Self-healing abilities of cement mortars containing microorganisms produced in the process of sewage sludge treatment

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Abstract. The enormous quantity of sewage water produced each day continues to present a serious challenge for its treatment and management. Sewage water is one of the most abundant sources of biomass, such as bacteria. Concrete, on the other hand, is the second most widely employed substance on the planet, after freshwater. Cracking of concrete is a major factor affecting the strength and durability of the material. The development of a crack pattern can contribute to increasing the permeability of concrete, which is typically associated with a significant decrease in its durability. Under specific circumstances, bio concrete is a self-healing biomaterial. Bacteria have the ability to precipitate calcite in concrete or form a layer of calcite precipitation, which plays a crucial role in the remediation of plastic shrinkage microcracks, thereby enhancing the structural integrity and durability of concrete over the long term. This paper summarises the study of investigating the possibility of using sewage water as a self-healing agent, using bacteria from different stages of treatment to heal cracks in concrete samples, and evaluating the effect of sewage water from different stages of treatment on fresh and hardened concrete properties. Based on the data collected from the experiments. Complete replacement of ordinary tap mixing water with sewage water from the Biological Reactor oxygen Zone achieved cracks healing of a crack width of 200 µm in less than 14 days without compromising the binder and mortar properties such setting time, slump value, compressive and flexural strength when compared to a reference sample made with tap mixing water.

1 Introduction

Concrete is the most popular construction material, which is typically made by combining Portland cement with sand, fine and coarse aggregate, and water [1]. It has a high compressive strength, good fire resistance, and low cost, making it a popular material for large-scale construction [2]. However, 7% of the world's total emissions of carbon dioxide are produced during the production of cement, and research studies to mitigate the negative environmental impact of cement production have increased significantly over the past decade [3]. To reduce the demand for cement, these studies examine the use of alternative binders, the capture and storage of CO_2 gas, and the improvement of the durability of concrete structures [4]. If a viable method for automatically healing cracks in concrete is created, it will increase and ensure the durability and functioning of concrete, save money, and reduce repair of cracks [5].

Self-healing concrete is a new way of designing durable concrete structures that is beneficial for both national and global economy [6]. It is inspired by the natural phenomenon of organisms such as trees or animals being able to heal their wounds autonomously [7]. Microbiologically induced calcium carbonate precipitation MICP is a process used to produce bio cement, which is a construction material made from calcium salt, urea, and urease-producing bacteria (UPB) [8]. Although the use of urease-producing microbes effectively addresses the problem of mortar weakness in concrete, it is not mass-produced due to high nutrient costs. However, a recently developed encapsulation technique could reduce production costs by 50% compared to existing methods and make it possible for the microbes to survive and grow within the concrete structure [9].

In the Middle East and Mediterranean areas, a shortage of water supply is a prominent problem that has forced authorities and experts to seek solutions to lower the sharpness of this crisis [10]. For example, in the Gaza strip sewage water is a major problem due to poor sanitation processes, inadequate treatment, and risky disposal of untreated or partially treated wastewater [11]. Wastewater is characterized by huge bacterial numbers

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and biodiversity, which can be a good source for isolating calcium carbonate precipitating bacteria, which have urea hydrolysing activity [12,13]. Studies have indicated that implementing the MICP mechanism will enhance the self-sealing capacity and durability of concrete structures, but the preparation process is costly and requires professional labour. It is essential to establish a simpler, environmentally friendly, economically viable, and sustainable method for enhancing the viability and efficacy of the healing process. Moreover, since there are essential parameters required for a self-healing process to occur in concrete structures, and these parameters are similar in both normal conditions and sewage water, it can be concluded that sewage water has the potential to serve as a healing agent for concrete structures by providing the essential parameters. Studies have shown that sewage water contains a high level of biodiversity [14] and that it is rich in urea, which is a major component of human and animal urine [15]. Additionally, sewage water treatment process contains oxygen [16], which further contributes to its potential usefulness as a substance for promoting the self-healing process. As a result, the necessary prerequisites for a self-healing concrete system are supposed to be met. Therefore, sewage water can be deemed as a possible healing agent within concrete.

