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Guidelines for using superabsorbent polymers (SAP) in concrete construction

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Abstract

Superabsorbent polymers (SAP) are highly promising chemical admixtures for concrete, offering numerous advantages in terms of water control within the mixture. These polymers present exciting possibilities for enhancing the rheological properties of fresh concrete and addressing challenges related to autogenous and plastic shrinkage through internal curing. An interesting characteristic of SAP is their ability to create stable pore systems regardless of the consistency of the concrete, the addition of superplasticizers, or the chosen method of placement and compaction. As a result, SAP emerges as a viable alternative to air-entrainment agents. While the benefits of using SAP are evident, there is a lack of standards regulating their application by concrete producers. In this regard, the recommendations offered by RILEM may pave the path toward formal regulation. This article aims to provide an overview of these recommendations.

Keywords: Concrete admixture; Superabsorbent polymers; Hydrogel; Mitigation of shrinkage; Durability enhancement

1 Introduction

Construction chemicals such as superplasticizers play a pivotal role in the advancement of concrete technologies. They offer innumerable opportunities to shape the properties of cement-based materials in their fresh, hardening, and hardened states. The use of Superabsorbent Polymers (SAP) as a new type of concrete admixture further broadens these possibilities by providing robust control over the key concrete ingredient, namely water. Through purposeful water absorption and/or release, SAP can influence multiple properties of concrete. Applications of SAP include modifying the rheology [1], mitigation of plastic [2] and autogenous shrinkage [3], improvement of freeze/thaw resistance [4], self-sealing [5], and self-healing of cement-based construction materials [6].

Answering the increasing interest of the research community and industry in SAP as a concrete admixture, RILEM TC 225-SAP was established in 2007. The TC 225-SAP coordinated the research efforts of different groups interested in the topic and explored possible fields of application. It also delivered a comprehensive State-of-the-Art Report [7] summarizing the scientific knowledge and the application potential of SAP in the concrete industry. Moreover, TC 225-SAP coordinated two interlaboratory studies on: i) mitigating autogenous shrinkage of high performance concrete [3], and ii) enhancement of freeze-thaw resistance of concrete [4]. The activities of the TC 225-SAP culminated in an international conference in 2014, which focused on the application of new additives, particularly SAP, in concrete construction [8].

The work was continued by the new RILEM committee, TC 260-RSC, which started in 2014. The major goal of this new TC was to facilitate the introduction of SAP into construction practice by preparing technical recommendations on the use of SAP in concrete. To establish a solid basis for that, the TC 260-RSC completed additional literature reviews and interlaboratory studies on the characterization of SAP and their performance in concrete: i) A review of characterisation methods for Superabsorbent Polymer (SAP) samples to be used in cement-based construction materials [9], ii) a RILEM Round-Robin Test on testing superabsorbent polymer (SAP) sorption properties prior to implementation in concrete [10], and iii) an interlaboratory test on the effect of Superabsorbent Polymers on the mitigation of plastic shrinkage cracking of conventional concrete [2]. Eventually, three RILEM recommendations were published: i) for testing sorption by SAP prior to implementation in cement-based materials [11], ii) for using SAP to mitigate autogenous shrinkage [12], and iii) for using SAP to improve the freeze-thaw resistance of cement-based materials [13]. These will be explained in greater detail in this article.

Another important activity of the TC was the 3rd International Conference on the Application of Superabsorbent Polymers (SAP) and Other New Admixtures Towards Smart Concrete organized by TC 260-RSC in Skukuza, South Africa, which brought together many experts working on SAP and gave them the chance to advance their understanding and identify the pending questions surrounding the application of SAP in concrete construction [14]. Furthermore, the committee

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prepared and published an update to the earlier RILEM State-of-the-Art Report [15]. It summarized the progress in the research and development of Superabsorbent Polymers related to application in cement-based building materials over the decade past since the publication of that book. The final contribution of the TC 260-RSC was the result of an interlaboratory study on verification of the presence of Superabsorbent Polymers (SAP) in fresh concrete. This article has been submitted to the Materials and Structures journal for publication [16].

