Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Self-Healing Concrete Using Alkaliphilic Bacteria from Sambhar Salt Lake of Rajasthan

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Abstract

The current study leads an investigation into the use of alkaliphilic bacteria isolated from Sambhar Salt Lake, Rajasthan, in the development process of self-healing concrete through Microbially Induced Calcium Carbonate Precipitation (MICP). In this study, isolated bacterial stains i.e *Halomonas salifodinae* UJSL1, *Oceanobacillus kimchi* UJSL2, *Halobacillus dabanensis* UJSL3, *Halomonas mongoliensis* UJSL4, and *Halomonas campaniensis* UJSL5mixed into concrete; using a control sample of M20 concrete, the results showed significant improvements in mechanical properties, including compressive and tensile strengths, along with a reduction in water absorption. It is the bacterial consortium that exhibited the best performance, providing the most substantial enhancements due to the MICP process. This leads to the remedy of effectively sealed cracks and pores within the concrete. This approach can have several benefits including sustainable and cost-effective solutions for increasing the durability and longevity of concrete structures, particularly under challenging environmental conditions in India. The study highlights the potential of using microbial resources for innovations in construction materials that can highly contribute towards reduction of maintenance costs, and environmental impact, while increasing structural resilience. The successful application of MICP in self-healing concrete with the bacterial consortium can lead to a significant advancement in building a sustainable construction scenario. It offers a pathway for future research and development in eco-friendly building materials.

Key words: Bacteria, sambhar lake, self healing concrete, MICP

Introduction

The area of Sambhar Salt Lake covers approximately 230 square kilometers and is situated in the Thar Desert of Rajasthan, India. It is the largest inland Salt Lake in the country and contributes to the overall output of salt[1]. It emerges as one of the largest contributors due to the hypersaline environment of the lake that can exceed the salinity levels of seawater. Sambar lake an be considered as an ideal laboratory for studying extremophiles, particularly halophilic and alkaliphilic microorganisms, where a high level of salt concentration limited freshwater inflow and extreme temperatures is found[2]. There are various basins located at shallow levels created by man-made embankments that help in controlled evaporation of water leading to a proper harvesting of salt[3]. Such conditions of the lake make it an interesting area of research especially in the areas of microbial ecology.The creation of such extreme environmental conditions in the vicinity of Sambhar Salt Lake in India have given rise to the evolution of specialized microorganisms termed halophiles and alkaliphiles[3]. While halophiles are considered microorganisms that thrive in high-salt environments and mostly look for a significant concentration of salt to grow; alkaliphiles, on the other hand, can be segregated based on their preferences for alkaline conditions, typically thriving at pH levels above 9[4]. Due to the unique characteristics of the region, a combination of hypersalinity and alkalinity is observed due to which the microbial community shows both halophilic and alkaliphilic characteristics.

Upon investigation, it is seen that these microorganisms have adequately adapted to be able to survive in harsh conditions based on the utilization of various mechanisms. These can be listed in the form of the production of compatible solutes, the regulation of ion exchange, and the formation of biofilms[5]. Looking into the most interesting aspects, it is the ability to precipitate minerals, particularly calcium carbonate, that generates maximum interest in the context of bio- cementation and self-healing concrete[6]. The microbial community of Sambhar Lake, is known to include species from the genera of *Halomonas, Oceanobacillus, Halobacillus, and Halomonad*[5]. It is found that they have remarkable mineral precipitation capabilities which makes them ideal candidates for using bio-based concrete technologies.

Microbially Induced Carbonate Precipitation (MICP) can be referred to as a bio-geochemical process wheremicroorganisms are involved in inducing the precipitation of calcium carbonate through their metabolic activities. In research, MICP has gained significant attention in recent years for the potential applications it allows in the construction industry, such as causingthe development of self-healing concrete[7]. The process includes ureolytic bacteria that hydrolyze urea into ammonia and carbon dioxide. It leads to an increase in pH and the subsequent precipitation of calcium carbonate. The reaction can be represented as:

$$CO(NH_2)_2+2H_2O \longrightarrow CO_2+2NH_3+2H_2O$$

The carbon dioxide then reacts with calcium ions in the solution to form calcium carbonate:

