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A Study on Self Healing Bacterial Concrete as a Sustainable Construction 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, thusensuringa safe life time of the structure. Bacterial concretec an 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 throughvariousmethods; however, bacterial concrete can be an effective response to sustainability.

Keywords: sustainable; self-healing; concrete; bacteria

I. 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 andheathofbuildinginhabitants[1,2].Alreadyinthe1970s,researchwascommencedintotheharmfuleffectof buildingmaterialsonusers'health.Asaresultoftheresearch,ecologicalmaterialswereintroduced,e.g.,silicate blocks,materialsbasedongypsumbinders,paints,wood,etc.Thesematerialsareintendedtopromotehumanhealth.Additionally,theyaresupposedtobeofonlyaminimalburdentotheenvironment.Theirburdenandlifecycleconsistsofseveralstages. It begins with the sourcing of raw materials for their production. The next stage is operation, during which they can be renewedorpreserved.Thefinalstageisthedisposalandrecyclingofmaterials.Therefore,green(sustainable)[3]buildingmaterialsshouldbedesignedandusedinsuch mannerastominimize 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 buildingmaterialsisanimportantfactorforthenewenergyefficientbuildingsystem[5].IntheEuropeanconstructionindustry,therightchoiceofbuildingmaterialsisan importantfactorinachievingsustainabledevelopment [1].TheEuropeanUnionpromotesactionsaimedatsustainable 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 ofmaterials.Principlesofsustainabledevelopmentare beingintroducedfortheentirelifecycleofbuildings.Thismayensureacompromisebetweeneconomic,aswell asenvironmentalandsocialperformance[6,7].Allthebuildingdesignsthatarebeingimplementedshouldbefunctionalwithregardtoincreasingthedurability,technicalandmaterialsperformance,andtoreducingthelifecyclecostofthebuilding[8].Sustainablebuilding materials are such materials that:

- reduce the consumption ofresources;
- minimise the impact on theenvironment;
- do not pose a threat to humanhealth.

Thesearematerialsthathelpinsustainablelandscapedesignstrategiesaswellasmaterialsfrom companies that pursue sustainable social, as well as environmental and corporatepolicies.

The building materials should be investigated because they play an important role from the momentofconceivingtheconceptofconstructingabuildinguntiltheendofthebuildingwhenitisto be dismantled, so that the materials might be recycled. Planners and architects, as well as engineers andbuilders,aresearchingfornewmaterialsandtechnologiestobeusedinneworfuturestructures whichwillbringbenefitssuchasenergyefficiency,waterresourcesandprotection,improvedairquality indoors,reducedlifecyclecostsanddurability.Inordertoachievetheseeffects,itisimportanttoapply the latest developments to various technologies, including the development of material studies and environmentallyfriendlybuildingmaterials,andtoachieveenergyefficiencyduringtheproductionof 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].

II. CONCRETE

In civil engineering, concrete is usually used for construction work. This is associated with alowcostofbuildingandconstructionmaterialsandals owithlowmaintenancecosts.However,bothconcretea ndreinforcementareahugeburdentotheenvironment, duetothehighenergyconsumption(Table1)duringpro ductionanduse.Table1presentsexamplesofbuildingm aterialsandtheamounts 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.Structuresdeteriorateduetodifferentreason s,suchastheimpactoftheexternalenvironment, 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 suchas:

- freeze-thawaction;
- shrinkage;
- hardening ofconcrete;
- low tensile strength of concrete,etc.

Eventually,theyleadtothedeteriorationofco mponents,facilitiesorbuildings.Thereareobviouslyse veralrepairmethods,e.g.,epoxyresins.Theyare,howe ver,costlyandrequireconstantmaintenance. The possible maintenance and repair of concrete structures is quite expensive. Sometimes it is not possible to do it. However ,they arerarelyincludedinthematerial'slifetime.Additional ly,theuseofchemicalscausesharmtotheenvironment. Whenanalyzingdurabilitytogetherwiththeassumptio nforuseassustainablebuildingandconstructionmateri als,itisnecessarybeabletoapplyanalternative, environmentally friendly and effective technique of removingcracks.

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

- autogenoushealing;
- autonomoushealing.

Inautogenoushealing,theselfhealingprocesstakespla cewiththeuseofproductsformedinthepresenceofcarb onmonoxidedihydrateandwater.Calciumcarbonate[1 1]orhydrationproductssuch 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 withpozzolan.Inthistreatment,chemicalfactorssucha scalciumlactateandbiologicalfactors,i.e.,bacteria,are distinguished. Their coupling enables better end results to beobtained.

Technique could be a method of biomineralisation in/on concrete [8]. Biomineralisation can beemployed on the surface of concrete or inside of it. The inside method consists of introducing calcite (calciumcarbonate)-precipitatingbacteriainspecificconcentrationsintoco ncrete.Microbiallyinduced calcite precipitation (MICP) is a process associated with biological mineralization. The overriding principle in this process is the fact that microbialureaseshydrolyseurea,producingammonia andcarbondioxide;then,theammoniabeingreleasedin totheenvironmentelevatesthepH.Thereleased carbon dioxide reacts with calcium ions, resulting in an insoluble calcium carbonate [8], which accumulates in the pores ofconcrete.

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).

Thefirsttypeisgeneticallycontrolledorregulatedbyor ganisms[11].Inthesecondtype,mineralsareformedas abyproductofthereactionbetweenorganismactivityan dtheenvironment.Bymeans of metabolic activity, bacteria can adapt to environmentalconditions.

