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Monitoring the bio-self-healing performance of cement mortar incubated within soil and water using electrical resistivity

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ABSTRACT

In research on self-healing concrete, the restorative performance can be evaluated by a wide range of techniques. However, most of these techniques can be challenging to apply to concrete samples embedded in soil without causing a significant disturbance to the test (as they require removing the samples from the soil, washing off any residue, and examining and returning them). To provide a solution to this issue, we investigated the potential application of an in-situ, non-destructive method utilising electrical resistivity (embedded electrodes). The study was conducted on bio-mortar specimens incubated within saturated soil and water for 11 weeks. The bio-specimens were cast by adding expanded perlite impregnated with *Bacillus subtilis* and nutrients to the fresh mix. Standard cement mortar (without bacterial agents) was also tested to serve as control specimens. Additional testing (capillary rise and absolute porosity) was conducted under typical conditions to provide context for interpreting the changes in electrical resistivity in relation to the healing process. The bio-mortar showed greater improvements in electrical resistivity (accompanied by a reduction in crack area, water absorption and absolute porosity) than the control mortar. The study demonstrated that the electrical resistivity technique could potentially monitor the self-healing performance of concrete embedded in soil without disturbing the concrete-soil system.

1. Introduction

Over the last two decades, autonomous self-healing concrete has increasingly been investigated as a promising solution to repair cracks and damage that occur over time due to environmental conditions or mechanical loads [1,2]. One common approach involves incorporating (encapsulated) microorganisms, nutrients, or other substances that can “self-heal” its micro-cracks by metabolic activities precipitating calcium carbonate [3]. Additionally, concrete may heal autogenously without the need for external stimuli or the addition of any substances [4,5]. Regardless of the healing approaches, performing a robust evaluation of the healing efficiency is vital. High levels of healing efficiency indicate full or almost full crack sealing with the recovery of physical properties, mechanical strength, and durability [6].

A broad range of methods [7,8] has been developed to evaluate the self-healing capacity of cementitious materials. These methods can generally be classified into three main categories: visualisation and determination (of the change in crack areas), assessment of regained resistance and tightness, and assessment of regained mechanical properties [7]. The first category involves observing and measuring the changes in crack areas, while the second category assesses the recovered material properties, such as resistance and tightness, by subjecting the healed material to tests such as permeability and water absorption. The third category evaluates the regained mechanical properties of the material, including compressive and tensile strength. The selection of a suitable assessment method is governed by the specific goals, limitations, and other aspects of the study, such as the incubation environment - where concrete is placed during the self-healing process.

The efficiency of various self-healing mechanisms has been evaluated in cementitious materials, traditionally incubated within humid air, water and seawater [9–12]. However, there has been a growing research interest in examining the self-healing capabilities of concrete in other environments, particularly soil, which is relevant for underground structures [13–17]. In concept, the method used for evaluating self-healing concrete placed in soil should follow several key criteria, including simplicity, quality, reliability, and safety (like all test methods in various fields of science). However, additional factors, such as low disturbance and in-situ applicability, are also essential for monitoring

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the healing process in underground concrete elements. During the healing process, such elements would be subjected to overburdened and lateral earth pressures and other ground conditions [13]. By considering these factors, it will be possible to adopt effective assessment methods for accurately and continuously assessing the performance of the self-healing concrete built within the ground or soil at any time without distracting or removing the concrete from the soil.

Non-destructive testing (NDT) techniques, such as thermogravimetric analysis [18], rapid chloride permeability [19,20], steel corrosion [21,22], ultrasonic pulse velocity method [23], and x-ray scan [24], can offer a better opportunity to evaluate the self-healing capabilities of concrete with minimal disturbance. For example, research [25] has shown that the ultrasonic pulse velocity technique can effectively measure the self-healing efficiency of concrete mixed with lightweight aggregate. Additionally, studies [21,22] have found that the inhibition of steel corrosion through ureolysis-based microbial calcium carbonate precipitation can be used to effectively provide an indication of crack sealing in concrete. Another study [26] used Acoustic Emission sensors to evaluate crack healing and found that the accuracy of transmitter localisation improved as the crack healed.

While non-destructive methods for evaluating self-healing concrete do not cause physical damage, some still require removing the concrete element from its environment for inspection. However, this can disturb the concrete-soil system. A more suitable approach for monitoring and evaluating self-healing in underground concrete would be a non-destructive technique that can be applied in-situ. One such technique that could be used is electrical resistivity, as it can be applied without removing the concrete element from its environment, thus avoiding disturbance to the concrete-soil system.

The concept of the electrical resistivity (ER) method is based on measuring the resistance of concrete to the flow of electrical current [27,28]. The ER of concrete is generally affected by several factors, including the water content, the composition of the concrete mix (including the type and amount of cement, aggregate, and admixtures) [29], the age of the concrete, and the presence of any impurities or contaminants. Additionally, the temperature and humidity of the environment can also affect the resistivity of concrete [30]. When these variables are controlled, the effectiveness of self-healing concrete can be determined by observing changes in its electrical conductivity as a result of cracks and defects [31]. The change in cracks and their fillings alter the electrical properties of the concrete because they change the connectivity and conductivity of the pore structures.

The ER method is widely used for detecting the initiation and progression of cracks in concrete, both in the laboratory and in-situ settings [7]. For instance, it has been utilised [32] to determine the development of microcracks in cementitious composite materials under tensile strength. Another study [33] used electrical resistivity on mortar samples (with *urease* bacteria as a self-healing agent) examined within three experimental curing media, including plain water, urea-calcium chloride, and urea-calcium lactate. Some properties of concrete, such as water absorption, chloride diffusion coefficient, and the corrosion rate of steel reinforcement, are closely related to electrical resistivity [34]. As a result, the resistance of concrete to chloride penetration has been evaluated using concrete resistivity [27], e.g. in the rapid chloride penetration (RCP) test [35]. In this context, resistivity measurement can be used to determine the level of the interconnectivity of pores in concrete [36].

Overall, the electrical resistance measurements have been successfully used to evaluate the conditions of concrete and the efficiency of bio-self-healing; however, they have not been applied to concrete incubated in soil. Therefore, we investigated the potential use of ER method by measuring the electrical resistivity to monitor the crack healing performance without disturbing the soil. The method is described in Section 2, where laboratory experiments were conducted using control and bio mortar specimens incubated in two different environments: (i) water-saturated soil and (ii) water alone, which was used for comparison. Additional tests, such as the capillary rise and absolute porosity, were performed to understand the relationship between electrical resistivity and the healing process. The results of these tests are presented and discussed in Section 3. Finally, Section 4 outlines the conclusions, which have both fundamental and applied relevance for concrete scientists and designers, as it investigates a way to monitor the progress of self-healing in underground cementitious materials over time.