2 Material and methodology

2.1 Sewage water

Samples of sewage water for this study were collected from the Płaszów sewage treatment plant. It is one of the two central treatment plants in the city of Cracow. In terms of size, it is the largest treatment plant in Cracow and the entire province of Lesser Poland. Samples were collected and labeled from the following stages as it shown on Table 1:

Table 1. Sewage water sample's location and label.

Sample label	Sample Location
S0	Tap water (normal reference water)
S1	After mechanical cleaning (after the sand trap)
S2	Primary sedimentation tank before the biological reactor
S3	Biological reactor - oxygen zone
S4	Biological reactor - anaerobic zone
S5	Biological reactor - at the outlet (secondary sedimentation tank)

2.2 Samples preparation

This study used locally available Ordinary Portland Cement (OPC) CEM I 42.5 R. In addition, sand according to standard PN EN 196-1 was utilised in mortar mixtures [17]. Mortar Samples with OPC and standard sand were prepared to evaluate self-healing ability for samples containing sewage water from different treatment stages, which totally replaced tap mixing water. In all cases water to cement ratios (w/c) were 0.50, while cement to sand ratios were 0.33.

Then samples were exposed to 54.1^{o} C for 30 minutes to ensure that all pathogens were killed to protect human health when handling sewage water [18]. This confirms that only thermo-tolerant and spore-forming microorganisms remains viable in heated samples [19].

The PN EN 196-1 Standard for Cement test methods - Part 1: Determination of strength [17] was used to prepare mortar samples. The prepared mixtures of mortar were then poured into 40 x 40 x 160 mm moulds. Since there was no reinforcement presented in the samples, the samples were devoid of ductility, and any attempt to load them would lead to their destruction through cracking. So, after casting, a 200 µm plastic sheet was placed inside the sample as shown in Figure 1 and later removed during the demoulding process.

The samples were stored in a humid environment. After 24 hours, the beams were demoulded, and the samples were submerged in tap water (at 21°C) for curing till the test day.

Fig. 1. Plastic sheet placement within the samples.

2.3 Evaluation of Self-healing

The most crucial aspect of this research is to evaluate and quantify the ability of sewage water as a healing agent to repair cracks. To fully comprehend the effects, several evaluation techniques were applied. This section will provide a concise explanation of the method's relevance to the evaluation of healing performance and clarify their methodologies such as Stereomicroscopy and SEM analysis. In way of comparison, fresh and mechanical properties of mortars were evaluated to determine the impact of adding sewage water on its mechanical performance. Tests were conducted for the mixtures and hardened materials, such as: slump value, setting time, compressive and flexural strengths, when compared to the reference sample made with tap mixing water.

2.3.1 Fresh binder and mortar properties

Normal consistency as well as setting time test were followed by EN 196-3 standard [20]. PN EN 1015-2 standard was used to assess the mixes workability by means of flow table method [21].

2.3.2 Mechanical properties of matured materials

Standard beam specimens with the dimensions of 40 ×40 ×160 mm were used to determine the flexural and compressive strengths. The beams were notched in the middle of the length 20 mm in depth. The notch was placed on the bottom face. The span between supports was 100 mm. Applied load rate was equal to 50 N/s. Figure 2 illustrates the tested element's geometry. In the case of compression strength test the rate was 2400 N/s in accordance with PN EN-196-1 [22]. Mechanical properties were determined using CONTROLS AUTOMAX PRO testing machine.

