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Review

Bacterial Concrete as a Sustainable Building Material?

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Abstract: The right selection of building materials plays an important role when designing a building to fall within the definition of sustainable development. One of the most commonly used construction materials is concrete. Its production causes a high energy burden on the environment. Concrete is susceptible to external factors. As a result, cracks occur in the material. Achieving its durability along with the assumptions of sustainable construction means there is a need to use an environmentally friendly and effective technique of alternative crack removal in the damaged material. Bacterial self-healing concrete reduces costs in terms of detection of damage and maintenance of concrete structures, thus ensuring a safe lifetime of the structure. Bacterial concrete can improve its durability. However, it is not currently used on an industrial scale. The high cost of the substrates used means that they are not used on an industrial scale. Many research units try to reduce production costs through various methods; however, bacterial concrete can be an effective response to sustainability.

Keywords: sustainable; self-healing; concrete; bacteria

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1. Introduction

Rapidly developing construction, particularly in developing countries, contributes to environmental pollution, high energy consumption and natural resources. These actions have a direct impact on the comfort and heath of building inhabitants [1,2]. Already in the 1970s, research was commenced into the harmful effect of building materials on users' health. As a result of the research, ecological materials were introduced, e.g., silicate blocks, materials based on gypsum binders, paints, wood, etc. These materials are intended to promote human health. Additionally, they are supposed to be of only a minimal burden to the environment. Their burden and life cycle consists of several stages. It begins with the sourcing of raw materials for their production. The next stage is operation, during which they can be renewed or preserved. The final stage is the disposal and recycling of materials. Therefore, green (sustainable) [3] building materials should be designed and used in such manner as to minimize the sources of pollution. Throughout the life cycle of buildings and constructions [4], they should save energy and be safe for human health. The energy of building materials is an important factor for the new energy-efficient building system [5].

In the European construction industry, the right choice of building materials is an important factor in achieving sustainable development [1]. The European Union promotes actions aimed at sustainable development. The priority is to reduce the consumption of energy and natural resources as well as to reduce the production of waste and pollution that may be caused by the transport of materials. Principles of sustainable development are being introduced for the entire life cycle of buildings. This may ensure a compromise between economic, as well as environmental and social performance [6,7]. All the building designs that are being implemented should be functional with regard to increasing the durability, technical and materials performance, and to reducing the life cycle cost of the building [8].

Sustainable building materials are such materials that:

- reduce the consumption of resources;

- minimise the impact on the environment;
- do not pose a threat to human health.

These are materials that help in sustainable landscape design strategies as well as materials from companies that pursue sustainable social, as well as environmental and corporate policies.

The building materials should be investigated because they play an important role from the moment of conceiving the concept of constructing a building until the end of the building when it is to be dismantled, so that the materials might be recycled. Planners and architects, as well as engineers and builders, are searching for new materials and technologies to be used in new or future structures which will bring benefits such as energy efficiency, water resources and protection, improved air quality indoors, reduced life cycle costs and durability. In order to achieve these effects, it is important to apply the latest developments to various technologies, including the development of material studies and environmentally friendly building materials, and to achieve energy efficiency during the production of such materials. Furthermore, the inclusion of sustainable building materials in construction projects will reduce the environmental impact of building materials. The impact associated with the mining, transporting, processing, manufacturing, as well as installing, reusing and disposing [9].

2. Concrete

In civil engineering, concrete is usually used for construction work. This is associated with a low cost of building and construction materials and also with low maintenance costs. However, both concrete and reinforcement are a huge burden to the environment, due to the high energy consumption (Table 1) during production and use. Table 1 presents examples of building materials and the amounts of energy produced by them [10].

Table 1. Emitted energy and CO_2 emissions for example building materials [10].

Building Materials	Energy (MJ/kg)	kg CO_2/kg
aggregate	0.083	0.0048
concrete (1:1.5:3 e.g., floor panels in situ, construction)	1.11	0.159
cement mortar (1:3)	1.33	0.208
steel (general—average recycled content)	20.10	1.37
bricks (all)	3.0	0.24

For this reason, concrete should be protected against external factors in order to increase its durability. Structures deteriorate due to different reasons, such as the impact of the external environment, overload or accidental damage, and then they need to be repaired in order to extend their lifetime. The defects that occur are typically cracks [9] resulting from reactions such as:

- freeze-thaw action;
- shrinkage;
- hardening of concrete;
- low tensile strength of concrete, etc.

