THE EVALUATION OF THE IMPACT OF NUTRIENTS ON THE BIO-BASED SELF-HEALING CONCRETE COMPRESSIVE STRENGTH

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ABSTRAKT

Tento článek se zabývá složením nutriční části biologické samohojícího činitele a stanovuje vliv těchto živin na tlakovou pevnost cementové pasty. Mnoho studií experimentovalo s přidáním samohojícího činidla (bakterií a živin) přímo do betonové matrice. Prokázalo se, že za určitých podmínek jsou některé mikroorganismy schopny produkovat $CaCO_3$, díky kterému pak dochází k samovolnému zacelování vzniklých trhlin v betonu. Ukázalo se však, že zejména nutriční část činidla může, pozitivně i negativně, významně ovlivnit materiálové charakteristiky. V této studii byly některé z nejčastěji aplikovaných živin přidány do cementové pasty. Na zkušebních trámcích vyrobených z této pasty pak byl sledován efekt přidaných složek na tlakovou pevnost materiálu. Výsledky ukázaly, že dusičnan vápenatý, mravenčnan vápenatý, laktát vápenatý i močovina mají obecně potenciál zvýšit tlakovou pevnost materiálu, zejména v raném stádiu. Naproti tomu použitá koncentrace kvasničného extraktu vedla k dramatickému poklesu tlakové pevnosti.

KLÍČOVÁ SLOVA

Samohojitelný • Biologický beton • Samohojící činidlo • Tlaková pevnost • Živiny

ABSTRACT

This paper investigates the composition of the nutritional part of the biological self-healing agent based on its impact on the compressive strength. A direct addition of the agent (bacteria and nutrients) into concrete matrix has been investigated by many studies. Under certain conditions, the microorganisms proved to be able to produce $CaCO_3$, thus autonomously seal microcracks in concrete. However, it has been shown that the self-healing agent, especially the indispensable nutrients, can positively or negatively influence the material characteristics. In this study, some of the most frequently proposed nutrients were directly added into cement mortar during the mixing process and their impact on the compressive strength was evaluated. Results show that calcium nitrate, calcium formate, calcium lactate, and urea have generally a potential to increase the compressive strength, especially in early ages. In contrast, the applied dose of yeast extract resulted in a drastic drop of compressive strength, thus further optimization of the concentration will be needed.

KEYWORDS

Self-healing • Bio-based concrete • Healing agent • Compressive strength • Nutrients

1. INTRODUCTION

In the field of cementitious building materials, microbiology has traditionally been included in the research from the perspective of negative effects: biodeterioration (Grengg et al. 2018), microbial stains (Morin et al. 2018), and human health issues. However, in some cases, the interaction between the material and microorganisms can result in positive actions as well. One of them, the so-called biocalcification process, has been extensively studied in the previous decades with the aim to increase durability of both existing and new structures.

The ability of certain microorganisms to produce $CaCO_3$ was firstly reported by Murray, Irvine, and Steinmann (Henry Lutz Ehrlich, Dianne K. Newman 2015) in the late 19^{th} century. Since then, researchers have deepened the knowledge of the microbially induced calcite precipitation and proposed numerous potential applications: protection and remediation of stone surfaces [4], biological repair systems of cracked concrete surfaces [5], and bio-based self-healing concrete.

This paper focuses on the lastly mentioned: a type of concrete with enhanced natural autogenous healing capacity by the incorporated self-healing agent (calcite-producing bacteria in the form of spores accompanied by nutrients). As it is widely known, the durability of concrete structures is largely influenced by the formation of microcracks. These cracks do not endanger the load-bearing capacity directly; however, if the crack widths exceed a certain level, water and agressive compounds can penetrate the material and cause concrete carbonation.

In the novelty biological concrete, the incorporated bacterial spores are activated due to water ingression caused by the cracking, and they start to metabolize the supplied nutrients. This action results in a formation of $CaCO_3$ by which the already existing cracks are then gradually sealed.

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As the concept of sustainable development has become an important and popular topic in the field of building materials, the bio-based self-healing concrete has been extensively studied in the recent decade. Numerous investigations identified suitable bacterial genotypes and described their limitations [6–9]; they proposed different types of bacteria protection (Wang, De Belie and Verstraete 2012, Wang, Snoeck, et al. 2014, Wang, Soens, et al. 2014, Chen, Qian and Huang 2016, Tziviloglou et al. 2016, Ersan, Boon and De Belie 2018); and they examined the self-healing efficiency through in-vitro and in-situ experiments [14,15].

