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Modeling rapid self-sealing of cracks in cementitious materials using superabsorbent polymers

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HIGHLIGHTS

- A model was proposed to evaluate rapid self-sealing of cracks by SAPs.
- Swelling exhibited by SAPs in cracks was less than those exhibited in a free state.
- Self-sealing efficiency increased with increases in SAP dosage.
- Self-sealing efficiency decreased with increases in crack width.
- The predicted reduction ratio of the flow rate exceeded the measured one.

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ABSTRACT

The aim of the study involves quantitatively evaluating rapid self-sealing of cracks in cementitious materials incorporating superabsorbent polymers (SAPs). To this end, the study proposes a model to predict changes in the amount of water runoff through cracks over time when spherical SAPs in cementitious materials exhibit rapid swelling by absorbing the first water ingress after the occurrence of cracks. X-ray computed tomography analysis demonstrates that the swelling of SAPs in the cracks of the specimens by distilled water was less than that in a free state. The water flow test results indicate that the ratio of water runoff over time decreases sharply in SAP-added specimens immediately after the commencement of the water flow test. Additionally, the reduction ratio of the flow rate for the specimens with a crack width range of 0.24–0.36 mm corresponds to 0.343–0.519, 0.524–0.716, and 0.631–0.826 in specimens S-0.5, S-1.0, and S-1.5, respectively. A nonlinear regression analysis was performed on the results of the water flow test, and this reveals that the modification factor for the volume fraction of cracks sealed by the swelling of spherical SAPs corresponds to 0.7056, 0.6642, and 0.6574 for SAP 0.5%, SAP 1.0%, and SAP 1.5%, respectively.

1. Introduction

Superabsorbent polymers (SAPs) are materials that exhibit significant swelling by absorbing water up to several hundred times their own weight due to a difference in osmotic pressure between the inside gel and outside solution [1–3]. Additionally, they exhibit the property of retaining or releasing absorbed water under varying environmental conditions without the dissolution of the gel structure [4]. Several studies examined the application of SAPs to cementitious materials [4–9]; this included studies with the aim of mitigating self-desiccation and autogenous shrinkage of high strength/high performance concrete with a low water-binder ratio via the internal curing effect of SAPs.

Recent studies on the application of SAPs to cementitious materials [10–13] involved the addition of SAPs to existing self-healing techniques to improve autogenous crack healing efficiency in cementitious materials and indicated that SAPs improve long term crack self-healing performance in cementitious materials. This is primarily because SAPs stimulate hydration by supplying water required to hydrate non-hydrated particles in cementitious materials through the internal curing effect that aids in the formation of self-healing products in the healing process [12,13]. Additionally, following the occurrence of cracks, SAPs in cementitious materials are exposed to crack surfaces and swell by absorbing ingress through the cracks. The swollen SAPs allow rapid self-sealing of cracks by blocking the inflow of water in cementitious

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material in a relatively short period of time [14–17], and this can eventually improve long-term crack self-healing efficiency [17].

Diverse experimental approaches [11–19] were employed to evaluate crack self-sealing and self-healing performances of SAP-added cementitious materials. The water flow test is the most frequently used method among these approaches [16,17]. Lee et al. [16] and Snoeck et al. [17] verified crack self-sealing effect of SAPs in cementitious materials through a water flow test. Lee et al. [16] indicated that given a SAP dosage of 5% by weight of cement, the cumulative water flow decreased up to 80% in paste specimens and 85% in mortar specimens. Snoeck et al. [11] performed a capillary absorption test by using neutron radiography and revealed that mortar specimens containing SAPs absorb less water along the cracks when compared to that in specimens without SAPs. Snoeck et al. [13] used X-ray computed tomography (CT) images to analyze the formation of self-healing products of SAP-added specimens under wet/dry cyclic conditions and different relative humidity (RH) levels and demonstrated that SAPs improve crack self-healing efficiency. Lee et al. [18] investigated the efficiency of self-sealing of cracks based on SAP type, dosage, and crack width through water permeability tests. They assumed that the swelling ratio of SAPs by cement pore solution was equal to that by water ingress through cracks and proposed a model to estimate the volume fraction of cracks sealed in specimens by the swelling of SAPs in which parameters corresponded to crack width and SAP dosages. The model proposed in their study [18] has limitations that the actual swelling behavior of SAPs in the cracks by ingress water was not evaluated, and the self-sealing efficiency was expressed in terms of volume fraction of cracks sealed rather than the change in the amount of water runoff through cracks. Furthermore, Hong and Choi [19] analyzed rapid swelling behavior of SAPs in cracks by water ingress by employing X-ray CT and cryofracture Scanning Electron Microscope (SEM) analysis and indicated that spherical SAPs are split along crack surfaces. Although several studies evaluated the efficiency of crack self-sealing and self-healing by SAPs in cementitious materials as shown above, only a few studies quantitatively investigated rapid self-sealing in cementitious materials by rapid swelling of SAPs by water ingress that occurs for the first time through cracks following the occurrence of the cracks. A primary objective of self-healing concrete includes improving the ability of concrete to block water ingress through cracks in cementitious materials, and thus it is expected that the rapid-sealing of SAPs to the first influent after the occurrence of cracking will significantly improve long-term self-healing efficiency in cementitious materials. Therefore, it is extremely important to quantitatively evaluate the efficiency of rapid crack sealing effects of SAPs.

