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RILEM TECHNICAL COMMITTEE

Recommendation of RILEM TC 260-RSC: using superabsorbent polymers (SAP) to mitigate autogenous shrinkage

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Abstract This recommendation is devoted to the use of superabsorbent polymers (SAP) in mitigating autogenous shrinkage of concrete and has been prepared by the working group acting within RILEM TC 260-RSC. The recommended procedure for designing mix compositions of concrete with SAP is given. Dry SAP particles of small size should be added to concrete along with additional mixing water that SAP absorb upon mixing. The SAP particles release water during hardening of concrete to compensate for chemical shrinkage and consequently reduce autogenous shrinkage. The procedure for designing mix composition is based on finding a trade-off between mitigation of autogenous shrinkage and possible negative effects on concrete properties (e.g., mechanical properties, workability). A theoretical guideline is provided based on compensating the volume of chemical shrinkage with (additional) internal curing water to be absorbed by the SAP and based on the measured absorption capacity of the SAP.

Keywords Concrete · Autogenous shrinkage · Superabsorbent polymers · Internal curing

This recommendation has been prepared by members of Work Group 3 Using SAP to Mitigate Autogenous Shrinkage – Mateusz Wyrzykowski, Shin-Ichi Igarashi, Pietro Lura and Viktor Mechtcherine – acting within RILEM TC 260-RSC Recommendations for Use of Superabsorbent Polymers in Concrete Construction and has been reviewed and approved by all members of TC 260-RSC.

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1 General provisions

1.1 Scope of this recommendation

This recommendation focuses on the application of superabsorbent polymers (SAP) as internal curing (IC)

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agents in controlling or mitigating the autogenous shrinkage of concrete.

1.2 Definition of terms

The definitions presented below stem from the state-of-the-art report of RILEM TC 225-SAP [1]. Here only the most important definitions are given; please refer to [1] for a complete list of definitions related to concrete with SAP.

Autogenous shrinkage—macroscopic (bulk) dimensional reduction (volumetric or linear) of the cementitious system, where reduction occurs under sealed isothermal, unrestrained conditions.

Chemical shrinkage—volume reduction of the hydration products of binders as compared to the volume of initial components: dry binder and water. After the setting of cement this causes desaturation of pores.

Self-desiccation—reduction in the internal relative humidity of a sealed system when vapour-filled pores are generated. This occurs when chemical shrinkage takes place at the stage where the paste matrix has developed a self-supportive skeleton.

External curing—traditional curing methods applied externally on the surface of the concrete. The methods of external curing include water ponding, water spraying, and applying wet burlap, plastic sheeting, curing compounds, and others.

Internal water curing—incorporation of a curing agent into fresh concrete serving as an internal water reservoir, which gradually releases this water as the concrete dries. Internal water curing methods include the use of superabsorbent polymers (SAP) or prewetted lightweight aggregates (LWA), wood-derived products.

Superabsorbent polymers—cross-linked polyelectrolytes which swell upon contact with water or aqueous solutions, thus resulting in the formation of a hydrogel. These polymers are able to absorb up to 1500 g of water per gram of SAP. In engineering practice SAP are mostly based on cross-linked polyacrylic acid.

Water-to-binder ratio—ratio between mass of water and mass of binder (including supplementary cementitious materials) used in concrete mix.

1.3 Internal curing with superabsorbent polymers: background and motivation

Internal curing with SAP is recommended in concretes that experience high self-desiccation and autogenous shrinkage, where, if not properly limited, these may lead to build-up of stresses under restrained conditions and subsequently to cracking. Autogenous shrinkage is especially prominent in concretes with low water-to-binder ratios (*w*/*b*, lower than approximately 0.4), in particular, high-performance concretes (HPC) or ultra-high performance concretes (UHPC) [2].

Internal curing is based on the incorporation into fresh concrete of a curing agent, which serves as an internal reservoir of water and can gradually release water as the pores in the concrete dry out due to self-desiccation or external drying [3]. These reservoirs can be provided by adding dry SAP during concrete mixing [1]. The SAP particles absorb water on mixing and form stable, water-filled inclusions of sizes usually below 1 mm in fresh concrete. During cement hydration, the pores of the hardening cement paste are partially emptied of their water due to ongoing hydration and chemical shrinkage. Due to the emptying of pores, the SAP particles release their water to compensate for chemical shrinkage. As a result, self-desiccation and the resulting autogenous shrinkage are limited or completely avoided [4]. Additionally, it has been observed that SAP may lead to some initial expansion shortly after setting [5]; this should further contribute to reducing the risk of early-age cracking brought about by autogenous shrinkage.

