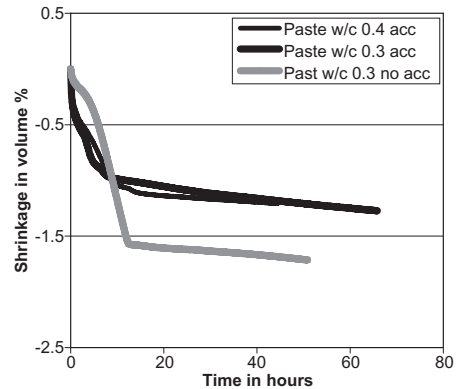

Figure 6. Results from experiments with autogeneous shrinkage. The method is described in Section 3.

experiments have been done with cement paste. Two of the pastes were mixed with an alkali-free set accelerator and one was ordinary cement paste. The ones with accelerator were put directly in the elastic rubber after mixing. The results show shrinkage during the first 10 hours and then a flattening of the curves, Figure 6. This was because after this initial time the strength was high enough to withstand the shrinkage. The "shotcrete paste" shrinks somewhat less than the ordinary paste but it was stiff almost from the start. This shows that the set accelerator does not hinder the early chemical shrinkage. In the shotcrete this will result in an increased porosity due to the stiff structure. In the ordinary fluid fresh concrete it will result in setting.

For the "shotcrete", the results indicate that the autogeneous shrinkage does not stop until the real cement hydration and strength start to develop.

These results are confirmed by a set of field experiments performed in a tunnel north of Stockholm. In these experiments, described in Azis (2005), real shotcrete as used in the tunnel, was sprayed onto wood panels. Directly after shooting, gauge studs were fixed onto the concrete and they were covered with plastic sheets to prevent drying. This was basically the same procedure used to study autogeneous shrinkage. During the first 24 hours, the concrete shrunk around 0.5 ‰. This shows that for shotcrete it is not sufficient simply to provide a covering or membrane curing, water must also be added.

4.2.2 Paste prisms

Three different types of commercial alkali free set accelerator and one type of water glass were tested. Different dosages were also used. The paste consisted of cement mixed with 5% silica fume and had a water/binder ratio of 0.38. Mixes with 5% silica fume are standard practice in Sweden.

The moulds were dismantled after 20 hours and the prisms were kept in humid conditions for 7 days.
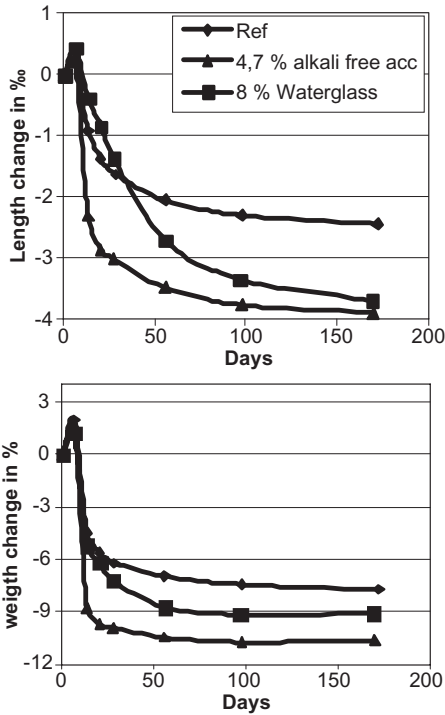
Figure 7. Length and weight change due to drying shrinkage. Results from experiments with cement paste and different types of set accelerators.

Thereafter they were put in a conditioning room at 65% RH. The results show that the prisms during the first week, when kept in humidity, swelled by around 0.3‰. In another experiment in which the specimens were kept in the humid room for 2 weeks they swelled by 0.4‰ (Lagerblad et al. 2007).

When the prisms were put in the conditioning room (65% RH), they started to shrink rapidly. The results show that both the hardened pastes with set accelerators shrank more than the reference concrete. The samples with alkali-free set accelerator shrank most, around 40% more than the reference paste prisms. Moreover the prisms with alkali-free set accelerator lost more water and lost it faster than the prisms with water glass and the reference. Results are presented in Figure 7. These results have been verified with more experiments where it also was found that shrinkage reducing agents reduced the shrinkage (Lagerblad et al. 2007).

5 DISCUSSION

It is a well known phenomenon that concrete shrinks. There are two different mechanisms behind it. Con-crete, or more precisely the cement paste within con-crete, shrinks because the products of cement paste hydration occupy a smaller volume than cement and water. The other mechanism that causes concrete to shrink is loss of water due to evaporation from the cement paste hydrate. The result of the shrinkage depends on the restraint within the concrete itself and on binding to the substrate. In most tests the free shrinkage of the concrete is measured rather than the restrained shrinkage.

The chemical or autogeneous shrinkage is 8–9 volume percent when the hydration is completed. The autogeneous shrinkage, however, will end when the cement paste is strong enough. Instead the shrinkage will result in an initial internal under pressure and later in an increased porosity.

Experiments show that paste mixed with an alkali free set accelerator after mixing will shrink more than 1 volume percent before the strength is high enough to withstand the shrinkage (Lagerblad et al. 2007). This shows that the set accelerator does not produce enough strength to withstand stresses associated with shrinkage. Normal paste without set accelerator in the same test set up will shrink more than 1.5 volume percent but in this case the fluid paste will set in the form. A 1.0% volume change will lead to a one dimensional shrinkage strain of 0.33%. If we assume 75% aggregate this will lead to a free shrinkage strain of 0.8‰ for the concrete. In an experiment described in Aziz (2005), and also in Lagerblad et al. (2007), panels with real shotcrete were measured following shooting. In this experi-ment, the panels were covered with plastic to pre-vent drying. After 24 hours they were water cured. The panels showed during the first day an average shrinkage of around 0.7‰, which is in accordance with the results from the paste experiments on autogeneous shrinkage. This shows that water must be added to the fresh shotcrete to avoid shrinkage.