While the cited works encompass all pertinent aspects of SAP in concrete construction, this article aims to present a concise overview of the recommendations for using SAP in concrete construction.

2 Testing sorption by SAP prior to implementation

Superabsorbent polymers can be synthesized principally through either bulk polymerization in substance or inverse-suspension polymerization. The former produces a block result, which is then crushed into small particles of the desired size and irregular shape, see Figure 1a. The latter method produces spherical particles, see Figure 1b. Both methods allow the use of different modes of cross-linking, for example, the addition of multivalent monomers in small amounts.

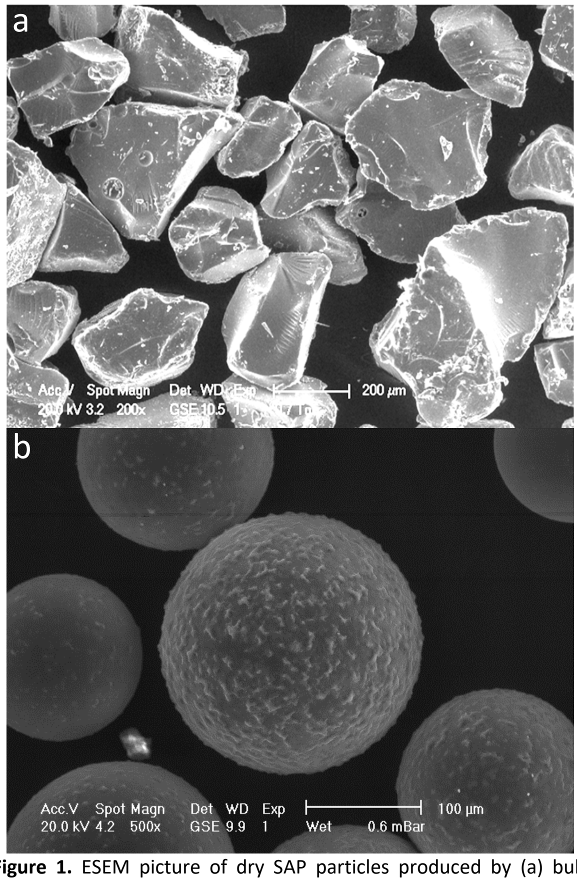

Figure 1. ESEM picture of dry SAP particles produced by (a) bulk polymerization and (b) inverse suspension polymerization; Images: TU Dresden.

For their application in concrete, the following properties of SAP are particularly relevant:

- Absorption and desorption behaviour in concrete (or, alternatively, in cement paste filtrate),
- Chemical stability in ionic solutions;
- Particle size (distribution).

The sorption of SAP and kinetics of the process can differ significantly depending on SAP composition and grading, as well as on properties of the sorbed fluid. It needs to be tested prior to implementation of SAP in cement-based materials. Therefore, RILEM issued a Recommendation on testing sorption by superabsorbent polymers [11]. It emphasizes the testing of SAP's free sorption capacity and kinetics when exposed to ionic liquids relevant to cement-based construction materials, namely their pore solutions. These function as pre-tests in screening SAP samples for their potential use as multifunctional admixtures in such binder systems. Two main sorption capacity testing methods are recommended: the tea-bag method and filtration methods.

The tea-bag method uses a saturated teabag filled with SAP and immersed in a predetermined fluid. At regular time intervals, the tea-bag is weighed. In this way, the kinetics and sorption capacity in the respective liquid are determined gravimetrically; see Figure 2. The sorption capacity SC is calculated as SC = $(m_3 - m_2 - m_0)/(m_2 - m_1)$, with $m_0 = m_B + m_A$. To ensure reliability of the results, three individual tea-bags should be prepared for each SAP sample.