2. Materials and methods

The purpose of the experimental program was to investigate the potential of using electrical resistivity as an in-situ, non-invasive method for evaluating the bio-self-healing of cracks in concrete within the ground. To achieve this, a series of laboratory experiments were conducted on cement mortar with and without bacteria and incubated within soil and water. The choice of using cement mortar was made as it can serve as an indicator of the properties of concrete. It has been widely used by researchers due to the ease of preparation and handling of mortar in the laboratory, as well as the ability to more precisely control its properties compared to concrete. On the other hand, the experimental work considered water (as an incubation environment) to enable a better understanding of the results for specimens that are incubated in saturated soil. Comparing and contrasting these two conditions (water and soil) would enable us to observe the different healing rates and understand the impact of the soil matrix on the healing process and electrical resistivity.

The experimental program, as illustrated in Fig. 1, consisted of several stages: the preparation of specimens, pre-incubation testing, incubation with electrical resistivity measurements, and post-incubation testing. The pre- and post-incubation testing was conducted in order to accurately quantify the final healing progress, which would, in turn, allow for the interpretation of the electrical resistivity measurements. The final stage of the research programme was the analysis of the results, focusing on the correlation between the electrical resistivity measurements and the healing ratio of the specimens. Further details regarding the materials and methods used in these stages can be found in the subsequent sections.

2.1. Preparation of specimens

To carry out the experiments, both control and bio cement mortar were prepared and used to cast a total of over 40 specimens (prisms). By using control and bio-cement mortars, we were able to compare and contrast the healing process in each type of mortar and draw more accurate conclusions about the effectiveness of using electrical resistivity as a method for assessing microbial healing in concrete.

Each type of specimens was divided into two groups; one group was used for the electrical resistivity, while the other group was used for additional tests such as absolute porosity and capillary rise tests. These additional tests were conducted in identical conditions to validate the results of the electrical resistivity test and to provide a better understanding of the relationship between electrical resistivity and the healing process. To ensure that the properties of the mortar were consistent across all specimens, they were all prepared and mixed according to a standardised protocol.

Control and bio cement mortar prisms with dimensions of 40x40x160 mm were prepared according to BS EN 196-1 [37], using the proportion detailed in Table 1. For the experimental programme, *Bacillus subtilis,* obtained from Philip Harris in the UK), was chosen. This selection was based on previous research [38,39] that employed similar strains, and the decision was primarily influenced by the ability of this genus to form resilient and long-lasting spores. *Bacillus subtilis* is an aerobic, gram-positive, rod-shaped bacterium capable of producing endospores. This particular bacterial strain is commonly found in natural soils and requires both oxygen and a certain level of moisture to grow

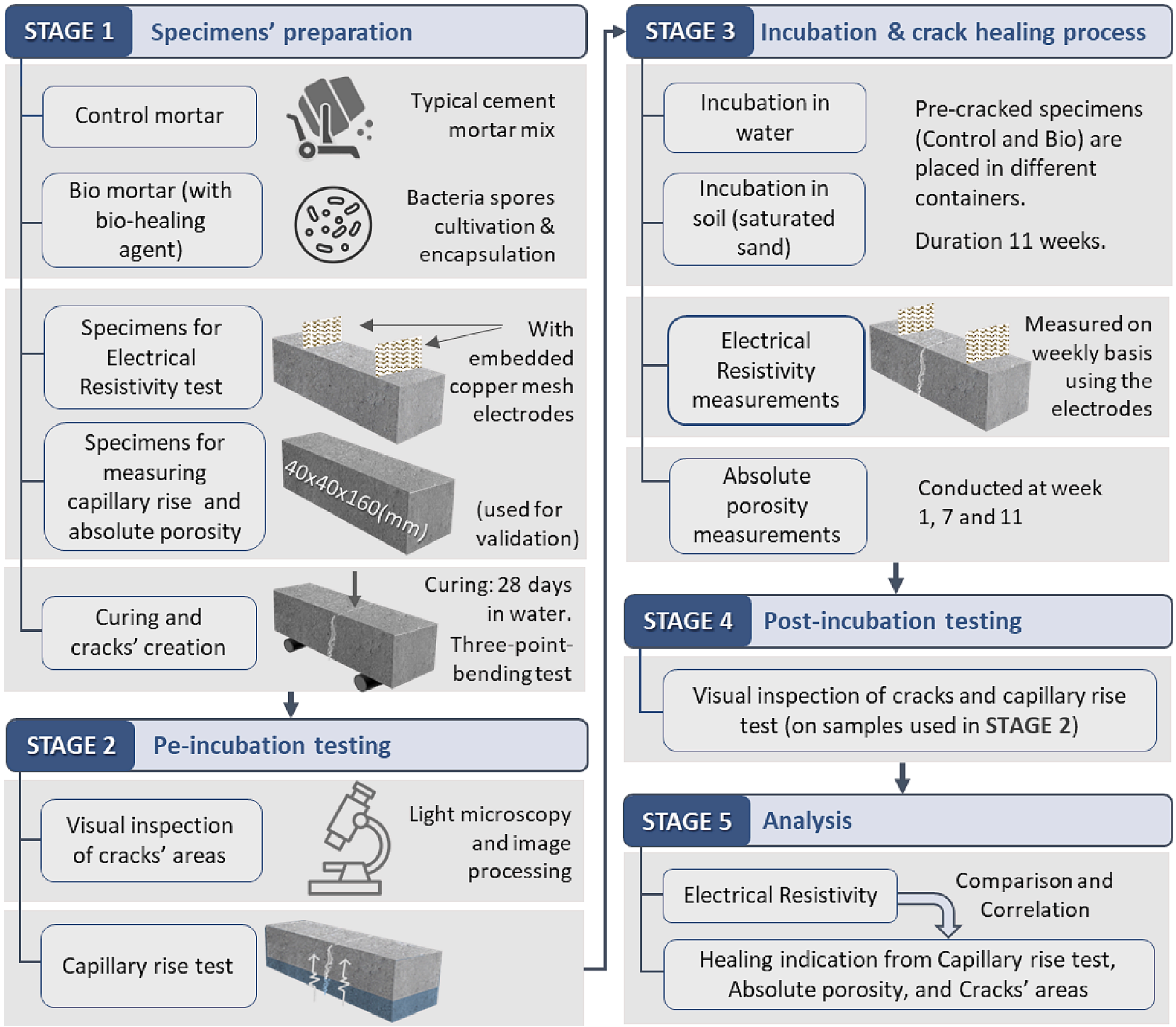

Fig 1. Overview of the research program.

Table 1
Mixing proportion of the cement mortar specimens.

Mixture ID.	Cement (Kg/m^3)	Sand (Kg/m^3)	Water (Kg/m^3)	Perlite + Bacteria + Nutrients (Kg/m^3)	Perlite (Kg/m^3)
Control	450	761	225	–	22.5
Bio	450	761	225	22.5	–

and generate calcium carbonate crystals [40]. The bacterial spores were cultivated, harvested, and encapsulated with nutrients into perlite [14]. The primary purpose of utilizing capsules is to safeguard the healing agents (bacterial spores) from the harsh conditions present in fresh concrete, such as high pH and temperature, and to prevent unintended agent release during the mixing process. The produced capsules contain approximately 0.3% of nutrients by perlite weight with a spore concentration of about $5.2x10^6$ Colony Forming Unit (CFU g^{-1}).

