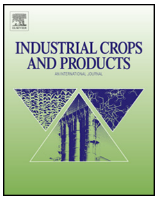
Industrial Crops and Products xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Industrial Crops and Products

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



Feasibility of lactate derivative based agent as additive for concrete for regain of crack water tightness by bacterial metabolism

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ARTICLE INFO

Article history:
Received 16 July 2016
Received in revised form 13 October 2016
Accepted 22 October 2016
Available online xxx

Keywords:
Lactate
Concrete
Microbial healing
Environmental impact
Cost-benefit

ABSTRACT

Lactate, produced by fermentation of e.g. cane or corn residues, can serve as a carbon source in bacterial healing for cement-based materials such as concrete. Bacterial spores, activation nutrients and a carbon source are mixed in with dry concrete or mortar constituents upon material production. Upon cracking of the concrete matrix and ingress of water, an active bacterial colony forms and starts to convert the included carbon source to CO_2. In the alkaline surrounding of concrete carbonates form and deposit as minerals on the crack surface, sealing the entrance to further ingress. In this work a lactate derivative based healing agent containing bacteria and activation nutrients is added to a commercial mortar, exerting negligible effect on the mortar strength development. Functionality of the agent is indicated by oxygen consumption under aerobic conditions and shown by regain of crack water tightness beyond the autogenous healing capacity in a permeability test. In order to indicate feasibility for healing agent application in a commercial setting, the environmental burden is discussed and a competitive production price is estimated.

1. Introduction

Lactic acid and its derivatives, such as calcium or sodium lactate or polylactide can be produced from microbial fermentation of a carbon source, for instance coming from corn or sugar cane (John et al., 2007). Lactic acid can be used as a carbon source in microbial induced precipitation of minerals (Jiang et al., 2014). CO_2 can be produced by the metabolic conversion of organic compounds such as lactic acid by heterotrophic bacteria. In solution an equilibrium forms between carbon dioxide, bicarbonate and carbonate. Alkalinity drives the carbonate equilibrium in favour of formation of ${CO_3}^{2-}$, which leads to an increased deposition of carbonate minerals (e.g. calcium carbonate or calcite) when cations such as calcium are present. Cement containing materials such as concrete naturally provide alkaline conditions and presence of cations, as the hydration of clinker in cement forms calcium hydroxide as a secondary reaction product. Formation of carbonate minerals in concrete leads to cementitious matrix densification (Chi et al., 2002) and sealing of continuous porosity such as cracks (Edvardsen, 1999), giving functionality and durability to the material. Concrete has a limited inbuilt mechanism that allows carbonates to deposit in or on the matrix, so called autogenous healing capacity (Palin et al., 2015). Promotion of additional carbonate depositions should further enhance the sealing function of concrete and limit the use of measures to keep cracks tight (de Rooij et al., 2013). In order to obtain this added, autonomous sealing capacity, the mechanism of bacteria-based metabolic conversion of organic components can be used (Jonkers, 2007). Application of (dormant) bacteria and organic compounds to concrete can be externally, in the form of a liquid (Wiktor and Jonkers, 2015) or a mortar (Sierra-Beltran et al., 2014), to allow repair or rehabilitation of the material, or internally to build in an autonomic repair capacity (Wiktor and Jonkers, 2011). Upon occurrence of cracks in the cementitious matrix and ingress of water, bacterial spores germinate and grow out into an active population. Formation of calcium carbonate starts by metabolic conversion of organic compounds. Mineral deposition blocks the crack from further penetration of water, e.g. resolving leakage issues (Fig. 1).

In order to incorporate the healing ability, the bacteria and organic compounds are to be mixed in with the concrete components during the material production phase. Concrete hardens as cement and water react. Lactates were selected as the main carbon source for bacterial metabolism as negligible effect was exerted on cement hydration (Jonkers et al., 2010; Singh et al., 1986; Young,

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http://dx.doi.org/10.1016/j.indcrop.2016.10.037
0926-6690/

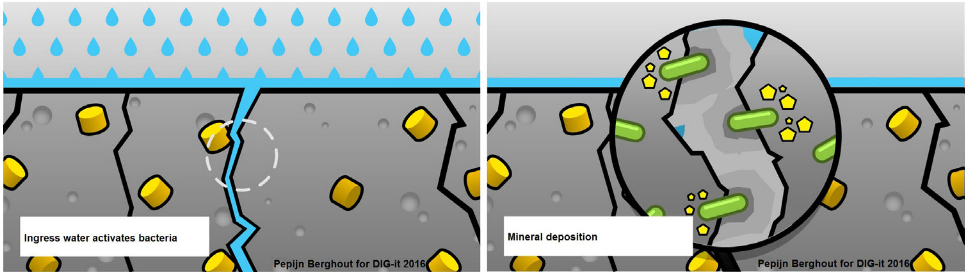

Fig. 1. Ingress of water through cracks activates the bacteria, converting nutrients into minerals, locally clogging the crack to regain water tightness.