The filtration method is a procedure used to determine the sorption kinetics and sorption capacity after filtration of a container with a specific quantity of initially dry and freely swellable SAP particles and a defined mass of fluid. By aligning the results of filtration setups at different sorption times, the swelling kinetics and capacity of the SAP sample in the respective fluid are obtained. The sorption capacity SC is calculated as SC = $(m_2 - m_3)/m_1$.

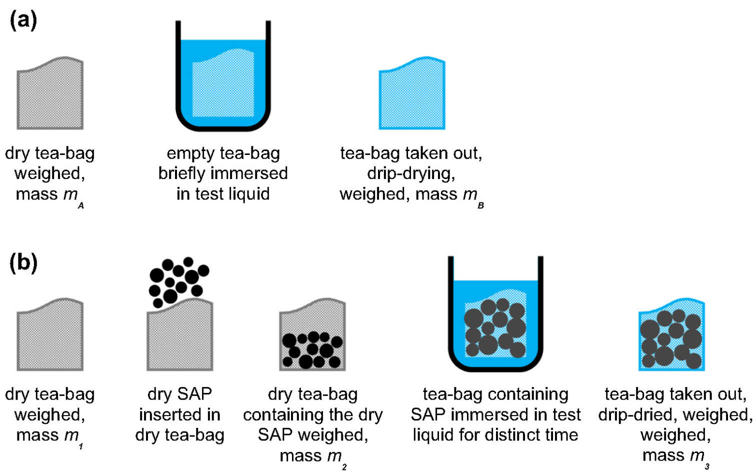

Figure 2. Tea-bag method steps: (a) assessment of wet dead load, to be averaged from at least ten individual tea-bags, and (b) assessment of SAP sorption [11].

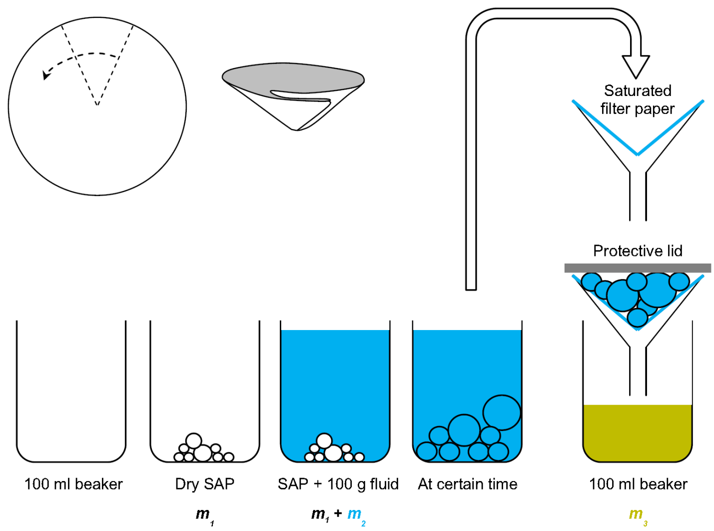

Figure 3. Filtration method steps [11].

3 Using SAP to mitigate autogenous shrinkage

Internal curing with SAP is recommended in concretes that experience high self-desiccation and autogenous shrinkage. If not properly limited, these may lead to the accumulation 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).

SAP particles, serving as internal reservoirs of water, can gradually release this water as self-desiccation dries out the pores in the concrete. Dry SAP particles are added during concrete mixing and absorb water in the process, forming 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. As a result of the pores emptying, the SAP particles released their water to compensate for chemical shrinkage. As a result, self-desiccation and the resulting autogenous shrinkage are limited or completely avoided [17].

The RILEM recommendation on the application of SAP to mitigate autogenous shrinkage [12] focuses on i) proportioning of concrete mixtures containing SAP, and ii) evaluation of the performance of SAP.