This paper concentrates on the composition of the self-healing agent, specifically on the nutrients. The selection of the nutritional compounds is primarily based on the mode of metabolic activity of the applied bacteria. Generally, the calcite precipitation by microorganisms is based on the shift of carbonate ions (CO_3^{-2}). The carbonate ions are accumulated in the system due to the presence of carbon dioxide released by the metabolic activity of bacteria. Then, under conditions of the high pH and high calcium ion (Ca^{+2}) concentration, the carbonate ions are shift to calcium carbonate [16]. However, several metabolic pathways are known to result in the carbonate ions formation: aerobic respiration [17], urea hydrolysis (Al-Salloum et al. 2017), and nitrate reduction (Ersan, Boon and De Belie 2018). All of the mentioned bio-calcification pathways need a suitable metabolic activator and calcium source. A wide range of these compounds was proposed and analyzed from the perspective of the crack sealing efficiency (Xu and Yao 2014), the impact on mechanical properties of concrete (Luo and Qian 2016, Chen and Al. 2018), and economic factors (Palin 2017). However, the selection based on the presented factors demand further clarification. Only a very limited number of studies compared the impacts of the nutrients to a larger extent and the reported results differ quite significantly. In this study, a variety of frequently applied nutrients (Jonkers et al. 2010, Xu and Yao 2014, Luo and Qian 2016, Chen and Al. 2018) (yeast extract, urea, calcium nitrate, calcium formate, and calcium lactate) was proposed. Subsequently, the pre-selected nutrients were directly added into a cement mixture and a large number of small prism specimens was prepared. This paper then evaluates the impact of the applied nutrients on the concrete compressive strength and discusses the most suitable self-healing agent composition.

2. METHODS

2.1. Mortar specimen preparation

In order to determine the impacts of the selected nutrients mentioned above, series of mortar specimens were fabricated. The base for all the series was ordinary Portland cement (CEM I 42.5 N) and sand with grains 0.1-1 mm and 1-2 mm. The water-to-cement ratio was 0.5 and the cement-to-sand ratio was 3 (

Table 1).

Table 1. *Mixing proportion of mortar used for all of the series.*

Material	Amount [kg/m^3]
CEM I 42.5 N	586.00
Water	293.00
Sand (1-2 mm)	439.50
Sand (0.1-1 mm)	1318.50

The nutrient series were prepared by an addition of the calcium lactate at a concentration 3% to cement weight (LAC), calcium nitrate at a concentration 3% to cement weight (NIT), calcium formate at a concentration 3% to cement weight (FORM), yeast extract at a concentration 0.85% to cement weight (YE), and urea at a concentration 2.5% to cement weight (UR). The group without any further addition served as a control sample (CTRL). The overview of the applied additions to the cement mortar can be seen in **Chyba! Nenalezen zdroj odkazů.**.

Table 2. *Applied nutritional admixtures to the basic cement mortar.*

Series	Admixture	Amount [% by c. w.]	Amount [kg/m^3]
CTRL	–	–	–
LAC	Calcium lactate	3.00	17.58
NIT	Calcium nitrate	3.00	17.58
FORM	Calcium formate	3.00	17.58
YE	Yeast extract	0.85	4.98
UR	Urea	2.50	14.65

Mortar prisms 40x40x160 mm were prepared in triplicate sets for each group for the compressive tests in 3, 7 and 28 days. Specimens were demolded after one day and placed in a room with temperature (20 ± 2 °C) into plastic water-filled containers where they were cured until 12 hours before testing.

2.2. The compressive strength tests

After the end of the respective curing period (i.e. after 3, 7 and 28 days from casting), all of the series were submitted to the compressive strength testing. The specimens were halved into 40x40x80 mm prisms and evenly loaded with pressure. The mode of failure was observed to exclude incorrectly damaged specimens. The maximum applied load was recorded and analyzed using a controlling software.

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For the purpose of comparing the impact of the applied nutrients, the obtained values were averaged by the arithmetic mean and their standard deviation (SD) was determined.

3. RESULTS

As outlined in the introduction, the impact of the self-healing agent on the compressive strength of concrete is one of the key factors that noticeably affect the applicability of the

Table 3. *The compressive strength (the mean value and its standard deviation.*

Testing age		Series					
		CTRL	**LAC**	**NIT**	**FORM**	**YE**	**UR**
3 days	[MPa]	22.9 ± 2.0	27.7 ± 3.5	26.4 ± 1.6	38.0 ± 3.0	10.7 ± 1.2	30.8 ± 2.8
7 days	[MPa]	28.9 ± 3.0	36.0 ± 2.2	33.5 ± 1.5	44.2 ± 3.7	19.6 ± 1.3	34.8 ± 1.2
28 days	[MPa]	45.3 ± 4.5	58.8 ± 2.2	41.1 ± 3.4	57.6 ± 2.1	35.1 ± 3.0	44.4 ± 4.2

novelty material. In order to compare different compositions of the self-healing agent which were applied in previous studies, a number of cement mortar specimens with and without the pre-selected nutritional admixtures were used compressive strength tests. Detailed list of obtained results is provided in

Table 3.

For the sake of simplicity, in **Chyba! Nenalezen zdroj odkazů.** and Figure 1, the mean values of the compressive strength results are presented. The results show that the pre-selected calcium sources (calcium formate, calcium nitrate, and calcium lactate) in the concentration of 3% to cement weight do not noticeably endanger the compressive values at any age. In this study, the addition of calcium lactate and calcium formate had a distinct tendency to even increase the values throughout the whole curing period.