InBCM,mineralsaredepositedon/orinorganicmatrice sorbubblesinacell.Thisallowsthebodytocontrolthenu cleationandgrowthofminerals,andthusthecomposition,size,habitandlocationof the intracellular mineral. The BCM mineral particlesarewellstructured.Theyhaveanarrowsizedistributionandaspeciesspecific,consistentcrystalhabit. TheBCMprocessesaresubjecttometabolic 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 fishotoliths.

MineralsresultingfromBIMprocessesareinvolvedinbothembryoandextracellulargrowth.This occurs as a result of the body's metabolic activity as well as subsequent chemical reactions involving metabolic byproducts.Itrequiresextraordinarycontrolofsize,morphologyandphaseselection,whichresultsincomplex, hierarchicalorganicinorganicstructureswithextraordinaryphysicochemical 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 asbacteria.

III. SELF-HEALINGMECHANISM

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,Bacilluspseudofirmus,Bacilluspasteurii,Bacillussphaericus,Escherichiacoli,Bacilluscohnii,Bacillusbalodurans,Bacillushalodurans,etc. Thesearebacteriathatcansurviveinenvironmentswith highalkali contents, i.e., these bacteria use metabolic processes such as sulphate reduction, photosynthesisandureahydrolysis.Theresultiscalciumcarbonateasabyproduct.Somereactionsalsoincreasethe pH from neutral to alkaline conditions, creating bicarbonate and carbonate ions. These precipitate withthecalciumionsintheconcretetoformcalciumcarbonateminerals.Theyarechemoorganotrophs,i.e., theydrawenergyfromtheoxidationofsimpleorganiccompounds.ThemicroorganismsareBacillus species and are not harmful to humans atall.

BacteriagenusBacillusareusedinthisprocess,aswellasbacterialnutrients.Thesecanbecalciumcompounds,nitrogenandphosphorus.Allthecomponentsareaddedtotheconcreteduringtheproductionprocess.Thelistedcomponentsremainnonreactiveinsidethematerialuntilthematerialisdamaged,whichcantakeupto200years.However,thisperiodcanbeshortenedwhentheconcreteisdamaged.Thewaterintheoutsideenvironmentwillthenstarttopenetratethedamage.Inthiscase, 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 inconcrete.

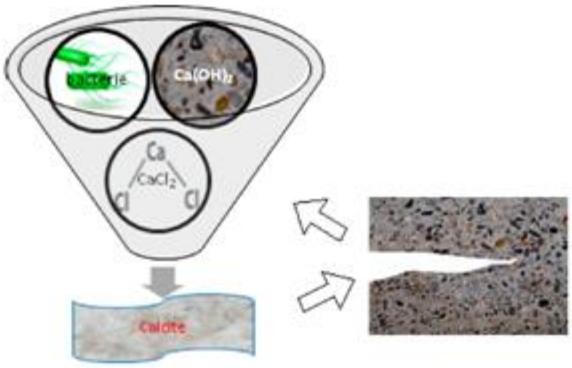

Figure1. Graphicrepresentationofthereactionofcalciumcarbonateproductionwithbacteria,calcium chloride andportlandite.

Theprocessofself-healingofbacteria-basedconcreteismuchmoreefficient,ascalciumnutrients are actively metabolized by the bacteria present in the concrete [2]. Carbon dioxide comes from bacterial metabolism. The reaction takes place according to(2):

$Ca(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O$ (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.

IV. INFLUENCE OF BACTERIA/BIOMINERALIZATION ON CONCRETEPROPERTIES

Accordingtoliteraturedata,theintroductionofselectedbacteriahasafavorableeffectonseveralproperties.Onesuchparameterisdiffusionkineticscausedbyachangeintheporestructure.Ithasafavorableeffectonthemoisturetransportofdifferentionsthatcausedamagetobuildingmaterials.Anincreaseinstrengthisalsoobservedwhenbiocalciumcarbonateisembeddedindamagedspaces and also in the pores of the material. Numerous investigations into this matter are being conductedbyscientistsacrosstheworld.Differentbacterialspecies,e.g.,Bacillussubtilis,Bacilluspseudofirmus,Bacillus pasteurii, Bacillus sphaericus, Escherichia coli, Bacillus cohnii, Bacillus baloduransand cellconcentrationsare 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 pHofconcrete.Furtheroninthepaper,theresultsofselectedliteratureresearcharebrieflypresented.

