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Research paper

Self-repairing polyethylene fiber-reinforced-concrete with bacillus subtilis bacteria a review

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Abstract

Fibers and bacterial additives in concrete have achieved significant success as a construction material. This paper presents the field of concrete self-repairing by introducing both Bacillus subtilis bacteria and polyethylene fiber as a dual-components. The main research goal is to reveal the principles of concrete self-repairing. At first, the research investigates the fiber-reinforced-concrete behavior, the concrete self-repairing process with the Bacillus subtilis bacteria for forming bacterial-concrete. And then, the study highlights the damage-repairing numerical simulation of fiber-reinforced-bacterial-concrete. The research shows the bacterial-concrete benefits to durability and mechanical properties besides to the polyethylene fiber assistance to enhance post-cracking tensile resistance and the pre-peak elastic modulus of concrete. The novelty of the fiber-reinforced-bacterial-concrete is the matrix combined improvement of both basic material properties and the post-cracking deflection capacity.

Keywords: *Bacillus Subtilis; Bacterial-Concrete; Fiber-Reinforced-Bacterial-Concrete; Fiber-Reinforced-Concrete; Polyethylene Fiber.*

1. Introduction

Conventional concrete (CC) is the most common building material and the backbone of the country's infrastructure cause of its affordable price, distinguished mechanical behavior in compressive, and casting flexibility. The low tensile strength is the main drawback causing micro-and macro-cracks in the CC. Temperature and humidity fluctuations cause micro-cracks (such as plastic shrinkage, plastic settlement, and thermal expansion cracks) due to different concrete ingredients' incompatibility. Also, high external exposures and deformations may form macro-cracks in the matrix. These problems cause an unattractive appearance and make the mechanical qualities weaker over time. So, the service life enhancement of the concrete structure reflects on serviceability, durability, and sustainability [1].

Since traditional materials cannot provide all necessities, the improvement of existing materials using synthetic fibers dose and bacterial self-repairing are essential. The current study aims to highlight the principles of the fiber-reinforced-concrete (FRC), the bacterial-concrete (BC), the fiber-reinforced-bacterial-concrete (FRBC) with both polyethylene (PE) fiber and Bacillus subtilis bacteria admixed to the concrete matrix.

2. Polyethylene fiber contribution

There are various fiber types, in several shapes and sizes, available for commercial and experimental use [2]. American Concrete Institute (ACI) Committee 544 defines FRC as "concrete made primarily of hydraulic cement, aggregates, and discrete reinforcing fibers" and divides it into four groups: SFRC (steel), GFRC (glass), SNFRC (synthetic), and NFRC (natural) [3]. Synthetic fibers, depending on their geometry, are subdivided into two major types: micro- and macro-fibers. The micro-fibers have a diameter less than 0.30 mm or a specific surface area exceeding 500 cm^2/g. In contrast, the macro-fibers are referred to bigger fibers in diameter and length with a diameter greater than 0.30 mm and a specific surface area of roughly10 cm^2/g [4, 5].

Polyethylene (PE) fiber is a synthetic fiber produced from ethylene obtained from petroleum resources [6]. The potential benefits of using PE are the many significant features as;

i) High serviceability cause of its non-electric/magnetic, alkali-proof, acid/salt-proof, and rust-proof properties [7, 8].
ii) Cheaper than the steel fiber on an equal volume dose cause of its low volumetric density [9].
iii) Variety of cross-sectional shapes with different surface finishes for further improvement in bond properties [10].
iv) Dimensionally stable against most bacterial species degradation except some as Brevi Bacillus borstelensis 707 [11], Pseudomonas fluorescens with Sphingomonas, Acinetobacter sp. 351 [12], Acinetobacter sp. 351 [13], and the bacteria from the Plodia interpunctella mealmoth larvae guts [14].

Discontinuous synthetic fiber randomly distributed in the concrete matrix mitigates the inherent brittleness and increases the durability [2, 15]. Many parameters are affecting on the response of FRC structures as;