1972) and selected alkaliphilic heterotrophic spore forming bacterial strains were able to respire and form mineral deposits under cementitious conditions (Jonkers, 2007; Wiktor and Jonkers, 2011). In order to include the healing components in randomly dispersed concentrated form, bacterial spores and calcium lactate were previously incorporated in the internal pores of expanded clay particles (Wiktor and Jonkers, 2011), a material typically used to produce light weight concrete. The first practical case of a light weight concrete mixture (Beltran and Jonkers, 2015) shows the potential for this technology to be applied in the concrete industry. As the inclusion of large amounts of expanded clay affects the mixture behaviour and substantially reduces final strength, dedicated concrete mixtures have to be used. In order to broaden the application range of healing components to commercially available mortar and concrete mixtures, an alternative additive was developed. As this so called 'healing agent' solely consists of spores of bacteria, activation nutrients and lactic acid derivatives, volume addition changes from 20% to 1% of the concrete volume for incorporation of the same healing potential. Limiting the additive content may exert negligible effect on concrete strength development and be more effective economically and environmentally. In this work the applicability of the proposed additive in a cement based system (mortar) is discussed, based on the mortar strength development, the functionality as indicated by the ability for bacterial respiration and crack sealing potential and the market feasibility by assessing the environmental and economic burden by means of a partial life cycle assessment (LCA) and competitive price indication respectively.

2. Material and methods

2.1. Materials

Healing agent (HA) flakes of size 1–4 mm made up of lactic acid derivatives, containing a calcium source, bacterial spores and activation nutrients were obtained from Corbion Purac, Gorinchem, The Netherlands and processed in collaboration with the department of Chemical Engineering, Delft University of Technology, The Netherlands.

Mortar samples were prepared from a commercially available dry mixture (weber.tec SBN 175 III/4, Weber Beamix, Eindhoven, The Netherlands) with tap water according to the producer specifications. HA was added 15 kg m^{-3}, leading to an approximate dosage of 4% by weight of cement.

2.2. Strength development

Mortar prisms of 4 × 4 × 16 cm were cast in two layers and compacted per layer by 15 strokes with a rod to limit inclusion of air. After one day the prisms were demoulded and directly tested or kept in plastic foil until 3, 7, 14, 28 or 56 days. Prisms were tested at these specific setting times for mechanical strength under bending and compression [NEN-EN 196-1] using a compressive bench (Cyber Plus Evolution, Macben).

2.3. Oxygen consumption

Aerobic bacterial metabolic conversion of nutrients consumes oxygen (Eq. (1)), therefore activity of bacteria can be indicated by bulk solution oxygen reduction of sample fragments.

$$C_3H_6O_3 + 3O_2 \rightarrow 3CO_2 + 3H_2O \tag{1}$$

Mortar half prisms remaining from strength measurements at 28 days of age were sawn wet using a diamond blade in layers of 1 cm and added to either demineralized or 0.1 M sodium carbonate bicarbonate buffered (pH 10.5) water.

For non-invasive measurements of oxygen concentration 0.15–0.3 g per mL of mortar plates were placed in a vial with an oxygen sensitive sensor (PSt3 sensor, Fibox 4 transmitter, PreSens, Regensburg, Germany; see Wiktor and Jonkers (2011) for a detailed description of the oxygen measurement technology). The flask was filled to the rim with water or buffer, closed without the inclusion or exchange of gas with the environment and kept stagnant during the measurement. Upon depletion of oxygen in the vial, the solution was resaturated with oxygen by using a pipette and resealed. The measurement was terminated when a stable oxygen concentration was reached or when the cumulative oxygen consumption of the HA containing sample was more than double that of the control sample.

HA particle location specific oxygen consumption was measured in stirred solution, using a needle-type optical oxygen micro sensor (PreSens Sensortype PSt1) as described by Wiktor and Jonkers (2011). Fig. 2 demonstrates the difference between non- and invasive measurement.

2.4. Water permeability reduction of cracked mortar specimens

Mortar was cast in two layers into cubic moulds with internal ribbons of 10 cm and compacted per layer by 15 strokes with a rod. After demoulding at 1 day of age, the cubes remained cured in foil until 28 days and were subsequently sawn in half at the cast surface by a rotating diamond blade cooled with water to obtain half cube specimens of similar material property. Samples were placed on the short side in a load controlled splitting setup and split to various crack widths by providing an increasing line load at the top and bottom until a crack became visible. Incorporated fibres in this commercial mortar kept the crack faces parallel at distance.

The surfaces on which the splitting force was exerted were sealed using viscous silicon glue. In this way a parallel crack remained, connected in one direction, such that the crack length was constant. An inverted polyvinyl chloride shower drain of 10 × 10 cm and height 10 cm was glued on one of the cracked surfaces. A drain pipe with rubber sealed tightening was connected to the inverted shower drain to add a height of 5 cm. Water flow

Please cite this article in press as: Mors, R.M., Jonkers, H.M., Feasibility of lactate derivative based agent as additive for concrete for regain of crack water tightness by bacterial metabolism. Ind. Crops Prod. (2016), http://dx.doi.org/10.1016/j.indcrop.2016.10.037