1.1. Influence of Bacteria on ConcreteProperties

Theauthorsof[14]observedintheirstudythatmicrobialmetabolicactivitytakingplaceinconcreteleadstoincreasedoverallconcreteperformanceincludingcompressivestrength.Others[15]observedthatconcrete'scompressivestrengthshowsasignificantanincreaseby42%fortheconcentration10^5 cells/mL and an increase in tensile strength by 63% after 28days.Theinvestigationalsoincludedtheeffectofacidonsuchconcrete,anditwasestablishedthatitpreventsmasslossduringexposuretoacid up to a specific limit value. Water absorption test demonstrated a lower mass increase for bacterialconcretecomparedwiththecontrolsample;therefore,itcanbeassumedthatconcretewillbecomelessporousleadingtoalowerwaterabsorptionrate.Resultsofatestforchloridecontentindicatethattheadditionofbacteriareducesmasslossduetoexposuretochlorideandincreasescompressivestrength.Inthepaper[16]Bacilluspasteuriibacteriumwasusedandasignificantincreaseintheinitialstrengthofconcretewasobserved.Biocalciumcarbonatefilledacertainvolumepercentageofvoidswhichmade the texture more compact and resistant to penetration. In another study, the authors of [17] proved thattheBacillussubtilisstrainusedbythemcansurviveintemperaturesrangingfrom−30˚Cto700˚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 bacteriawhicharenotreportedascalciteprecipitating, Bacillusflexus,exhibitedmaximumcompressive 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.Thismixturereplaced70%ofcement.InthispapertheBacilluspasteuriibacteriumwasused for fly ash and GGBFS. The result was a significant enhancement of compressive strength by 30% in theconcretemixturewithbacteriaandbyover15%withflyashandby20%inGGBS.Itwasobserved 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. pasteuriibacteria and fly ash increase the compressive strength of concrete by 22% at 28 days of the experiment.Thereisafour-folddecreaseinwaterabsorptionandapracticallyeight-foldreductionin chloridepermeability.

Aerobic bacteria Bacillus pasteuriiwere 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. pasteuriicells 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 MPahigher. On the other hand, the authors in article[27],whousedaconsortiumofBacilluspseudofi rmusandBacilluscohnii,obtaineda10%increase in mortar compression strength after 28 days. In the publication [28], they tested the compressive strengthofmortarsusingindustrialby-products(sideproducts)withlactosemotherliquor(LM L)

and corn steep liquor (CSL) as nutrient sources. They recorded a 17% increase in the compressive strengthofmortarsat28days[2]whenusingLMLtocult ureS.pasteurii.Ontheotherhand,theuseof CSL medium noticed an improvement in mortar compressive strength by 35% after 28 days [28,29]. Thestrengthwaslowerwithstandardmedia.Researche rsinthearticle[30]establishedthatArthrobactercrysto poietesis a good bacterial isolate for self-healing concrete. Furthermore, [31] observed a 28% enhancementofthecompressivestrengthofconcretem odifiedbyBacillussubtiliscomparedtocontrol concrete.Theseresearchersnoticedthattheoverallincr easeinstrengthwasalsoaresultofthepresence ofanappropriatequantityoforganicmatterinthematrix derivedfromthebiomassofmicroorganisms. 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 mortarwithaddedBacillussphaericus.Theyrecordeda 65%90%reductioninwaterabsorptioninthemortarsa mplesasaresultoftheformationofacalcitelayeronthes urface.ThedepositionofBacillussphaericuscausedare ductioninwaterpermeabilityinconcreteinwhichcracks wererepaired.Thetaskthattheauthorsof[34]undertoo kwastouseahydrogelbasedonchitosantoencapsulatet hesporesofBacillussphaericusbacteriaat10^{9}spores/ mL.TheyshowedthatthepHatwhichitworks well, i.e., has lower swelling, is between 7 and 11. The compression strength decreased slightly—by about5%withtheadditionof1%hydrogel.Theyalsosh owedthehighestdecreaseinwaterflowfrom 81%–90%. The same was true of sealingcracks.

Theresearchersinthepaper[35]evaluatedthewaterper meabilityandcrackwidthoftheconcrete using spore encapsulation of Bacillus sphaericusbacteria (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).Asbioreagentstheyusednutrients,i.e.,yeastextr actanddepositionagents,i.e., ureaandcalciumnitrate.Thestudiesshoweda68%decr easeinthewaterpermeabilityofbioconcrete comparedtoconventionalconcrete.Theyalsoobtained thatthewidthofcracksthatcanbetreatedis about 0.5mm.

The authors of [36], replaced 10% of cement with fly ash with the addition of Bacillus sphaericusbacteria. They obtained a tensile strength by splitting 29.37% higher than the control value. On the otherhand,thecompressionstrengthwas10.8%higher, andtheflexuralstrength5.1%higherthanthe controlledconcrete.ConcretewiththeadditionofBacil luspasteuriigivesslightlylowerstrengththan Bacillussphaericus.Peptone,yeastextractandBacillus subtiliswereusedinthearticle[37].Theporosity was reduced and the strength of the dynamic modulus increased. The permeability to gases and chlorinepermeabilitywerealsoreduced.Theeffective nessofthemixturewaseffectiveuntil28thday of life, but no significant changes were observed until 210thday.

Tests carried out on lightweight aggregate concrete showed [38] the use of Sporosarcinapasteuriato increase the resistance of light concrete to the penetration of chloride ions after 91 days by 38%. However,otherauthors[39]conductedstudieswiththe bacteriumSporosarcinapasteuriiandSkutarcinaureae immobilizedwithzeoliteinamortarreinforcedwithgla ssfiberorwithoutthisaddition.Chloride ion diffusion decreased by approximately 60% and 54% after 240 days for Sporosarcinapasteuriiand Skutarcinaureae,respectively.However,forthesamec ompositionbutwithoutfibers,thereductionwas by 56% and53%.Theauthorsin[40],isolatedbacteriafromcarb ideslag.ItconsistsprimarilyofCaOandCa$(OH)_2$ andhasapHofupto12.5. ThestraintheyisolatedwasBacilluscereus. Asaresultoftheapplication,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 ofmagnitude.