Consequently, the purpose of this study involves quantitatively evaluating the self-sealing of cracks in cementitious materials that incorporate SAPs due to the rapid swelling of SAPs caused by water ingress that first penetrates following cracking in cementitious materials. To this end, mortar specimens were prepared with variable SAP dosages, and swelling ratios of SAPs in the mortar specimens absorbing different solutions before/after cracking were quantitatively analyzed using X-ray CT analysis. A water flow test was performed on the specimens to measure the reduction ratio of water runoff through cracks per unit time, and rapid self-sealing efficiency was evaluated. Additionally, a model was presented to predict the reduction ratio of flow rate by considering the shape of SAPs and crack widths. Further, the results from this model were compared with the experimental results. This was followed by an analysis of the realistic swelling behavior of SAP at the crack surface in the specimens that causes a difference between the predicted and the measured flow rate.

2. Experiment

2.1. Materials and mixture proportions

In the study, type-I ordinary Portland cement (OPC) (fineness: 3499 g/cm^2, density: 3.13 g/cm^3) conforming to ISO 679 and standard sand of a particle size of 0.59 mm or less and with a density of 2.60 g/cm^3 were used to prepare the mortar specimens. In this experiment, standard sand with relatively small particle sizes was used because it was intended to fabricate mortar specimens with uniform characteristics by minimizing variations of physical and chemical properties of sand including particle size distributions. Table 1 lists the mixture proportions of the specimens used in the test. In the specimens, SAP dosages are used as a variable and the number following S in the specimen name refers to the SAP dosage (%) by weight of cement in the mixtures. The water-to-cement (w/c) and sand-to-

Table 1
Mixture proportion of the specimens.

Specimen	SAP dosage* [%]	Cement [kg/m^3]	Sand [kg/m^3]	SAP [kg/m^3]	Water [kg/m^3]	Water in SAP [kg/m^3]
REF	–	678.8	1154.0	–	399.4	–
S-0.5	0.5	638.2	1084.9	3.2	319.1	57.4
S-1.0	1.0	602.2	1023.7	6.0	301.1	108.4
S-1.5	1.5	570.1	969.2	8.6	285.1	153.9

* SAP dosage by weight of cement.

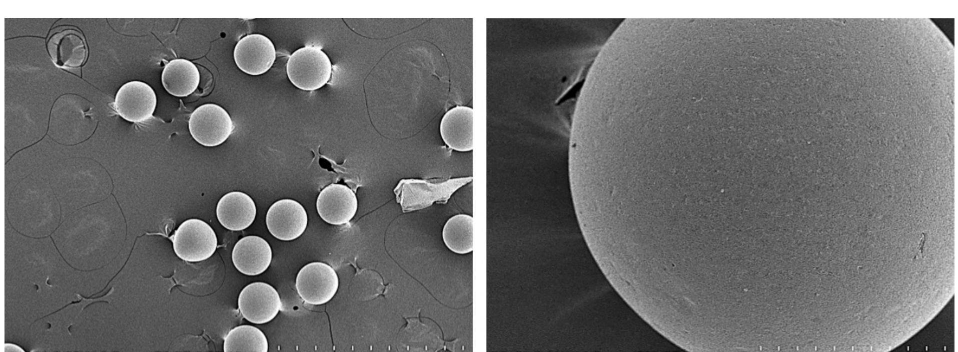

Fig. 1. Scanning electron micrographs of spherical SAP particles used in the test.