Construction and Building Materials xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Characterization of sustainable bio-based mortar for concrete repair

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HIGHLIGHTS

- O_2 consumption was used to characterized bacterial activity in bio-based mortar.
- Bio-based agents used in SHCC enhanced its self-healing capacity.
- Bio-based SHCC exhibits good mechanical and bonding behaviour as a repair material.

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Concrete repair
Bio-based mortar
Bacteria
Crack healing
Bond stress
Restrained shrinkage

ABSTRACT

The paper describes mechanical properties, self-healing capacity and bonding behaviour of a sustainable bio-based mortar repair system for concrete. Two different mixes of strain-hardening cement-based composites (SHCC) have been used. The bio-based agent added to the SHCC consists of both bacteria and food for the bacteria. The metabolic activity of bacteria was monitored by oxygen profile measurements, which reveals O_2 consumption by bacteria-based samples, but not by control samples. The mechanical properties of the mortar (flexural behaviour, compression strength and drying shrinkage) are evaluated. The bonding behaviour with the concrete substrate is evaluated based on pullout tests and restrained shrinkage.

1. Introduction

Currently available concrete repair systems face durability-related problems that have a huge impact on national economies. In the United States of America, for instance, the annual direct costs for maintenance and repair of concrete highway bridges due to corrosion of the reinforcement sum up to 4 billion dollars [1]. Most of the durability-related problems of repair systems are due to the lack of compatibility with the concrete substrate. A combination of physical, chemical and mechanical processes results in the failure of concrete repair [2,3]. Restrained volume changes due to drying shrinkage or differential thermal expansion induce surface cracking in the repair system and interface delamination between repair and concrete substrate. Additionally, currently available repair systems are largely based on environmental unfriendly materials such as epoxy systems, acrylic resins or silicone-based polymers. This paper focus on the characterization of a concrete compatible and sustainable bio-based repair system that features better bonding and improved durability and sustainability characteristics compared to existing repair systems.

The European Standards describe the principles and methods for protection and repair of concrete structures [4]. The repair system studied in this paper was designed as a product for concrete restoration by applying or spraying mortar (repair methods 3.1 and 3.3), structural strengthening by adding mortar (repair method 4.4) or replacing contaminated or carbonated concrete (repair method 7.2) [4].

A special type of strain-hardening cement-based composite (SHCC), called Engineered Cementitious Composite (ECC) has been studied as repair material for concrete structures for overlay applications and patch repair [5–7]. ECC was micro-mechanically designed to have a large strain capacity with a low percentage of randomly distributed polymer fibres [8]. Because of the presence of fibres the material develops multiple micro-cracks prior to failure. The crack width remains below 0.1 mm [9]. In concrete repair materials fibres are also used to control drying shrinkage and service load-related cracking [5]. Repair materials crack when subjected to differential shrinkage: the early-age shrinkage deformation of the new repair material is restrained by the old concrete substrate that has already undergone shrinkage. Tensile stress is developed in the repair layer and a combination of tensile and shear stresses built up along the interface between the repair layer and the concrete substrate [5]. When applied as a repair

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0950-0618/$ - see front matter
http://dx.doi.org/10.1016/j.conbuildmat.2014.01.012

material, ECC is capable of carrying more tensile load and accommodate larger tensile strain than other repair systems [6]. Under differential shrinkage ECC will suppress localized brittle fracture in favour of distributed micro-crack damage [5,6].

Autogenous healing can be understood as a natural process of filling and sealing cracks without any external operations and works [11]. Li and Yang [10] investigated autogenous crack healing in ECC. They reinforced ECC with only 0.5% per volume of PVA fibres in order to achieve wide cracks. They reported that ECC with a maximum crack width of 50 μm achieved full recovery of mechanical and transport properties due to autogenous healing. Between 50 and 150 μm, partial recovery could be attained. Autogenous healing behaviour in SHCC heavily depends on the availability of unhydrated cement and other supplementary cementitious materials, such as blast furnace slag or fly ash. Low water/binder material ratio and high percentage of binder material and a control small crack width appear to promote autogenous healing in ECC [12,13].

Conventional ECC is designed without coarse aggregates and with only a small amount of fine sand in order to control the fracture toughness of the matrix [8]. This characteristic leads to higher water to cement/binder ratio and eventually to a high value of shrinkage [14]. Li [5] and Yang et al. [15] reported drying shrinkage strain values of 1200×10^{-6} to 1800×10^{-6} for conventional ECC, and Zhou [6] reported a drying shrinkage strain value of 2900×10^{-6} for ECC designed using limestone powder instead of sand as filler. In similar drying conditions of 20 °C and 60% relative humidity, normal concrete has a drying shrinkage strain of 400×10^{-6} to 600×10^{-6} [16]. Conventional ECC uses micro-silica with maximum grain size of 200 μm [10,17]. In this way the fibres in ECC are only separated by fine aggregate particles which are allowed to move freely between the fibres. Particles that are bigger than the average distance between fibres will cause the fibres to concentrate in balls and lead to an irregular distribution of the fibres [18]. As mentioned above, the particle size is limited in ECC in order to limit the fracture toughness to a level in which the crack initiation could occur before the tensile load reaches the maximum fibre-bridging stress that will result in failure of the fibre bridges [17].