When the real cement hydration has started, the concrete is strong enough to withstand most of the chemical shrinkage but it will shrink when dried. In normal drying shrinkage tests, the prisms are first stored humid for a week and later subjected to drying in a climate chamber. In Sweden the cli-mate chamber normally maintains a RH of 50%. The results from the pastes (Figure 7) show that the drying shrinkage increases from around 2.4 to 3.9‰. The water glass accelerator gives almost the same increase in shrinkage but it is slower. The weight changes show a similar pattern. In a few examples from real shotcrete on wooden panels an increase in shrinkage strain from around 0.75 to 0.9‰ could be observed (Lagerblad et al. 2007). If we assume 75 vol. % aggregate the paste sam-ples would lead to an increase in drying shrink-age strain from 0.60 to 0.98‰, which is somewhat more than in real shotcrete.
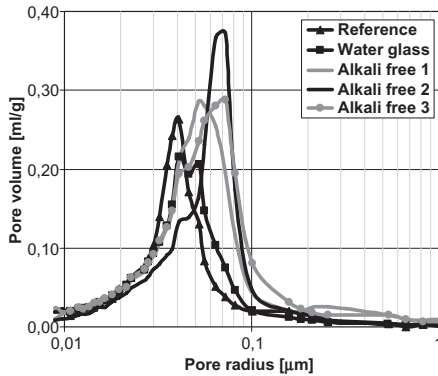
Figure 8. Mercury porosity measured on paste. These are the same pastes that were used in the shrinkage tests (Section 3).

The larger shrinkage and greater loss of water indicate that the shotcrete is more porous than ordinary cast concrete. This can be confirmed by mercury porosity, Figure 8. The results also show that porosity is larger especially in the paste with alkali free set accelerator. This is presumably a result of the fact that hydration occurs in an already stiffened paste.

This data shows that shotcrete is different from ordinary cast concrete. The difference is mainly due to differences in paste structure, which in turn are due to the set accelerator and structure of the paste and concrete. At the wall, the shotcrete has already developed a structure in the case of water-glass based on a loose C-S-H gel, and with the aluminate accelerator on a fibrous network of ettringite crystals. This makes the shotcrete, especially with alkali free set accelerator, very susceptible to early drying and shrinkage. However, the shotcrete also has a different structure in the hardened stage. This must be due to the fact that the main cement hydration reactions take place in an already stiff structure that hinders contraction.

The problem with shrinkage and importance of water curing will be worse in Sweden due to the slow cement. The mechanism will, however, be the same.

6 CONCLUSIONS

Shotcrete is different from ordinary cast concrete. Thus it is not possible to draw conclusions regarding the properties of shotcrete from ordinary cast concrete. The major difference is a result of the fact that the shotcrete is stiffened already at the wall and that major cement reactions take place in a stiff structure. It is, however, not stiff enough to withstand the force of chemical shrinkage. Water must be added to the shotcrete to avoid shrinkage cracking during the early period. Chemical shrinkage in a stiff but not hard structure also gives the shotcrete more and coarser porosity. This will increase drying shrinkage.

Thus it seems that the problems of cracking in shotcrete are due to the fact that shotcrete shrinks more than ordinary concrete. It also appears that shotcrete with an alkali-free set accelerator develops more shrinkage than the type of water glass accelerator used earlier. This is probably due to the fact that an alkali-free accelerator generates a stiffer structure more quickly than water glass set accelerators.

REFERENCES

Aziz, S. 2005. Experimentell undersökning av plastfiber-armerad sprutbetong. TRITA-BKN. Examensarbete 227, KTH, Betongbyggnad.

Dove, P.M. & Rimstedt, J.D. 1994. Silica-water interaction, in: Reviews in mineralogy, Silica, physical behavior, geochemistry, and material applications, Ed. Heany, P.j., Prewitt, Gibbs, G.V., Mineralogical Society of America, Reviews in Mineralogy. Vol 29, pp. 259–301.

Hammer, T.A. 1999. Test methods for linear measurements of autogeneous shrinkage before setting. In Tazawa, E. (ed.), *Autogeneous shrinkage of Concrete*, Proceedings of the International Workshop organized by JCI, Hiroshima 1999.

Holt, E.E. & Leivo, M.T. 1999. Autogeneous shrinkage at very early ages. In Tazawa, E. (ed.), *Autogeneous shrinkage of Concrete*, Proceedings of the International Workshop organized by JCI, Hiroshima 1999.

Justnes, H., Sellevold, E.J., Reyniers, B., Van Loo, D., Van Gemert, A., Verbowen, F. & Van Gemert, D., 1999. The influence of cement characteristics on chemical shrinkage. In Tazawa, E. (ed.), *Autogeneous shrinkage of Concrete*, Proceedings of the International Workshop organized by JCI, Hiroshima 1999.

Lagerblad B., Holmgren J., Fjällberg L. & Vogt C. 2006. Hydratation och krympning hos sprutbetong, SveBeFo Rapport K24, Stockholm.

Lagerblad B., Fjällberg L. & Westerholm M. 2007. Sprutbetongs krympning- modifiering av betongsammansättning, SveBeFo Rapport 86, Stockholm.

Taylor H.F.M. 1997. Cement Chemistry, 2nd edition, Thomas Telford Publishing, London.