Durability was tested by the authors of various publications using changes in flexuralor compressive strength. The process was further aided with the help of water adsorption and chloride ions.Thedurabilityofabuildingmadeofbacterialceme ntdependsontheenvironmentinwhichitis located. It will be resistant to stress, water and chloride flow. However, other environments will be abletoadverselyaffectit.Forexample,anacidicenviron mentaswellascarbonateacidcorrosionmayoccurunde rappropriateconditions.Itseemsappropriatetofirstfin damethodofproducingthis concrete and only then check its resistance to other corrosive environments. However, this is a topic for anotherarticle.

1.2. Self-Healing Properties Induced byBacteria

The researchers [41] noted that the utilization of Sporosarcinapasteuriiconsiderably 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 wasformed.

Otherresearchers[42]studiedtheeffectiveness ofBacillussphaericusinhealingcracksusingvarious chemicalcompounds,i.e.,calciumnitrateand/orcalciu macetate.Inthepaper[43]polyurethaneandmelamine basedmicrocapsuleswereused,insideofwhichwassili cagelwithBacillussphaericusspores in it to increase the viability (life) of bacterial endospores in the concrete. On the other hand, [44] prepared acement material with alowalkalicontent, composedofcalciumsulphoaluminateand20%silicaf umetoincreasethecompatibilityofthebacterialmediu m.Thiswastoincreasethecompatibility of the bacterial carrier material. They used Sporosarcinapasteuriifor 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 ureolyticbacteria.

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]aswellasexpandedclayparti cles,expandedperlite[54],anddiatomaceous earth.Theywereusedascarrierstoprotectbacteriafrom thealkalineenvironmentofconcrete.Inthe “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 manystudies.

However,otherresearchersusedricehuskash(15%RH A)andBacilluspasteuriibacteriaaswellasmicrosilica(10%byweightofcement)inselfcompactingconcrete(S CC).Theyobtainedanincreaseinbacterialstrengthat1 0^5cells/mLafter28daysby21%comparedtothecontrol sample.Incontrast,the best stability for 10^7 cells/mL[55].

Authorsof[56],testedconcretecontainingBacillussub tiliswithdifferentbacterialconcentrationsintherangef rom10^3to10^7cells/mL.Theirevaluationshowedthatt hehighestcompressivestrengthwasobtainedforaconc entrationof10^5cells/mL.However,thehighestconcent rationofbacteriaimprovedpermeabilityandcrackrepai r.Thisobservationwasexplainedbythedifferenceincal citeprecipitation patterns for different bacterialconcentrations.

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. TheresultsshowedthatPPfiberandPVAfibercausedad ecreaseinbacterialconcentration.Theyalso 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 forconcrete.

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 to700 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.

Consideringthefactthatnanomaterialsarealreadywell establishedinthestudies,thereforethe 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 mediawasbestforhealingcracksupto1.2mmwide.The compressivestrengthwasabout85%higherthanthatoft hecontrolsamples.Bentoniteimmobilization,ontheot herhand,showedcrackshealinguptoabout0.15mmand 0.45mmcrackshealingwidth.Forthesevaluestheyachi evedthestrengthof 45% and 65% respectively.

In the study [61], bacteria were immobilized through recycled coarse aggregate (RCA) and fine aggregate (FA). Bacillus subtilisbacteria were included in the RCA. The results showed that samples containingRCAand50%FAasbacterialimmobilizersshowedthemosteffectiverepairofcracksata width of up to 1.1 mm and allowed to recover compressive strength of85%.

1.3. OtherMechanisms

Thereareseveralmechanismsofinternalself mutilation.Thefirstgroupofmechanismsbelongstothe naturalfamily,inwhichchemical,physicalandmechanicalself-surgeisdistinguished.Thesecond groupismadeupofchemicalmethods. Thethirdgroupisbiologicalmethods. Thefourthisthespecial method[62,63].

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

Theeffectivenessofchemicalmethodsdependsonmanyfactors,i.e.,thetypeofthecuringagent,thenumberofcarriers(capsules,tubes,thelayoutofvesselnetworks),thedegreeoftheirdispersionintheconcrete,theirdiameter(suchthatitispossibletofitanappropriateamountofthecuringagentin them). Natural treatment may be effective for cracks up to0.1mmwide[64].Thetreatmentagentcarriersshould bemadeofnonreactivematerialswithconcreteandthetreatmentagentandmustnot 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 theconcrete 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 andthe 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 ontheirquantitativeandqualitativeselection.Thereisnoundesirableinternaltensionintheconcreteduetoswelling.Onthebasisofwaterpermeabilitytestsinconcreteitwasfoundthatitispossibletoclose the crack to a width of 0.22 mm[65].

V. THE COST OF PRODUCING SELF-HEALINGCONCRETE

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 higherthanthepriceofconventionalconcretewithlowerquality.Thehighcostofbacterialculturesusedindevelopingthematerial(bacteriaandnutrients 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 significantlyreduced.

The high costs are difficult to justify to investors. The property of bacterial concrete to self-repairandthusextendthelifeofthebuilding—andthusreducingthetotalcostofthebuilding—isnotnoticed by investorsordesigners. They only see the high cost of production and, consequently, the initially highcostofthematerial.Anotherproblemisthatmostcontractorsprovidewarrantyforbuildingsfor10yearsand thisdoesnotincludecracks.Benefitsfromsuchconcretemaynotbevisibleforseveralor 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 pricelessobjects.