Eventually, they lead to the deterioration of components, facilities or buildings. There are obviously several repair methods, e.g., epoxy resins. They are, however, costly and require constant maintenance. The possible maintenance and repair of concrete structures is quite expensive. Sometimes it is not possible to do it. However, they are rarely included in the material's lifetime. Additionally, the use of chemicals causes harm to the environment. When analyzing durability together with the assumption for use as sustainable building and construction materials, it is necessary be able to apply an alternative, environmentally friendly and effective technique of removing cracks.

Concrete can be repaired in two directions, i.e., through:

- autogenous healing;

- autonomous healing.

In autogenous healing, the self-healing process takes place with the use of products formed in the presence of carbon monoxide dihydrate and water. Calcium carbonate [11] or hydration products such as C-S-H [12] are formed in order to cause crack healing. In addition, directly introduced expansive measures such as magnesium oxide and bentonite [13], can achieve high sealing efficiency of cracks with an initial width of about 0.18 mm. The second type of healing treatment—i.e., autonomous—is based on the use of bacteria, organic compounds and encapsulated materials with pozzolan. In this treatment, chemical factors such as calcium lactate and biological factors, i.e., bacteria, are distinguished. Their coupling enables better end results to be obtained.

Technique could be a method of biomineralisation in/on concrete [8]. Biomineralisation can be employed on the surface of concrete or inside of it. The inside method consists of introducing calcite (calcium carbonate)-precipitating bacteria in specific concentrations into concrete. Microbially induced calcite precipitation (MICP) is a process associated with biological mineralization. The overriding principle in this process is the fact that microbial ureases hydrolyse urea, producing ammonia and carbon dioxide; then, the ammonia being released into the environment elevates the pH. The released carbon dioxide reacts with calcium ions, resulting in an insoluble calcium carbonate [8], which accumulates in the pores of concrete.

In the outside method, biomineralisation is first employed when cracks and defects appear on the surface of the structure. The biological mixture is applied to the surface. The calcium carbonate crystals produced precipitate inside the cracks and then seal them.

Biomineralization is the formation of minerals in a biological process. It can be divided into the following two types:

- biologically controlled mineralization (BCM);
- biologically induced mineralization (BIM).

The first type is genetically controlled or regulated by organisms [11]. In the second type, minerals are formed as a byproduct of the reaction between organism activity and the environment. By means of metabolic activity, bacteria can adapt to environmental conditions.

In BCM, minerals are deposited on/or in organic matrices or bubbles in a cell. This allows the body to control the nucleation and growth of minerals, and thus the composition, size, habit and location of the intracellular mineral. The BCM mineral particles are well structured. They have a narrow size distribution and a species-specific, consistent crystal habit. The BCM processes are subject to metabolic and genetic control. The internal bubble conditions, e.g., pH, are controlled by the body. Therefore, mineral formation is not as sensitive to external environmental parameters as in BIM. BCM calcium carbonate usually occurs in eucaryotes. Examples of calcium carbonate structures formed with BCM are the shells of molluscs, urine spikes and fish otoliths.

Minerals resulting from BIM processes are involved in both embryo and extracellular growth. This occurs as a result of the body's metabolic activity as well as subsequent chemical reactions involving metabolic by-products. It requires extraordinary control of size, morphology and phase selection, which results in complex, hierarchical organic–inorganic structures with extraordinary physicochemical properties. Biologically induced $CaCO_3$ mineralization does not include the direct control of the biomineralization process by organisms. BIM occurs either passively, due to metabolic changes in the bulk solution chemistry or around living organisms, or actively—when the organism and/or its metabolic by-products provide nucleation sites for mineralization. BIM calcium carbonate usually occurs in the presence of single-cell organisms, such as bacteria.

