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Enhanced impact energy absorption in self-healing strain-hardening cementitious materials with superabsorbent polymers

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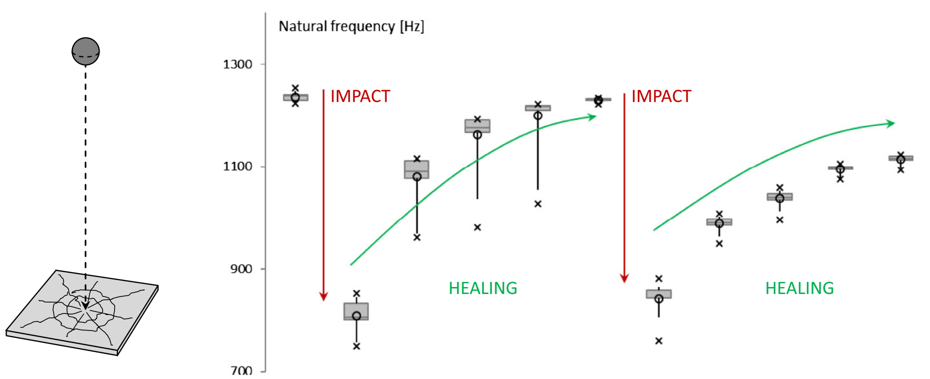
HIGHLIGHTS

- SAP samples were more ductile upon impact compared to reference samples.
- Superabsorbent polymers act as stress initiators increasing multiple cracking.
- Healing was monitored using natural frequency analysis.
- In a relative humidity condition, SAP specimens show healing.

GRAPHICAL ABSTRACT



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ABSTRACT

Concrete is the most-used man-made construction material worldwide. One of its major flaws remains the susceptibility to cracking upon impact loading. In this study, plates containing different amounts of superabsorbent polymers were impacted at four different ages (1 week, 1 month, 4 months and 6 months) and stored at different healing conditions (wet/dry cycles and 95 ± 5% RH). After 28 days of healing the plates were impacted and healed again. When the deformations during impact and the rebound after the impact were analysed, the specimens containing SAPs showed a more ductile behaviour during impact loading compared to reference samples. A good healing was confirmed by natural frequency analysis. Even during a second impact loading of healed samples a significant regain in natural frequency was obtained. The evolution of the natural frequencies also showed a superior healing caused by wet/dry cycles compared to healing at 95 ± 5% RH. Only in specimens with SAPs, the healing condition of 95 ± 5% RH resulted in a regain in natural frequencies due to the moisture uptake by the SAPs and subsequent healing.

1. Introduction

Cementitious materials may show a low tensile strength, a brittle behaviour and crack formation. Cracks are to be avoided as they allow harmful particles in fluids and gases to enter the cementitious matrix causing a negative effect on the durability. These brittle characteristics are especially important when impact loading is involved. In an advanced stage of damage the only option is to repair or replace the impaired elements. However, this is mostly linked with high restoration and repair costs and a huge amount of discomfort. As a solution, a lot of these problems can be avoided

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by means of biomimicry, i.e. self-healing, as cracks may close by themselves, leading to a regain in mechanical properties [1–3].

Three conditions must be fulfilled for autogenous healing to occur; crack widths should remain small, sufficient water has to be available and finally the necessary building blocks for healing must be available [4–6]. The three main mechanisms responsible for the autogenous healing are the further hydration of unhydrated cement particles, pozzolanic activity by supplementary cementitious materials, and the precipitation of calcium carbonate [1,7–9]. In this research the autogenous healing is promoted by the addition of superabsorbent polymers (SAPs), a new and promising admixture in cementitious materials [10–16]. When SAPs come into contact with water they are able to absorb up to 1000 times their own weight, resulting in a hydrogel. By retaining water during wet periods, SAPs will be able to release their water towards the cementitious matrix [17] due to capillary forces and suction of the drying cementitious matrix to sustain the formation of healing products by the mechanisms described above [5,18–20]. A complete regain in mechanical properties is possible in wet/dry cycles and a complete visual healing of cracks is feasible up to 130 μm [5]. A major disadvantage to the use of SAPs is that SAPs cause macropores in the cementitious matrix causing a possible strength reduction [7,21,22]. By properly adjusting the mixture composition and by using the appropriate amount of SAPs, this effect can be overcome [5].

As stated above not only water is needed for autogenous healing to occur; the crack widths need to be limited. Synthetic microfibers can be added to cementitious materials as a type of reinforcement. If the fiber itself and the connection to the matrix are strong enough, cracks will be bridged under increased loading, thus increasing the multiple cracking and strain-hardening behaviour of the material [23,24]. A benefit of this multiple cracking behaviour is that a multitude of small cracks are formed which can be healed much easier than few larger cracks [1,4,23].