The cement mortar specimens were prepared by mixing the Hanson Sulphate Resisting Cement (CEMIII/A + SR supplied from the UK) with water in a digital mortar mixer (Controls Testing Equipment Ltd) for about 30 s at a low speed (140 ± 5 r/m). Then, the sand (aggregate) was added gradually to the cement paste, and the mixing continued for 30 s at high speed (285 ± 10) - according to BS EN 196–1 [37]. Afterwards, the mixer was stopped for one minute to scrape the adhering paste from the mixer's walls, and then it was operated again at high speed until the mix became homogenous.

For the specimens of the electrical resistivity measurements, additional work was carried out. A pure copper wire mesh with 0.6 mm of wire diameter and a square mesh of 1.5 mm was used as an electrode, as shown in Fig. 2a. The copper mesh electrodes were embedded within the cementitious matrix parallel with a distance of 120 mm between the two electrodes using the same process used in casting carbon electrodes. In order to make the copper electrodes straight, small wooden pieces were used to support the electrodes during the casting. The wooden pieces were removed 15 min later after finishing the casting. After 24 h, all mortar specimens were gently removed from their moulds and cured for 28 days until they were tested.

2.2. Crack creation

After curing, all specimens were cracked using a three-point bending test. The prisms were installed at two parallel beams at the bottom of the sample, with the distance between these beams measuring approximately two-thirds of the sample's total length. The sample was subjected to compression on the top surface by a central beam. Linear Variable Differential Transducers (LVDT) were attached to the bottom of the specimens to monitor the induced cracks. The load was applied at a velocity of 0.001 mm/s until a crack formed.

Generating cracks in unreinforced mortar specimens without reaching full failure is a very difficult task. However, it was important to

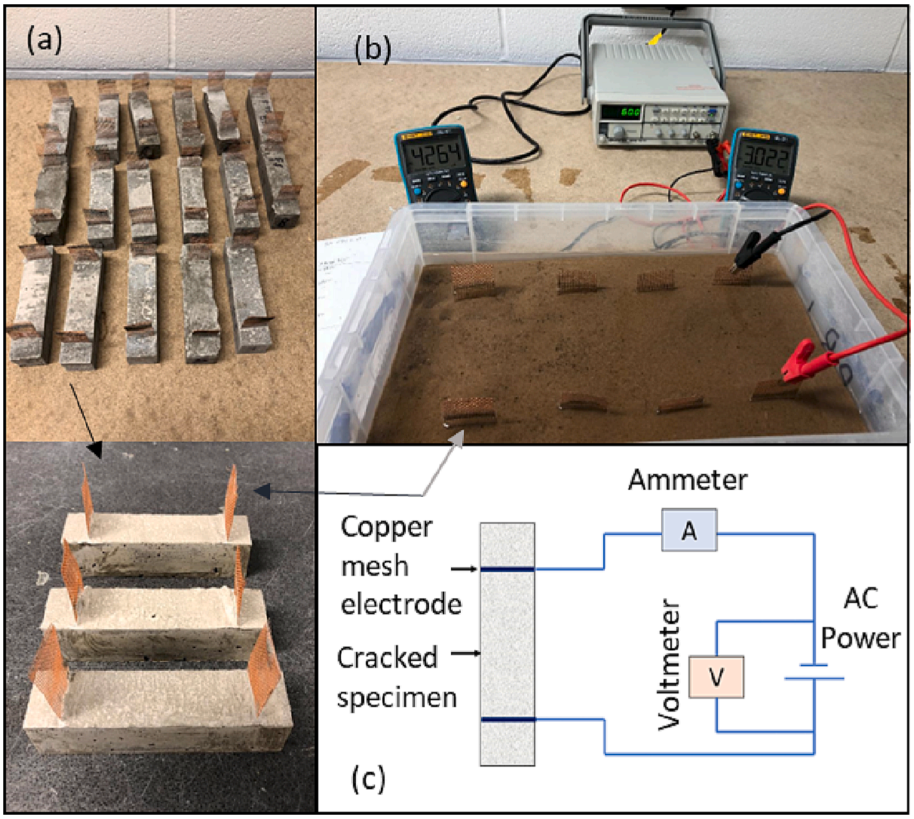

Fig 2. Electrical resistivity measurements: (a) some of the prisms in preparation for the test, (b) four of the samples during incubation within the soil, and (c) simplified schematic diagram showing the electrical circuit used in the test.

refrain from using any internal reinforcement in the specimens to avoid any possible interference with the measurements of electrical resistivity, especially if the reinforcement is in close proximity to the electrodes. To overcome this issue, we first gained experience with the specimen behaviour and ultimate strength during the three-point bending test. Building on that experience, we adopted a suitable loading rate based on the LVDT measurement of the specimen deflection. Additionally, during the three-point bending test, the specimen was supported by a steel sheet as external reinforcement, temporarily glued to the base at a few locations away from the centre. This procedure helped to reduce the stress concentration and prevent the sample from fracturing too quickly or suddenly.

Immediately after the creation of the cracks, their widths were measured at regular intervals using Shuttlepix Editor software. The three-point tests generated various cracks in the specimens with widths ranging between 100 μm and 280 μm. It is important to note the direction of cracks in relation to the electrical current passing between the electrodes is probably highly influential on the conductivity results i.e. crack parallel to the current direction would not increase conductivity much, but a perpendicular crack would increase it significantly. In this study, the cracks were all perpendicular to the electrical current direction.

2.3. Preparing the incubation environments

The two different incubation environments (water and saturated sand soil) were considered in this study to understand better the potential influence of soil versus water on the healing process and electrical resistivity. Soil encompasses a diverse range of types and compositions (including gravel, sand, silt and clay), and our research program presented in this study specifically focuses on the inclusion of saturated sand as it can be found in many actual ground conditions. Soil conditions saturated with water are prevalent in countries with high annual precipitation, including the UK. In the current study, the differences in the two conditions (water and saturated sand soil) arise from their distinct physical properties and characteristics. When the cement mortar is immersed in water, it experiences a full water environment with direct contact between the mortar and the water. This condition allows for the efficient transport of dissolved substances, including by-products of the healing process.

On the other hand, when the cement mortar is placed in saturated sand soil, the soil matrix creates a more complex environment. The sand particles in the soil create a network of interconnected pores, which affects the transport of gases and liquids. This can influence oxygen availability for bacterial activity and the movement of gases, such as carbon dioxide (CO_2), produced during the healing process. Therefore, studying the healing of cement mortar in water and saturated sand soil allows us to observe the variations in healing rates due to differences in these environmental factors.

For preparing these incubation environments, precautions were taken to avoid cross-contamination of the cracked specimens (both the control and the bio-mortar). Therefore, these specimens were incubated in separate plastic boxes, some filled with water and others with saturated soil. Half of the specimens were incubated in saturated soil consisting of sub-rounded grain shape sand containing free chemicals. This type of soil is commonly found on construction sites and has been described in detail in [17] in terms of its mechanical and chemical characteristics. To neutralise the effects of soil bacteria, the soil was subjected to heating in an oven at a temperature of 120 °C for a period of two days.

