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# Self-sealing of cracks in concrete using superabsorbent polymers

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ABSTRACT

Cracks in concrete can self-heal when exposed to prolonged wetting, but this is limited to narrow cracks. In practice, cracks > 0.2 mm cause leakage and impair performance of structures. The potential of superabsorbent polymers (SAPs) to self-seal such cracks was investigated via transport experiments, microscopy and modelling. Forty samples containing SAP and through-thickness cracks were subjected to 0.12 wt.% NaCl at 4 m/m pressure gradient to simulate groundwater seepage. Results show that SAP can re-swell and seal cracks, for example in the case of 0.3 mm cracks reducing peak flow rate and total flow by 85% and 98% respectively. Increasing SAP dosage accelerates sealing, but imparts a strength penalty and this limits practical applications. Modelling suggests that the effectiveness of SAP can be enhanced by increasing its re-swelling ratio and particle size, and depressing its initial swelling. These variables increase the SAP exposed in a crack and the gel volume available to seal it.


## 1. Introduction

Concretes that are appropriately formulated and manufactured tend to be durable and have good resistance to water penetration. However, concrete is prone to cracking when exposed to structural loading or non-structural factors such as shrinkage, thermal effects and physio-chemical reactions [1]. Indeed, a fundamental principle of structural design is that concrete is cracked in the tension zone. Cracking causes leakage and affects watertightness, a critical serviceability requirement for many structures such as basements, retaining walls, reservoirs, dams, tunnels, pipelines and waste repositories. Cracks also act as pathways for aggressive agents, thereby accelerating deterioration mechanisms [2]. When cracks percolate, their influence on transport far outweighs that of capillary pores because of their larger size and shorter flow lengths. Therefore, cracks not only affect watertightness, but also long-term durability of concrete structures.

Cracks may heal when exposed to water [3–6,44], but this is usually limited to narrow cracks (<0.3 mm) and dependent on many conditions such as mix composition, hydraulic pressure and temperature. The crack width limit for self-healing has been reported in some studies as 0.05 mm or below [6,26]. According to current design guidance, concretes with cracks wider than 0.1 mm are expected to lose their watertight characteristics [2,7,8]. For example, ACI 224R-01 [7] recommends a crack width limit of 0.1 mm for water-retaining structures while Eurocode 2 [8] specifies that full thickness cracks should be less than 0.2 mm to limit leakage for structures exposed to a hydrostatic pressure gradient of ≤5. Crack width can be limited by appropriate reinforcement detailing and provision of movement joints. However, special measures (e.g. external liners and pre-stressing) will be required if no leakage is permitted [8]. Methods such as surface coating, resin injection and integral water resisting admixtures are also often used to prevent leakage, but are not always effective, for example where there is significant movement, e.g. ground subsidence. Coatings deteriorate and require maintenance or reapplication. Water resisting admixtures are generally divided into hydrophobic or water-repellent chemicals, finely divided solids and crystalline materials. Finely divided solids and hydrophobic waterproofing admixtures are not considered effective in crack blocking. Some crystalline type admixture may seal very fine cracks, but only by reacting with unreacted cement and moisture to form crystalline products [9]. Many claims have been made concerning the effectiveness of these admixtures, but most reported tests focus on their effect on the reduction of permeability of un-cracked concrete. There seems to be a lack of independent data to substantiate their effect on crack blocking [10].

Advances in materials science have led to the development of a range of smart adaptive materials that heal themselves when cracks develop. A well-known example is a self-healing polymer containing embedded microcapsules filled with a healing agent that is ruptured during cracking, releasing the agent into the crack where it mixes with a catalyst and polymerises [11]. There have been other similar attempts to induce self-healing in concrete using brittle glass fibres or capsules containing adhesives [12,13]. More recently, much emphasis has been placed on developing bacteria-induced precipitation to heal cracks e.g. the work of Van Tittelboom et al. [14] and Jonkers et al. [15]. For successful application in civil engineering structures, new materials need to satisfy many criteria including affordability, availability, robustness, durability, performance across a range of exposure environments, chemically inertness and low toxicology. Superabsorbent polymer (SAP) is a promising class of materials that potentially meets these criteria.