The behaviour and self-healing of cementitious materials with synthetic microfibers and superabsorbent polymers during and after a static four-point-bending test have already been studied in detail [5–7]. It is however not known how this material with SAPs reacts when subjected to impact loading. The behaviour of strain-hardening cement-based composites (SHCC) with microfibers upon high-strain rates looks promising [25,26], as well as for fabric-reinforced cement composites [27]. Nowadays, where major terrorist attacks or earthquakes can happen in the blink of an eye this is a valid question to be asked. When an impact loading is applied, there is no gradual increase of the loads compared to a four-point-bending test, it leads to high strain rates and energy peaks with a more local failure behaviour [28–30]. When dealing with impact loading, the direction and magnitude of the forces are far more difficult to interpret. Randomly distributed fibers in a cementitious matrix act as an ideal reinforcement type as they enlarge the tensile strength of the cementitious material in all directions. When studying fiber-reinforced cementitious materials, the ductile behaviour seems promising in order not to have brittle failure [31]. Design codes rely on static models and the dynamic effect of impact loading or earthquakes are introduced by applying dynamic load factors to static values. This static method, however, is not able to fully establish impact phenomena like load duration, load rate or even the maximum impulsive loading. Extensive research is important as it allows for a safer design of high-rise buildings or power plants, amongst others.

When investigating impact loading, different set-ups can be used but the general idea is the same: a projectile has to hit a cementitious specimen. There are many mechanisms used to launch the projectile towards the sample such as: free fall, rockets, air guns or actuators. Aside from the mechanism, also the projectiles themselves can differ in shape, size and weight. The dynamic behaviour of the samples due to impact is very complex and clearly depends on a lot of factors such as the velocity, size and shape of the projectile, contact area, impact zone, size and shape of the target, amongst others. The most commonly used test is a drop-weight test using gravity as the main driving force. A projectile, mostly a ball-shaped one, is dropped from a certain height and falls on top of a specimen. The impact energy can then be measured by means of a force transducer or optically by using a high-speed camera to capture the rebound height [32–34].

In this study, the behaviour and self-healing of cementitious materials with synthetic microfibers and superabsorbent polymers during and after impact loading are analysed. Different mortar mixtures containing various amounts of SAPs are impacted by means of a drop-weight test at different initial curing ages (1 week, 1 month, 4 months and 6 months). Afterwards the specimens are healed in two specific healing conditions (wet/dry cycles and a relative humidity RH of 95 ± 5%) and the healing is monitored in time by means of acoustic frequency analysis. After healing, the entire process is repeated to analyse the secondary healing capacity.

2. Materials and methods

In this section, the four different studied mixtures are described (2.1). Next, the cracking method (impact) and the healing and microscopic analysis are discussed in Sections (2.2) and (2.3). In the end, the acoustic test with the performed natural frequency analysis to investigate the healing in time of the cracked material is explained (2.4).

2.1. Studied mixture compositions

Four mortar mixes (REF, S0.5A, S0.5B and S1B) were studied in detail and consisted out of cement (CEM I 52.5 N, Holcim, Belgium), fly ash (Class F, OBBC, Belgium), fine silica sand (M34, D_{50} = 170 μm, Sibelco, Belgium), a polycarboxylate-type superplasticizer (Glenium 51 conc. 35%, BASF, Belgium), PVA microfibers (2 v%; oil-coated, 15 dtex, 8 mm cutting length, 12 cN/dtex, Kuraray, Japan), water and, depending on the mixture, superabsorbent polymers. The chemical composition of the cement and fly ash can be found in [7,17].

Two different SAPs were used; SAP A and SAP B at different amounts expressed as mass percentage (m%) of cement weight. The nomenclature of the SAP is the same as in previous research of the authors [5,7,9,35]. SAP A consists of acrylamide and sodium acrylate and it is produced by means of bulk polymerization. The copolymer has a particle size of 100.0 ± 21.5 μm (n = 100) and a swelling time both in demineralized water and cement filtrate solution of around 10 s in standard laboratory conditions. It is able to absorb 305 ± 4 g/g SAP in demineralized water and 61 ± 1 g/g SAP in cement filtrate solution. The bulk-polymerized SAP B is a cross-linked potassium salt polyacrylate with a particle size of 476.6 ± 52.9 μm (n = 100) and a swelling time of approximately 60 s. It is able to absorb 283 ± 2 g/g SAP in demineralized water and 58 ± 2 g/g SAP in cement filtrate solution. The absorption capacity was determined using the filtration method and the swelling time using the vortex method [12]. Furthermore, both SAPs are able to absorb 26%, 83% and 394% of their weight in moisture at 60, 90 and 98% relative humidity (RH) as determined by means of Dynamic Vapour Sorption (DVS) tests [36].

The mortar composition can be found in Table 1 and is based on the research of Li *et al.* [4,24] and Snoeck *et al.* [5,7]. The fly ash-to-cement ratio was 1, the sand-to-binder ratio was 0.35, the superplasticizer-to-binder ratio amounted to 0.005 and the water-to-binder ratio was 0.3 for all mixtures. An amount of 2 v% of PVA fibres was added to ensure strain-hardening. The SAP-to-