3. Self-Healing Mechanism

Biological concrete as well as a self-healing, or MICP, produces $CaCO_3$ using bacteria. It fills cracks that appear in concrete materials. Several types of bacteria are used in concrete, e.g., *Bacillus subtilis*, *Bacillus pseudofirmus*, *Bacillus pasteurii*, *Bacillus sphaericus*, *Escherichia coli*, *Bacillus cohnii*, *Bacillus* *balodurans*, *Bacillus halodurans*, etc. These are bacteria that can survive in environments with high alkali contents, i.e., these bacteria use metabolic processes such as sulphate reduction, photosynthesis and urea hydrolysis. The result is calcium carbonate as a by-product. Some reactions also increase the pH from neutral to alkaline conditions, creating bicarbonate and carbonate ions. These precipitate with the calcium ions in the concrete to form calcium carbonate minerals. They are chemoorganotrophs, i.e., they draw energy from the oxidation of simple organic compounds. The microorganisms are *Bacillus* species and are not harmful to humans at all.

Bacteria genus *Bacillus* are used in this process, as well as bacterial nutrients. These can be calcium compounds, nitrogen and phosphorus. All the components are added to the concrete during the production process. The listed components remain non-reactive inside the material until the material is damaged, which can take up to 200 years. However, this period can be shortened when the concrete is damaged. The water in the outside environment will then start to penetrate the damage. In this case, the bacterial spores will be able to grow in convenient conditions. Soluble nutrients are transformed into insoluble calcium carbonate. Then, it solidifies on the damaged surface or inside the material. In this way, the concrete is sealed [6]. The bacteria consume oxygen during their growth, which is why the reinforcement does not corrode. This increases the durability of the concrete [1].

On the surface, calcium carbonate is formed as a result of Reaction. The reaction of calcium hydroxide with calcium chloride and the products of bacterial metabolism causes the formation of calcite (calcium carbonate). Figure 1 shows a representation of Reaction in concrete.

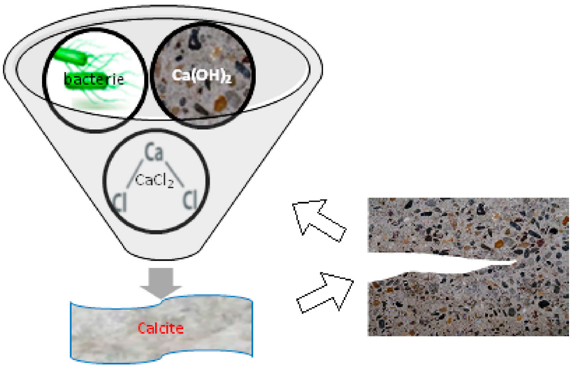

Figure 1. Graphic representation of the reaction of calcium carbonate production with bacteria, calcium chloride and portlandite.

The process of self-healing of bacteria-based concrete is much more efficient, as calcium nutrients are actively metabolized by the bacteria present in the concrete [2]. Carbon dioxide comes from bacterial metabolism. The reaction takes place according to (2):

$$Ca(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O \tag{1}$$

Therefore, calcium carbonate is formed in the process of bacterial metabolism. The effect of the process is the sealing of the cracks through the use of bacteria.

4. Influence of Bacteria/Biomineralization on Concrete Properties

According to literature data, the introduction of selected bacteria has a favorable effect on several properties. One such parameter is diffusion kinetics caused by a change in the pore structure. It has a favorable effect on the moisture transport of different ions that cause damage to building materials. An increase in strength is also observed when bio-calcium carbonate is embedded in damaged spaces and also in the pores of the material. Numerous investigations into this matter are being conducted by scientists across the world. Different bacterial species, e.g., *Bacillus subtilis*, *Bacillus pseudofirmus*, *Bacillus pasteurii*, *Bacillus sphaericus*, *Escherichia coli*, *Bacillus cohnii*, *Bacillus balodurans* and cell concentrations are studied (e.g., 10^3 cells/mL, 10^5 cells/mL, 10^8 cells/mL). Various additives are added to enhance the material properties and enable better bacterial growth and their protection against the high alkaline pH of concrete. Further on in the paper, the results of selected literature research are briefly presented.