i) The fiber volume fraction V_f; Generally, the fiber content preferred to be less than 2% macro-synthetic fiber and 3% for micro-synthetic fiber to make sure an adequate balance between obtaining optimum strength and workability benefit [9, 16, 17]. The higher fiber dosage could cause an aggregated conveyor belt on the concrete or the mortar [18].
ii) The fiber aspect ratio $AR_f = l_f / d_f$ (longer length per unit diameter); The higher aspect ratio, the larger surface area that improves both the bond of macro-synthetic fibers and the strength of the concrete. So, the aspect ratio less than 75 causes relative strength and toughness reduction [19, 20].
iii) The fiber length l_f; Shorter fiber length means many more fibers with the same fiber volume content can transmit tensile stresses across the cracks leading to the overall improved response of FRC [15].
iv) The fiber geometry; The end-hooked, twisted, enlarged ends, sinusoidal ends, double deform, cross crimped, and star crimped fibers have enhanced anchorage properties more than the straight smooth fiber [21].
v) The fiber orientation and the fiber distribution in the matrix; Fibers that have more acute angles to crack (arranged perpendicular to the applied load) cannot transmit appreciable tensile stresses across the crack [22].
vi) The fiber strength and concrete matrix properties; The high tensile strength macro-synthetic fiber prevents failure by brittle fiber fracture that improving ductility. Also, the higher matrix material strength, the higher bond strength between the fiber and the matrix. The bond strength improvement increases the crack control effectiveness, the ultimate load, and overall ductility by resisting sufficient tensile stresses without fiber pull-out. However, the fiber elasticity modulus should be much higher than the matrix elasticity modulus for efficient stress transmission [10].

3. Damage bio-managing techniques

The concrete repair and treatment with synthetic products re-applied every 10–15 years because of concrete gradual degradation with time. The maintenance-free self-repairing replaced the traditional maintenance due to the indirect cost reduction besides solving the detection and retrofitting difficulty in deep and unreachable cracks with in-situ materials added by the man from outside [23].

The automatically self-repairing technique triggered without human intervention when exposed to different environmental conditions (passive modes) or mechanical loads (active modes). Adopting the self-repairing produces the smart infrastructure systems that can provide a unique beneficial response of sensing and action properties. This smart technique can guarantee the service life extension by a degradation rate reduction, damage maintenance frequency reduction, and strength monitoring or damage detection costs reduction [24].

Self-healing (SH) / Self-repairing (SR) is a process by the material itself during the service lifetime involving the partial or the complete recovery of voids or cracks that reducing its performance [25]. Concrete SR classified into two categories:

i) Autogenic repairing is an own material property triggered with hydration of the un-hydrated cement remaining in the matrix without any external activation but only by moisture that penetrates the crack.
ii) Autonomic repairing is a designed mechanism from the inside out that requires the use of foreign engineered additions. The autonomic concept could change the autogenic limitations as low un-hydrated cement particles with concrete age and the repairing large cracks lack. The autonomic SR techniques include hollow fibers, chemical encapsulation, mineral admixtures, shape-memory materials and biological repairing [26].

Some biogenic origin can induce precipitation of calcite minerals through processes pathways such as ureolysis (ureolytic bacteria), photosynthesis (cyanobacteria & algae), ammonification (myxobacteria), denitrification (nitrate-reducing bacteria), methane oxidation (methanogens), and sulfate reduction (sulfate reduction bacteria). Degradation of urea with ureolytic bacteria is the easiest to operate and control. The biological concrete production involves three various guidelines [27];

i) Selection of biological species.
ii) Isolation, growth of biogenic origin, and preparation of the specimen.
iii) Evaluation of crack SR.

The ureolytic bacteria as B. subtilis achieve sustainable micro-biologically enhanced crack remediation (MECR) as soon as cracks formation where the water starts to flow in through. In the presence of nutrients and oxygen, bacteria start biologically activated and produce proteases & enzymes. This process enables degrading natural substrates and contributes it to nutrient cycling where bacteria's spores germinate and start multiplying. Hence, B. subtilis bacteria transform organic soluble nutrients (calcium-based nutrient) into inorganic insoluble calcite crystals $CaCO_3$ (limestone) that solidifies the cracked surface [28]. The micro-cracks healing is different from the macro-cracks where the crack size and geometry effect results [25]. B. subtilis strain 168 in cement mortar may repair crack width of 0.3 mm within 1-5 days in the laboratory [29] or may take several weeks to repair macro-cracks up to 0.46 mm [30].

4. Evaluation of micro-organisms contribution

Researchers explained bacterial precipitation through two approaches; the first S. Stocks-Fischer et al. 1999 approach is the hydrolysis of urea $Co(NH_2)_2$ by ureolytic bacterial metabolism to carbonate ion (CO_3^{2-}) and ammonium (NH_4^+). Then, the increasing carbonate concentration and soluble calcium ions (Ca^{2+}) deposited to the limestone $CaCo_3$ around the cell. This method presents the simplest controllable mechanisms and produces high amounts of limestone within a short period [31].

Thus, the rate of specific urea degradation (SUD) is determined using; the ammonia production (AP) (g/l) "measured as a function of bacterial growth per unit time t (hr)" and the optical density (OD) measured with a spectrophotometer. Also, the supersaturation level (S) is the driving force for $CaCO_3$ precipitation defined by the ratio of the ionic products and the solubility product K_{so} (4.8×10^{-9} for calcite at 25°C) [32].