For the time being, this material has not gained much recognition in the construction industry. However,withregardtotheabovequotedliteraturedataonlaboratorytestingandtheresultsobtained,thismaterialiscapableoffulfillingtheintentionsofthescientists.Obviously,furtherresearchwillbeneededinordertoreducethecostofculturingbacteriasothatthematerialmight havealowerinitial cost and be accepted bycontractors.

VI. SUGGESTIONS FOR THEFUTURE

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 sectioninordertoshowhowmanyscientistsandresearchinstitutesaredealingwiththisproblem,andalsotoshowthatthepropertiesofthematerialscanbeenhanced.Iti smerelyanattemptatansweringthequestionwhetherthistypeofmaterialcanbeasustainablebuildingmaterialandcreateabuilding with properties compliant with the definition of such amaterial.

The ability to self-repair (self-healing) the material is based on the assumption that the repair materialisplacedinsidetheconcrete,duringtheproductionoftheconcretebeforethedamageoccurs. 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 areactivated.

"Activeself-repair"ischaracterizedbyexternalactivationoftherepairmaterial.Forexample,by heating.Passiveself-repair,ontheotherhand,ischaracterizedbyanautomaticreactiontoanexternal agent. It occurs without human intervention[68].

Theresultsofvariousresearchcenterspresentedaboveshowthatthereisgreatpotentialinthesematerials.Everynewormodifiedbacterialandadditiveconformationleadstobetterandbetterresults. 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]. Bacterialconcretehasgreatopportunitiestoimprovethequalityofbuildingmaterials.Atthemoment,however,itisnotusedonanindustrialscale.Forthisreason,itisdifficulttopredictthefuturetechnologyofsuchamaterial.Intheliterature[14],authorshavepresentedseveralproblemsfacedbybacterialconcrete.Theseinclude:

- the construction community is not accustomed to microbiologicalprocesses;
- bacteria are considered to be harmful tohealth;
- the product and performance of MICP may be varied geographically and environmentally and require adaptation to the localconditions;
- standard protocols need to be developed concerning the testing and acceptancecriteria;
- survival of bacteria in the alkaline pH environment ofconcrete;
- encapsulation of bacterial cells using polyurethaneas well as silica gel andmicrocapsules;
- reduction in productioncost.

Answerstotheabovequestionsandproblemsmustbefound.Mostoftheseproblemsarecurrentlybeinginvestigatedbyscientistswhoareachievingpromisingresults.However,oneproblemwasnot mentioned in the paper quoted. We are dealing with bacteria. The effects resulting from the use of them (sealing of thestructure)arewellknown.Unfortunately,thereisnoresearchintothedurability of such materials or the possible effects of such a biological cementitious environment on potential biological corrosion. Willt he calcium carbonate formed protectthematerial(researchsuggeststhatitwill),andhowwillitaffectthedepositionandgrowthofthesporesofothermicroorganismspresent in the air? These materials, as such, are not harmful to human health because the bacteria used in their production are onessuchas Bacillus Sphaericus, Bacilluspasteurii, BacillussubtilisandBacilluslexus. These bacterial species donot exert any negativeimpactson humanhealthanddis play a higherability to precipitatecalcite.

VII. 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 conventionalsamples.
- Theuseofamixture(consortium)ofBacilluspseudofirmusandBacilluscohniiresultedincreasein compressivestrength.
- The Bacillus sphaericusspecies showed a reduction in waterabsorption.
- Inorganic porous materials such as ceramite, zeolites and others are used to protect the bacteria from highpH.
- Inlightweightaggregateconcrete,theuseofSporosarcinapasteuriaincreasedresistancetochlorideionpenetration.
- Expandedperliteparticlesimmobilizedbybacterialsporesandwrappedinalowalkalimaterial ensure the best crack healing and reduced waterpermeability.
- The use of various substances, e.g., silica gel, protects bacteria from alkalinereactions.
- The use of autoclaved bacteria or their dispute reduces porosity and thuspermeability.
- Bacillus Pasteuriireduce water absorption. The durability of concrete is increased and the permeability of chlorides isreduced.
- TheencapsulationofBacillusSphaericusinclosedmicrocapsulesshowedagreatereffectivenessof crack treatment and lower waterpermeability.
- ThePPandPVAfiberusedcausedadecreaseinbacterialconcentration.Thesurfacerepairlevel for samples with bacteria and fibers was slightly lower than for the bacteriathemselves.
- The diffusion of chlorine ions decreased by for Sporosarcinapasteuriiand Skutarcinaureaeusingzeolite and glass fiberreinforcement.
- 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 of85%.

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 carbond ioxide from the momen tofbeingproduceduntilthemomentofnaturaldegradation.Itisalsoexpectedthatsuchmaterialsandstructureswillbedurableandsurviveatleast50years(accordingto the standard) and that their repair will be effective, economically viable and even maintenance-free. The composite described above isone of the answers to the expectations of theindustryandmarket.

