Enhancing Performance of High Strength Concrete with Self-Healing Properties

Avadhesh maurya, Satish Parihar, Vaibhav Dubey
Faculty of Engineering & Technology, Rama University, Mandhana, Kanpur, U.P. India
Email Id: er.avadhesh.civil@gmail.com

ABSTRACT

Strong concrete is indeed a different move in the realm of solid technology. It incorporates compressive strength of 40 MPa or greater. Since HSC is an alternate type of solid, it has not been widely used by the architects. Now, we will attempt to determine the optimal proportion of mineral mixture with cement to achieve maximum compacting density and develop a mixture design based off the acquired outcomes. Due to a lack of research, it has just been deployed in certain reinforced concrete members and a handful of large and accurate structures.

We will be utilizing five mineral mixtures as a puzzling material in cement. The mineral mixtures used were Quartz dust, Fly ash, Metakaolin, Ultra-fine sludge, and Rice-husk ash. A third-generational super plasticizer will also be further used to create the blend design with a specific objective to minimize the water need for cement hydration.

Crack development is also another immense challenge that is encountered by solid. Crack formation in high strength concrete is not a frequent event due to greater pore refinement and interface refinement. However, with subsequent stages if fractures arise, it will degrade the structure. We can likewise manage it by filling those crevices, but it's not a sustainable method. In this examination, we will strive to design a solid that will be capable of recovering its crack with the assistance of calcite precipitating bacteria. So that it can deliver us a more sustainable structure.

In this research, we will also like to confront two hurdles that are usually challenged with solid. One is the undesirable impact produced on the environment due to massive Carbon Dioxide release during cement production. We will aim to encapsulate some greener materials partially substituting the cement to diminish the harsh influence on the environment.

The range of this examination is vast as recently due to limited room; we need to develop a framework that may take up space as minimally as feasible meanwhile deliver strong support. So, HSC is a major player for this situation. The Self-Healing concrete will help us to create a resilient and sustainable structure. It will also aid in structures where crack formation is a common occurrence and the repair is challenging such as Dams and Bridges etc.

The experimentation will be carried out in four phases. The primary stage involves identifying different characteristics of materials like precise weight and water retention. The second phase includes optimization of dual blend by reaching maximum compacting density utilizing the formula provided by Puntke. Following the analyses using various materials, visual representation was executed to achieve the advanced proportion. The third stage which can run in parallel with other phases is the formation of calcite precipitating bacteria settlements. In the final phase we will establish an optimum mix design which we will determine from the aforementioned three stages. We will carry out experimental work for it and ascertain the suitability of this concrete.

Keywords: High strength concrete, Bacteria, Self-healing concrete, Crack, Mineral precipitation, Biomineralization.

INTRODUCTION

In recent years, concrete has become the second most consumed material globally, following water. Historically, concrete mixes of lower grades or strength sufficed for our needs. However, with recent innovations and the construction of large structures, it became evident that past methodologies were inadequate. Consequently, researchers embarked on finding new methods and materials to meet evolving requirements. This quest led to the development of High Strength Concrete (HSC), a term coined to denote a new dimension in "High-performance concrete". HSC holds significant promise in the construction and development industry due to its superior mechanical and durability properties compared to traditional cement. It can even replace structural steel in certain applications through the incorporation of fiber reinforcement.

Achieving HSC involves adhering to standards such as packing density and microstructural enhancement. HSC offers advantages such as water resistance and enhanced strength. Extensive studies have been conducted to determine the mechanical and durability properties of HSC. The results indicate that HSC exhibits higher compressive and flexural strength and reduced water penetrability. The maximum compressive strength typically falls between 120-150 MPa.

At times, the strength may even surpass 200 MPa. At such high compressive strengths, the coarse aggregates become the weakest link in concrete, rendering it susceptible to failure. To achieve high compressive strength, coarse aggregates can be eliminated to ensure consistency and homogeneity in the mix. Materials with pozzolanic properties such as silica fume, fly ash, etc., are utilized to enhance density and strength.

High Strength Concrete (HSC) incorporates higher-grade cement (typically OPC 53), quartz powder, quartz sand, steel fibers, silica fume, steel aggregates, and a third-generation superplasticizer. Superplasticizers are employed to reduce the water-cement ratio while improving workability.