Producing ammonium (NH_4^+) as a by-product can produce negative side-effects. Hence, the second approach investigated by Bachmeier et al., 2002. The bacteria use oxygen, moisture, and calcium compound as Ca-lactate (Nutrients) to carry out their metabolic activity and produce both calcium carbonate and carbon dioxide CO_2. Also, the CO_2 reacts with the still un-hydrated cement portlandite particle "calcium hydroxide $Ca(OH)_2$" to produce large quantities of limestone in the fresh concrete [33].

The efficiency of concrete SR depends on many factors to achieve fast optimum steady-state bacterial precipitation of $CaCO_3$ as;

i) The pH environment [34].
ii) The environment temperature [35].
iii) The concentration of dissolved inorganic carbon (DIC).
iv) The calcium ion concentration.
v) The moisture availability.

vi) The crack width present nucleation sites areas for calcite precipitation [36]. The bacteria themselves could be nucleation sites [37].
vii) The concrete age where crack repairing efficiency increased with increasing curing days [38, 39].
viii) Survival of bacteria in the long-term [40-42].
ix) The proper bond created between calcite and concrete besides to the calcite densification degree [43].

The summary of techniques and tests for crack SR assessment and guarantee the recovery of mechanical and durability properties referenced in Table 1 [44, 45].

Table 1: Review of Techniques to Evaluate Healing Efficiency with Cited Example Tests

Assessment Techniques	Test
Deposited Crystal Visualization and Biominerals Characterization	Environmental/Scanning Electron Microscopy (SEM/ESEM) [46], Fourier Transform Infrared Spectroscopy (FTIR) [47], Optical Microscopy with Image Analysis [48], Light Microscopy [49], X-ray Diffraction (XRD) [50], X-Ray Tomography [51], Energy-Dispersive X-ray Spectroscopy (EDX/EDS) [52], Transmission Electron Microscopy (TEM) [47], Neutron Diffraction [53], Thermogravimetric Analysis (TGA) [54], and Differential Thermal Analysis (DTA) [55].
Durability Properties Recovery	Water/Gas Permeability (Low Pressure and High Pressure) [56], Water Absorption [46], and Acid Attack Test [57].
Mechanical Properties Recovery (Strength Improvement)	Destructive Testing as; Proof Test [58], Fracture Test [59], Compressive [60], Split Tensile Test, and Bending Test (3-point and 4-point) [61]. Non-destructive Testing (NDT) as; Ultrasonic Pulse Velocity (UPV) and Rebound Hammer Test [62]

5. Review B. subtilis SR

The SR process prevents micro-cracks from growing and limiting the paths for liquids and gasses contain harmful chemical substances [63]. Also, the SR process seals the macro-crack by bio-mineralization that improving both mechanical and transport properties [30, 64]. The produced limestone can increase concrete resistance to alkaline, sulfate and freeze-thaw attack. So, it will extend the concrete service life by decades. The SR process can improve sustainability by increasing concrete strength, lessening its maintenance, and reducing both its financial and environmental costs [26]. Numerous literature process B. subtilis to observe the improved durability and strength of the specimens as in Table 2.

Table 2: Some Literature Process B. Subtilis as A Healing Agent

Researcher	Specimens	Tests
Sunil et al., 2010 [57]	cement mortar and concrete with B. subtilis (JC3) at 10^4, 10^5, 10^6, and 10^7 cells/ml water	SEM and acid attack test with 5% H_2SO_4 tests
Vempada et al., 2011 [50]	B. subtilis (JC3) in cement mortar at 10^4, 10^5, 10^6, and 10^7 cells/ml water	SEM and XRD tests
Reddy et al., 2012 [65]	cement mortar and concrete with B. subtilis (JC3) at 10^4, 10^5, 10^6, and 10^7 cells/ml water	SEM, XRD, and Acid attack with 5% HCl and 5% $H2SO_4$ tests
Park et al., 2012 [66]	B. subtilis 168 for the surface treatment of cement mortar with cells count 0.8 and 1.4 OD_{600}	water permeability, crack remediation, compressive, surface treatment, and SEM tests
Pei et al., 2013 [67]	curing cement mortar and concrete by B. subtilis 168	XRD and SEM/EDX results
Nguyen and Nguyen, 2014 [68]	B. subtilis in cement mortar at 10^9 and 10^{11} cfu/g	XRD and SEM tests
Huynh and Son, 2014 [47]	B. subtilis HU58 in cement mortar at 1.26% by mass	XRD, TEM SEM, and FTIR tests
Manikandan and Padmavathi, 2015 [69]	B. subtitles strain 121 in M20 grade concrete with cells count on OD600	NDT and the temperature sustainability test
Meera and Subha, 2016 [70]	B. subtilis (JC3) in M20 grade concrete at 10^3, 10^4, 10^5, and 10^6 cells/ml water	compressive, split tensile and acid attack tests
Monishaa and Nishanthi, 2017 [71]	B. subtilis (JC3) and PE fiber 0.4% in M20 grade at 10^4, 10^5, and 10^6 cells/ml water	compression, split tensile, and flexural tests
Rao et al., 2017 [62]	B. subtilis (JC3) in different concrete grades at 10^4, 10^5, 10^6, and 10^7 cells/ml water	compressive, split tensile, flexural, UPV, and water absorption tests
Schwantes-Cezario et al., 2017 [52]	B. subtilis AP91 (10 mL of total volume formulated)	SEM and EDS tests
Prasad and Lakshmi, 2018 [72]	B. subtilis in M40 concrete with concentrations of 10^5 cells/ml water	abrasion resistance and flexural strength tests
Sridevi, 2018 [73]	B. subtilis in M30 grade concrete with 5, 10, 15, 20, and 25 mL from the total volume	compressive test
Saleh, 2018 [74]	B. subtilis JC3 in concrete with/out fibers at 10^4, 10^5, 10^6, and 10^7 cells/ml water	compression, split tensile, and flexural tests
Nain et al., 2019 [75]	B. subtilis in M30 grade concrete at 10^8 cells/ml water.	SEM, EDX, compression, and split tensile tests
Hussein et al., 2019 [76]	B. subtilis in M40 grade concrete at 10^3, 10^6, and 10^9 cells/ml water	Water Absorption, UPV, Compressive Strength, SEM tests

