Use of Superabsorbent Polymers in Concrete

An overview of the possibilities offered by using these smart materials as concrete admixtures

by O. Mejlhede Jensen

Throughout the life of concrete, water has central importance:

- It is an essential ingredient in the mixing, curing, and hardening of concrete;
- Its exchange with the surroundings causes hardened concrete to shrink, swell, and possibly crack;
- Its presence in hardened concrete influences strength and creep; and
- It plays a central role in deterioration caused by frost action or alkali-silica reactions.

Obviously, control of water is important to concrete. This article gives an overview of some of the opportunities offered by the use of superabsorbent polymers (SAPs) for achieving that control. Parts of the article are sourced from a previous publication.[1]

SAPs are polymeric materials that have the ability to absorb a large amount of liquid from the surroundings and retain it within their structure.[2] SAPs are mainly developed for absorption of aqueous solutions and, in extreme cases, they may have a water uptake of 5000 times their own weight. Standard, industrial-quality SAPs typically have a water absorption of 100 to 400 g/g dry (Fig. 1), and they can be produced in almost any size and shape (Fig. 2).

SAPs belong to the group of so-called "smart materials"—materials that, in a controlled way, significantly change their properties in response to an external stimulus. When SAPs are exposed to water, they swell, and when subsequently subjected to drying, they reversibly shrink. These key properties can actively be used in relation to concrete.

Early Investigations

In 1997, the late Per Freiesleben Hansen and I initiated a series of experiments involving a new curing technology concept. We called this technology "water entrainment" due to similarities with air entrainment. It was the culmination of a 10-year search for potential ways to mitigate autogenous shrinkage in high-performance concrete products.[6] Water entrainment is a technique for incorporation of designed, water-filled cavities in concrete. Straightforward and free of significant drawbacks, water entrainment can be induced with fine SAP particles as a concrete admixture.

At the same time, we also suggested a number of other potential uses of SAP in relation to concrete. These included frost protection, rheology modification, and controlled release of admixtures.

Influence on Strength

A SAP can ensure very efficient internal water curing, which is defined as "incorporation of a curing agent serving as an internal reservoir of water, gradually releasing it as the concrete dries out."[7] Internal water curing has been used for decades to promote hydration of cement and to control the shrinkage of concrete during hardening. Saturated lightweight aggregate was previously the only material used as an internal curing agent. But there are some major problems connected to the use of lightweight aggregates for internal water curing, including difficulties in controlling consistency and significant reductions in strength and elastic modulus. These difficulties are minimized with the use of SAPs.

From a strength point of view, the addition of SAPs to concrete has two opposite effects[8]: while the SAP generates voids in the concrete and thus reduces strength, the internal water curing provided by the SAP enhances the degree of hydration and thereby increases the strength. Which of these two effects is dominant depends on the water-cement ratio (*w/c*), the maturity of the concrete, and the amount of SAP addition. The total effect seems to be described well with existing models, such as the gel-space ratio concept.[9] In particular, at a high *w/c* (>0.45), SAP addition has very little effect on hydration and therefore generally reduces compressive strength. At a low *w/c* (<0.45), SAP addition may increase the compressive strength. An experimental study and a more detailed discussion of the influence of

SAP addition on mechanical properties can be found in References 10, 11, and 12.

Shrinkage Reduction

The shrinkage of concrete due to loss of water to the surroundings is a well-known cause of cracking both in the plastic and in the hardened state. This type of cracking can effectively be mitigated by slowing down or preventing the water loss. By acting as a water source, SAPs may potentially be used in relation to this, but these types of shrinkage are basically surface-related phenomena and it may be difficult to focus the action of the SAP towards this interface.

Autogenous shrinkage is a phenomenon that is closely connected with high-performance concrete.[13] Autogenous shrinkage may lead to cracking and affect strength, durability, and aesthetics of concrete. This has been a technological challenge that has limited the use of high-performance concrete.