However, two new challenges emerge. Firstly, the extensive production of cement and concrete leads to hazardous environmental effects, posing a significant sustainability concern. Secondly, the durability of concrete is compromised by cracks, whether micro or macro. To address these challenges, concrete is partially replaced with greener alternatives such as fly ash, blast furnace slag, or rice husk ash.

Cracks significantly impact the durability and service life of concrete by allowing moisture, carbon dioxide (CO_2), sulphates, gases, and other liquids to penetrate the concrete, leading to deterioration. Micro cracks can be self-rehabilitated through a process known as "autogenic healing" or "self-healing." Specific healing materials mixed into the concrete matrix facilitates this process.

Bacteria can be classified into five groups based on their basic shapes:

i) Spherical (Cocci)
ii) Comma-shaped (Vibrios)
iii) Spiral (Spirilla)
iv) Rod-shaped (Bacilli)
v) Corkscrew-shaped (Spirochaetes)

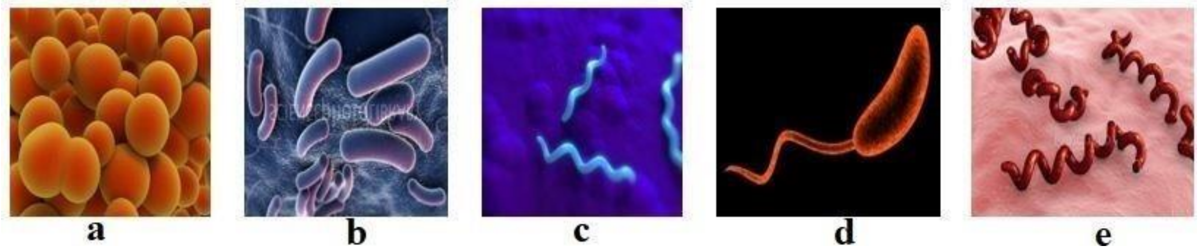

Figure 1 Classification of bacteria based on shapes.

The study by Lee et al. (2009) explored the potential of using Reactive Powder Concrete (RPC) as a repair material for existing concrete structures. They conducted accelerated aging tests involving freezing-thawing cycles to assess the durability and bond stability of RPC with existing cement. The results demonstrated that RPC exhibited promising outcomes, enhancing the compressive and flexural strength of old concrete samples. Additionally, RPC maintained its strength even after undergoing 1000 freeze-thaw cycles, indicating its durability as a repair material. [25]

The trial demonstrated that Reactive Powder Concrete (RPC) exhibited excellent performance, making it a suitable material for repair and retrofitting applications. RPC significantly enhanced both the compressive and flexural strength of old concrete samples. Specifically, when RPC with a thickness of 10 mm was applied, there was a remarkable increase of approximately 150% in flexural strength and 200% in compressive strength compared to ordinary quality cement. Furthermore, even after subjecting RPC to 1000 freeze-thaw cycles, its compressive strength remained robust, indicating its durability and suitability for long-term use in various concrete structures. Overall, these findings highlight RPC's effectiveness in improving the strength and durability of existing concrete, making it a promising material for repair and retrofitting projects.

In a separate study by Yanzhou Peng et al. (2010), the authors investigated the effect of different pozzolans rich in silica on the packing density of cementitious materials. They utilized steel slag, silica fume, and ultra-fine fly ash in various proportions with cement to achieve different packing densities in binary, ternary, and quaternary mixtures.

Furthermore, they observed a further increase in the composite's packing density with the combination of different mineral admixtures, attributed to the greater packing effect achieved. Overall, these findings highlight the potential of incorporating silica-rich pozzolans to improve the packing density and performance of cementitious materials, offering opportunities for enhancing the properties of concrete mixtures. [24]

Furthermore, they observed a further increase in the composite's packing density with the combination of different mineral admixtures, attributed to the greater packing effect achieved. Overall, these findings highlight the potential of incorporating silica-rich pozzolans to improve the packing density and performance of cementitious materials, offering opportunities for enhancing the properties of concrete mixtures. [24]

The formation of calcium carbonate crystals required a high concentration of calcium and carbonate resources. In environments rich in calcium, such as caves, soil, and limestone, the utilization and production of carbonates through metabolic activities, such as urease driven hydrolysis, may serve as the basis for $CaCO_3$ precipitation.