The rest of the specimens were incubated in tap water, which had a pH level ranging from 6.8 to 7.3, with a Sulphate concentration of less than 250 mg/l as measured by handheld devices. These values were also obtained for the saturated soil to ensure a controlled comparison of the healing processes in the different incubation environments. The specimens were incubated for a total duration of 11 weeks; this period was chosen based on the expected time of the self-healing process in the bio-mortar specimens. Our previous studies (and similar research in the literature) on self-healing concrete [14,41] have shown that the healing process can take several weeks to months, depending on the type of healing mechanism involved. Therefore, the 11-week duration was chosen as a moderately conservative option to allow sufficient time for the self-healing process to occur and to observe any changes in electrical resistivity, crack area, water absorption, and absolute porosity in the bio-mortar and control mortar specimens.

2.4. Electrical resistivity method

Several electrical resistivity testing approaches have been developed for evaluating the properties of concrete. Accordingly, the electrical resistivity is measured using either a two-probe or a four-probe strategy. The four-probe method involved using four electrical contacts, with the inner two being used to measure voltage and the outer two to pass current [42]. This resulted in the contact resistance not being included in the measured resistance. In contrast, the two-probe method uses two electrical contacts that serve as both voltage and current electrodes [43].

In this study, we utilised the two-electrode technique to measure the specimens' resistivity due to several factors, such as cost, ease of implementation, and compatibility with the experimental setup. To ensure accurate measurements of the electrical resistivity, we used copper electrodes. Copper is a commonly used material for this purpose [44–46], as it has a low resistance and high conductivity, enabling precise resistivity measurements. The two electrodes were embedded in fresh mortar, with their free sides as electrodes, as shown in Fig. 2. An alternating current (AC) voltage of 3 V was applied across the two electrodes from a function generator. The AC voltage was supplied at a frequency of 60 Hz to eliminate the influences of polarisation [47].

Previous studies [48,49] have shown that direct current (DC) can increase resistance over time due to the polarisation effect. This is because the electric current passing through the cementitious matrix produces oxygen and hydrogen, creating a thin film between the cementitious matrix and the electrodes [50]. This film reduces the electric current at a given applied voltage. Therefore, we used AC at a 60 Hz frequency in this study to partially resolve polarisation problems, as also shown in Chen's study [51].

In order to calculate the material resistivity, two readings were obtained from the measured current (C) and voltage (V). The electrical resistivity of the concrete is then calculated as follows [52]:

$$\rho = \mathrm{R}\,\frac{\mathrm{A}}{\mathrm{L}} \tag{1}$$

$$\mathrm{R} = \frac{\mathrm{V}}{\mathrm{C}} \tag{2}$$

In these equations, ρ is the electrical resistivity of the specimen, R is the electrical resistance, A is the cross-sectional area of the electrode perpendicular to the current flow (35 × 40 mm^2), L is the distance between two electrodes (120 mm), V is the applied voltage, and C is the measured current.

The resistivity readings were taken every seven days for all samples (with and without the bacterial agent) incubated within soil and water to observe the resistivity differences reflecting the healing performance of cracks. The current was only switched on to take the measurements and not always on.

The literature [27] indicated that temperature impacts ionic mobility and that the electric current flow in cementitious material is caused by ionic movement within the pores. Ionic mobility generally increases with temperature, which resultantly reduces electrical resistivity. Since a 1.8°F (1 °C) change can cause a 3% change in the electrical resistivity of concrete [27], it is essential that temperature changes are monitored when concrete samples for electrical resistivity are tested. Consequently, in the course of the experimental measurements of this work, consideration was given to the impact of temperature on electrical resistivity.

2.5. Capillary rise test

The capillary rise test is a non-invasive test to measure the tightness in cementitious materials, making it a practical way to quantify the water tightness of specimens before and after cracking. Capillary suction occurs due to the difference in surface tension between the fluid–fluid and fluid–solid interfaces [53]. In this study, the water absorption rate in the capillary suction of oven-dried mortar specimens was measured to calculate the change in the sorption coefficient (S) before and after the healing process.

In the beginning, the cracked mortar prisms were dried in an oven at 40 °C for at least one week until their mass changed by less than 0.2% within two hours [54]. The sides of the prisms were coated with epoxy resin to make them waterproof, except for a small area of 20 mm × 40 mm around the crack on the bottom surface. The weight of the specimens was recorded at the start of the experiment. The test face of each specimen was then placed on plastic strips in a tray with a loose lid to prevent air circulation around the specimens. Then, the tray was filled with distilled water to a depth of about 2 mm above the plastic strips, i.e. submerging the specimen face.

The change rate in water absorption of the control and bio-specimens before and after incubation was determined using an electronic balance with an accuracy of 0.01 g. Before weighing, the specimens were wiped with a damp cloth to remove surface water. Water uptake was measured at 12 min, 30 min, 1 h, 2 h, 3 h, 4 h, and 6 h. The coefficients of absorption and sorptivity (I and S) were determined using the equations provided in BS EN 480–5:2005 [55].

$$I = \frac{m_t}{a \times d_w} \tag{3}$$

$$S = \frac{I}{\sqrt{t}} \tag{4}$$

In these equations, I is the coefficient of absorption (mm), m_t is the change in mass of the specimen in grams at time t (s), a is the exposed area of specimen (mm^2), d_w is the density of water (g/mm^3), and S is the coefficient of sorption (mm/$\sqrt{\text{s}}$).

2.6. Absolute porosity method

Absolute porosity significantly affects concrete resistivity, where resistivity decreases as the absolute porosity increases. In this study, the absolute porosity of control and bio-mortar specimens were measured for three different periods (1, 4, and 11 weeks) to investigate the bio-healing agent's effect on the cementitious porosity matrix. This test was conducted for water-incubated specimens. The test measures the bulk porosity, which represents the overall porosity of a material, and includes all the voids, pores, and cracks within the bulk of the material.

To conduct the test, additional specimens were prepared identically and immersed in a typical water environment used in the electrical resistivity tests. At each specified duration (1, 4, and 11 weeks), some specimens were removed from the incubation environments, cleaned, and gently wiped with a clean cloth to ensure the surface was dry. The specimens were immediately weighted to obtain the saturated surface-dry mass (W_s) using an electronic scale with 0.01 g accuracy. Then they were oven-dried at 100 ± 5 °C until getting constant weight to determine the oven-dry mass (W_d). The absolute porosity of concrete was calculated [56] as follows:

$$A_p = \frac{(W_s - W_d)/d_w}{V} \times 100 \tag{5}$$

In this equation, A_P is the absolute porosity (%), d_w is the density of water, W_s is the saturated surface-dry mass of the specimen, W_d is the oven-dry mass of the specimen, and V is the sample volume. Therefore, the absolute porosity of the material represents the proportion of the volume of pore space to the volume of the specimen, and its value is usually expressed as a percentage of the specimen volume.