4.1. Influence of Bacteria on Concrete Properties

The authors of [14] observed in their study that microbial metabolic activity taking place in concrete leads to increased overall concrete performance including compressive strength. Others [15] observed that concrete's compressive strength shows a significant an increase by 42% for the concentration 10^5 cells/mL and an increase in tensile strength by 63% after 28 days. The investigation also included the effect of acid on such concrete, and it was established that it prevents mass loss during exposure to acid up to a specific limit value. Water absorption test demonstrated a lower mass increase for bacterial concrete compared with the control sample; therefore, it can be assumed that concrete will become less porous leading to a lower water absorption rate. Results of a test for chloride content indicate that the addition of bacteria reduces mass loss due to exposure to chloride and increases compressive strength. In the paper [16] *Bacillus pasteurii* bacterium was used and a significant increase in the initial strength of concrete was observed. Bio-calcium carbonate filled a certain volume percentage of voids which made the texture more compact and resistant to penetration. In another study, the authors of [17] proved that the *Bacillus subtilis* strain used by them can survive in temperatures ranging from −30 °C to 700 °C. They further observed an increase in the compressive strength of concrete. The study [18] showed high early compressive strength, however, this decreased with time. The authors also found that bacteria which are not reported as calcite precipitating, *Bacillus flexus*, exhibited maximum compressive strength. In this research study [19] cement-based concrete with added GGBFS (ground granulated blast furnace slag) and silica fume was tested for compressive strength at 28 days. It was found that the concrete mixture containing 35% of GGBFS had a compressive strength value of 56 N/mm^2. It was also found that, following the addition of silica fume as a mineral admixture, the mixture reached its maximum strength (37 N/mm^2) with an addition of 12.5% of silica fume. According to the authors of [20], the enhanced compressive strength of concrete reaches the maximum value for a cell concentration of approx. 10^5/mL. The authors of [21] used 30% fly ash and 30% GGBS to obtain concrete. This mixture replaced 70% of cement. In this paper the *Bacillus pasteurii* bacterium was used for fly ash and GGBFS. The result was a significant enhancement of compressive strength by 30% in the concrete mixture with bacteria and by over 15% with fly ash and by 20% in GGBS. It was observed that bacterial concrete reached its maximum tensile strength and flexural strength when 40 mL and 50 mL of bacterial solutions were used. In studies [22] 5% bacterial additives and calcium lactate were used. It was found that the compressive strength of the concrete was 49.5 MPa at 28 days. This value was higher than for control concrete. The addition of calcium lactate in the amount of 10% and bacteria to the concrete results in a significant increase in compressive strength. According to [23], *S. pasteurii* bacteria and fly ash increase the compressive strength of concrete by 22% at 28 days of the experiment. There is a four-fold decrease in water absorption and a practically eight-fold reduction in chloride permeability.

Aerobic bacteria *Bacillus pasteurii* were cultured [24] on media modified with urea and calcium chloride. The highest compressive strength of cement mortar (65 MPa), was measured at 28 days compared to control mortars (55 MPa), to which bacterial cells had not been added. The authors of [25] recorded an increase in compressive strength in mortars by 17% at 7 days, and by 25% at 28 days, respectively.

The authors of the study [26] used *S. pasteurii* cells for biocementing and did not notice any changes in the tensile strength values between the controls (7.78 N/mm^2) and the bacterial samples (7.45 N/mm^2). The tested parameter was only 0.33 MPa higher. On the other hand, the authors in article [27], who used a consortium of *Bacillus pseudofirmus* and *Bacillus cohnii*, obtained a 10% increase in mortar compression strength after 28 days. In the publication [28], they tested the compressive strength of mortars using industrial by-products (side products) with lactose mother liquor (LML) and corn steep liquor (CSL) as nutrient sources. They recorded a 17% increase in the compressive strength of mortars at 28 days [2] when using LML to culture *S. pasteurii*. On the other hand, the use of CSL medium noticed an improvement in mortar compressive strength by 35% after 28 days [28,29]. The strength was lower with standard media. Researchers in the article [30] established that *Arthrobacter crystopoietes* is a good bacterial isolate for self-healing concrete. Furthermore, [31] observed a 28% enhancement of the compressive strength of concrete modified by *Bacillus subtilis* compared to control concrete. These researchers noticed that the overall increase in strength was also a result of the presence of an appropriate quantity of organic matter in the matrix derived from the biomass of microorganisms. This biomass is formed due to the death of cells or the transformation of bacteria into endospores, which then act like organic fibers [32]. The authors of the publication [33] conducted tests on cement mortar with added *Bacillus sphaericus*. They recorded a 65%–90% reduction in water absorption in the mortar samples as a result of the formation of a calcite layer on the surface. The deposition of *Bacillus sphaericus* caused a reduction in water permeability in concrete in which cracks were repaired.