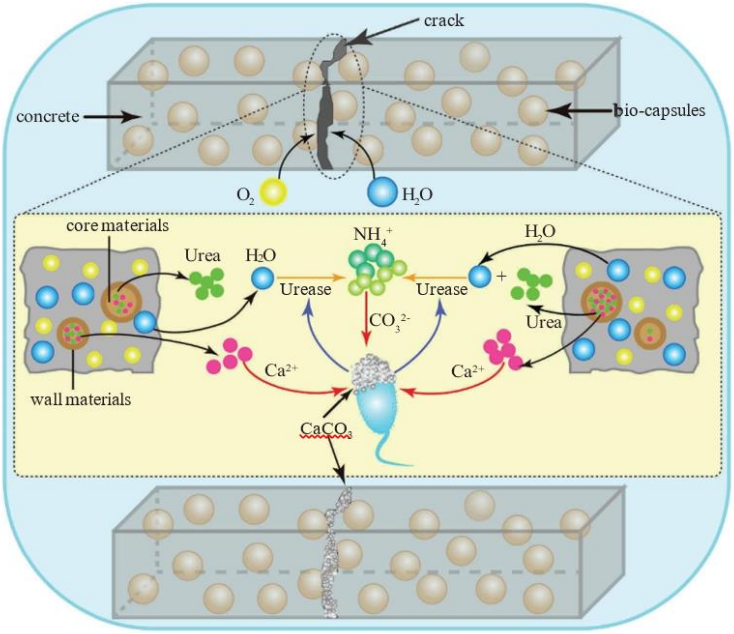

Figure 2: Mechanism of bio capsule self-healing concrete cracks. Reproduced from ref. [35] with permission of Elsevier Ltd., © 2020.

All three strains demonstrated urease activity, which facilitated both biologically induced and organically influenced calcium carbonate precipitation under optimal alkaline environmental conditions.

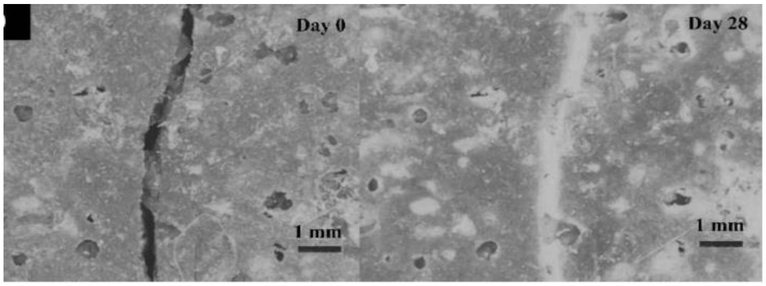

Figure 3: Self-healing of concrete after 28 days

The step-by-step flow methodology adopted for the study can be outlined as follows:

1. Procurement of Raw Materials: Identify and procure the raw materials required for concrete production, including cement, Metakaolin, Quartz powder, aggregates, water, and bacterial culture.

2. Characterization of Raw Materials: Determine the physical and chemical properties of each raw material, including particle size distribution, specific gravity, chemical composition, and fineness.

3. Optimization of Mix Proportions: Conduct experiments to optimize the mix proportions of binary, ternary, and quaternary concrete mixes to achieve the highest packing density. Vary the proportions of cement, Metakaolin, Quartz powder, and aggregates while maintaining a constant water-to-cement ratio.

4. Bacteria Isolation and Screening: Collect samples for bacterial isolation from suitable environments, such as soil, cementitious materials, or wastewater treatment plants. Isolate and screen bacteria capable of precipitating calcium carbonate by conducting culture-based assays and molecular techniques.

5. Concrete Sample Preparation: Prepare concrete samples according to the optimized mix proportions, incorporating the selected bacterial culture at a predetermined concentration (e.g., 105 cells/ml). Cast concrete specimens in standard molds, such as cubes or cylinders, for subsequent testing.

6. Mechanical Testing: Perform mechanical testing on the prepared concrete samples to evaluate their compressive strength, flexural strength, and tensile strength using standard testing procedures. Assess the influence of bacterial incorporation and supplementary cementitious materials on the mechanical properties of the concrete.

7. Porosity and Water Absorption Analysis: Determine the porosity and water absorption characteristics of the concrete samples using suitable methods, such as mercury intrusion porosimeter or water absorption tests.