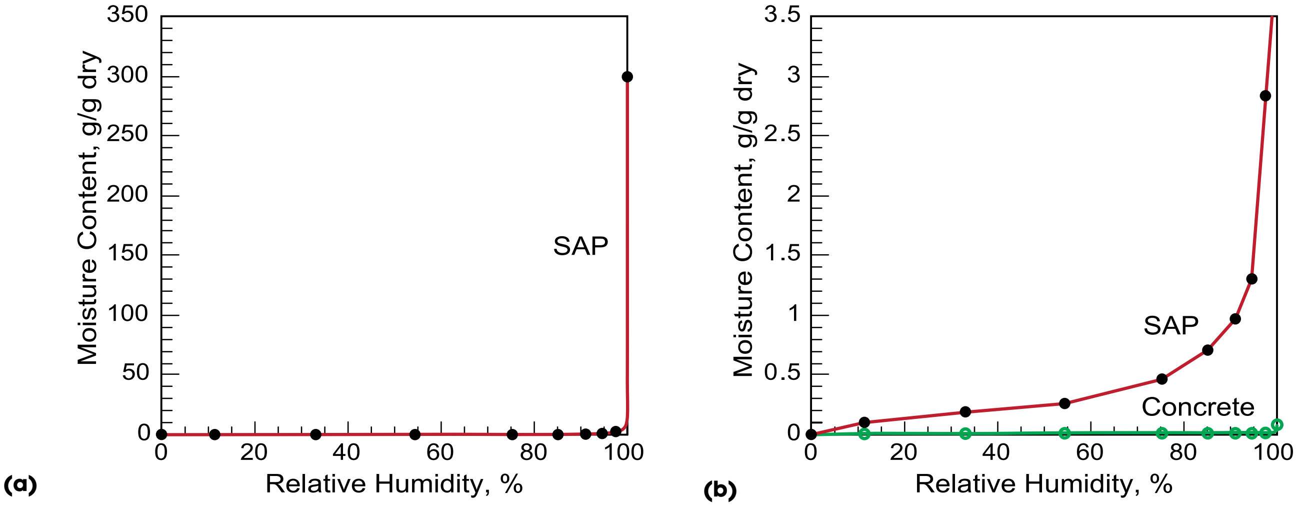

Fig. 1: An example of a sorption isotherm for a SAP (absorption and desorption values are identical): (a) the maximum water absorption of a SAP typically amounts to 100 to 400 g/g dry. If the liquid has a high ionicity, such as is the case for cement paste pore fluid, this value may be reduced to 10 to 30 g/g dry[3,4]; and (b) a highly magnified view of the SAP sorption isotherm shown in (a). A representative example of a sorption isotherm for concrete is shown for comparison (based on Reference 5). For the use of SAP in concrete, the relevant part of the sorption isotherm is the portion near 100% relative humidity, where the rapid absorption can be considered as nearly an on/off phenomenon