3.1 Proportioning of concrete mixtures containing SAP

The dosage of SAP necessary for mitigating autogenous shrinkage depends on the properties of the SAPs, especially on their sorption capacity in cement pore fluids; see Section 2. The sorption capacity of SAP used for internal curing in concrete is usually within the range of 10–30 g of pore solution per gram of SAP. 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.

The recommended approach to determining the dosage of SAP consists of the following steps.

Step 1 involves determining which part of the total *w/b* of a mix should participate in the internal curing process. Total *w/b* is 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 the mitigation of autogenous shrinkage and potential negative effects on mechanical properties, workability, or any other property that may be important to the concrete considered; see Section 3.2. It is assumed that the amount of internal curing water needed to fully mitigate autogenous shrinkage corresponds to the amount of water required to compensate for the volume of chemical shrinkage [18]. This leads to the following equation:

$$w/b_{SAP} = CS \cdot \alpha_{max} \cdot \rho_w \tag{1}$$

in which *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 parameters should be experimentally determined for the concrete with a specific binder under consideration. However, the results of some existing experimental studies can be used as a rough estimation [12].

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}).

In **Step 2**, the amount of SAP to be added to the dry concrete mixture should be determined based on the sorption capacity SC in cement filtrate (emulating the pore solution absorbed by the SAP during mixing) and the total amount of internal curing water, $w/b_{SAP} \cdot m_{binder}$: $m_{SAP} = (w/b_{SAP} \cdot m_{binder})/SC$. The sorption capacity SC can be determined according to the recommendation described in Section 2.

The typical amount of SAP used to mitigate autogenous shrinkage will range between 1–3 kg/m^3 of concrete. Despite the small amount of dry SAP compared to the main constituents of concrete (cement, aggregates, etc.), proper distribution of SAP particles in the mix volume is crucial. 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 better control of the sorption process. The extra curing water is then added with the mixing water.

It should be noted that concretes with SAP usually still require external curing to be applied to concrete surfaces after placement, e.g., to limit the effects of evaporative drying, especially under harsh environmental conditions.

3.2 Evaluating performance of SAP

The performance of the SAP should be evaluated not only in terms of the reduction in autogenous shrinkage, but also the possible negative influence of SAP addition on other concrete properties.

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 [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. When the purpose of performance evaluation of SAP is to determine the autogenous deformation behavior 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 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. A further side 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*. This can usually be compensated by increasing the amount of superplasticizer. 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 the addition of SAP; i.e. the net effect of SAP can be assumed as negligible.

4 Use of SAP for improving freeze–thaw resistance

The major positive effect of SAP in concrete and other cement-based materials is the creation of size- and shape-designed pore systems within these materials to improve their durability, especially in terms of freeze-thaw resistance [4]. Such application can be particularly relevant as an alternative to traditional air-entraining agents (AEAs) where long concrete placement hauling durations, highly flowable mixtures, or high ambient temperatures can lead to the loss of a portion of the entrained air. Shotcrete with well-controlled and stable SAP voids can also be produced, while the use of conventional AEAs leads to the loss of a significant, and often difficult to estimate, portion of air bubbles upon shooting. Pore systems built up as a result of SAP addition are robust and remain stable during the initial stages of stiffening, setting, and hardening—regardless of the consistency of the fresh mixture, the addition of further chemical admixtures, such as superplasticizers, or the method of placement and consolidation. These facts represent pronounced improvements by SAP compared to conventional air-entrainment.