8. Microscopic and SEM Analysis: Conduct continuous microscopic and scanning electron microscopy (SEM) analysis to observe the crack healing capacity of the concrete specimens. Analyze the formation of calcium carbonate precipitates and their distribution within the microstructure of the concrete.

9. Data Analysis and Interpretation: Analyze the experimental data obtained from mechanical testing, porosity analysis, and microscopic observations. Interpret the results to draw conclusions regarding the effectiveness of bacterial-induced self-healing and the influence of supplementary materials on concrete properties.

10. Report Preparation and Presentation: Compile the findings of the study into a comprehensive report, including methodology, results, discussions, and conclusions. Present the research outcomes through publications, presentations, or technical reports to disseminate knowledge within the scientific community.

Isolation and confirmation of bacteria:

Materials and Chemicals required

This section outlines the necessary chemicals and materials for the isolation of bacillus, primarily focusing on Calcite-precipitating bacteria. Additionally, it includes materials required for optimizing mortar samples and casting them. Table 1 provides a summary of the culture media for the targeted microbes.

Table 1: Chemical required for isolation of bacteria

S. No.	Material & Chemical Name	Purpose
1	Sodium Bicarbonate ($NaHCO_3$)	Nutrient Media
2	Urea (CH_4N_2O)	Nutrient Media
3	Nutrient Broth	Nutrient Media
4	Ammonia Chloride (NH_4Cl)	Nutrient Media
5	Calcium Chloride two Hydrate ($CaCl_2.2H_2O$)	Nutrient Media
6	Agar ($C_{14}H_{24}0_9$)	Solidification of Nutrient Media
7	Soil and water sample from different locations	Isolation of bacteria

Table 2 comprises various samples taken for the isolation of alkaliphilic bacteria. These bacteria are primarily found and can be isolated from alkaline soils, sewage, and water. A total of twelve samples, including six alkaline soil samples rich in iron oxide and lime, and six sewage samples, were collected from different locations in districts Bilaspur and Solan (H.P).

Table 2: Samples collected till date for the isolation of bacteria.

S. No.	Sample Type	Location
1.	Soil Sample 1	UltraTech cement limited, Salarpur khadar (U.P.)
2.	Soil Sample 2	J K Cement Factory limited, Gaziabad (U.P.)
3.	Soil Sample 3	Rama Universisty campus, mandhana (U.P.)

4.	Soil Sample 4	Iscon tample, kanpur (U.P.)
5.	Soil Sample 6	Kargil Park, kanpur (U.P.)
6.	Soil Sample 6	Ganga barrage, kanpur (U.P.)
7.	Bore well Water 1	UltraTech cement limited, Salarpur khadar (U.P.)
8.	Bore well Water 2	J K Cement Factory limited, Gaziabad (U.P.)
9.	River Water Sample	Ganga ji, Kanpur (U.P.)
10.	Lake Water Sample	Moti jheel, Kanpur (U.P.)
11.	Bore well Water 3	Rama Universisty campus, mandhana (U.P.)
12.	Bore well Water 4	Blue warld water park, Kanpur (U.P.)

The list of materials that is required for testing of cement, mortar and concrete is given in Table 3

Table 3: Material used for cement, mortar and concrete testing.

S. No.	Material
1.	Cement (PPC-Fly Ash Based) for plastering
2.	Cement OPC (43/53 Grade)
3.	Benzene or Kerosene
4.	Bricks For Wall making
5.	Plastering with River Sand
6.	Metakoilin
7.	Fine Aggregates (FA)
8.	Coarse aggregates (CA)

This table lists the chemicals required for conducting urease activity tests on bacteria.

Table 4: Chemicals for Urease Activity Tests

S. No.	Materials
1.	Deionized Water
2.	Urease (CH_4N_2O)
3.	Phenol Red ($C_{19}H_{14}O_5S$)

Equipment required for isolation and growth of bacteria:

This table lists the necessary equipment for the isolation and growth of bacteria, along with their respective purposes.

Table 5: Equipment's for Bacteria Isolation and Growth

S. No.	Equipment used	Purpose
1.	Laminar Airflow	Provides Sterilised Environment
2.	Autoclave	To Sterilised Media & Glass Plates
3.	Digital Weighing Balance (1-220 gm)	Weighing Materials
4.	Inoculating Loop	For Inoculating Bacteria
5.	BOD Incubator (@ 38°C)	For Growth of Bacteria
6.	Freezer (@ 4°C)	Prevent culture against over growth and contamination
7.	pH Meter	To measure pH value
8.	Conductivity Meter	To measure bacterial activities
9.	Microwave Oven	To use for melting Agar

Table 6: Glassware required for the preparation of bacteria culture.