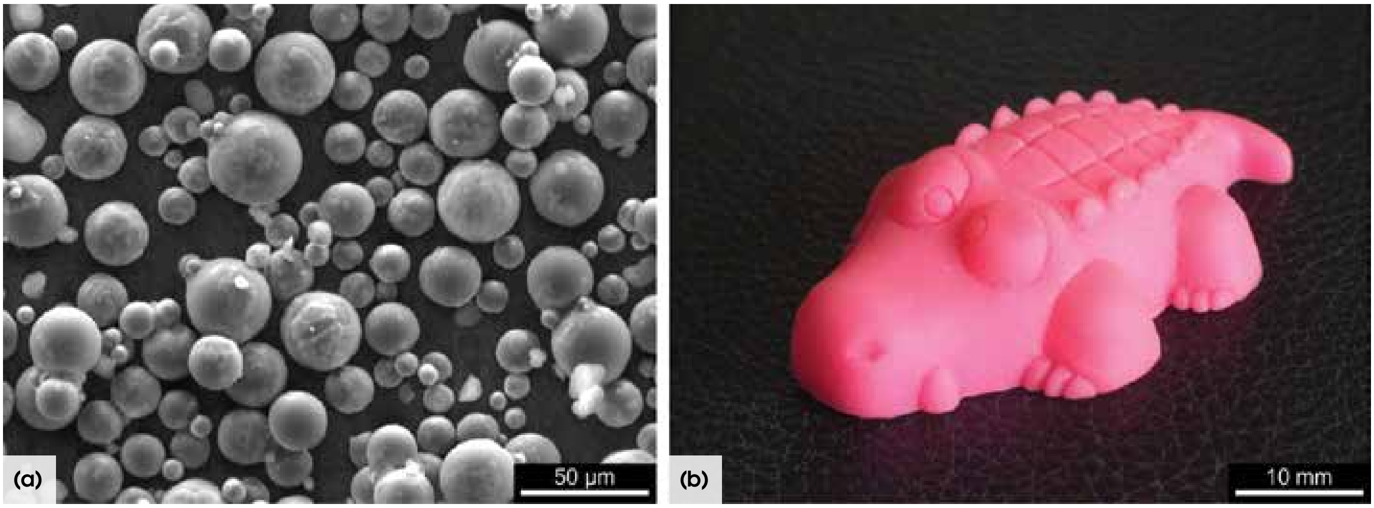

Fig. 2: Extreme examples of potential physical appearances of SAPs: (a) SAP in its simplest form—individual, spherical particles produced by suspension polymerization. This represents an example of the size of SAP particles that may be used in concrete for mitigating autogenous shrinkage (from Reference 3); and (b) a casting of solution polymerized SAP. When exposed to demineralized water, the dimensions of the particles or the SAP casting will expand by seven times, but the shape (proportions) will remain unchanged (Note: 1 mm = 0.03937 in.)

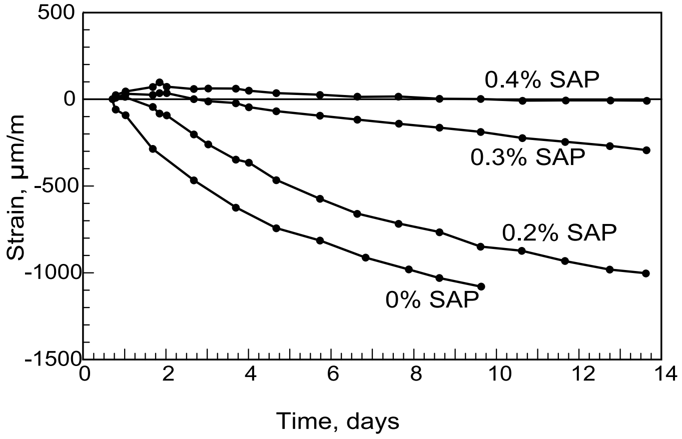

Fig. 3: Data from a 1998 study showing autogenous strain of cement pastes with basic *w/c* = 0.30, 20% silica fume addition, and different additions of SAP (expressed as a percent of cement weight). Extra water needed for the swelling of SAP is also added. The first measurement was made 17 hours after water addition. The test was conducted isothermally at 20°C (68°F) based on the technique described in ASTM C1698-09.[14] The internal relative humidity of sealed samples with 0% SAP will drop to about 80% during 2 weeks of hardening, whereas in the case of a mixture with 0.4% SAP, the relative humidity will stay close to 100% over the same period (refer to Reference 5)