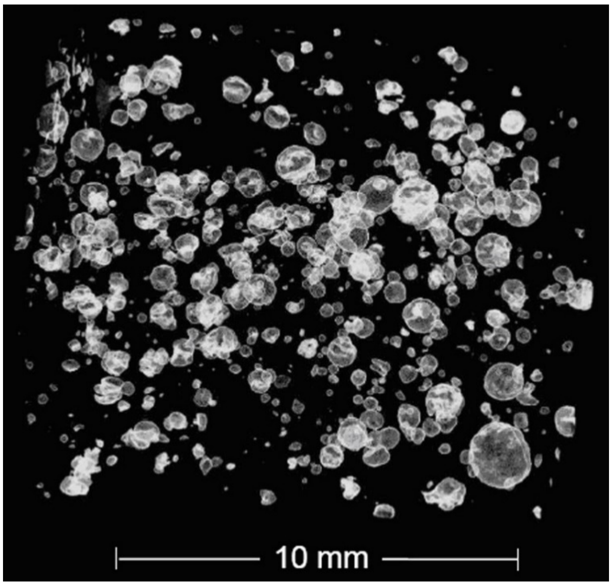

Figure 5. CT image of SAP void distribution in hardened cement paste [20].

The RILEM Recommendation for using SAP to improve freeze-thaw resistance aims to consolidate the information needed for a successful selection of SAP material, its proper application in concrete mixture design, and verification of its performance.

4.1 Proportioning concrete mixture containing SAP

The working mechanism of SAP entrainment appears to be similar to that of entrained air bubbles, as explained in [21]. During the hardening and/or desiccation process, SAP particles release absorbed water and leave behind cavities of the same size as the swollen SAP particles; these cavities act like air voids. Therefore, the principles of an effective entrained air pore system applicable to AEA (regarding spacing factor and other characteristic parameters of the micro air pore system) hold true, in principle, when using SAP. However, the existing beneficial effects of SAP are still subject to fundamental scientific studies. Several questions have not yet been answered, including, for example, the role of re-absorption of water by dried-out SAP moieties residing in the voids. The air void counting/measuring method on hardened concrete can also be applied to concrete with SAP. While this is straightforward with spherical SAP, research is ongoing to modify it for the case of crushed SAP particles. On the other hand, the generally performed testing of the total air content in fresh concrete, as a verification of an appropriate air content to enhance freeze-thaw resistance, cannot be transferred to cement-based materials containing SAP. Note that besides the SAP voids, there are always some air voids entrained into concrete in the process of mixing, even in the absence of AEA. Since some of these air voids are also effective in freeze-thaw resistance, they can be taken into account.

The following steps present an approach for determining the SAP dosage for enhanced freeze-thaw resistance of concrete.

In **Step 1** we specify the targeted air pore volume $V_{air;target}$ (%), which is necessary for satisfactory freeze-thaw resistance, and subtract the original air pore volume V_{air} (%) of the concrete mixture: $V_{SAP} = V_{air;target} - V_{air}$, where V_{SAP} is the entrained volume represented by swollen SAP particles. The volume of pores produced by first swollen and then desorbed SAP is presumably equal to the amount of absorbed water (for simplicity, the volume of dry SAP particles is neglected).

In **Step 2** we estimate water-to-cement ratio (w/c). If extra water is added for SAP absorption, the total w/c is given by $(w/c)_{total} = (w + w_{SAP})/c$, where w and c represent the masses of water and cement, respectively, in kg/m^3 of concrete. If no extra water for SAP absorption is added, the SAP will absorb some of the mixing water, reducing the content of free water that is available for hydration and formation of capillary pores. In this case, the total w/c remains constant, but the effective w/c of the cement paste becomes $w/c = (w - w_{SAP})/c$.

In **Step 3**, using the sorption capacity (CS, see Section 2) in the cement pore solution, the amount of SAP m_{SAP} (kg/m^3) can be calculated: $m_{SAP} = w_{SAP}/CS$. In relation to the amount to cement, we can state that $m_{SAP\%c} = m_{SAP}/c$.

With regard to obtaining a finely distributed pore system and small spacing factors, it is recommended to choose SAP with an absorption behavior that yields relatively small swollen SAP particles. Some existing guidelines consider the maximum pore size in void counting on hardened concrete samples as 300 µm. However, results from [4] indicate that SAP particles of greater sizes also contribute to enhancing freeze-thaw resistance. The effect of different ranges of SAP pore sizes on frost durability has not yet been extensively investigated. Therefore, no limit values can be provided at this stage. Nevertheless, spacing factors demanded by existing codes can be used for the system of voids (comprising SAP voids plus air bubbles). Note that suspension polymerized SAP may contain surfactants, which can lead to air entrainment, thus positively influencing frost durability. Such air entrainment can be measured in fresh concrete using the pressure method.