S. No.	Equipment used	Purpose
1.	Petri Dish (90×15 mm)	To culturing Bacteria
2.	Conical Flask	Mixing Media
3.	Measuring Cylinder	Measuring Media & Distilled Water
4.	Centrifuge Tubes (2 ml, 20 ml and 50 ml)	For Centrifuge Cells.
5.	Test Tube	For making Slants & Growing Bacteria

Table 7: Equipment and apparatus that are required for testing of Cement, concrete and Mortar samples

S. No.	Equipment	Purposes
1	Vicat Apparatus	Consistency, Initial Setting Time and Final setting Time
2	90-micron sieve	Fineness of cement
3	Le-chatelier Flask	Cement specific gravity
4	Le-chatelier Mould	Soundness
5	Digital weight machine	Weighting sample
6	Pycnometer	Specific Gravity of sand

Biological Processes of Microbial Induced Calcite Precipitation (MICP)

Various types of bacteria and abiotic factors such as salinity, pH, temperature, and nutrient composition influence the precipitation of calcium carbonate across diverse environments (Knorre and Krumbein, 2000; Rivadeneyra et al., 2004). Key factors governing MICP include calcium concentration, dissolved inorganic carbon concentration, pH, and availability of nucleation sites (Hammes and Verstraete, 2002).

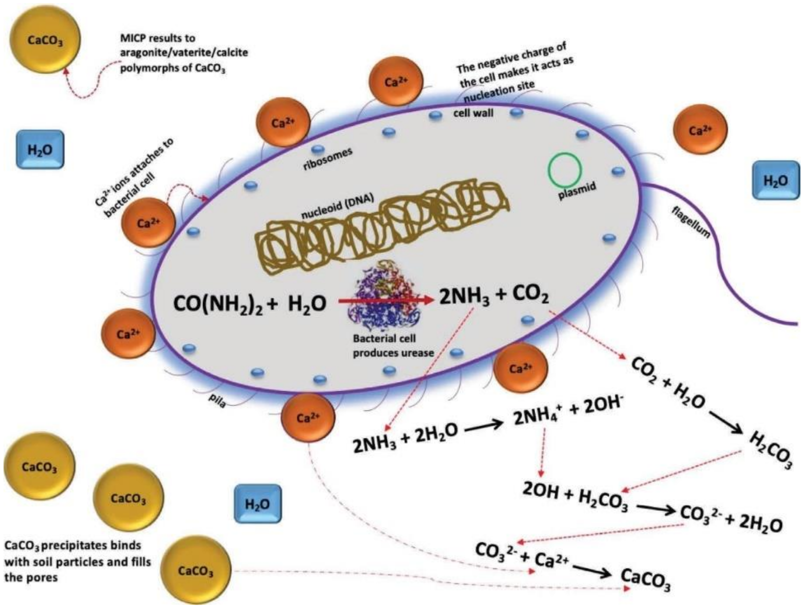

FIGURE 3: Overview of bio-mediated calcite precipitation using ureolysis. Reproduced from ref. [36] with permission of the Korean Society of Environmental Engineers. © 2021.

Urease enzymes produced by bacteria decompose urea into ammonium and carbonate ions, initiating the precipitation process.

$$CO(NH_2)_2 \rightarrow 2NH_4^+ + CO_3^{2-} \tag{1}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \tag{2}$$

Ammonium ions released increase local pH, facilitating calcium carbonate precipitation. Under anaerobic conditions, denitrifying bacteria oxidize organic carbon using nitrate, leading to increased CO_3^{2-} and HCO_3^- ions, which react with Ca^{2+} to form calcium carbonate (Lee and Park, 2018).

$$5HCOO^- + 2NO_3^- \rightarrow 3HCO_3^- + 2CO_3^{2-} + H_2O + N_2 \tag{3}$$

$$HCO_3 + H^+ \rightarrow CO_3^{2-} \tag{4}$$

Additionally, bacteria serve as nucleation sites for calcium carbonate crystallization by attracting Ca^{2+} ions and promoting crystal deposition on their cell walls, thereby facilitating further crystal formation.