The task that the authors of [34] undertook was to use a hydrogel based on chitosan to encapsulate the spores of *Bacillus sphaericus* bacteria at 10^9 spores/mL. They showed that the pH at which it works well, i.e., has lower swelling, is between 7 and 11. The compression strength decreased slightly—by about 5% with the addition of 1% hydrogel. They also showed the highest decrease in water flow from 81%–90%. The same was true of sealing cracks.

The researchers in the paper [35] evaluated the water permeability and crack width of the concrete using spore encapsulation of *Bacillus sphaericus* bacteria (concentration 10^9 cells/mL) together with bioreagents in hydrogel with triblock copolymer of poly(ethylene oxide) and poly(propylene oxide) (i.e., PEO–PPO–PEO). As bioreagents they used nutrients, i.e., yeast extract and deposition agents, i.e., urea and calcium nitrate. The studies showed a 68% decrease in the water permeability of bioconcrete compared to conventional concrete. They also obtained that the width of cracks that can be treated is about 0.5 mm.

The authors of [36], replaced 10% of cement with fly ash with the addition of *Bacillus sphaericus* bacteria. They obtained a tensile strength by splitting 29.37% higher than the control value. On the other hand, the compression strength was 10.8% higher, and the flexural strength 5.1% higher than the controlled concrete. Concrete with the addition of *Bacillus pasteurii* gives slightly lower strength than *Bacillus sphaericus*. Peptone, yeast extract and *Bacillus subtilis* were used in the article [37]. The porosity was reduced and the strength of the dynamic modulus increased. The permeability to gases and chlorine permeability were also reduced. The effectiveness of the mixture was effective until 28th day of life, but no significant changes were observed until 210th day.

Tests carried out on lightweight aggregate concrete showed [38] the use of *Sporosarcina pasteuria* to increase the resistance of light concrete to the penetration of chloride ions after 91 days by 38%. However, other authors [39] conducted studies with the bacterium *Sporosarcina pasteurii* and *Skutarcina ureae* immobilized with zeolite in a mortar reinforced with glass fiber or without this addition. Chloride ion diffusion decreased by approximately 60% and 54% after 240 days for *Sporosarcina pasteurii* and *Skutarcina ureae*, respectively. However, for the same composition but without fibers, the reduction was by 56% and 53%.

The authors in [40], isolated bacteria from carbide slag. It consists primarily of CaO and $Ca(OH)_2$ and has a pH of up to 12.5. The strain they isolated was *Bacillus cereus*. As a result of the application, they obtained water absorption and chloride permeability rate reduced by 12.0% and 10.9%, respectively. They healed cracks 100–800 µm for 28 days. The permeability of healed samples decreased by about two orders of magnitude.

Durability was tested by the authors of various publications using changes in flexural or compressive strength. The process was further aided with the help of water adsorption and chloride ions. The durability of a building made of bacterial cement depends on the environment in which it is located. It will be resistant to stress, water and chloride flow. However, other environments will be able to adversely affect it. For example, an acidic environment as well as carbonate-acid corrosion may occur under appropriate conditions. It seems appropriate to first find a method of producing this concrete and only then check its resistance to other corrosive environments. However, this is a topic for another article.

4.2. Self-Healing Properties Induced by Bacteria

The researchers [41] noted that the utilization of *Sporosarcina pasteurii* considerably reduced the depth of water penetration. According to them, the calcium carbonate formed caused a lower permeability of concrete because a calcium carbonate interphase region was formed.