Internal curing with SAP is advantageous in comparison with conventional (external) curing methods, since it can deliver curing water uniformly in the whole volume of hardening concrete, while during external curing the water can penetrate into the interior of concrete elements to some limited extent only [6]. In addition, when external curing is applied in the form of water spraying or ponding, it can be efficiently applied only on free horizontal surfaces and these are not accessible for many concrete elements.

2 Proportioning of concrete mixtures containing SAP

2.1 General rules

SAP differ in their production methods, sizes, shapes, and absorption/desorption properties. The SAP suitable for concrete need to be active in solutions of high pH and ionic strength and, moreover, still swell in the presence of monovalent, divalent and trivalent ions (K^+, Na^+, Ca^{2+}, Al^{3+}). A detailed description of SAP types applicable to concrete is presented in [1]. It is recommended that the SAP to be used in concrete are always tested in laboratory trials before field application; see Sect. 3.

The dosage of SAP necessary for mitigating autogenous shrinkage depends on their properties, especially on their sorption capacity in cement pore fluids. The methods for determining the sorption capacity of SAP and their applicability in concrete construction are described in detail in a report [7] and a recommendation by RILEM TC 260-RSC [8]. Note that sorption kinetics of SAP are also important to the success of internal curing [9]. It should be noted that the solution absorbed by the SAP during mixing is different than pure water, as it already contains ions dissolved from the binder; hence, it is further referred to as pore solution. Consequently, the absorption potential of SAP is usually evaluated using (synthetic) pore solutions rather than pure water [8].

The sorption capacity of SAP applicable to internal curing in concrete is usually within the range of 10–30 g of pore solution per gram of SAP [1, 10]. Because of this high sorption capacity, small amounts of SAP are usually added to the concrete mix; the SAP themselves (i.e. excluding the absorbed pore solution) customarily have negligible volume with respect to the mix design.

A recommended procedure for determining SAP dosage is by testing its effect on autogenous shrinkage and at the same time its influence on those concrete properties relevant to the concrete mixture under consideration, see Sect. 2.2. Consequently, an iterative procedure should be applied, where a trade-off can be found between limiting autogenous shrinkage and any possible negative impact on important concrete properties, e.g., workability or strength.

2.2 Determination of the amount of SAP for mitigating autogenous shrinkage

A recommended approach to determining the dosage of SAP consists of the following steps:

1. Determine which part of the total *w*/*b* of a mix should take part in the internal curing process. Total *w*/*b* is understood as the total mass of water used in the mix divided by the total mass of binder. Consequently, the total *w*/*b* of the mix can be considered as the sum of the basic *w*/*b*, with water acting as regular mixing water, and the w/b_{SAP}, with water that will act to provide internal curing. The latter corresponds to the water that is added along with the normal mixing water but is absorbed by the SAP upon mixing. The w/b_{SAP} should be determined based on an iterative process, in which a trade-off is found between mitigation of autogenous shrinkage and possible negative effects on mechanical properties, workability or any other property that may be important to the concrete considered; see Sect. 3.3.
   As a guide, a theoretical approach for mitigating autogenous shrinkage may be used according to [11] or [12]. This approach is based on determining the amount of internal curing water that should compensate for the volume of chemical shrinkage. According to this approach, when chemical shrinkage is compensated, self-desiccation theoretically would not take place and autogenous shrinkage would be fully mitigated. This leads to the following equation:

   $$w/b_{SAP} = CS \cdot \alpha_{max} \cdot \rho_w \qquad (1)$$

   where CS [cm^3/g of binder] is the chemical shrinkage of the binder, α_{max} [–] is the estimated maximum degree of hydration of the binder, and ρ_w [g/cm^3] is the density of water. The first parameter is a property of the specific binder, while the second parameter depends on the mix composition (binder and *w*/*b*) and possibly on other parameters, e.g., temperature or additives that affect hydration. The parameters of Eq. (1) should be experimentally determined for the concrete with a specific binder under consideration. For the specific case of ordinary Portland cement, there exist a number of experimental studies that can be used as a reference, e.g., [11, 12]. In such a case, CS can be assumed as equal to 0.07 cm^3/g of cement reacted, while α_{max} can be estimated using the Powers model for saturated conditions [13, 14]. For convenience, α_{max} can be also assumed to be equal to 1, leading to a maximum theoretical amount of internal curing. Note that, in the reaction of silica fume (or other silica-rich supplementary cementitious materials) with portlandite, considerably higher CS takes place, up to 0.20 cm^3/g of silica fume reacted [4]. CS can also be determined experimentally, e.g., according to the ASTM standard [15].