6. B. subtilis as a self-repairer

There are many bacterial species precipitating induced calcium carbonate as; B. subtilis, B. cereus, B. sphaericus, B. thuringiensis, B. pumilis, B. fusiformis, B. pseudifirmus, B. cohnii, B. megaterium, B. lichenformis, B. lentus, Sporosarcina pasteurii, Acinetobacter sp., Arthrobacter sp., Shewanella sp., Desulfovibrio desulfuricans, Mytilus californianus, Micrococcus sp., Proteus vulgaris, Aerobacter aerogenes, Proteus mirabilis, Pseudomonas putida, Myxococcus xanthus, and Nocardia calcarean [63].

The Bacillus species have no pathogenic potential except B. cereus and B. anthracis [77-79]. B. subtilis has many significant features as;

i) Aerobic (oxygen diffuse through matrix capillaries).
ii) An alkaliphile (alkali-resistant).
iii) Gram-positive bacterium (that suitable for remediation).
iv) Rod-shaped (2-3 µm in length and 0.6-0.8 µm in width).
v) With thick wall cell (20–80 nm thickness [80] that enduring extreme conditions of salt, temperature, pH, and pressures [57]).
vi) Lie sleeping up to 200 years (where spores are dormant bacterial cells).
vii) Separated in the laboratory from the air, water, soil, tropical beach sand, and decomposing plant residue.
viii) Collected from natural alkali lakes, carbonate-rich desert [81], soda lakes and soil [82], and milk products [83].

There are different selective growth media for the microbial activities forming inorganic solids [84]. B. subtilis needs nutrient broth dissolved in the matrix mixture. The nutrient broth does not negatively affect the concrete strength and the setting time [85-87]. The pure culture colonies inoculation could be done in a conical flask containing distilled water, HCl, NaOH or $NaHCO_3$ that adjusted the solution to the required pH [38]. The solution sterilization in the autoclave is essential to kill the other existed bacteria where the solution becomes contaminated-free in clear-orange color.

The slant culture should be preserved under refrigeration (4°C) until the next usage (2-3 days). Whenever required, the periodically streaking on nutrient agar plates done for the contamination-free examination [57, 70]. Then, the conical flask covered with a thick cotton plug and silver foil incubated in an orbital shaker. After 24 hours, the bacteria solution color changes from clear-orange to turbid-whitish-yellow that indicating the growth of B. subtilis bacteria [72], [88].

The bacterial strain determined by the incubation chemical media with calcium source as; C-Ca: Calcium chloride $CaCl_2$, A-Ca: Calcium acetate $Ca(CH_3COO)_2$, L-Ca: Calcium lactate, N-Ca: Calcium nitrate $Ca(NO_3)_2$ [41, 42]. The different accession number strains could be isolated from a biocatalytic ureolytic calcification reactor [89]. Moreover, the crystallizing and efficiency of providing calcium ions for the urea- L-Ca medium are the greatest [55, 90].

Diluting the mass cultured bacteria as per requirements is vital. For diluting, the bacterial small pinch added to the solution flask in a laminar airflow chamber. Researchers measured the bacterial count or concentration of cells per millimeter of water using the following three ways;

i) Percentage % by mass of the bacterial solution [47].
ii) Hemocytometer under the microscope [71].
iii) Finding optical density (OD) value (nm) using a spectrophotometer that measures the cell suspension absorbance (the amount of light scattered where visible light passes through the cells) [69, 75].