CONCLUSION

Results from this investigation reveals that, in concrete microbial cells can be used for purpose of crack healer of both Macro and Micro sizes. From isolation stage, 11 bacterial cultures having potential are isolated, and when the further screen proceeding, the number reduced to just 2. It is because of the concrete's high alkaline harsh environment. The survival of major group of bacterial becomes difficult in such a high pH environment. In this way, it can be said that only those isolates which can survive in high pH environment needs to be isolates, separated for use in concrete.

Test conduct on concrete reveals that the performance of concrete with microorganisms in it showed higher strength and better characteristics when compared to control concrete (without bacteria). This is happened due to the presence of calcite precipitating bacteria in concrete which filled the pores inside matrix and the cracks appeared on the surface with thin calcium carbonate crystals. Bacteria is only one that can able to precipitate Calcium carbonate when it gets nutrition i.e. rich calcium course and moisture.

However the moisture requirement and food requirement of colony of bacteria is so less that it can be fulfilled with the moisture present in air and minute food particles travelling in air. Whitish-yellow-colored crystals was observed near the crack surfaces when visual inspection of the crack was done at 7 days of concrete cast. According to the investigations further continued for 28 days, it was observed that the highest crack healed in comparison to both isolate and control concrete was found in the Standard concrete system.

REFERENCES

[1] D. Y. Yoo and N. Banthia, "Mechanical properties of ultra-high-performance fiber- reinforced concrete: A review," *Cem. Concr. Compos.*, 2016.

[2] L. G. Li and A. K. H. Kwan, "Packing density of concrete mix under dry and wet conditions," *Powder Technol.*, 2014.

[3] H. H. C. Wong and A. K. H. Kwan, "Packing density: a key concept for mix design of high performance concrete," *Mater. Sci. Technol. Eng. Conf. Hong Kong*, 2005.

[4] A. K. H. Kwan and W. W. S. Fung, "Packing density measurement and modelling of fine aggregate and mortar," *Cem. Concr. Compos.*, 2009.

[5] M. S. Ismail and A. M. Waliuddin, "Effect of rice husk ash on high strength concrete," *Constr. Build. Mater.*, 1996.

[6] J. Stark and K. Bollmann, "Delayed Ettringite Formation in Concrete," *ZKG Int.*, 2000.

[7] N. J. Carino and J. R. Clifton, "Prediction of Cracking in Reinforced Concrete Structures," *Natl. Institue Stand. Technol.*, 1995.

[8] S. Krishnapriya, D. L. Venkatesh Babu, and G. Prince Arulraj, "Enhancement of strength of concrete by bacterial calcite precipitation," *Int. J. Appl. Eng. Res.*, 2014.

[9] J. Y. Wang, D. Snoeck, S. Van Vlierberghe, W. Verstraete, and N. De Belie, "Application of hydrogel encapsulated carbonate precipitating bacteria for approaching a realistic self- healing in concrete," *Constr. Build. Mater.*, vol. 68, pp. 110–119, 2014.

[10] R. Mors and H. Jonkers, "Bacteria-based self-healing concrete-introduction," *... Durab. Reinf. Concr.*, 2012.

[11] M. Wu, B. Johannesson, and M. Geiker, "A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material," *Construction and Building Materials*. 2012.

[12] K. Vijay, M. Murmu, and S. V Deo, "Bacteria based self healing concrete – A review," *Constr. Build. Mater.*, vol. 152, pp. 1008–1014, 2017.

[13] A. Talaiekhozan, A. Keyvanfar, A. Shafaghat, R. Andalib, M. Z. A. Majid, and M. A. Fulazzaky, "A Review of Self-healing Concrete Research Development," *J. Environ. Treat. Tech.*, vol. 2, no. 1, pp. 1–11, 2014.

[14] F. Nosouhian, D. Mostofinejad, and H. Hasheminejad, "Influence of biodeposition treatment on concrete durability in a sulphate environment," *Biosyst. Eng.*, 2015.

[15] J. Wang, Y. C. Ersan, N. Boon, and N. De Belie, "Application of microorganisms in concrete: a promising sustainable strategy to improve concrete durability," *Applied Microbiology and Biotechnology*. 2016.