2.7. Visual inspection and image analysis

The healing ratio of cracked specimens was also evaluated through visual inspection using a digital microscope (Nikon P-400R). Cracks were marked at intervals along their length and photographed before and after incubation. Ultrasonic cleaning was performed to remove residual soil particles prior to crack inspection. Using the ShuttlePix Editor Software (Nikon) and ImageJ [57], the decrease in the area of the cracks was measured. A total of 86 microscopic images were analysed, and the average healing ratio (H_{av}) was calculated using Equation (6), which is based on the decrease in the area fraction of the cracks as identified by black pixels in the images.

$$H_{av} = \frac{1}{n}\sum_{1}^{n}(A_i - A_f)/A_i \tag{6}$$

In this equation, A_i represents the initial area of an individual crack at a specific location, A_f represents the final area of the same crack at that location, and n is the total number of areas of the cracks analysed.

3. Results and discussion

3.1. Electrical resistivity measurements

The electrical resistivity for both types of cracked specimens (control and bio-mortar) was measured during the healing process on weekly bases. The relationship between the electrical resistivity and time of incubation for these specimens in water and soil is presented in Fig. 3.a and 3.b, respectively. In order to control for variations in the initial specimen conditions and the effect of soil and water, the mean values of electrical resistivity (ρ) were normalised by the initial values (ρ_0) measured at the beginning of the first week. From the graphs, it can be observed that the electrical resistivity for all specimens generally increased over time.

For specimens incubated in water (Fig. 3.a), the increase in resistivity in the first four weeks of incubation was almost similar for both types of specimens (bio and control). However, after that, the increase in resistivity of bio-mortar specimens was higher than the control specimens. After 11 weeks of incubation, the final increase for bio and control specimens was about 2.0 and 1.6 (respectively) times the initial resistivity (ρ_0). The notable improvement in electrical resistivity of the bio-mortar specimens can be interpreted as a result of calcium carbonate deposition within the cracks that reduces mortar permeability [14] and electric current passing through mortar pores. In other words, the healing decreases moisture content so that the cavities are aligned so that no fluid can be conducted along the pores, leading to the increased electrical resistance of the mortar.

For soil-incubated samples (Fig. 3.b), the electrical resistivity for both specimens (bio and control) increased over time – but with some fluctuations between Weeks 3 and 7. After 11 weeks, the final increase in resistivity for bio-mortar specimens was approximately 1.7 times their initial resistivity (ρ_1), whereas the final increase for control specimens was roughly 1.4 times their initial resistivity.

In general, the increase in the electrical resistivity of specimens incubated in water was higher than in soil. This was attributed to the increase in healing performance in water compared to soil incubation, which confirms previous results conducted by the authors [14]. The presence of soil matrix might have influenced the transport of oxygen and other resources to the bacteria, which could restrict their ability to produce CO_2 and Calcium Carbonate $CaCO_3$, sealing the cracks.

Regression analysis was performed to identify the mathematical expression that best describes the relationship between incubation time (T) and the normalised mean values of electrical resistivities (ρ/ρ_0), where ρ_0 are the initial values. The results, shown in Fig. 4, suggest that the data for water incubation fits an exponential curve, implying that the healing process may have continued to increase - even after 11 weeks. In contrast, the electrical resistivity data for soil incubation did not fit well with an exponential curve or other common functions. Among these functions, the data were best represented by a quadratic equation, which yielded an R^2 value of 0.835. This suggests that the healing process in soil was less consistent than that in the water, likely due to fluctuations in the healing rate resulting from the slower exchange of CO_2 and oxygen through the soil pore water.

3.2. Capillary water rise and visual inspection of cracks

Capillary water rise and visual inspection of cracks were conducted as part of pre- and post-incubation testing to confirm the healing ratio in light of the electrical resistivity changes. Fig. 5 presents digital photos taken for several samples before and after incubation, displaying the typical healing observed at the crack surface. Based on the visual inspection results (using a light microscope and image processing), the average hearing ratio was calculated using Equation (6) and presented in Fig. 7.

The visual inspection was supported by the capillary rise test to quantify the difference in water absorption of the healing process. The rate at which water absorbs through cracks due to capillary suction before and after incubation was studied to understand the connection between surface-level crack closure and absorption rate. The relationship between the mass of water absorbed per unit inflow area with the square root of time is shown in Fig. 6. The results indicate that after

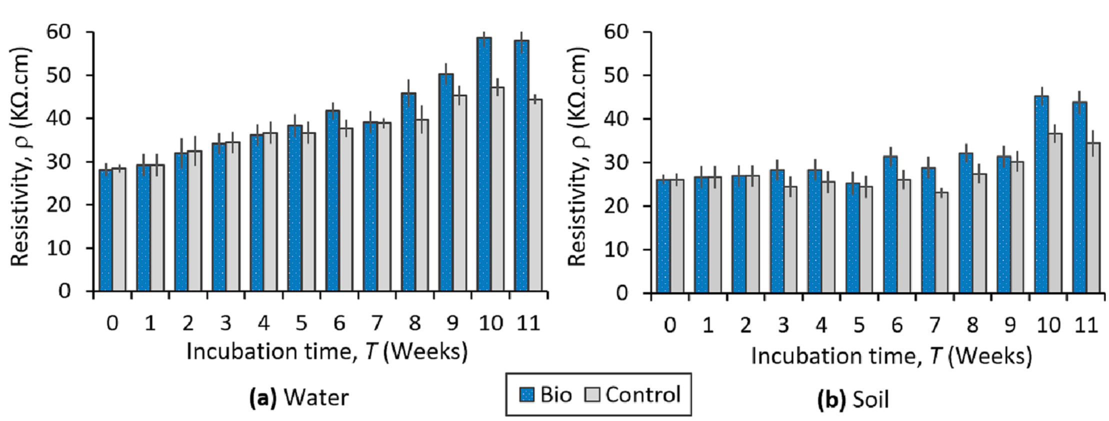

Fig 3. The electrical resistivity measurements with time for the bio and control specimens incubated in (a) water and (b) soil.