According to the theoretical approach for Portland cement, w/b_{SAP} should be lower than 0.07 [11, 12], which should allow for full mitigation of autogenous shrinkage. As shown by experimental studies, intermediate values should still allow for a reduction of autogenous shrinkage.

Furthermore, according to the theoretical approach for Portland cement, autogenous shrinkage should not take place in concretes with a *w/b* above about 0.42–0.46, where the cement reaches full hydration, even in the absence of any curing at all. However, for binders different from ordinary Portland cement, i.e. including supplementary cementitious materials, this boundary may be considerably higher.

An important issue regarding the determination of w/b_{SAP} arises from the impact of the entrained water on mechanical properties and workability. When the performance of concrete is evaluated with regard to a reference concrete, it is important to decide whether w/b_{SAP} is added on top of the *w/b* of the reference concrete, or whether the total *w/b* of the concrete with SAP and of the reference concrete are the same (in the latter case, the basic *w/b* of the concrete with SAP is lower than the total *w/b* of the reference concrete, i.e., basic *w/b* = total *w/b* − w/b_{SAP}), see Sect. 2.2.

2. Having determined the desired w/b_{SAP}, the amount of SAP to be added to the dry concrete mixture should be determined based on the sorption capacity AC in cement filtrate (emulating the pore solution absorbed by the SAP during mixing) and the total amount of internal curing water, $w/b_{SAP} \cdot m_{binder}$:

$$m_{SAP} = \frac{w/b_{SAP} \cdot m_{binder}}{AC} \quad (2)$$

The sorption capacity AC can be determined according to the recommendation [8].

As a guide, for a given SAP with 15 g/g sorption capacity and following the theoretical approach described in step 1) for the case of full mitigation of autogenous shrinkage in concrete made with Portland cement at basic *w/b* of 0.30, the w/b_{SAP} should be equal to 0.054, leading to an amount of SAP equal to 0.33% SAP by mass of binder (cement), and the total amount of mix water corresponding to the total *w/b* of 0.300 + 0.054 = 0.354. In this case, the amount of SAP will typically be in the range 1–2.5 kg/m^3 of concrete.

It is possible that for some SAP and some mix compositions of concrete, the actual absorption of the SAP in the mix may be lower than that determined in a free sorption test, e.g. [4]. If this is the case, less water will act as internal curing water than the amount that is theoretically necessary to eliminate autogenous shrinkage. At the same time, the additional water added to the mix and not absorbed by the SAP will contribute to increase the basic *w/b*. This higher basic *w/b* will not allow to reduce self-desiccation or autogenous shrinkage as efficiently as the water entrained in the SAP. If the mix with added SAP still undergoes autogenous shrinkage according to the evaluation methods proposed in Sect. 3, an iterative procedure based on increasing gradually the amount of added SAP, while controlling the possible negative impact on workability, is recommended.

2.3 Application of SAP in concrete mixes: practical issues

Absorption of SAP may be affected by temperature. While it was found in [16] that temperature in the range of 10–30 °C has only negligible effect on the sorption capacity, this may change at more extreme temperatures. Further, sorption rates in the first minutes after mixing may be delayed at low temperatures. Thus, the temperature at which the sorption capacity of the SAP is determined should correspond to that at which concrete mixing is performed, in particular if it takes place at concrete temperatures outside the range of 10–30 °C.

Before mixing, the SAP should be stored under conditions that prevent polymer degradation or premature moisture absorption. The SAP samples should at all times be stored in sealed, preferably opaque containers or bags to minimize contact with moisture and protect from light. Before placing them in containers, they should be equilibrated at < 60% RH and (20 ± 2) °C until there is no further mass change. They should not be placed in direct sunlight, since UV-light may change their properties.

According to a numerical study [17] that addressed the need of uniform distribution of curing water from the SAP to the surrounding cement paste, the SAP should preferably not exceed a particle size of about 1 mm in the swollen state. For a given SAP of absorption capacity AC equal to 15 g/g with spherical particles and density of dry particles equal to 1.4 g/cm^3 [7], this means that their volume will increase by about 20 times upon absorption in the cement paste. This means further that in order not to exceed the recommended limit of the particle size in the swollen state (1 mm), their diameter in the dry state should not be larger than about 350 μm.

Due to the small amount of dry SAP (up to few kg/m^3 of concrete) in comparison to the main constituents of concrete (cement, aggregates, etc.), attention should be paid to distributing SAP particles properly in the mix volume. The recommended practice is to add SAP in the dry state to a dry mix, which promotes the uniform distribution of the SAP and additionally allows a better control of the sorption process. The extra curing water is then added with the mixing water.