There is different experimental cell concentration of B. subtilis JC3 microorganisms (10^3 cells/ml, 10^4 cells/ml, 10^5cells/ml, 10^6 cells/ml, 10^7 cells/ml, and 10^9 cells/ml) added to the mixing water. Following observations are summarized;

i) The compressive strength of cement mortar cubes 70.6 mm x 70.6 mm x 70.6 mm is optimum at the cell concentration of 10^5 cells/ml of mixing water (increased by about 16.2% at age 28 days) as shown in Fig. 1 [57, 62, 65]. Also, the increasing could reach 19.3% for the specimens at age 28 days [50]. The limestone coats the bacterial surface after filling the crack. This process prevents the flow of oxygen and nutrients to the cells. The cells either die or turn into endospores and act as organic fiber [91] that increase the compressive strength on the 7th day but not on the 28th day [67].
ii) The compressive strength of M20 concrete cubes 150 mm x 150 mm x 150 mm is optimum at 10^5 cells/ml (increased by about 42.5 % at age 28 days) as shown in Fig. 2 [70].

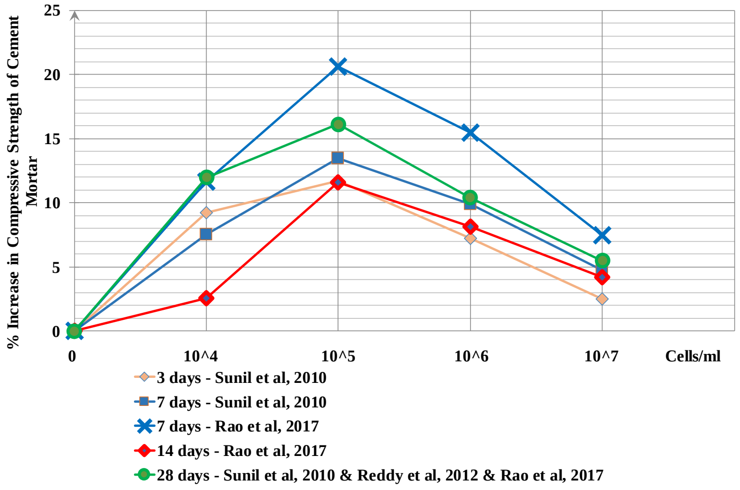

Fig. 1: Effect of the B. Subtilis JC3 Bacteria Addition with Different Cell Concentrations on Cement Mortar Cubes 70.6 mm X 70.6 mm X 70.6 mm Compressive Strength.

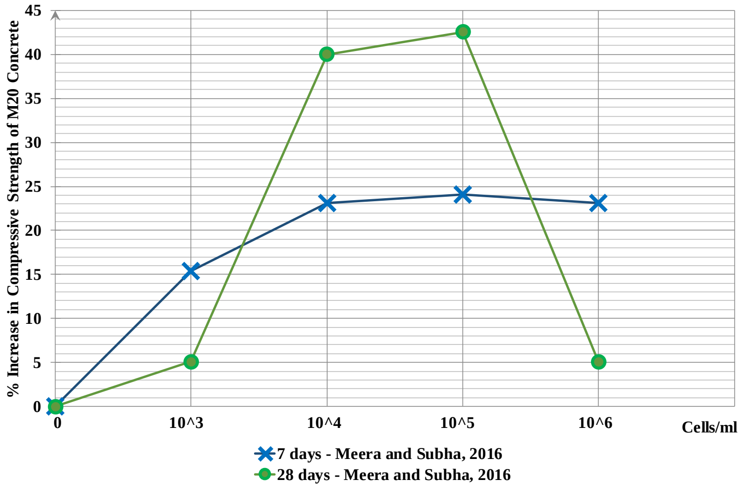

Fig. 2: Effect of the B. Subtilis JC3 Bacteria Addition with Different Cell Concentrations on M20 Grade Concrete Cubes 150 mm X 150 mm X 150 mm Compressive Strength.

7. Damage-repairing behavior simulating

Besides the calcification tests with biotechnology micro-lab work and fracture testing equipment, the numerical simulations can reduce the cost and time-consuming [23]. Simulation of the FRBC damage-repairing behavior on both the microscopic level and the macroscopic level may present great help to verify and develop SR concepts. The damage-repairing behavior could be simulated as follows;

7.1. Discontinuous models (DM)

The DM could be more suitable for damage-repairing simulating by using a pseudo reverse damage process (reversed cohesive constitutive model) [9] where DM holds less mesh dependence than continuous models. In this model, the crack surfaces rebounding starts from a finite width to almost zero at the end of the healing process [92]. The cohesive zone strength restoration depends on crack opening and time. For concrete, the mixed-mode traction-separation law as a discontinuous model describes the relationship between the crack opening width ζ and the traction between the crack two surfaces [93].