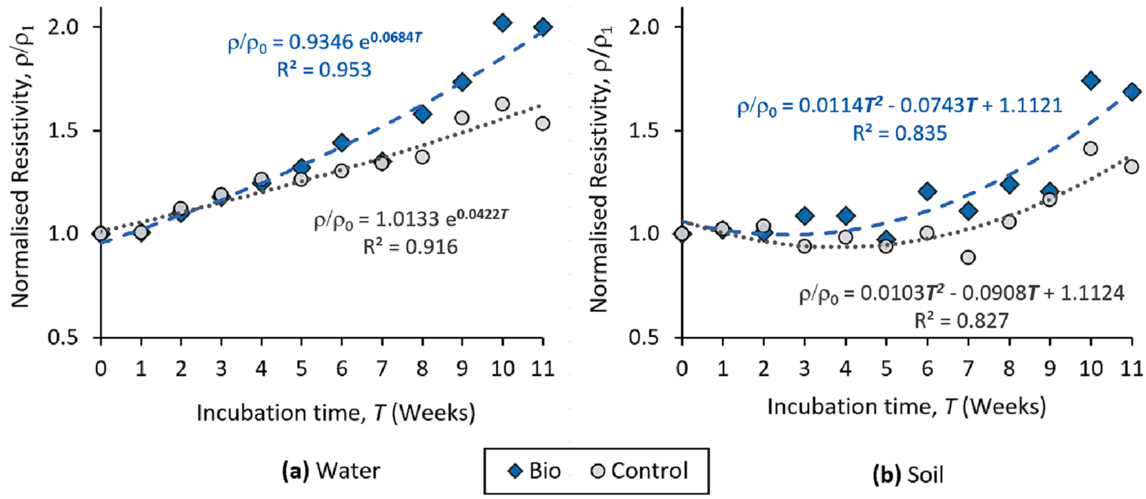

Fig 4. The correlation between the normalised electrical resistivity and time for the bio and control specimens incubated in (a) water and (b) soil.

Fig 5. Observation of crack healing before and after incubation for bio-mortar specimens.

incubation, the sorptivity index (S) for both Bio and Control specimens decreased, indicating improved water tightness. However, this improvement was more significant in the Bio-specimens, which were impregnated with the bacterial agent. The S values for Bio-specimens decreased by 74% in water and 69% in soil, while the S values for Control specimens decreased by 43% in water and 36% in soil. On the other hand, the control specimens healed naturally (autogenously) by the process of secondary hydration of the un-hydrated cement particles within the crack region, which has been observed in other research studies [1,14].

The results showed that specimens incubated in the water had a greater reduction in the absorption rate compared to specimens incubated in soil, indicating more effective crack healing in the water-incubated specimens. This reduction was consistent with the healing ratios observed through visual inspection (as shown in Fig. 7), where a higher percentage of crack closure was observed in the water-incubated specimens. The sorptivity index decreases as the crack closure (healing percentage) increases because the closure blocks moisture transport into the specimens' cracks.

As depicted in Fig. 7, the repair effect of underwater incubation was superior, with a higher healing ratio compared to incubation in the soil. This difference may be due to various factors, including the presence of water, dissolved oxygen, and partial pressure of carbon dioxide. In contrast, for specimens incubated in the sand, water availability may be limited by the pores of the porous media, which could hinder bacterial activity.

The healing ratio in this study was based on both the visual inspection and water absorption methods, which have been widely used in previous research [58] and were found to be effective. Moreover, our recent research work [14] (which included the same type of specimens and soil conditions used in this study) has confirmed the presence of calcium carbonate on the crack using Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Analysis (EDX). Further details about the biological and chemical process for the precipitation of calcium carbonate are provided in that study [14].

3.3. Absolute porosity

The absolute porosity (A_p) of the control and bio-mortar specimens was calculated using Equation (5), and the results are plotted in Fig. 8. As shown in the figure, there was only a minimal difference (2%) in the absolute porosity values between the two types of specimens after the first week of incubation in water. Therefore, it can be concluded that the change in porosity did not significantly impact the electrical resistivity measurements at this early stage.

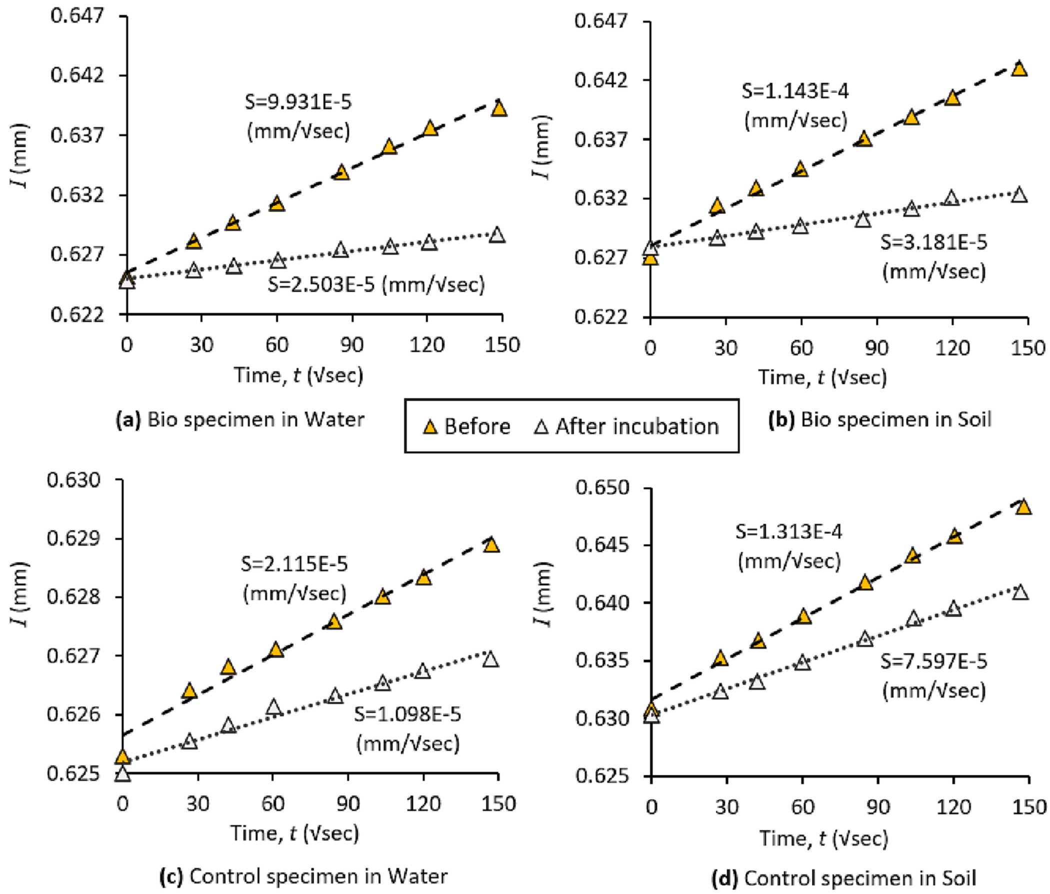

Fig 6. The relationship between coefficient of absorption (I) of the (a, b) Bio and (c, d) Control specimens before and after incubation in water and soil. Sorptivity index (S) is the slope of the fitted trend lines.