Other researchers [42] studied the effectiveness of *Bacillus sphaericus* in healing cracks using various chemical compounds, i.e., calcium nitrate and/or calcium acetate. In the paper [43] polyurethane- and melamine-based microcapsules were used, inside of which was silica gel with *Bacillus sphaericus* spores in it to increase the viability (life) of bacterial endospores in the concrete. On the other hand, [44] prepared a cement material with a low alkali content, composed of calcium sulphoaluminate and 20% silica fume to increase the compatibility of the bacterial medium. This was to increase the compatibility of the bacterial carrier material. They used *Sporosarcina pasteurii* for processing of recycled aggregate concrete [45]. Furthermore, [46] studied the properties of concrete containing rice husk ash and dust from cement bag filter as well as ureolytic bacteria.

Many researchers have used inorganic porous materials [47]. These include: ceramsite [48], polyurethane and glass tubes [49], lightweight aggregates [50,51], graphite nano-platelets [52], hydrogel [53], zeolite [39] as well as expanded clay particles, expanded perlite [54], and diatomaceous earth. They were used as carriers to protect bacteria from the alkaline environment of concrete. In the "pores", an environment is created for the safe growth of bacteria. The authors of [54] used sugar coating to immobilize bacteria and nutrients. A kind of cocoon was made, in which the bacteria were immobilized in a porous carrier (perlite), on which a layer of nutrients was applied. The whole was covered with a protective coating. They showed in their research that expanded perlite particles immobilized with bacterial spores and wrapped with low alkali material resulted in the best healing of cracks and reduced water permeability. They achieved a healing level of 1.24 mm after 28 days. A maximum of 0.8 mm was obtained in many studies.

However, other researchers used rice husk ash (15% RHA) and *Bacillus pasteurii* bacteria as well as micro-silica (10% by weight of cement) in self-compacting concrete (SCC). They obtained an increase in bacterial strength at 10^5 cells/mL after 28 days by 21% compared to the control sample. In contrast, the best stability for 10^7 cells/mL [55].

Authors of [56], tested concrete containing *Bacillus subtilis* with different bacterial concentrations in the range from 10^3 to 10^7 cells/mL. Their evaluation showed that the highest compressive strength was obtained for a concentration of 10^5 cells/mL. However, the highest concentration of bacteria improved permeability and crack repair. This observation was explained by the difference in calcite precipitation patterns for different bacterial concentrations.

Other researchers [57] also used bacteria-based beads for use in marine concrete structures in climates where temperatures reach 8 °C. Research has shown that in sea water self-treatment is a complex process. Various extreme environmental conditions cause additional production costs and practical application problems.

In the research [58] contained in the authors, they used PP fibers, PVA fibers and bacteria. The results showed that PP fiber and PVA fiber caused a decrease in bacterial concentration. They also obtained that the surface repair rate for samples with bacteria and fibers was slightly lower than for bacteria alone. However, the water tightness and flexural recovery rate improved. The authors have noted that the effect of PP fiber, PVA fiber and bacteria can potentially provide adequate self-healing properties for concrete.

In subsequent studies [59], the authors used bacterial spores immobilized in a biocarbon in combination with polypropylene fibers or superabsorbent polymer particles based on sodium polyacrylate. In both cases large amounts of calcium carbonate precipitated and cracks up to

700 μm were sealed. An improvement in strength by 38% and a decrease in water penetration and absorption by 65% and 70% was observed by immobilizing the spores in a biocarbon, compared to directly added spores. The addition of PP fiber resulted in recovery of strength and impermeability. On the other hand, superabsorbent polymer ensured higher precipitation of calcium carbonate.

Considering the fact that nanomaterials are already well established in the studies, therefore the authors of [60] used nanoparticles/microparticles of iron oxide and nanoparticles/microparticles of bentonite to immobilize the bacteria. The results showed that immobilization with iron oxide-based media was best for healing cracks up to 1.2 mm wide. The compressive strength was about 85% higher than that of the control samples. Bentonite immobilization, on the other hand, showed cracks healing up to about 0.15 mm and 0.45 mm cracks healing width. For these values they achieved the strength of 45% and 65% respectively.

In the study [61], bacteria were immobilized through recycled coarse aggregate (RCA) and fine aggregate (FA). *Bacillus subtilis* bacteria were included in the RCA. The results showed that samples containing RCA and 50% FA as bacterial immobilizers showed the most effective repair of cracks at a width of up to 1.1 mm and allowed to recover compressive strength of 85%.