Table 4. *The impact of nutritional admixtures on the compressive strength mean values compared to control mortar.*

Series	3 days [%]	7 days [%]	28 days [%]
CTRL	100	100	100
LAC	121	125	130
NIT	116	116	91
FORM	166	153	127
YE	47	68	77
UR	135	120	98

As calcium nitrate and calcium formate are used as hydration accelerators, a steeper growth of the compressive strength was expected and the results are in an agreement with the assumption. Additionally, unlike calcium nitrate, the mortar with calcium formate reached an even higher final value of the compressive strength when compared to the control series. The strength measured in 28 days was improved by 30% in the case of calcium lactate, whereas the addition of calcium nitrate resulted in a slight drop of 9%.

In this study, a higher dose of urea (2.5% to cement weight) had predominantly a positive impact on the compressive strength in the investigated ages. The final value of mortar with urea did differ only minimally from the control series.

The addition of yeast extract in the dose of 0.85% to cement weight caused a drastic drop of the compressive strength. Especially in the early age (3 days), the strength of the YE series reached as little as 47% of the strength of the control series. Furthermore, two of the samples prepared for the testing in 3 days and 28 days have been spontaneously damaged and excluded from mechanical tests; a large crack appeared on the samples when they were immersed in tap water in the storage containers. Unfortunately, the extensive number of specimens did not allow to perform any long-term measurements in this experiment; however, it would be a very interesting topic for future research.

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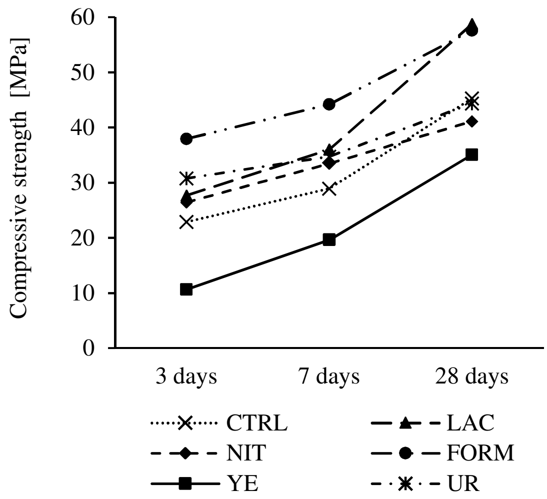

Figure 1. *Dependence of the mean values of the compressive strength on the measuring time.*

4. DISCUSSION

The results from our compressive strength tests performed on the cement paste specimens with incorporated nutrients are mostly in general agreement with previous research. In this study, the 3% addition of calcium lactate and calcium formate respectively caused an advantageous improvement of the compressive strength of about 30%. Luo et al. (Luo and Qian 2016) in their research reported an almost identical effect of the calcium lactate addition but they detected only a slight improvement caused by the calcium formate addition. The 3% calcium nitrate addition led to a decrease in the compressive strength of approximately 10% in our research, whereas Luo et al. (Luo and Qian 2016) reported a dramatic 20% strength drop.

The effect of the calcium formate, calicum lactate and calcium nitrate addition on the strength development is generally in line wih the expectations. All of the mentioned chemicals are commercially used as hydration accelerators, thus the compressive strength of specimens with the additives in early ages reaches higher values then the reference sample. However, the addition of an hydration accelerator does not automatically induce a higher compressive strength at the final 28 day, as it can be seen in the case of the calcium nitrate.

The impact of the urea and yeast extract addition in our concentrations were not previously directly determined by mechanical tests, thus our obtained data provide a useful extension of the known impacts. The drastic drop of the compressive strength casued by the yeast extract addition was expected. As the organic compounds are easily absorbed on the surface of mineral particles, they limit the concanct of cement and water, and hence decrease cement hydration [6].

5. CONCLUSION

The aim of this study was to provide an overview of the effects of nutritional compounds used as a part of the self-healing agent in bio-based self-healing concrete on the compressive strength.

This paper concludes that all of the pre-selected calcium sources (calcium formate, calcium lactate, and calcium nitrate) are, at the proposed concentrations, applicable without any considerable negative impacts on the compressive strength of cement mortar. Furthermore, the addition of calcium formate and calcium lactate led to a cementitious material with significantly higher compressive strength values at all ages. The presence of urea, the nutritional compound for ureolytic bacteria, at a concentration of 2.5% to cement weight did not negatively affect the material's properties as well.

Based on the results, the addition of yeast extract to cement mortar seems to be the most problematic admixture. Our data suggest that the concentration of 0.85% to cement weight causes a dramatic fall of the material's strength at all ages. Potentially, this negative effect could be balanced by the presence of the other nutritional compounds; however, the investigation of the interactions is beyond the scope of this study.

Future work should focus on the optimization of the nutrient concentration and evaluate their effect on other material's characteristics: hydration kinetics, tensile strength and long-term effect on the compressive strength. Furthermore, it is important to acknowledge that the bio-based self-healing concrete will be, in all probability, rather financially demanding material. It implies that it will find its use in complex and highly important parts of structures. For that reason, future studies should also certainly further optimize the self-healing agent in terms of not only the efficiency of the crack sealing process but also from the perspective of the impacts on the materials characteristics.

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