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Review

From straw in bricks to modern use of microfibers in cementitious composites for improved autogenous healing – A review

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HIGHLIGHTS

- This review gives an overview of strain-hardening cementitious materials.
- Biomimicry and cementitious materials are linked with each other.
- Improvement of autogenous healing in cementitious materials is discussed.

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ABSTRACT

Cracks in concrete are inevitable and for durability reasons, the cracks should be repaired. Concrete has the intrinsic property to heal itself. But, the passive form of autogenous healing plays only an inferior role for a complete repair of a cementitious material. The main cause is that only cracks of limited width may heal completely. For that reason, microfibers are added to the mixture, as they cause the formation of multiple small cracks. In this way, a ductile material is designed with the property to heal itself efficiently. This paper will overview the different fiber reinforced cementitious composites of the last decade, the link with autogenous healing, results from the literature and future prospects.

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Nomenclature

Chemical abbreviations

Ca^{2+}	calcium ion
$CaCO_3$	calcium carbonate
$Ca(OH)_2$	calcium hydroxide
C–S–H	calcium silicate hydrates
CO_2	carbon dioxide
CO_3^{2-}	carbonate ion
HCO^{3-}	hydrogen carbonate ion
H_2O	water
OH^-	hydroxide ion

Abbreviations

ECC	engineered cementitious composites
FRC	fiber reinforced concrete
FRCC	fiber-reinforced cementitious composites
HTPP	high tenacity polypropylene
HPFRCC	high performance fiber reinforced cementitious composites
MFCFRCC	multiple fine cracking fiber reinforced cementitious composites
PE	polyethylene
PP	polypropylene
PVA	polyvinyl alcohol
SAP	superabsorbent polymer
SHCC	strain hardening cementitious composites
TRC	textile reinforced concrete

1. Introduction

Concrete is a material which can cope with high compressive stresses, but has a low tensile strength. Adding reinforcements increases the strength in tension but the composite will crack nevertheless. Cracking in plain concrete is thus inevitable. It can be the result of one or a combination of factors such as drying shrinkage, thermal contraction, restraints, differential settlement, and applied loads. Cracks are aesthetically unwanted and they will cause durability issues as they form a pathway for intruding potentially harmful substances. After crack formation and water intrusion, the pH will drop in the vicinity of reinforcements, leading to steel corrosion and possible structural declination. The ingress of chlorides will accelerate corrosion by de-passivating the protective film around reinforcements. Intruding carbon dioxide will react with the calcium hydroxide $Ca(OH)_2$ in the pore fluid causing a decrease of the pH and thus de-passivation and increased corrosion. The ingress of sulfates can result in the formation of ettringite, a subsequent volume expansion and a damaged microstructure. All these deteriorating processes need to be stopped before it is too late.

The amount of cracking can be controlled after taking the causes into account and repairs can be applied to seal the cracks from intrusion. But these repairs are time-consuming and costly. It would therefore be beneficial if the material would heal on its own. The self-healing concrete should hereby provide a complete or partial regain of the mechanical properties after crack formation. This happens in situ, meaning that no interaction has to be undertaken like manual repair. This would improve the reliability and the lifetime of structures.

Autogenous healing, which will be discussed later-on, can only close small cracks. A way to obtain these small cracks in concrete is the use of microfibers. In this paper, the history of fiber-reinforced cementitious composites will be addressed first. Different advantages and disadvantages of using different fibers in cementitious materials will be covered like the effects on degradation, steel corrosion and crack width restriction. The second part will be a close-up of autogenous healing and the needs for attaining a complete healing of a cementitious composite. The third part will focus on the basic knowledge on the optimization of self-healing with the addition of microfibers. The future of this kind of self-healing cementitious materials with fibers will be discussed at the end.

2. From straw in bricks to modern use of microfibers in cementitious composites

2.1. Microfibers through history

Fiber-reinforced composites are used frequently nowadays and its properties have been used for a long time. One of the first written references to fiber reinforced composites can be found in the Biblical book Exodus [1]:

> "Pharao praecepit ergo in die illo praefectis operum et exactoribus populi dicens nequaquam ultra dabitis paleas populo ad conficiendos lateres sicut prius sed ipsi vadant et colligant stipulam. – *Exodus **5** (6–7)*"

> "That same day Pharaoh gave the order to the slave drivers and overseers in charge of the people that they are no longer to supply the people with straw for making bricks and that the people should go and gather their own straw. – *Exodus **5** (6–7)*"

In ancient times the Egyptians, Sumerians, Babylonians and other civilizations used straw or horse hair to reinforce clay bricks. In this way, the bricks were stronger and were more durable in time. In the case of the Babylonians, this reinforcement could be beneficial in view of the liability of the constructor. Think about the Code of Hammurabi, a Babylonian law code, in which the builder is responsible for good practice and would lose his life if the owner of the house was killed due to poor construction. The use of reinforced materials was therefore imposed and the composites are still used today.

In 1963, fiber reinforced concrete found its way to the scientific community [2,3] and since then, the material has been intensively studied. Review papers on fiber reinforced cement-based composites can be found in [4] and [5]. Generally, fiber reinforced concrete is a material containing dispersed randomly oriented fibers. There are several materials which can be used in cementitious materials: natural fibers (e.g. akwara, bamboo, cellulose fibers, coconut husk, elephant grass, flax, hemp, jute, malva, musamba, plantain, sisal, sugar cane bagasse, water-reed, wood), glass fibers, carbon fibers, metal fibers (e.g. alumina, steel), and synthetic fibers (e.g. acrylic, aramid (Kevlar), nylon, polyester, polyethylene, polypropylene, polyvinyl alcohol) [1–34]. Also asbestos was used, but that material is has been banned due to human health issues.

2.2. Glass, steel and natural fibers: degradation in an alkaline environment and corrosion

One of the main concerns of the use of non-cementitious materials in a cementitious matrix is the (change in) alkaline environment. The strength of the composite may decrease and in case of the fibers, the bond with the matrix can change due to chemical and physical interactions, or the fibers may degrade. These interactions are due to the alkaline pore fluid (pH > 13) combined with the intrusion of potentially harmful substances through a crack. The alkaline environment poses a threat for glass fibers [20,21,35] and natural fibers [36–41], but almost none for synthetic fibers. Si–O–Si bonds are destroyed in the glass network due to the