When SAP are added to a concrete mix where the total *w*/*b* is not changed compared to the reference mix without SAP, any adjustment of the volume of the mix is normally unnecessary due to the small amounts of SAP that are usually added. In this case, the loss of workability can usually be compensated with superplasticizer. When the w/b_{SAP} is added to increase the total *w*/*b*, i.e. "on top" of a mix composition, the resulting increase of mixture volume is not negligible and should be accounted for.

Finally, it should also be noted that concretes with SAP may still require external curing to be applied on concrete surfaces after casting, e.g., to limit the effects of evaporative drying, especially under harsh environmental conditions.

3 Evaluation of performance of SAP

3.1 General rules

The performance of the SAP should be evaluated not only in terms of their absorption capacity, but primarily in terms of the reduction in autogenous shrinkage and the possible negative influence of SAP addition on other concrete properties; see Sect. 2.2.

3.2 Testing methods for autogenous shrinkage

One of the most commonly applied test methods for autogenous shrinkage is the corrugated tube protocol described in ASTM C1698-09. Length changes after the time of final set are measured using specimens of cement paste or mortar containing SAP enclosed in corrugated plastic tubes that are placed on a rigid framework, see [18, 19]. An important limitation of the ASTM C1698-09 method regards its application to cement pastes, mortars, or concretes with small aggregates only, i.e., below 4.75 mm according to the standard, due to the need of pouring the fresh mix into a corrugated tube of minimum internal diameter of only 24 mm. However, this characteristic size is relevant for high-performance mortar or UHPC where autogenous shrinkage needs to be prevented. This means that the method can be directly used for such mixtures; see [7]. Moreover, testing on cement paste or mortar with small aggregates should still enable comparison of the effects of different types and dosages of SAP with respect to the reference mixes without SAP. Several other sophisticated methods have been proposed; for more details see e.g. [20].

When the purpose of performance evaluation of SAP is to determine the autogenous-deformation behaviour of specimens with greater cross-sections, which may be the case for concretes with large aggregates, other test methods can be used. In particular, if stresses induced by restrained shrinkage are of interest, measuring stress development at early ages is necessary in addition to measuring deformation, e.g., by employing ring-tests or other restrained shrinkage tests.

The duration of autogenous shrinkage tests or measurements of corresponding stress development should be decided depending on the specific mix that is considered, as to allow the major part of its autogenous shrinkage to be assessed. Typical measurement times are in the range 1 week to 1 month.

3.3 Possible negative effects of applying SAP

In conjunction with the effect of SAP addition on the reduction of autogenous shrinkage, some negative side effects on different material properties may occur.

It should be mentioned that the addition of SAP along with additional curing water may have a negative effect on the mechanical properties of concretes, since the SAP form empty cavities after they release the curing water and thereby increase the porosity of the concrete. This effect is, however, usually not larger than that of a simple increase of *w/b* in the mix design. In many studies, no substantial decrease and in some cases even an enhancement of mechanical properties was observed when compared to concrete without SAP and the same *w/b* as the total *w/b* of the mix with SAP [5].

A further negative effect may arise from the reduction in workability occurring when SAP are added, in particular when the water absorbed by the SAP is not properly accounted for in the *w/b*. An extreme case is when the SAP are added to the concrete without changing its total *w/b*, consequently leading to a decrease in the basic *w/b* and less water is available as mixing water. This can usually be compensated by increasing the amount of superplasticizer. On the other hand, when SAP are added along with the extra water that they will absorb, some change of rheological properties may still take place. Similarly to other chemical admixtures, SAP affect the plastic viscosity and yield stress of fresh mortar or concrete in different ways. Particular effects, especially on the development of these two parameters over time, depend on the type and particle size of the SAP on the one hand, and on the mix composition on the other [21].

A further side effect related to a possible reduction of workability may be due to the entrapment of air in the mix (if the air cannot escape when the mix becomes less workable), and, consequently, a further negative effect on mechanical properties.

It is always recommended to check the effect of the SAP on the following properties of concrete to assess any negative effect: fresh concrete properties (workability, pumpability, air content, etc.), and hardened concrete properties (mechanical properties, durability characteristics, etc.). If with the addition of SAP the w/b of the mix is increased by additional internal curing water, the changes in mechanical properties should not exceed those induced by the increased w/b without addition of SAP; i.e. the net effect of SAP can be assumed as negligible [5].

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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