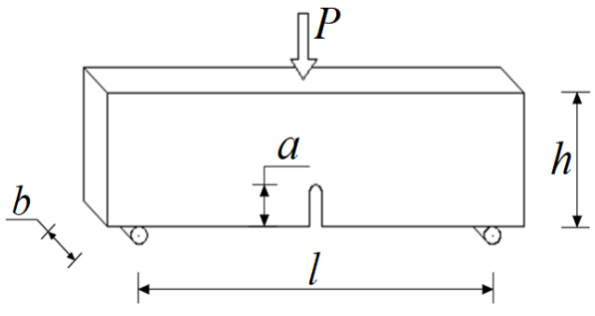

Fig. 2. Schematic diagram for beam specimen subjected to bending test [22].

2.3.3 Stereomicroscopic evaluation and SEM

For the optical inspection of samples VHX digital microscope used. In order to assess the effectiveness of the healing, samples were evaluated every two weeks until the crack was observed to have closed. During the setup phase, the dimensions of each pixel were assigned using a microscale rod. This used for the measurement of crack width and closure percentage. Images were captured at scale of 100x. Morphology of the surfaces of cracks were inspected with a Zeiss Evo10 Environmental Scanning Electron Microscope (ESEM).

3 Results and discussion

3.1 Normal consistency and setting time

In all cases S1-S5, the standard consistency was maintained with the same amount of water as the reference tap water and was 0.29.

Initial setting time indicates how quickly cement begins to lose its plasticity, while final setting time indicates how long it takes for cement to lose all of its plasticity and gain sufficient strength to resist pressure. Figure 3 shows the time at which binders made with sewage water samples from various stages of treatment begin to lose their plasticity relative to the reference sample, which was made from tap water. This can be attributed to the organic matter content at each stage of treatment. For instance, samples from Stage S4 have the longest initial and final setting time due to the high organic matter content at this stage, whereas samples from stages S2, S3, and S5 have shorter initial setting times due to the lower organic matter content at those stages and is comparable to reference values. The presence of organic matter in concrete can have several effects on its setting time. When organic matter is present in concrete, it can interfere with the chemical reactions that take place during the setting process. The organic matter can react with the components of the cement, such as calcium hydroxide, and form compounds that can slow down the formation of the cementitious materials. This can lead to longer setting times, which can affect the strength and durability of the concrete. Additionally, the organic matter can also interfere with the hydration process of the cement. This can result in a reduction in the overall strength of the concrete, as well as an increased susceptibility to cracking and other forms of damage [23].

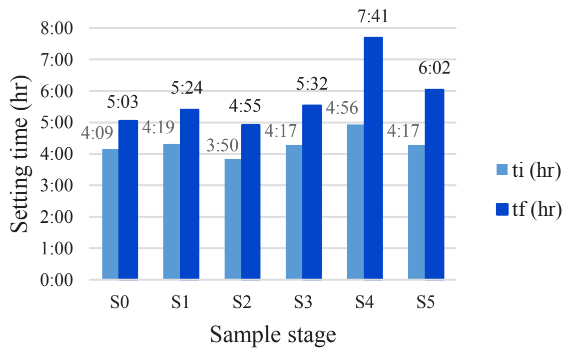

Fig. 3. Setting time results.

3.2 Fresh mortar workability (Flow Table Method)

As shown in Table 2, the flow value of samples from sewage water taken at stages S1 (after mechanical cleaning, S2 (initial settling tank before the biological reactor) and S5 biological reactor at the outlet) respectively, is very close to the slump value of the reference sample. In the remaining cases of water S3 (biological reactor - oxygen zone) and S4 (biological reactor - anaerobic zone), the flow is slightly less, but the mixture is still workable.

3.3 Flexural and compressive strengths

Table 2 shows flexural and compressive strength values that have been determined for samples from all treatment stages. Through Figure 4, it was observed that sewage

Table 2. Summary of fresh and mechanical mortar test results.