4.3. Other Mechanisms

There are several mechanisms of internal self-mutilation. The first group of mechanisms belongs to the natural family, in which chemical, physical and mechanical self-surge is distinguished. The second group is made up of chemical methods. The third group is biological methods. The fourth is the special method [62,63].

The effectiveness of natural self-healing methods of concrete will depend on the composition of its matrix and the presence of water and carbon dioxide. The matrix determines the possibility of chemical reactions at the time of crack formation.

The effectiveness of chemical methods depends on many factors, i.e., the type of the curing agent, the number of carriers (capsules, tubes, the layout of vessel networks), the degree of their dispersion in the concrete, their diameter (such that it is possible to fit an appropriate amount of the curing agent in them). Natural treatment may be effective for cracks up to 0.1 mm wide [64]. The treatment agent carriers should be made of non-reactive materials with concrete and the treatment agent and must not be damaged during mixing. The use of pipes and vessel networks is possible only for prefabricated elements. They must be inserted manually into the mold before filling it with concrete [62].

The most effective chemical self-healing method of concrete is to disperse a cure agent in the concrete mixture that will react with cement hydration products in the concrete. The result will be a crack-filling compound.

The effectiveness of biological methods depends mainly on the viability of bacterial spores and the presence of water leaking through the crack. The efficacy is random due to the randomness of simultaneous cutting of the crack capsules with the bacterium and with the food. However, from an economic point of view, the cost of capsule production is currently significantly higher (two to three times) than in normal concrete.

The effectiveness of the method of self-treatment of concrete with mineral additives depends on their quantitative and qualitative selection. There is no undesirable internal tension in the concrete due to swelling. On the basis of water permeability tests in concrete it was found that it is possible to close the crack to a width of 0.22 mm [65].

5. The Cost of Producing Self-Healing Concrete

The authors of [20] studied the cost of utilization of microbial concrete as compared with conventional concrete. It is one of the main reasons for which this material is not mass produced and used in the construction industry at the moment. The cost analysis demonstrated that the price of microbial concrete is 2.3 to 3.9 times higher than the price of conventional concrete with lower quality. The high cost of bacterial cultures used in developing the material (bacteria and nutrients account for approx. 80% of the cost of raw materials [66]) is the reason why the initial costs are an order of magnitude higher than for traditional concrete. The authors [20] seek further reductions in the production cost of bacterial concrete in using nutrient ingredients, i.e., inexpensive industrial waste with a high protein content, e.g., stromata, liquid corn or lactose mother liquor from the starch industry—which they deal with in [26]. Due to this, the total cost of the process would be significantly reduced.

The high costs are difficult to justify to investors. The property of bacterial concrete to self-repair and thus extend the life of the building—and thus reducing the total cost of the building—is not noticed by investors or designers. They only see the high cost of production and, consequently, the initially high cost of the material. Another problem is that most contractors provide warranty for buildings for 10 years and this does not include cracks. Benefits from such concrete may not be visible for several or even over ten years. Therefore, the probability that contractors will be investing in this material is rather low. There are, however, situations where the benefits of self-healing concrete are beyond any economic discussions. Several such cases are referred to in [67]. There are descriptions of problems where money is less important than the protection of priceless objects.

For the time being, this material has not gained much recognition in the construction industry. However, with regard to the above quoted literature data on laboratory testing and the results obtained, this material is capable of fulfilling the intentions of the scientists. Obviously, further research will be needed in order to reduce the cost of culturing bacteria so that the material might have a lower initial cost and be accepted by contractors.

6. Suggestions for the Future

Many scientists are studying various compositions of bacterial, i.e., self-healing concretes. The purpose of this study is not to present the ideas; however, they are referred to in the previous section in order to show how many scientists and research institutes are dealing with this problem, and also to show that the properties of the materials can be enhanced. It is merely an attempt at answering the question whether this type of material can be a sustainable building material and create a building with properties compliant with the definition of such a material.

The ability to self-repair (self-healing) the material is based on the assumption that the repair material is placed inside the concrete, during the production of the concrete before the damage occurs. The activation of the repair material will take place when the internal stresses in the material exceed the assumed level. The methods of self-treatment differ primarily in the way they are activated.