To improve the durability of the concrete repair system as well as to improve the bonding with the concrete substrate this paper proposes a bio-based agent to be included in the ECC mix. The bio-based agent consists of alkali-resistant bacteria and a food source for those bacteria. When applied in concrete, this bio-based agent has the capacity to produce calcite-based minerals inside cracks thus reducing the permeability of the concrete [19,20]. The precipitated minerals lead to the closure of cracks with a maximum crack width of 460 μm [20]. In case of surface cracking in the repair mortar due to restrained shrinkage or other mechanical processes the bio-based agent is capable of healing these cracks to ensure the durability of the repair product.

Repair materials are frequently subject to limited evaluations driven by manufacturers rather than by users [21]. This is due to a lack of widely accepted testing methods. If only the isolated properties of repair materials are studied the more important properties of the composite system are neglected. In this research, the performance of the composite repair system as well as the interaction between the repair and concrete substrate have been investigated. Restrained shrinkage tests have been conducted on a simulated repair system, that contains one layer of old concrete substrate and one layer of new repair material to simulate real repair conditions.

For this study, two ECC-type mortars with particles containing a bacterial-based agent have been studied as a sustainable bio-based repair system for concrete. The mechanical properties of the ECC materials are evaluated by means of flexural and compression tests and free drying shrinkage measurements. The behaviour of the ECC material as a repair mortar is evaluated by means of restrained shrinkage measurements and the bonding behaviour with the concrete substrate is evaluated based on pullout.

2. Experimental investigation

2.1. Materials

Ordinary Portland cement CEM I 42.5N, fly ash (FA), blast furnace slag (BFS), limestone powder (LP), sand (S) have been used. The chemical composition of the powder materials are given in Table 1 and the mix designs in Table 2. The sand has an average and maximum grain size of 250 μm and 500 μm respectively. In the mix design, BFS, FA and Portland cement are considered as binder materials, and the limestone powder is considered as inert filler material. Polyvinyl alcohol (PVA) fibres with a length of 8 mm and diameter of 40 μm have been used in the content at 2% by total volume. These PVA fibres have a tensile strength of 1600 MPa. The surface of the fibres is coated with 1.2% oil by weight to optimize the fibre-cement matrix bond [22].

The bio-based agent considered for this research is an alkaliphilic (alkali-resistant) spore-forming bacteria and calcium lactate as a nutrient source for the bacteria. Both the bacteria and the food source are embedded in lightweight aggregates. Bacteria from genus Bacillus and more specifically related to the species *B. cohnii* [23], originally isolated from alkaline soil samples were chosen for this research [24]. Previous studies show that these bacteria are capable of healing cracks by direct and indirect calcium carbonate ($CaCO_3$) formation [19,20]. The direct $CaCO_3$ precipitation is due to the bacterial metabolic conversion of calcium lactate according to the following reaction:

$$CaC_6H_{10}O_6 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O \quad (1)$$

The indirect formation is due to reaction of metabolically produced CO_2 molecules with $Ca(OH)_2$ minerals (portlandite) present in the concrete matrix, according to:

$$5CO_2 + 5Ca(OH)_2 \rightarrow 5CaCO_3 + 5H_2O \quad (2)$$

The latter reaction is homologous to carbonation, a slow process that naturally occurs in concrete due to inward diffusion of atmospheric carbon dioxide, whose rate is however substantially enhanced by the metabolic conversion of calcium lactate [24]. The production of in total six calcium carbonate equivalents is possible due to the process of bacterial calcium carbonate conversion, which will result in efficient crack sealing.

To prepare the bio-based agent, lightweight aggregates (LWA) were first impregnated with calcium lactate (150 g/L) and yeast extract (7.5 g/L) solution followed by a second impregnation with a bacterial spore solution. Between impregnations the LWA were dried in an oven at 37 °C for 5 days. The obtained impregnated LWA contains 15% (by weight) calcium lactate and 1.2×10^7 bacterial spores per gram of particles. The LWA particles have sizes ranging between 0.25 and 2 mm.

Bacterial spores are known to be able to withstand high mechanical forces and are characterized by a long-term viability of up to 200 years under dry conditions [25]. When mixed directly into concrete the number of viable spore cells in concrete decrease in time [24]. Later studies by the same author established that bacteria immobilized in porous expanded clay particles prior to concrete mix addition substantially increased bacterially-mediated self-healing in comparison to unprotected addition of bacteria [19,20]. Furthermore bacterial spore viability increased to more than 6 months when added protected inside porous particles to a concrete mixture [19]. Oxygen consumption measurements provided evidence of bacterial activity in concrete specimens up to several months after concrete casting [20].

Table 1
Chemical composition (weight%) of the powders materials.

Compound	CEM I 42.5	BFS	FA	LP
CaO	63.3	40.8	7.1	–
SiO_2	19.5	35.4	48.4	0.3
Al_2O_3	5.6	13	31.4	0.1
Fe_2O_3	2.3	0.5	4.4	0.1
MgO	1.1	8.0	1.4	0.2
K_2O	0.9	0.5	1.6	–
Na_2O	0.3	0.2	0.7	–
SO_3	2.7	0.1	1.2	–
$CaCO_3$	–	–	–	98.8

Please cite this article in press as: Sierra-Beltran MG et al. Characterization of sustainable bio-based mortar for concrete repair. Constr Build Mater (2014), http://dx.doi.org/10.1016/j.conbuildmat.2014.01.012