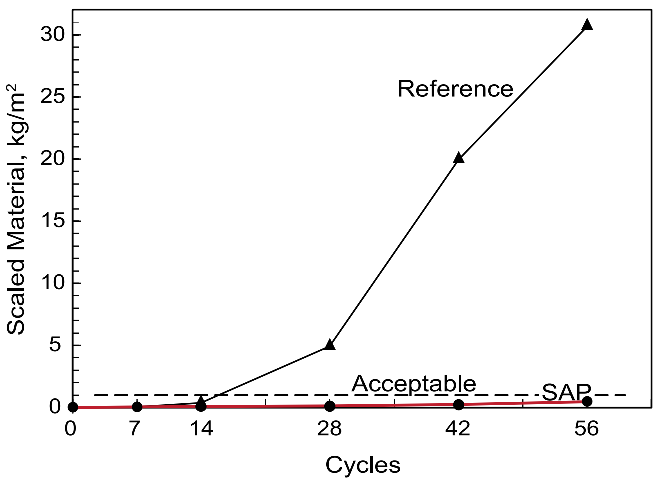

Fig. 4: Cumulative scaled material for concretes subjected to freezing-and-thawing cycles according to the Swedish standard.[15] The reference concrete has a *w/c* of 0.45 and no entrained air. Apart from the addition of 0.3% dry SAP relative to the cement weight and the extra water needed for the swelling of the SAP, the SAP concrete is identical to the reference mixture. The diameter of the dry SAP particles is about 60 μm and the diameter of the formed cavities is about 200 μm. The Powers spacing factor of the SAP particles is about 0.25 mm (based on Reference 16) (Note: 1 kg/m² = 0.2 lb/ft²)

Figure 3 shows how the autogenous shrinkage in an ultra-high-performance cementitious binder can be controlled by the addition of very small amounts of SAP. Subsequent tests have shown that the shrinkage reduction due to the SAP addition is related to a corresponding increase in the internal relative humidity of the cement paste. Furthermore, it has been shown that the SAP addition results in a reduction or elimination of the stress buildup and the related cracking during restrained hardening of these high-performance cementitious systems.[5]

SAP added to a concrete mixture during mixing permits an active control of geometric and thermodynamic properties of the water phase. The water in the formed SAP inclusions is essentially free water, and the size and shape of the inclusions are governed by the initially added SAP particles. Water entrainment can thus be considered "engineered water phase distribution."

Frost Protection

SAPs may also be used as a means to engineer the pore structure of cementitious materials. During cement hydration, the SAP particles shrink and leave gas-filled voids.

This can potentially be used for controlled air entrainment to improve the frost resistance of concrete. The method normally used for entraining air is connected with a number of significant technological difficulties, including coalescence of air bubbles in the fresh concrete, loss of air during vibration or pumping, and problems with compatibility between air-entraining admixtures and high-range water-reducing admixtures. The use of SAPs offers the possibility of actively controlling the entrained air in the hardened concrete, including the total air content, the spacing of the air bubbles, and the size (and even the shape) of the individual cavities—we refer to this as "engineered air-entrainment of concrete."

Figure 4 shows the influence of SAP addition on the freezing-and-thawing resistance of concrete. During the 56-day cyclic freezing-and-thawing test, the reference concrete exhibited scaling that was much higher than the performance criterion considered "acceptable" according to the Swedish standard.[15] With the addition of SAPs to this concrete, the amount of scaled material is reduced by a factor of 60, thereby significantly improving the freezing-and-thawing resistance. Based on an air-void analysis of the hardened concrete, the porosity generated by the SAP addition (entrained air content) is about 2.8% of the concrete volume.

Rheology Modification

The addition of dry SAP during mixing results in a considerable change in the rheology of fresh concrete if extra water is not added to compensate for the SAP absorption. For example, with a water absorption of around 15 g/g dry SAP,[5] the addition of just 0.4% SAP relative to the cement weight will lead to a lowering of the free *w/c* by 0.06. This change in *w/c* will cause the yield stress to triple and the plastic viscosity to increase by 25% for a concrete with an initial *w/c* of 0.4.[17] In addition to this pure water binding effect, a further increase in the yield stress and plastic viscosity will be caused by the physical presence of the swollen SAP particles.

If the thickening effect caused by the SAP is unwanted, it may be mitigated by addition of plasticizing admixtures. Alternatively, the effect may be used to advantage.