“Active self-repair” is characterized by external activation of the repair material. For example, by heating. Passive self-repair, on the other hand, is characterized by an automatic reaction to an external agent. It occurs without human intervention [68].

The results of various research centers presented above show that there is great potential in these materials. Every new or modified bacterial and additive conformation leads to better and better results. Analyzing these results, however, it seems that the use of full concrete with bacterial input is not necessary and involves costs. As is the case with concrete with nano-TiO_2. It would be sufficient to use bacterial concrete as a coating or topping plaster (façade). Research is already underway on the use of bacterial concrete in repair mortar or concrete spraying [11]. Bacterial concrete has great opportunities to improve the quality of building materials. At the moment, however, it is not used on an industrial scale. For this reason, it is difficult to predict the future technology of such a material. In the literature [14], authors have presented several problems faced by bacterial concrete. These include:

- the construction community is not accustomed to microbiological processes;
- bacteria are considered to be harmful to health;
- the product and performance of MICP may be varied geographically and environmentally and require adaptation to the local conditions;
- standard protocols need to be developed concerning the testing and acceptance criteria;

- survival of bacteria in the alkaline pH environment of concrete;
- encapsulation of bacterial cells using polyurethaneas well as silica gel and microcapsules;
- reduction in production cost.

Answers to the above questions and problems must be found. Most of these problems are currently being investigated by scientists who are achieving promising results. However, one problem was not mentioned in the paper quoted. We are dealing with bacteria. The effects resulting from the use of them (sealing of the structure) are well known. Unfortunately, there is no research into the durability of such materials or the possible effects of such a biological cementitious environment on potential biological corrosion. Will the calcium carbonate formed protect the material (research suggests that it will), and how will it affect the deposition and growth of the spores of other microorganisms present in the air? These materials, as such, are not harmful to human health because the bacteria used in their production are ones such as *Bacillus Sphaericus*, *Bacillus pasteurii*, *Bacillus subtilis* and *Bacillus lexus*. These bacterial species do not exert any negative impacts on human health and display a higher ability to precipitate calcite.

7. Conclusions

After the literature study, the following conclusions can be drawn:

- The majority of Bacillus bacteria have a positive effect on the compressive strength of concrete and on bending strength compared to conventional samples.
- The use of a mixture (consortium) of *Bacillus pseudofirmus* and *Bacillus cohnii* resulted increase in compressive strength.
- The *Bacillus sphaericus* species showed a reduction in water absorption.
- Inorganic porous materials such as ceramite, zeolites and others are used to protect the bacteria from high pH.
- In lightweight aggregate concrete, the use of *Sporosarcina pasteuria* increased resistance to chloride ion penetration.
- Expanded perlite particles immobilized by bacterial spores and wrapped in a low alkali material ensure the best crack healing and reduced water permeability.
- The use of various substances, e.g., silica gel, protects bacteria from alkaline reactions.
- The use of autoclaved bacteria or their dispute reduces porosity and thus permeability.
- *Bacillus Pasteurii* reduce water absorption. The durability of concrete is increased and the permeability of chlorides is reduced.
- The encapsulation of *Bacillus Sphaericus* in closed microcapsules showed a greater effectiveness of crack treatment and lower water permeability.
- The PP and PVA fiber used caused a decrease in bacterial concentration. The surface repair level for samples with bacteria and fibers was slightly lower than for the bacteria themselves.
- The diffusion of chlorine ions decreased by for *Sporosarcina pasteurii* and *Skutarcina ureae* using zeolite and glass fiber reinforcement.
- RCA and 50% FA as bacterial immobilizers showed the most effective repair of cracks up to 1.1 mm wide and allowed to recover the compression strength of 85%.

In the coming years, and with a larger number of full-scale tests, the properties of this concrete will be better known and the methods of production less costly. As of today, it provides a promise to be a durable solution to the current problems faced by the concrete industry. Both the industrial world and the civil population are waiting for materials that will use little energy and produce little carbon dioxide from the moment of being produced until the moment of natural degradation. It is also expected that such materials and structures will be durable and survive at least 50 years (according to the standard) and that their repair will be effective, economically viable and even maintenance-free. The composite described above is one of the answers to the expectations of the industry and market.

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