Sample Number / Test	S0	S1	S2	S3	S4	S5
Flow value (cm)	16.5	14.5	15.5	13.5	13.5	16
Normal consistency w/c (-)	0.29					
Compressive strength (N/mm^2)	57.33	59.98	57.38	58.03	49.37	51.56
Flexural strength (N/mm^2)	8.13	7.88	7.52	5.51	5.92	6.03

water from the S1 and S3 stages had a similar effect on compression as the reference sample, with slight increase. This can be explained by the presence of MCIP bacteria in sewage water at stage S3. Additionally, at this stage of mechanical treatment, sewage water becomes 60 to 70 percent free of suspended solids, thereby reducing the presence of organic matter. At the subsequent stages (S4, S5), sewage water becomes partially treated and disinfected, which leading to kill all bacteria; hence, no improvement is observed at these stages in compression. However, during stages (S1, S2, S3), the results showed that the addition of sewage water had a neutral or positive effect on the samples, in contrast to the negative effects observed in other stages. On the other hand, for flexural strength slight drop noticed on the values of flexural strength for the sewage water from the whole stages when compared to the reference sample.

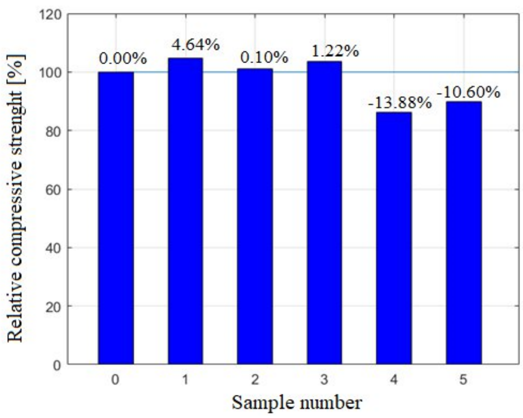

Fig. 2. Relative compressive strength.

3.4 Stereomicroscopic evaluation and SEM

On cracked mortar beams containing sewage water, self-healing phenomenon was evaluated using a thin plastic sheet with a constant width of 200 µm. To evaluate the healing process using stereomicroscopy, entire specimens were analysed and evaluated on the second day of healing and after 14 days. And tracking the progress of healing in each sample.

Intriguingly, stage S3 as it shown in Figure 5 (a, b) exhibited a complete crack sealing effect, with an average crack width of 0.20 mm (200 µm). Whereas some samples demonstrated the ability to seal cracks, others did not exhibit any precipitation during the curing period. The ability of bacteria to heal cracks was assessed as a key component of this study. Samples from each stage of treatment were tested to determine how effectively each stage of treatment worked to close a crack that was 200 µm wide. The results of a comparison of the crack-closing abilities of water from various sewage treatment plants are summarized in Figure 6.

Early stages of sewage water treatment (S1, S2, S3), where the presence of bacteria is obvious, showed a healing effect. This demonstrates that bacteria present in sewage water are the source of the participated material in the crack. At those stages, sewage water underwent primary treatment, which essentially involves the physical removal of large and small particles through filtration and sedimentation processes, so there hasn't been a direct impact on bacterial life yet. However, at stages (S4, S5), secondary treatment involves the removal of suspended solids (TSS) and biodegradable organic matter (BOD) through the processes of aeration.

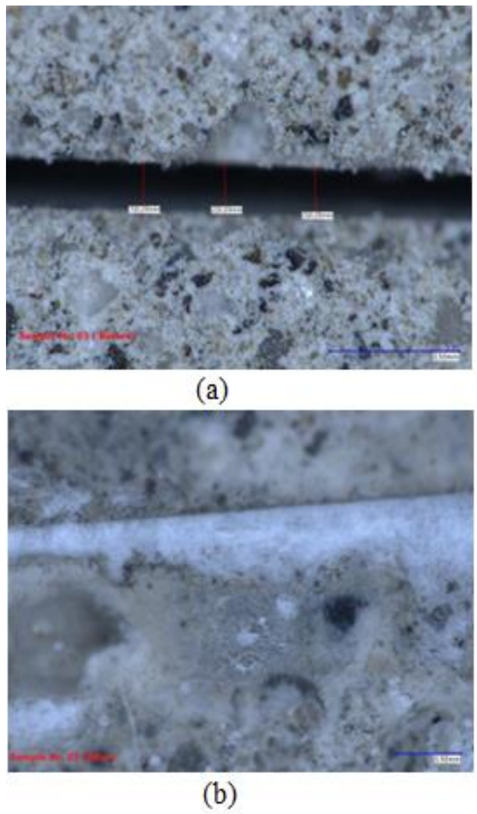

Fig. 5. Stereomicroscopic photo of Sample S3 (a) S3 sample at age of 2 days; (b) S3 sample at age of 14 days