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REFERENCES

[1]. Franzoni,E.Materialsselectionforgreenbuildings:Whichtoolsforengineersandarchitects?ProcediaEng.
[2]. **2011**, 21, 883–890. [CrossRef]
[3]. Melchert,L.Thedutchsustainablebuildingpolicy:Amodelfordevelopingcountries?Build.Environ.**2007**,
[4]. 42, 893–901. [CrossRef]
[5]. Häkkinen, T.; Belloni, K. Barriers and drivers for sustainable building. Build. Res. Inform. **2011**, 39, 239–255. [CrossRef]
[6]. Chen, Z.S.; Martinez, L.; Chang, J.P.; Wang, X.J.; Xionge, S.H.; Chin, K.S. Sustainable building material selection: A QFD- and ELECTRE III-embedded hybrid MCGDM approach with consensus building. Eng. Appl. Artif. Intell. **2017**, 85, 783–807.[CrossRef]
[7]. Invidiata, A.; Lavagna, M.; Ghisi, E. Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. Build. Environ. **2018**, 139, 58–68.[CrossRef]
[8]. Stanaszek-Tomal, E.; Kozak, A. Mineral and organic coatings modified nano-TiO_2 addition as elements of sustainable building. In Energy Efficient, Sustainable Building Materials and Products; Hager, I., Ed.;Wydawnictwo PK: Kraków, Polska, 2017; pp.89–117.
[9]. Thormark, C. The effect of materials choice on the total energy need and recycling potential of abuilding.
[10]. Build. Environ. **2006**, 41, 1019–1026. [CrossRef]
[11]. Akadiri,P.O.;Chinyio,E.A.;Olomolaiye,P.O. Designofasustainablebuilding:Aconceptualframeworkfor implementing sustainability in the building sector. Buildings **2012**, 2, 126–152.[CrossRef]
[12]. Roodman, D.M.; Lenssen, N. A Building Revolution: How Ecology and Health Concerns are Transforming Construction; Worldwatch Paper 124; Worldwatch Institute: Washington, DC, USA, 1995; p.5.
[13]. Achal, V.; Mukherjee, A. A review of microbial precipitation for sustainable construction. Constr. Build.Mater. **2015**, 93, 1224–1235.[CrossRef]
[14]. Sisomphon, K.; Copuroglu, O.; Koenders, E.A.B. Self-healing of surface cracks in mortars with expansive additive and crystalline additive. Cem. Concr. Compos. **2012**, 34, 566–574.[CrossRef]
[15]. Huang,H.;Ye,G.;Damidot,D.Characterization andquantificationofself-healingbehaviorsofmicrocracksdue to further hydration in cement paste. Cem. Concr. Res. **2013**, 52, 71–81.[CrossRef]
[16]. Qureshi,T.;Kanellopoulos,A.;Al-Tabbaa,A.Autogenousself-healingofcementwithexpansiveminerals-I: Impact in early age crack healing. Constr. Build. Mater. **2018**, 192, 768–784.[CrossRef]
[17]. Saifee, S.N.; Lad, D.M.; Juremalani, J.R. Critical appraisal on Bacterial Concrete. IJRDO J. Mech. Civ.Eng.
[18]. **2015**, 1, 10–14.
[19]. Meera,C.M.;Subha, V. StrengthandDurabilityassessmentOfBacteria BasedSelf-HealingConcrete.IOSRJ. Mech. Civ. Eng. **2016**, 50,1–7.
[20]. Ravindranatha, R.; Kannan, R.N.; Likhit, M.L. Self healing material bacterial concrete. Int. J. Res. Eng.Technol. **2014**, 3,656–659.
[21]. Manikandan,A.T.;Padmavathi,A.AnExperimentalInvestigationonImprovementofConcrete Serviceability by using Bacterial Mineral Precipitation. Int. J. Res. Sci. Innov. **2015**, 2,46–49.
[22]. JagadeeshaKumar,B.G.;Prabhakara,R.;Pushpa,H.EffectofBacterialCalcitePrecipitationon Compressive
[23]. Strength of Mortar Cube. Int. J. Eng. Adv. Technol. (IJEAT) **2013**, 2, 486–491.
[24]. Depaa, R.A.B.; Kala, T.F. Experimental Investigation of self healing behavior of concrete using silica fume and GGBFS as mineral admixtures. Indian J. Sci. Technol.

2015, 8.[CrossRef]

[25]. Reddy, V.S.; Seshagiri Rao, M.V.; Sushma, S. Feasibility Study on Bacterial Concrete as an innovative selfcrack healing system. Int. J. Mod. Trends Eng. Res. **2015**, 2,642–647.

[26]. Goyal, M.; Chaitanya, P.K. Behaviour of Bacterial Concrete as Self-Healing Material. Int. J. Emerg. Technol. Adv. Eng. **2015**, 5,100–103.

[27]. Ganesh Babu, N. An experimental study on strength and fracture properties of self healing concrete. Int. J.Civ. Eng. Technol. (IJCIET) **2016**, 7,398–406.

[28]. Chahal,N.;Siddique,R.;Rajor, A.Influenceofbacteriaonthecompressivestrength,waterabsorptionand rapid chloride permeability of fly ash concrete. Constr. Build. Mater. **2012**, 28, 351–356.[CrossRef]

[29]. Ramakrishnan, V.; Deo, K.S.; Duke, E.F.; Bang, S.S. SEM investigation of microbial calcite precipitation in cement. In Proceedings of the 21st International Conference on Cement Microscopy, Las Vegas, NV, USA, 25–29 April 1999; pp.406–414.

[30]. Ghosh,P.;Mandal,S.;Chattopadhyay,B.D.;Pal,S.Useofmicroorganismtoimprovethestrengthofcement mortar. Cem. Concr. Res. **2005**, 35, 1980–1983.[CrossRef]

[31]. Jonkers,H.M.;Schlangen,H.E.J.G.Crackrepairbyconcreteimmobilizedbacteria.InProceedingsoftheFirst InternationalConferenceonSelfHealingMaterials,NoordwijkAanZee,TheNetherlands,18–20April2007; pp.1–7.