With respect to incorporating SAP into concrete, as well as potential negative effects of SAP on the rheological and mechanical properties of concrete, please refer to Section 3.

4.2 Testing methods to characterize effect of SAP

Firstly, we address here the methods for verifying the presence of superabsorbent polymers (SAP) in freshly mixed concrete and estimating the quantity of SAP. Traditional methods used to assess air entrainment, such as the pressure method, cannot be applied for this purpose. Instead, RILEM TC 260-RSC suggests new methods based on flushing concrete with excess water [16]. These methods allow the separation of light, water-sorbed hydrogel particles from the mineral components in the fresh concrete, making these particles available for further testing. Two types of tests were proposed: Test 1 is used for visual verification of the presence of SAP (qualitative test), while Test 2 enables the quantification of the mass of the collected SAP, serving as a proxy for their concentration in concrete (quantitative test). Based on the results of an extensive interlaboratory study, it was suggested that Test 1 should be applied in the field, while the quantification method according to Test 2 was found to need further refinement.

Any method used to assess frost resistance or deicing salt scaling resistance of cement-based materials is suitable for assessing the effect of SAP on such properties. This was confirmed by the outcomes of a comprehensive interlaboratory study [4].

Traditional void counting methods, such as those outlined in reference [22], can be used to evaluate voids generated by SAP. The spacing factor, and in some norms, an additional parameter, characterize the air void system of hardened concrete. If the content and particle size distribution of the dry SAP, as well as its absorption capacity, are known, the number and size of cavities formed in the concrete due to SAP addition can be theoretically calculated, providing an estimation of the real void system. The air-void system can be evaluated using the ASTM C457 [23] test method, which is designed to determine the air content, specific surface, and spacing factor of air bubbles in hardened concrete.

The test method described in [22] is based on the assumption of spherical pores. Consequently, angular pores generated by bulk polymerized SAP do not qualify for such void counting due to their irregular shapes. In such cases, the method provides only approximate results. A more precise way to evaluate a 2-D sample based on image analysis is described in [33]. These methods take into account all air or SAP-induced voids. To differentiate SAP-induced voids from other air voids, in the case of angular SAP voids, a shape analysis can be performed. To detect single SAP pores, hardened concrete samples or prepared thin sections can be examined under a microscope. The dehydrated SAP particle can be found on the pore walls.

5 Summary

The use of superabsorbent polymers (SAP) as a new type of concrete admixture broadens the possibilities for shaping and controlling concrete properties in its fresh, hardening, and hardened states. However, the widespread use of SAP in concrete construction is still emerging. Transitioning from the research lab to practical construction requires considerable effort. In response to this, RILEM initiated two subsequent technical committees focusing on the use of SAP in concrete construction. The first committee, TC 225-SAP, issued a comprehensive state-of-the-art report and performed some crucial interlaboratory studies. The second committee, TC 260-RSC, expanded interlaboratory studies and round robin tests. Subsequently, based on the accumulated knowledge, the committee prepared and published a series of RILEM Recommendations for practitioners. These recommendations cover the most relevant aspects related to the use of SAP in concrete construction, namely, testing sorption by SAP prior to implementation in cement-based materials, using SAP to mitigate autogenous shrinkage, and using SAP to improve the freeze-thaw resistance of cement-based materials. This article provides an overview of the goals, genesis, and contents of these documents. It aims to encourage practitioners and researchers to use these recommendations as reliable references in their work. The positive experiences gained from applying SAP and the recommendations in construction practice may eventually pave the path toward formal regulations by national and international standardization bodies.

Acknowledgements

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