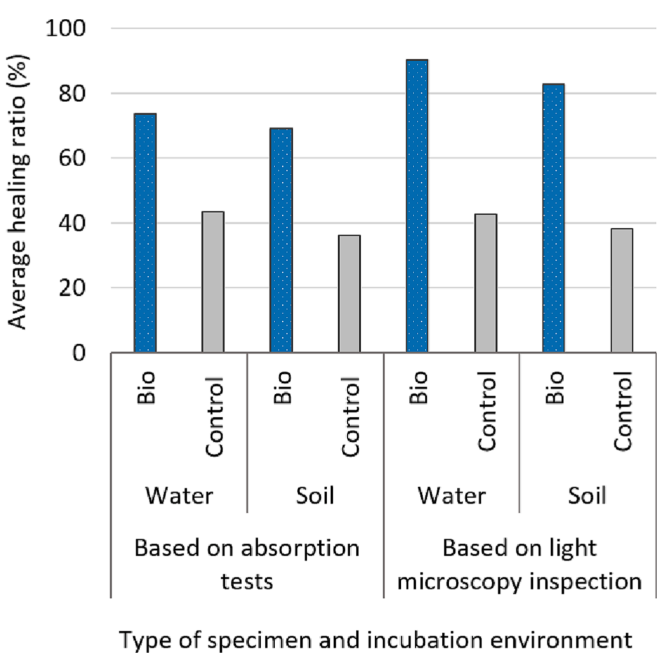

Fig 7. Average healing ratios based on absorption tests and visual inspection of all types of specimens (Bio and Control) before and after the end of their incubation (in Water and Soil).

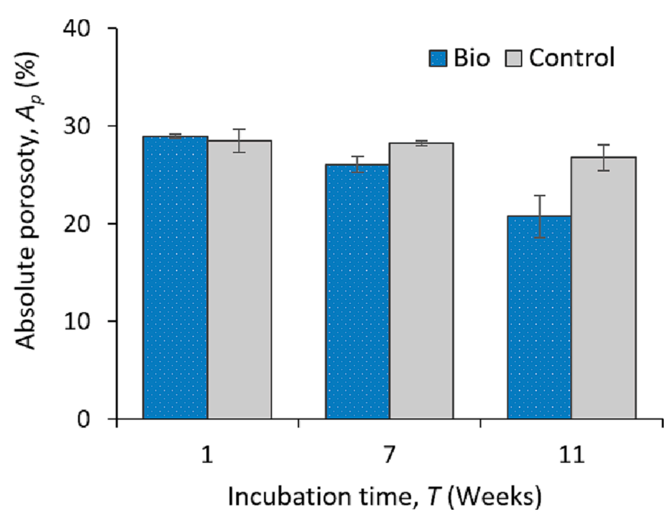

Fig 8. The absolute porosity values at different periods for the bio and control specimens incubated in water.

Over time, the absolute porosity of the bio-mortar specimens decreased, suggesting the formation of calcium carbonate crystals in the specimen crack, which can reduce the porosity. On the other hand, the porosity of the bio-mortar specimens after 11 weeks was 22.5% lower than that of the control specimens, implying that the bacteria had a significant effect on the impregnated mortar.

3.4. Correlation between average healing ratio and normalised electrical resistivity

As the electrical resistivity values were consistently changing with the healing ratios, it would be reasonable to conduct regression analysis to correlate them. However, this was only possible for the ER measurements taken at the beginning and end of incubation (when the healing ratio was determined by visual inspection and capillary rise tests).

In order to control for variations in specimen conditions, the final electrical resistivity measurements (ρ_n) at week 11 were normalised by the initial values (ρ_0). As shown in Fig. 9, the data indicates a strong positive correlation ($R^2 \geq 0.97$) between the average healing ratios H_{av} and ρ_n/ρ_0 values, with a linear relationship being the best fit for the data. For all soil-incubated specimen types, an increase in healing ratio H_{av} was observed to correspond with an increase in ρ_n/ρ_0 at a rising rate. This linear relationship was similarly found in the water-incubated specimens (Fig. 9 – the lower line), indicating that changes in electrical resistivity are driven by the healing ratio. This finding may also suggest that the healing process is consistent and predictable across the different types of specimens and incubation conditions.

3.5. Discussion on parameters affecting electrical resistivity measurements

There are several parameters that can affect the electrical resistivity measurements of self-healing concrete specimens incubated in soil and water. Firstly, the presence of water in the pores and cracks of the cementitious material can impact the electrical resistivity measurements. Water has a much higher electrical conductivity than air; therefore, when the pores of the material are saturated with water, the overall electrical conductivity increases, resulting in a smaller electrical resistivity. This is because the dissolved ions or free electrons within the water molecules act as conduits for the flow of electrical charge through the material. However, as the healing process progresses, the cracks are filled with calcium carbonate, which in turn reduces the amount of water in the cracks, leading to an increase in electrical resistivity – as observed in Fig. 3. On the other hand, the increase in electrical resistivity was not the same, i.e. for specimens incubated in water, there was a more significant improvement in electrical resistivity than those incubated in soil. This is likely due to the soil matrix causing a slower exchange of CO_2 and oxygen through the soil pore water to the bacteria [14], which can limit their capacity for the production of calcium carbonate. As a result, there is a smaller increase in electrical resistivity, as observed in Fig. 3.b. Moreover, the soil matrix can contain various constituents, including salts and minerals, that can potentially dissolve and affect the electrical resistivity measurements. However, in this study, the soil used was sand with no added chemicals and prepared in an identical way for all tests. This enabled us to isolate and study the specific effects of other parameters considered in this investigation.

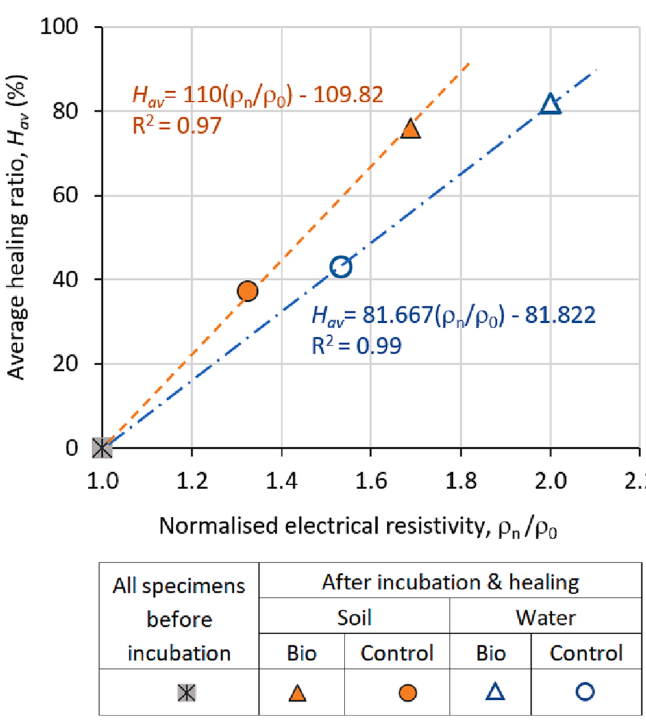

Fig 9. The relationship between the average healing ratio with the normalised electrical resistivity at week 11.

