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Controlled Air-Entrained Concrete with Superabsorbent Polymers (SAP): A Robust Approach to Freeze-Thaw Durability

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TECHNICAL NOTE

Superabsorbent polymers (SAP) are cross-linked polymers that are capable of absorbing and retaining several times their own dry weight in aqueous solutions. When incorporated into fresh concrete, these polymers release the absorbed water during the ongoing hydration process and subsequently shrink, thereby creating an artificial air void structure within the hardened concrete. The specific properties of SAP enable their application in a wide range of concrete technology scenarios. Historically, SAP have primarily been used to regulate the internal moisture balance of high-performance or ultra-high-performance concretes, serving as an internal curing agent to mitigate autogenous shrinkage [1, 2, 3]. Furthermore, systematic studies have investigated the use of SAP for modifying rheological properties [4, 5] and for promoting self-healing of cracks in concrete [6, 7, 8].

The formation of stable artificial air voids in hardened concrete also enables the use of SAP as an alternative to conventional air-entraining agents (AEA) to enhance the freeze–thaw and de-icing salt resistance of concrete [9, 10, 11]. These artificial pores function as expansion chambers for freezing water and, due to their specific size, interrupt capillary transport within the concrete matrix [12]. Conventional air-entraining agents, such as those based on wood resins or synthetic compounds, are subject to a wide range of physical and chemical influences that affect air void formation and stability. These influences arise from production-related variables, mix design parameters, and environmental conditions [13, 14, 15]. In contrast, artificial air

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void systems generated by SAP are significantly more robust, primarily because the air voids are introduced into the fresh or hardened concrete through purely physical processes.

Superabsorbent polymers (SAP) significantly alter the fresh concrete properties - particularly its rheological behaviour - compared to conventional air-entrained concretes, due to the water-absorbing capacity of SAP. As a result, the amount of water that is rheological effective in the fresh mix is reduced. To compensate for this, and in accordance with [16] an additional 18 kg of water per kg of SAP is added - without being included in the effective water-to-cement (w/c_{eq}) ratio - corresponding to approximately 50% of the maximum sorption capacity of the SAP used. Nevertheless, the altered fresh concrete properties and the reduced rheological active water content manifest clearly in an increased demand for superplasticizers to achieve the desired workability. Compared to conventional air-entrained concretes, SAP-modified concretes require significantly higher dosages of superplasticizer to attain equivalent consistency. Despite this, SAP concretes exhibit excellent fresh concrete stability, particularly with regard to resistance against segregation of the coarse aggregates [17].

Due to their physical mode of action, SAP exhibits highly robust behaviour in introducing artificial air voids into fresh concrete, even when the raw materials or cement type are varied. In contrast, the use of conventional air-entraining agents (based on wood resins) shows pronounced interactions between the admixture and the type of cement. Typically, the dosage required to achieve a consistent air void content in fresh concrete must be adjusted within a range of 0.8 kg/m³ to 2.4 kg/m³ depending on the cement used. Since the micro-air void content (Ø ≤ 300 µm) in the hardened concrete structure is a decisive factor for achieving high freeze–thaw resistance, these effects must also be verified in the hardened state. Investigations conducted on concretes with very low paste volumes indicate that SAP can reliably ensure a sufficient micro-air void content (Ø ≤ 300 µm) in the hardened concrete, thereby enabling high resistance to freeze–thaw damage [17]. The typical dosage of SAP ranges from 1.0 to 2.0 kg/m³ [16].

Figure 1 illustrates the temporal progression of the relative dynamic modulus of elasticity (left) and surface scaling (right) for the investigated concrete mixtures [18]. Regardless of the type of air-entraining agent used, no significant decline in the relative dynamic modulus was observed over the freeze–thaw cycles. This indicates that both the conventional air-entraining agent and the superabsorbent polymers (SAP) effectively introduce a stable artificial micro-air void system into the concrete matrix, ensuring high freeze–thaw resistance.

However, with respect to surface scaling, the conventional air-entrained concrete with 360 kg/m³ CEM II/C-M (S-LL) and a w/c ratio of 0.5 exhibited somewhat increased scaling as freeze–thaw cycles progressed (Figure 1, right). After 28 cycles, the cumulative surface scaling for the AE concrete reached 642 g/m², while the SAP-modified concrete showed only 116 g/m². According to the threshold of 1000 g/m² after 28 freeze–thaw cycles [18, 19], both concretes demonstrate sufficient freeze–thaw durability.

A notable observation was the markedly lower capillary water absorption of the SAP concrete after 7 days of one-sided water exposure. The SAP-modified concrete absorbed 0.86 wt.% water, compared to 1.83 wt.% for the AE concrete. This suggests that SAP usage results in a denser capillary pore structure, which likely contributes to the reduced surface scaling under freeze–thaw stress.

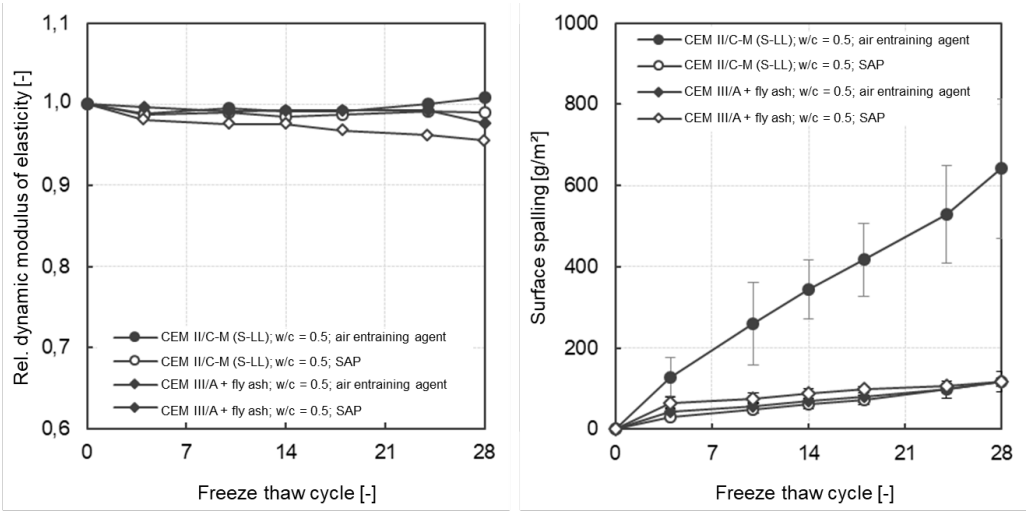

Figure 1: Relative dynamic modulus of elasticity (left) and surface scaling (right) of two concrete compositions with both air-entrainer and SAP [18]

In summary, it can be concluded that superabsorbent polymers (SAP) are well suited for the targeted production of air-entrained concrete. Such concretes exhibit mechanical and durability-related properties comparable to or even exceeding those of concrete produced with conventional air-entraining agents (e.g., based on wood resin). Notably, the robustness of SAP-modified concrete against variations in raw material composition is a key advantage, as the air voids are introduced into the fresh and hardened concrete through purely physical processes. The influence of additional material variability and environmental conditions has been further investigated in systematic studies [20].

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