The damage-repairing system considered as parallel springs. So, the total equivalent tensile stress T_{eq} (ζ) at the different conditions of loading and un/reloading depends on a few physical healing parameters as follows [94];

i) The original material traction denoted as T (ζ) involves the uniaxial tensile cracking strength and the fracture energy for macro-synthetic FRC.
ii) The level of penetration and contact between the healing agent and the original material denoted as α where $\alpha = 0$ when the maximum crack opening $\zeta_{mx} = 0$ and $\alpha = 1$ when the corresponding traction $T_{mx} \approx 0$ (big crack opening).
iii) The time-dependent healing agent behavior denoted as H (ζ, Δt) depending on two healing parameters as follows; (1) The healed material traction denoted as $H_\infty(\zeta)$ mimicked the original concrete traction T (ζ) and involve the ultimate strength and fracture energy of healing substance. (2) The mature healing degree of agent denoted as R (Δt) attributed by resting time for healing $\Delta t = t - t_r$ where t_r is the time when healing bacteria spores germinate. When Δt is big enough for complete healing, an Arrhenius-type law could describe the healing rate. The healing rate is proportional to the chemical affinity of healing substance $A^{\sim}$ fitted with exponential function of the healing agent speed coefficient A_h (h^{-1}) [94]. Noting that the cracks rebounding on the chemical side should immediately follow the crack generation to avoid catastrophic failure in practical application [95].

7.2. Fracture mechanics models

The fracture mechanics models named as fracture process zone (FPZ) could analyze the non-linear fracture behavior of concrete and FRC [96]. The continuum damage healing mechanics (CDHM) considers the damage-healing as reduction-increasing of stiffness and strength “as positive-negative damage” to simulate crack bonding. The cohesive zone damage-healing model (CZDHM) belongs to the family of CDHM [97, 98]. The cohesive zone approach is a useful law that incorporates the healing process characteristics, especially when a fracture takes place along well-defined interfaces [85].

The CZDHM lumped the process zone in the existing crack. Moreover, the constitutive behavior of the cohesive segment related to the stress state in the bulk material. This relation violates the fracture criterion and avoids sudden stresses jump at the inserted discontinuity. The initial traction in this model is equal to the normal direction traction component $t_{n,0}$ (of the bulk material matrix and fiber) with neglecting the shear direction traction [85, 99].

When the cohesive segment opens a cleavage crack, the cohesive traction in the normal direction t_n decreases monotonically from their initial values $t_{n,0}$ to zero depending on both the normal displacement jump Δn and the critical normal opening displacement Δcr (as a function of the matrix fracture toughness at which the crack has fully developed and the traction has reduced to zero).

The subsequent total traction including the healing effect (rebounding of the crack due to the healing agent catalyst) depends on two parameters as follows;

(i) The normal opening of the crack $\Delta n,r$ at the beginning of the catalyst and surfaces rebounding t_r.
(ii) The recovery factor r because of the chemical reaction ($0 \leq r \leq 1$). A recovery up to $r = 1$ implies that the interface has fully recovered (the interface has the same properties as it had before cracking). This recovery depends on time and a healing parameter h(t) [85].

8. Fiber-reinforced-bacterial-concrete

The FRBC is FRC that self-repaired by bacteria is rather preferred where the composite system incorporation inside the concrete leads to more stability over shelf-life. Not only the study of FRBC basic material properties (compressive and tensile strength) is essential, but also the specific new material properties as flexure strength and flexure toughness are important [100, 101]. Adding fibers to the conventional concrete and SR concept of FRC could accomplish many advantages for so-called FRBC such as follows;

i) The FRBC produces better concrete properties that could be very useful in the special infrastructures as high-rise, long-span, storm surge barriers, nuclear reactors, dikes, dams, and tunnels.
ii) The FRBC can reduce Co_2 emissions as an eco-friendly smart infrastructure with sensing and actuation properties that save costs of strength monitoring, damage detection, maintenance, and raw materials.
iii) The life-cycle-assessment model (LCA) showed that concrete materialization and construction are contributing to a large amount of CO_2 emissions [102]. Adding renewable-energy alternatives is critical to mitigating these emissions. The FRBC has significant multiple environmental footprints where FRC is an eco-friendly technique to recycle the un-biodegradable thermoplastic polymer as PE [103]. Also, the BC excels CC by having a half overall environmental impact [104].
iv) The bacterial precipitations improve both the mechanical and transport properties [30, 64] that increasing fracture toughness and bond strength [105]. So, considering the SR capacity can prevent driving deterioration factors of practice codes. Also, fibers can achieve comparable shear strength of conventionally shear reinforcement minimum amounts [106].
v) The bacterial conversion increases the embedded steel durability by both reductions of the capillary permeable porosity and consuming oxygen needed for steel corrosion [23].
vi) The fibers can improve post-cracking tensile resistance across cracks and exhibiting multiple microcracking with crack width less than 100 μm [107, 108]. Then, the smaller width crack pattern of host materials requires fewer healing products to fill [109].
vii) The bridging discontinuous fibers serve as nucleation sites for the calcite crystals and simultaneously improve the material quality especially in tension [110].
viii) The fibers can enhance the pre-peak elastic modulus causing an increase in flexure strength and shear capacity of structural members [111, 112].
ix) The enhancement of SR could extend the FRC structure’s service life and durability [113]. The bacterial SR fills the cracks, fractures, and fissures [24] besides fiber existence [114].
x) The fibers can exhibit multiple microcracking with a strain-hardening response under tensile loading [107]. Also, fibers can increase the energy-absorbing ability during the fracture (characterized by the area under the stress-strain curve) [115] that improve post-peak ductility [116].