Secondly, variations in crack width and orientation can impact the resistivity measurements in concrete specimens [59]. As cracks form and propagate, they can create irregular and complex paths for electrical currents to flow through the concrete. This can lead to variations in resistivity measurements across the specimen, making it difficult to obtain accurate and reliable data. In addition to crack width, the orientation of cracks can also affect resistivity measurements. For example, cracks that are oriented perpendicular to the current flow direction can create a higher resistance path than those oriented parallel to the current flow direction. This is because the current must flow through a longer path in the perpendicular orientation, increasing the measured resistance. In this study, cracks with widths ranging from 100 μm to 280 μm generated in both the control and bio-mortar specimens. Based on the crack width range, the specimens were classified into three groups: small (100–150 μm), medium (150–200 μm), and large (200–280 μm). For each test, representative specimens from these groups were equally included to ensure that the results were representative of the different crack widths. The reported data (Fig. 3) include the mean values of electrical resistivity with standard deviation. Moreover, to normalize the results to the crack properties, the electrical resistivity measurements were divided by the initial measurement (at the beginning of the incubation). This normalization allowed for a direct comparison of the healing performance of the bio-mortar and control mortar specimens with different crack widths.

Thirdly, electrode corrosion can affect the electrical resistivity measurements due to changes in several factors, including the geometry and surface area of the electrodes, the chemical composition of the electrode surface, and the formation of localized galvanic cells between the electrodes and the concrete [60]. However, the use of copper electrodes (adopted in this study) helped to minimize this issue, as copper is chemically stable and resistant to corrosion [61]. Copper is a naturally corrosion-resistant metal, as it forms a protective oxide layer on its surface when exposed to air. This layer called a patina, helps prevent further corrosion of the metal.

Fourthly, the soil constituents can potentially affect the electrical conductivity and self-healing properties of cementitious materials. For example, the presence of salts and minerals in the soil can increase the electrical conductivity of the surrounding environment, which can affect the electrical resistivity measurements of the specimens. Additionally, certain soil conditions, such as low pH or high salinity, can negatively impact the growth and activity of microorganisms responsible for self-healing in bio-based concrete [14]. However, this study used neutral sand with no chemicals, and the control and bio-mortar specimens were incubated in identical soil conditions. Hence, the soil constituents were not a significant factor in the observed differences in self-healing between the two types of specimens.

Apart from the factors mentioned above, other variables, such as the cement ratio and curing conditions, also have an impact on the electrical resistivity measurements of cementitious materials [62]. The curing time of the specimens, for instance, plays a significant role in the development of the microstructure and hydration products, which can affect the electrical properties of the material. A prolonged curing time can result in increased electrical resistivity due to the formation of a denser microstructure with reduced pore connectivity. Likewise, a lower cement ratio can lead to higher electrical resistivity because of the presence of larger pores and voids. Hence, this study carefully considered these factors by ensuring a consistent preparation of the specimens, which included using a uniform cement-to-water ratio and curing conditions.

3.6. Discussion on the bio-self-healing process

The overall process of bio-self-healing involves the precipitation of carbonate through the equilibrium between Ca^{2+} and CO_2 with $CaCO_3$, as shown in Equation (7):

$$Ca^{2+} + H_2O + CO_2 \leftrightarrow CaCO_3 + 2H^+ \tag{7}$$

In this process, CO_2 is generated by microorganism activity, while Ca^{2+} is sourced from the surrounding soil, water, and cement matrix. However, there are likely additional biological and abiotic factors influencing these processes, which require further investigation for a comprehensive understanding.

Comparing the healing performance of bio-mortar specimens to that of control mortar specimens (Fig. 7), it is evident that all bio-mortar samples exhibit higher healing ratios. This improvement can be attributed to the precipitation of white calcium carbonate minerals, which result from the metabolic conversion of nutrients by bacteria. The presence of mineral precipitation was observed through visual inspection and was also confirmed in our previous study [14] that utilized EDX-SEM scanning techniques on similar specimens.

The findings suggest that the self-healing process of mortar specimens generally follows a similar pattern in both saturated sand and water environments. However, the healing ratios in water were generally larger than in sand, as the pore-water movement in porous media like sand slightly restricts bacterial activity. This can be attributed to the higher concentration of dissolved oxygen in water and exposure to light, which stimulates the photosynthesis pathway for calcium carbonate precipitation [2]. Consequently, the repair effect observed during underwater incubation was superior, with a higher healing ratio compared to sand.

4. Conclusion

This study aimed to investigate the feasibility of using the electrical resistivity technique (with embedded electrodes) to monitor the bio-self-healing performance in pre-cracked cement mortar specimens incubated in soil and water. The electrical resistivity measurement was validated by additional tests (capillary rise, absolute porosity and visual inspection of cracks) to provide insights into the relationship between electrical resistivity and the healing process.

The electrical resistivity results showed no notable differences in electrical resistance at early stages between the pre-cracked specimens that contained bacteria (bio-specimens) and those that did not (control specimens). However, as the specimens aged and bacterial activity increased, calcite sediments formed in the bio-mortar, leading to a more solid material with higher electrical resistance. The improved electrical resistivity of bio-specimens was remarkably greater than control specimens, particularly for water incubation, where bio-healing agents can work more effectively than soil.

The regression analysis revealed that the relationship between normalised electrical resistivity and the incubation time in water adhered to an exponential curve, implying that the healing process may have persisted beyond the experimental duration of 11 weeks. In contrast, the electrical resistivity data for specimens incubated in soil were adequately described by a polynomial function of at least the second degree, likely due to fluctuations in the healing rate caused by the slower exchange of CO_2 and oxygen through the soil pore water.

The average total healing ratios of specimen types demonstrated a linear correlation with the normalised electrical resistivity, indicating a strong association between changes in electrical resistivity and the healing ratio. This finding may suggest that the healing process is predictable and consistent across different types of specimens and incubation conditions. Nevertheless, further research is necessary to confirm this relationship in other types of cementitious materials and soils as well as other variations of curing methods and crack widths.

The healing process in the bio mortar was enhanced by the presence of microbial activity, compared to the control mortar, which did not have this benefit. The use of bio mortar resulted in a faster and more efficient healing process due to the ability of the bacteria to repair cracks and damage in the material. This suggests that incorporating microbial activity in underground cementitious material can improve its durability and longevity. However, the healing ratios tend to be higher in water compared to sand. This discrepancy can be attributed to the limited movement of pore-water in porous media like sand, which slightly restricts bacterial activity. This restriction may hamper the availability of necessary resources for CO_2 production. In contrast, the higher concentration of dissolved oxygen in water, coupled with exposure to light, stimulates the photosynthesis pathway, leading to increased calcium carbonate precipitation.

Overall, the electrical resistivity method provides a non-destructive and easy-to-use means of evaluating the performance of self-healing concrete and could potentially be used in the field to monitor the effectiveness of self-healing processes in underground structures. The technique could also be used as a diagnostic tool for bio-self-healing concrete repair and rehabilitation in these structures.

While this study conducted electrical measurements at short intervals in order to understand the relationship between electrical resistivity and incubation time, it is essential to consider the long-term effects of electrical current on microbial behaviour. Extending the duration of the electrical monitoring will allow for a deeper understanding of any potential changes or fluctuations in bacterial behaviour that may occur due to the electrical current.

CRediT authorship contribution statement

Mohamed Esaker: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Omar Hamza:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **David Elliott:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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