[32]. Jonkers, H.M.; Schlangen, H.E.J.G. Development of a bacteria-based self healing concrete. In Tailor Made Concrete Structures; Walraven, S., Ed.; Taylor & Francis Group: London, UK, 2008; pp.425–430.

[33]. Achal, V.; Mukherjee, A.; Reddy, M.S. Biocalcification by Sporosarcinapasteurii using Corn steep liquor as nutrient source. Ind. Biotechnol. **2010**, 6, 170–174.[CrossRef]

[34]. Achal, V.; Mukherjee, A.; Reddy, M.S. Isolation and characterization of urease producing and calcifying bacteria from cement. J. Microbiol. Biotechnol. **2010**, 20, 1571–1576.[CrossRef]

[35]. Park,S.;Park,Y.;Chun,W.;Kim,W.;Ghim,S.Calciteformingbacteriaforcompressivestrengthimprovement in mortar. J. Microbiol. Biotechnol. **2010**, 20, 782–788.[CrossRef]

[36]. Afifudin, H.; Hamidah, M.; Hana, H.; Kartini, K. Microorganism precipitation in enhancing concreteproperties. Appl. Mech. Mater. **2011**, 99, 1157–1165.[CrossRef]

[37]. Ramachandran, S.K.; Ramakrishnan, V.; Bang, S.S. Remediation of concrete using microorganisms. ACIMater. J. **2001**, 98,3–9.

[38]. De Muynck, W.; Cox, K.; De Belie, N.; Verstraete, W. Bacterial carbonate precipitation as an alternative surface treatment for concrete. Constr. Build. Mater. **2008**, 22, 875–885.[CrossRef]

[39]. Wang,J.;Mignon,A.;Trenson,G.;VanVlierberghe,S.;Boon,N.;DeBelie,N.AchitosanbasedpH responsive hydrogel for encapsulation of bacteria for self-sealing concrete. Cem. Concr. Compos. **2018**, 93, 309–322. [CrossRef]

[40]. Wang,J.;Snoeck,D.;VanVlierberghe,S.;Verstraete,W.H.;DeBelie,N.Applicationofhydrogelencapsulated carbonate precipitating bacteria for approaching a realistic self-healing in concrete. Constr. Build. Mater.**2014**, 68, 110–119.[CrossRef]

[41]. Jagannathan, P.; SatyaNarayanana, K.S.; Devi Arunachalamb, K.; Kumar Annamalaib, S. Studies on the mechanicalpropertiesofbacterialconcretewithtwobacterialspecies.Mater.TodayProc.**2018**,5,8875–8879. [CrossRef]

[42]. Nguyen,H.T.;Ghorbel,E.;Fares,H.;Cousture, A.Bacterialself-healingofconcreteanddurabilityassessment.

[43]. Cem. Concr. Compos. **2015**, 104, 103–340. [CrossRef]

[44]. Balam,N.H.;Mostofinejad,D.;Eftekhar,M.Effectsofbacterialremediationoncompressivestrength,water absorption, and chloride permeability of lightweight aggregate concrete. Constr. Build. Mater. **2017**, 145, 107–116.[CrossRef]

[45]. Bhaskar,S.;Anwar,K.M.;Lachemi,M.;Wolfaardt,G.;Otini,M.Effectofself-healingonstrengthand

[46]. durability of zeolite-immobilized bacterial cementitious mortar composites. Cem. Concr. Compos. **2017**, 82, 23–33. [CrossRef]

[47]. Wu, M.; Hu, X.; Zhang, Q.; Xue, D.; Zhao, Y. Growth environment optimization for inducing bacterial mineralization and its application in concrete healing. Constr. Build. Mater. **2016**, 209, 631–643.[CrossRef]

[48]. Achal,V.;Mukherjee,A.;Reddy,M.S.Effectofcalcifyingbacteriaonpermeationpropertiesofconcrete

[49]. structures. J. Ind. Microbiol. Biotechnol. **2011**, 38, 1229–1234. [CrossRef] [PubMed]

[50]. VanTittelboom,K.;DeBelie,N.;DeMuynck,W.;Verstraete,W.Useofbacteriatorepaircracksin