[16] K. Van Tittelboom and N. De Belie, *Self-Healing in Cementitious Materials—A Review*. 2013.

[17] V. Achal, A. Mukherjee, and M. S. Reddy, "Microbial concrete: A way to enhance durability of building structures," in *2nd International Conference on Sustainable Construction Materials and Technologies*, 2010.

[18] M. Luo, C. Qian, and R. Li, “Factors affecting crack repairing capacity of bacteria-based self-healing concrete,” *Constr. Build. Mater.*, vol. 87, pp. 1–7, 2015.

[19] S. K. Ramachandran, V. Ramakrishnan, and S. S. Bang, “Remediation of concrete using micro-organisms,” *ACI Mater. J.*, 2001.

[20] N. Chahal, R. Siddique, and A. Rajor, “Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of fly ash concrete,” *Constr. Build. Mater.*, vol. 28, no. 1, pp. 351–356, 2012.

[21] A. P. Report and B. O. F. Technology, “BIO CONCRETE: A BACTERIA BASED SELF-HEALING CONCRETE Mr . Abhilash Shukla Vinayak Sharma (151648) Ayush Thakur (151660) to STUDENTS’ DECLARATION,” vol. 2019, no. 151660, 2019.

[22] P. C. Aïtcin, “Ultra high strength concrete,” in Science and Technology *of Concrete Admixtures*, 2016.

[23] Y. Peng, S. Hu, and Q. Ding, “Preparation of reactive powder concrete using fly ash and steel slag powder,” *J. Wuhan Univ. Technol. Mater. Sci. Ed.*, 2010.

[24] M. G. Lee, Y. C. Wang, and C. Te Chiu, “A preliminary study of reactive powder concrete as a new repair material,” *Constr. Build. Mater.*, 2007.

[25] N. H. Yi, J. H. J. Kim, T. S. Han, Y. G. Cho, and J. H. Lee, “Blast-resistant characteristics of ultra-high strength concrete and reactive powder concrete,” *Constr. Build. Mater.*, 2012.

[26] Y. W. Chan and S. H. Chu, “Effect of silica fume on steel fiber bond characteristics in reactive powder concrete,” *Cem. Concr. Res.*, 2004.

[27] C. T. Liu and J. S. Huang, “Fire performance of highly flowable reactive powder concrete,” *Constr. Build. Mater.*, 2009.

[28] H. M. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu, and E. Schlangen, “Application of bacteria as self-healing agent for the development of sustainable concrete,” *Ecol. Eng.*, 2010.

[29] J. Y. Wang, H. Soens, W. Verstraete, and N. De Belie, “Self-healing concrete by use of microencapsulated bacterial spores,” *Cem. Concr. Res.*, 2014.

[30] M. Luo, C. Qian, R. Li, and H. Rong, “Efficiency of concrete crack-healing based on biological carbonate precipitation,” *J. Wuhan Univ. Technol. Mater. Sci. Ed.*, 2015.

[31] S. Krishnapriya, D. L. Venkatesh Babu, and P. A. G., "Isolation and identification of bacteria to improve the strength of concrete," Microbiol. Res., 2015.

[32] S. Bhaskar, K. M. Anwar Hossain, M. Lachemi, G. Wolfaardt, and M. Otini Kroukamp, "Effect of self-healing on strength and durability of zeolite-immobilized bacterial cementitious mortar composites," Cement and Concrete Composites, vol. 82, pp. 23–33, 2017.

[33] E. Tziviloglou, V. Wiktor, H. M. Jonkers, and E. Schlangen, "Bacteria-based self-healing concrete to increase liquid tightness of cracks," *Constr. Build. Mater.*, 2016.

[34] H. J. Kim *et al.*, "Calcium carbonate precipitation by Bacillus and sporosarcina strains isolated from concrete and analysis of the bacterial community of concrete," *J. Microbiol. Biotechnol.*, 2015.

[35] M. Wu, X. Hu, Q. Zhang, W. Cheng, D. Xue, and Y. Zhao, "Application of bacterial spores coated by a green inorganic cementitious material for the self-healing of concrete cracks," Cement and Concrete Composites, vol. 113, Article ID 103718, 2020.

[36] A. I. Omoregie, E. A. Palombo, and P. M. Nissom, "Bio- precipitation of calcium carbonate mediated by ureolysis: a review," Environmental Engineering,vol. 26, no. 6, 2020