For example, the thickening effect associated with the absorption of water by the SAP may be particularly useful for wet-mix shotcreting, a process that can have a number of technological difficulties. To allow normal concrete mixtures to be pumped, a high slump is needed. However, to minimize rebound and to allow a proper buildup thickness during shotcreting, a low slump is needed. In practice, the producer of the concrete may need to "balance on a knife blade" and keep the slump at 80 mm (3 in.). In addition to exercising precise control of the fresh concrete slump, it is normally necessary to add a set-accelerating admixture at the nozzle. Unfortunately, the set-accelerating admixture leads to marked reductions in long-term compressive strength.[18]

The concept of using SAPs to adjust the slump of wet-mix shotcrete has been tested in practice (Fig. 5). Dry SAP was added in the nozzle and its rapid uptake of water was shown to create a viscosity change during placing, which allowed the buildup of thick layers without the use of set-accelerating admixtures. In the case shown in Fig. 5, the SAP was added for the sake of rheology modification, but SAP addition can result in other positive effects, including internal water curing, mitigation of autogenous shrinkage, and reduced susceptibility to damage due to freezing and thawing.

The latter benefit is particularly intriguing because it is very difficult to control the air entrainment of placed shotcrete. As shotcrete is placed, major changes in the air-void structure will occur if it is based on a normal, air-entrained admixture. With SAPs, however, it is possible to accurately design the final air-void structure, which will be unaffected by the pumping and placing procedure.

Outlook

As mentioned in the introduction, SAPs have extreme water absorption characteristics; this makes them particularly interesting in relation to concrete. Due to the water absorption, SAPs may also be considered a means to control porosity, which is another important property for concrete. Because SAPs can be designed with other specific properties, however, many additional uses of SAPs in concrete may be relevant. Examples include:

- SAPs can be used as an internal sealant in cement-based materials. When the SAP is exposed at a crack, for example, intruding water will cause the SAP to swell and partially block the crack.[19] This has similarities to the use of SAPs in fiber-optic cables, where swollen SAP prevents water migration along the sensitive optic fibers.

Fig. 5: A nozzleman places shotcrete incorporating SAP as a rheology-modifying admixture

- A special use of SAPs in concrete could be as a controlled release agent. This mechanism is used in several other fields. Within medicine, for example, a release of medicine is triggered by the pH change occurring from the stomach to the intestinal system. An example of beneficial use of controlled release in concrete could be for certain plasticizing admixtures, which have a stronger effect if their initial release occurs shortly after the initial contact between water and cement. Possibilities within this area have been examined by a major construction chemicals company.
- SAP with fibrous shapes potentially can be used to make high-permeability concrete. In the de-wetted state, which will be achieved after external drying or self-desiccation, elongated voids will exist in the concrete. Such voids may be useful, for example, to hinder pressure buildup and explosive spalling of high-performance concrete exposed to a fire. This is similar to the technology used, for example, in the tunnel elements of the Swedish Hallandsåsen, where the concrete contains polymer fibers that will melt during a fire and create passageways for vapor to escape from the concrete.

The principle of using SAPs as a concrete admixture has received considerable interest—both from the concrete research society and from the industry. On this particular subject, an international conference has been held,[20] and a technical committee is working under the international materials research organization, RILEM.[21] Also, the first structures using this technology have been constructed. Completed projects include the FIFA World Cup 2006 pavilion in Kaiserslautern, Germany,[7] and parts of the Chinese high-speed railway.[22]

Surely, implementation of the technologies described in this article will not be simple. Application of SAPs requires extensive documentation of the desired effect as well as careful scrutiny of shortcomings and problems. The first problem that SAP addition was intended to remedy—crack formation in high-performance concrete—was realized by the concrete industry only years after the introduction of high-performance concrete. This unfortunate course should not be repeated by likewise premature introduction of new techniques.

Acknowledgments

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Selected for reader interest by the editors.

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