9. Demerits of FRBC

The mitigating of FRC bio-mineralization demerits affects the behavior of the FRBC and create more confidence among contractors and owners of structures. Successful field implementation of remediation techniques requires bridging the gap to real applications by applying SR agents on a larger scale. The proper fiber selection is difficult where the fibers have a large variety of physical and mechanical properties. The synthetic-fibers may reach the melting point due to surrounding circumstances as the high temperature. There are difficulties related to applying, manufacturing, and evaluating of fiber dimensions, fiber anchorage geometry, fiber orientation, and fiber distribution. The microbe and nutrient availability at bacterial spray treated (BST) depend upon the fluid transport through the heterogeneous concrete pathways and micro-cracks after hardening. Bacteria may become inactivated or die off when covered by carbonates overtime. So, more BST injections are important for sealing large voids. The presence of bacteria endospores can lead to uncontrolled growth. Limiting the nutrient availability solves this problem and leads to die-off the un-preferable bacteria [117]. The main deficiencies of the ureolytic bio-concrete are the by-products that may pose environmental and health risks. Dismissing the undesired by-products after the application is costly. The alternative approach investigated by Bachmeier et al., 2002 prevents these secondary product generations. The extremely harsh conditions lead to the limitation of restoration and microbial life restriction as follows;

i) Desiccation decreases concrete moisture content. Adopting bacteria with spores that activated in the water and oxygen is essential. Another solution is to apply protection immobilized thorough various carrier compounds as silica gel, polyurethane (PU) [118], graphite-nano-platelets (GNP), melamine based microcapsules [119], hydrogel [49], diatomaceous earth [120], light-weight-aggregate (LWA) as expanded clay particles Liapor [121-123] and immobilized on nano-/micro-additives [124].
ii) Most organisms did not survive in a pH value above 10. The extremely thick cell walls of Bacillus genus be the reason for the survival at the pH value of 13 at cement and water mixture. Then, the pH of the highly alkaline concrete lowers from 13 to a value in the range (10 - 11.5) when a crack occurs that encourages the pH-sensitive bacterial spores to become activated causing bacteria growth and cracks healing [91].
iii) The nutrient-rich environment conditions are rare in concrete. The cost of the soluble organic nutrients is quite high, but cheap replacements for calcium lactate as corn steep liquor and lactose mother liquor are effective.
iv) Spore-forming organisms such as B. subtilis, B. cereus and B. pumilus are completely killed at temperature equals 50°C - 80°C, pressure equals 27.5 MPa, and supercritical CO_2 conditions [125].
v) The ideal salt concentration in growth medium for bacteria $CaCo_3$ precipitation is 2.12-35 g/l [89, 126].
vi) The low light intensity limits the biomass productivity of some bacterial species. On the other hand, high light intensity causes photo-inhibition of phototrophic microorganisms [127, 128].

10. Discussions

i) The evaluation divergence in the improvement results through the review studies is due to the differences in; (i) Experimental procedures and efficiency evaluation between the different studies. (ii) The concrete physical and chemical properties as well as the cement grade and other ingredients quantity and quality. (iii) The bacteria cell concentration and the growth media. (iv) The application method as dropping, immersing, surfaces spraying (BST), admixture to the fresh matrix known as bacterial admixed treated (BAT) or immobilized with other substances. (v) The period required as an age of testing.

ii) For mechanical properties, the compressive strength *f*c' improvement for any concrete grade at 28 days using B. subtilis (JC3) at 10^5 cells/ml of water concluded by researchers equals 23% (an average for any concrete grade) as in Fig. 3 [62, 65]. Also, the split tensile strength f_t at 28 days using B. subtilis (JC3) bacterial-concrete with 10^5 cells/ml of water concentration improved in a range of (13.7 - 25.3%) as in Fig. 3. However, over-estimated improvement in f_c' concluded equals 42.5 % at 28 days and improvement in f_t concluded equals 63% at 28 days [70].