Image analysis was performed to determine the effective percent of healing by measuring the actual area of the crack prior to healing after demoulding the plastic sheet, and then, 14 days later, calculating the area of the crack after it had been filled by the participated material during the curing stage. In Figure 6, data are presented as a relative percentage of healing in comparison to the reference sample made with tap mixing water. And it demonstrated that S3 stage was able to completely seal the crack, while having no negative effect on the mechanical properties of concrete. SEM evaluations were conducted on samples that self-healing was observed.

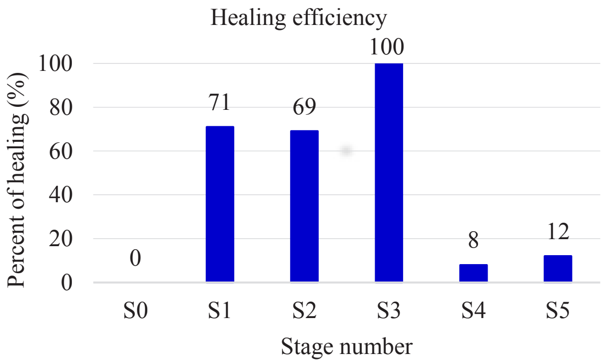

Fig. 6. Healing efficiency

Images of crack surfaces obtained from S3 at 7 and 14 days old samples can be seen in Figure 7. Similar crystal morphologies were observed in the S3 sample. Bacilli-shaped indications of bacterial cells were also observed on the crystal formations. Calcite appears to be the most predominant mineral phase in precipitating calcium carbonate. Bacteria have left distinct fingerprints on coarse hexagonal crystals. [24].

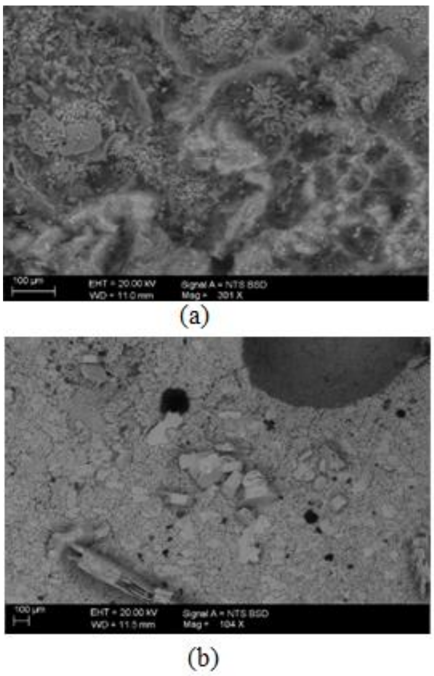

Fig. 7. SEM images of 14 day cracked samples from S3 stage: (a) precipitated crystals morphologies at the surface of sample; (b) coarse hexagonal crystals of calcium carbonate

4 Conclusion

This study investigated the potential use of sewage water as a self-healing agent within cement mortar samples. The replacement of ordinary mixing water with sewage water from the oxygen zone of the biological reactor's stage S3 was deemed as a successful attempt. Tests and data indicate that it is a promising approach that could be used as an effective healing agent in the future or alternative material for mixing water. The study found that substituting sewage water for ordinary mixing water at certain stages (S3) has no negative impact on the fresh properties of concrete (workability, consistency, and setting time). Mechanical properties such as compressive was preserved in comparison to the control sample.

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