concrete.
[51]. Cem. Concr. Res. **2010**, 40, 157–166. [CrossRef]
[52]. Wang,J.Y.;Soens,H.;Verstraete,W.;DeBelie, N.Self-healingconcretebyuseofmicroencapsulatedbacterial spores. Cem. Concr. Res. **2014**, 56, 139–152.[CrossRef]
[53]. Xu,J.;Wang,X.Self-healingofconcretecracksbyuseofbacteria-containinglowalkalicementitiousmaterial.
[54]. Constr. Build. Mater. **2018**, 167, 1–14. [CrossRef]
[55]. Qiu,J.;Tng,D.Q.S.;Yang,E.-H.Surfacetreatmentofrecycledconcreteaggregatesthroughmicrobialcarbonate precipitation. Constr. Build. Mater. **2014**, 57, 144–150.[CrossRef]
[56]. Siddique, R.; Singh, K.; Kunal, P.; Singh, M.; Corinaldesi, V.; Rajor, A. Properties of bacterial rice husk ash concrete. Constr. Build. Mater. **2016**, 121, 112–119.[CrossRef]
[57]. Alazhari, M.; Sharma, T.; Heath, A.; Cooper, R.; Paine, K. Application of expanded perlite encapsulated bacteria and growth media for self-healing concrete. Constr. Build. Mater. **2018**, 160, 610–619. [CrossRef]
[58]. Chen,H.;Qian,C.;Huang,H.Self-healingcementitiousmaterialsbasedonbacteriaandnutrientsimmobilized respectively. Constr. Build. Mater. **2016**, 126, 297–303.[CrossRef]
[59]. June, J.; Politecnica, U.; Wang, J.Y.; Van Tittelboom, K.; De Belie, N.; Verstraete, W. Potential of applying bacteriatohealcracksinconcrete.InProceedingsoftheInternationalConferenceonSustainable Construction MaterialsandTechnologies,UniversitàPolitecnicadelleMarche,Ancona,Italy,28–30June2010;pp.1807–1818, ISBN978-1-4507-1490-7.
[60]. Chen, H.-J.; Peng, C.-F.; Tang, C.-W.; Chen, Y.-T. Self-Healing Concrete by Biological Substrate.Materials
[61]. **2012**, 12, 4099. [CrossRef] [PubMed]
[62]. Zhang,J.;Liu,Y.;Feng,T.;Zhou,M.;Zhao,L.;Zhou,A.;Li,Z.Immobilizingbacteriainexpandedperlitefor the crack self-healing in concrete. Constr. Build. Mater. **2017**, 148, 610–617.[CrossRef]
[63]. Khaliq,W.;Ehsan,M.B.Crackhealinginconcreteusingvariousbioinfluencedself-healingtechniques.
[64]. Constr. Build. Mater. **2016**, 102, 349–357. [CrossRef]
[65]. Wang, J.; Dewanckele, J.; Cnudde, V.; Van Vlierberghe, S.; Verstraete, W.; De Belie, N. X-ray computed tomography proof of bacterial-based self-healing in concrete. Cem. Concr. Compos. **2014**, 53, 289–304. [CrossRef]
[66]. Jiang,L.;Jia,G.;Jiang,C.;Li,Z.Sugar-coatedexpandedperliteasabacterialcarrierforcrack-healingconcrete applications. Constr. Build. Mater. **2017**, 232, 117–222.[CrossRef]
[67]. America, F.; Shoaeib, P.; Bahramia, N.; Vaezia, M.; Ozbakkalogluc, T. Optimum rice husk ash content and bacterial concentration in self-compacting concrete. Constr. Build. Mater. **2010**, 222, 796–813.[CrossRef]
[68]. Mondal, S.; Ghosh, A. Investigation into the optimal bacterial concentration for compressive strength enhancement of microbial concrete. Constr. Build. Mater. **2018**, 183, 202–214.[CrossRef]
[69]. Palin, D.; Wiktor, V.; Jonkers, H.M. A bacteria-based self-healing cementitious composite for application in low-temperature marine environments. Biomimetics**2017**, 2, 13. [CrossRef][PubMed]
[70]. Feng,J.;Su,J.;Qian,C.CoupledeffectofPPfiber,PVAfiberandbacteriaonself-healingefficiencyof
[71]. early-age cracks in concrete. Constr. Build. Mater. **2015**, 228, 116810. [CrossRef]
[72]. Gupta, S.; Kua, H.W.; Pang, S.D. Healing cement mortar by immobilization of bacteria in biochar: An integrated approach of self-healing and carbon sequestration. Cem. Concr. Compos. **2018**, 86, 238–254. [CrossRef]
[73]. Shaheen, N.; Khushnood, R.A.; Khaliq, W.; Murtaza, H.; Muhammad, R.I.; Khan, H. Synthesis and characterization of bio-immobilized nano/micro inert and reactive additives for feasibility investigation in self-healing concrete. Constr. Build. Mater. **2011**, 226, 492–506.[CrossRef]
[74]. Khushnood,R.A.;Qureshi,Z.A.;Shaheen,N.; Ali,S.Bio-mineralizedself-healingrecycledaggregateconcrete for sustainable infrastructure. Sci. Total Environ. **2010**, 703, 135007.[CrossRef]
[75]. Zajac,B.;Gołebiowska,I.Samoleczeniebetonu. Cz.1.Metodynaturalneichemiczne.Inż.Apar.Chem.**2016**,
[76]. 55, 160–161.
[77]. Zajac,B.;Gołebiowska,I.Samoleczeniebetonu.Cz.2.Metodybiologiczneispecjalne.Inż.Apar.Chem.
[78]. **2016**, 55, 160–161.

[79]. Li, V.C.; Herbert, E. Robust the self-healing for sustainable infrastructure. J. Adv. Concr. Technol. **2012**, 10, 207–218.[CrossRef]

[80]. Shim, K.B.; Kishu, T.; Choi, S.C.; Ahn, T.H. Cementitious materials for crack self-healing concrete. J. Ceram. Proc. Res. **2015**, 16,1–13.

[81]. De Muynck, W.; De Belie, N.; Verstraete, W. Microbial carbonate precipitation in construction materials: Areview. Ecol. Eng. **2010**, 36, 118–136.[CrossRef]

[82]. BravoSilva,F.;Boon,N.;DeBelie,N.;Verstraete,W.Industrialapplicationofbiologicalself-healingconcrete: Challenges and economical feasibility. J. Commer. Biotechnol. **2015**, 21, 31–38.[CrossRef]

[83]. Łukowski,P.;Adamczewski,G.Samozaleczanieisamonaprawabetonu.Inż.Bud.**2017**,8,421–424.

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