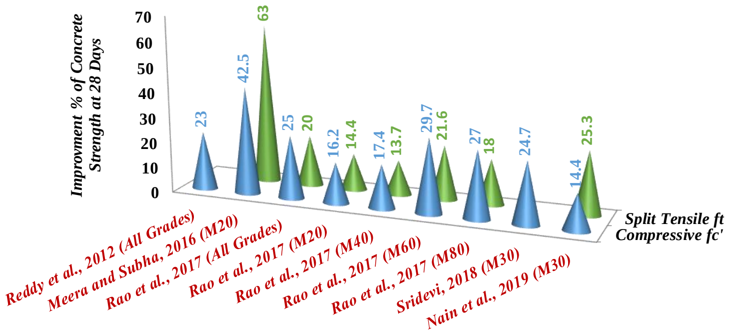

Fig. 3: The Improvement of Compressive Strength f_c' and Split Tensile Strength f_t at 28 Days in BC (at 10^5 Cells/ml B. Subtilis JC3) Concluded By Different Literature Reviews.

iii) While bacterial self-repairing of M20 grade concrete with 0.4% PE fiber increases the f_c' at 28 days by 13.2% [71], bacterial self-repairing of M20 grade concrete increases the f_c' at 28 days by 16.2% (greater than 13.2%) [62]. This goes with the conclusion that fibers' addition has little effect before cracking and affect the concrete compressive strength with ± 4% [16, 129].

iv) There is some recovering effect on the flexure strength of FRC self-repaired with B. subtilis JC3 after 28 days depending on the width of the pre-loading cracks (80% until 100 µm and recovered less by tendency from 39 to 52 % for bigger cracks 150 µm to 400 µm) [74].

v) For durability, many requirements help to mitigate the attack severity as; permeability, sulfate resistant, freeze-thaw resistant, abrasion resistant, low alkali-aggregate reactions, embedded steel corrosion resistant and so on, where the assumption that the high strength concrete would also be durable enough is not true [130].

vi) Self-repairing with B. subtilis has an optimistic effect on the concrete matrix durability with proper and immediate rehabilitation that preventing widely expansion of cracks as follows; (1) The less porosity by 70% due to the growth of new dense calcite crystals [62, 75]. (2) The less water absorption capacity (WAC) by 50-80% for low- to high-grade concretes [62]. (3) The larger acid durability factor (ADF) and less acid attack factor (AAF) that leading to decreasing in chemical penetration [70]. (4) The abrasion resistance increased to 10% at all ages [72].

vii) The self-repairing enhances fiber bridging of pre-existing microcracks reopened after reloading. The smaller microcrack width requires fewer healing products that enhance fiber embedment length. Furthermore, the healed crack effect on the micro-scale and the macro-scale among all the fibers bridging crosses the crack. Hence, the post-cracking deflection capacity improved from virgin specimens by 65–105% after water curing and 40–60% after air curing. Also, the initial linear stage stiffness of the self-repaired specimen is much larger due to the healing substance's presence inside the crack that strengthened the bridging fiber [109].

viii) The microbially induced calcite precipitation (MICP) pre-treatment has enhanced effects on the microstructural and mechanical properties of cementitious material reinforced with fibers where the $CaCO_3$ was successfully deposited on the surface of fibers with thickness around 20-50 µm as observed by the SEM and EDX analyses. The fiber pullout test yielded the increase of the total fiber extraction energy for two or three times cause of the improved fiber/matrix bonding properties. Moreover, the MICP could increase the post-cracking resistance and energy absorption capacity of FRC beam specimens by about 58% and 69%, respectively [115]. While the SR of the fiber-reinforced cementitious systems enhances recovery of mechanical and permeability properties, the SR could be critical to enhance the serviceability and durability of concrete under multiple damage-healing cycles [113].

11. Conclusions

Fiber-reinforced-concrete self-repaired with Bacillus subtilis bacteria is a revolutionary concept encouraging better concrete with extra strength, stiffness, and durability. Thus, the future possibilities are bright for these materials and their actual applications in real life. The B. subtilis bacteria and the high-properties PE fibers have a shared benefit where the healing products enhance fiber embedment length and fibers serve as a nucleation site for bacteria. Bacteria can improve both permeability and mechanical properties. On the other hand, the macro-fibers can enhance post-cracking tensile resistance and the pre-peak elastic modulus. As a novel high-quality concrete, fiber-reinforced-bacterial-concrete has both improvement capacity of the basic material properties and the post-cracking deflection capacity.

12. Future research suggestions

Both the short-term and the long-term properties for other types of loading, fiber parameters, matrix materials, and SR techniques need more investigations in each of the biotechnology micro-lab work, the fracture testing, and the numerical simulations.

13. Conflict of interest statement

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

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