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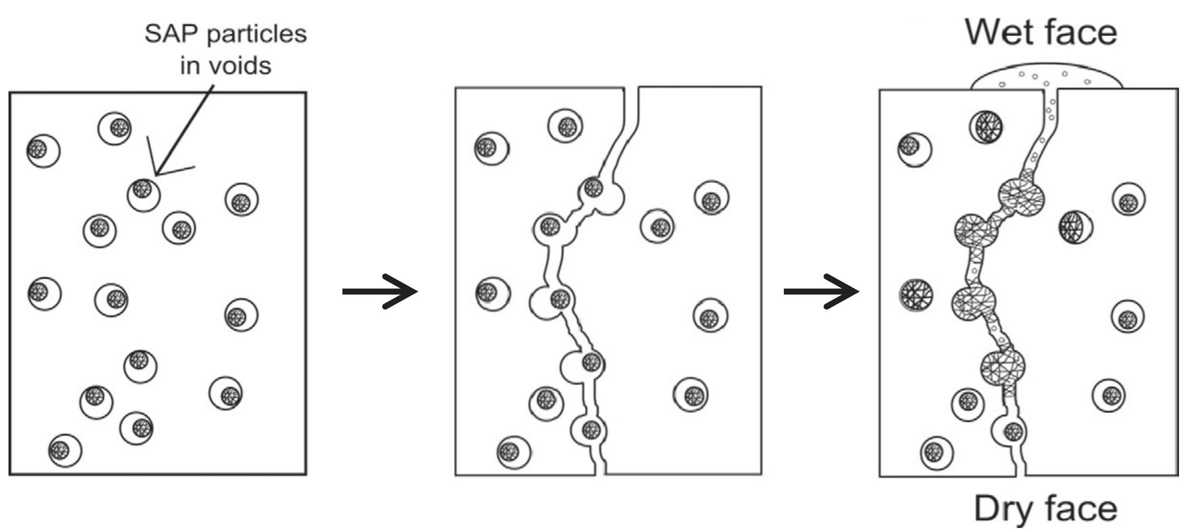
Superabsorbent polymers, also known as hydrogels, are cross-linked polymers that have the ability to absorb a disproportionately large amount of liquid, expanding to form an insoluble gel. A unique characteristic of SAP is that its swelling rate and capacity can be altered depending on the polymer type and properties of the liquid including composition, temperature and pressure. For example, the swelling ratio of SAP in deionised water can be greater than 500 g/g, but it drops to about 10–20 g/g in typical concrete pore solution. The swollen gel forms a barrier to flow and it gradually releases absorbed water when the surrounding humidity drops. The main application of SAP is in personal hygiene products (diapers). Other uses include biomedical (bandages), pharmaceutical (drug delivery), agricultural (soil conditioning), waste solidification, meat packaging and water blocking tapes for undersea cables [16]. In concrete technology, research on SAP has mainly focused on its use as an internal curing agent to mitigate autogenous shrinkage in low w/c mixes [17,18]. Other proposed applications include rheology control, frost protection [19,20] and crack sealing/healing [21–26]. A state-of-the-art report on the application of superabsorbent polymers in concrete has been published by RILEM [27].

The use of SAP as an admixture for self-sealing cracks in cement-based materials was described by Tsuji et al. [21,22] and this concept was further explored by Lee et al. [23,24] and Snoeck et al. [25,26]. In the work of Tsuji et al. [22], mortar specimens with w/c ratio 0.5 and sand/cement ratio 1.0 containing up to 3% vol. of SAP (5 wt.% cement) were prepared and mechanically loaded to form a single 0.1 mm wide through crack. The flow rate of water through the crack was monitored for 3 h. Their result showed that the initial flow rate for mortars containing SAP was 90% lower than that of the control sample and the flow rate rapidly decreased over the following 3 h. Using neutron radiography to study water penetration, Snoeck et al. [25], found that mortars containing SAP had lower capillary absorption in comparison to the control sample. Snoeck et al. [26] also demonstrated the use of SAP to promote self-healing in microfibre-reinforced mortars exposed to wet-dry cycles in water. They observed that cracks up to 0.13 mm in width healed completely by $CaCO_3$ precipitation, which led to decrease in permeability and regain in mechanical properties.

The aim of this study is to investigate the feasibility of SAP as an admixture for self-sealing cracks in concrete. Our focus will be cracks wider than 0.1 mm because they have limited ability to self-heal naturally, cause leakage and impair the watertightness of concrete. Forty samples containing four types of SAP based on partially neutralised acrylates or acrylate/acrylamide copolymers at varying dosages were prepared. A single through-thickness crack of between 0.1 and 0.4 mm width was induced in each specimen, which was then subjected to a flow of 0.12 wt.% NaCl at hydrostatic pressure gradient of 4 m/m to simulate groundwater ingress. Flow was monitored continuously to study the effect of SAP type and dosage, and crack width on healing, and the results were compared against control samples that did not contain SAP. In addition, an analytical model was developed to predict the fraction of crack sealed as a function of crack width and SAP particle size, dosage and swelling characteristics. The model was applied to support experimental results and to provide further insights on factors influencing the efficiency of SAP for crack sealing.

## 2. Crack sealing mechanism

Fig. 1 illustrates the envisaged self-sealing mechanism. When concrete is batched, the mix water reaches a very high pH (~12.5–13) and ionic concentration (~150–700 mmol/L) within minutes in contact with cement because of rapid dissolution of the cement compounds releasing ions including $Ca^{2+}$, $K^+$, $Na^+$, $OH^-$ and $SO_4^{2-}$ [28]. As such, SAP that is added during batching will initially swell at a much reduced capacity compared with SAP in freshwater. Calcium ions in the mix water forms a bidentate complex with the acrylates of the SAP [29], which further limits its swelling [30,31]. The initial swelling is also confined by the mixing and compaction processes. As cement hydrates and concrete self-desiccates, the SAP gradually releases its absorbed water and shrinks, leaving behind voids of tens to hundreds of microns in size in the cement paste (Fig. 1a). These voids can be viewed as macro-defects, and so cracks that form during the service life of the concrete structure are likely to propagate through them (Fig. 1b). The SAP lies dormant in the microstructure until a crack occurs through the SAP voids, exposing the polymer to the external environment. When the concrete is then subjected to wetting, ingress of water triggers the SAP to swell again. External fluids such as precipitation and groundwater have much lower ionic concentration compared to concrete pore solution and so the re-swelling of SAP will increase significantly. The reduced physical confinement will also increase the re-swelling capacity of the SAP. The swollen SAP forms a soft gel that expands beyond the void and into the crack, subsequently slowing down or preventing




(a) SAP is added to concrete during batching. Initial swelling ($S_1$) is confined. As concrete hardens, the SAP shrinks and lies dormant in the microstructure.

(b) Subsequent cracking propagates through SAP voids, exposing the polymer.

(c) Ingress of water causes SAP to swell ($S_2$), expanding into the crack and restricting further flow.

Fig. 1. Schematic of the crack self-sealing mechanism using SAP [23].