$$Ca^{2+} + CO^{2-}_3 \longrightarrow CaCO3$$

Many researchers have included MICP in their studies to know about its effectiveness in improving the properties in concrete such as the compressive strength, durability and tensile strength that it exhibits[7–9]. One such instance is where researchers involve in examining the effect of incorporating ureolytic bacteria, such as *Sporosarcina pasteurii* and *Bacillus sphaericus* into concrete to amplify the mechanical properties by increased water holding capacity and reduced water permeability. [10]. It is seen that the precipitated calcium carbonate acts as a natural binder within the concrete matrix and helps to fill in the micro-cracks and voids. This results in improving the overall integrity of the material. Such attempts also state that MICP engages in the improvement of the structural properties of concrete and also contributes to its self-healing capabilities[11] for effectively sealing the cracks and restoring the concrete's integrity. Research on alkaliphilic bacteria from Sambhar Lake for self-healing concrete offers a sustainable, cost-effective solution to structural deterioration, leveraging bacteria that thrive in harsh, alkaline conditions to autonomously repair cracks through calcium carbonate precipitation. This reduces the need for expensive repairs, lowers carbon emissions, and enhances infrastructure durability, aligning with UN’s sustainability goals. The study aims to advance scientific knowledge and innovation by using indigenous microbial strains, paving the way for new construction materials tailored to India's needs. Its findings have broader implications, contributing to global sustainable construction practices and strengthening India's position as a leader in eco-friendly technologies.

3. Material & Methodology

The current study encompasses a robust methodology with a framework for assessing the ability of bacterial strains isolated from Sambhar Lake to enhance the self-healing properties of concrete considering M20 concrete as the baseline for comparison. M20 concrete a standard grade of concrete commonly used in construction was prepared and subjected to mechanical testing to evaluate the enhancement of self-healing properties. M20 concrete refers to a mix that has a characteristic compressive strength of 20 MPa (megapascals) after 28 days of curing. Hence, the current study's experimentation cycle has been kept in Figure 1.

3.1 Bacterial strain and cultivation conditions

Collection of bacterial samples was done from various locations around Sambhar Lake which is characterized by its high salinity and alkalinity. The samples were transported to the laboratory under sterile conditions to prevent contamination. The water was then used to isolate bacteria by cultivating on liquid and solid medium supplemented with 10% NaCl. This was meant to simulate the hypersaline environment of the lake and to support the growth of halophilic and alkaliphilic bacteria. The literature demonstrates good potential for halophilic and alkaliphilic bacteria with higher resilience in extreme conditions to induce the process of MICP which is essential for applications in self-healing concrete

3.2 Selection& Characterization of Bacterial Strains

Further B4 medium was used to select the strains based on mineral precipitation capacity. This is specifically designed to induce biomineralization. The B4 medium has been used in many prior studies for this purpose as it contains calcium ions and other nutrients which are pivotal in the formation of calcium carbonate, a key component in self-healing concrete. The strains were monitored for their ability to thrive on the medium. Only strains demonstrating significant and consistent growth were selected for further analysis. The selected alkaliphilic strains that are capable of thriving in the high pH environment of concrete were particularly noted and were subjected to 16s RNA sequencing for characterization.

3.4 Mechanical Testing of Self-Healing Concrete (Cube Test)

Three categories of concrete cubes a) incorporating the selected bacterial strains, b) incorporating bacterial consortium of the selected bacterial strains c) M20 concrete cubes as a control sample. The cube test involved the following procedures:

a) **Compressive Strength Test**: The compressive strength of all three categories of cubes was measured on days 7 and 28 using a universal testing machine. Compressive strength is a critical indicator of concrete's load-bearing capacity. The bacterial strains are expected to promote additional mineralization, leading to an increase in compressive strength over time compared to the M20 control.

b) **Split Tensile Strength Test**: This test was conducted on days 7 and 28 to evaluate the tensile properties of the bacterial concrete. Tensile strength is vital for resisting cracking and improving overall durability. To determine the impact of bacterial activity on tensile strength, a comparison was made with the M20 control samples and the bacterial concrete. It was supposed the bacteria would fill micro-cracks with precipitated minerals, thereby enhancing strength.

c) **Water Absorption Test**: Bacterial activity is expected to reduce porosity by filling voids and micro-cracks, thereby improving resistance to water ingress and environmental degradation. Thus, the water absorption test was performed on days 7 and 28 to assess the porosity of the bacterial concrete comparing it with M20 control samples. A lowering in water absorption indicates reduced porosity, which is beneficial for durability.

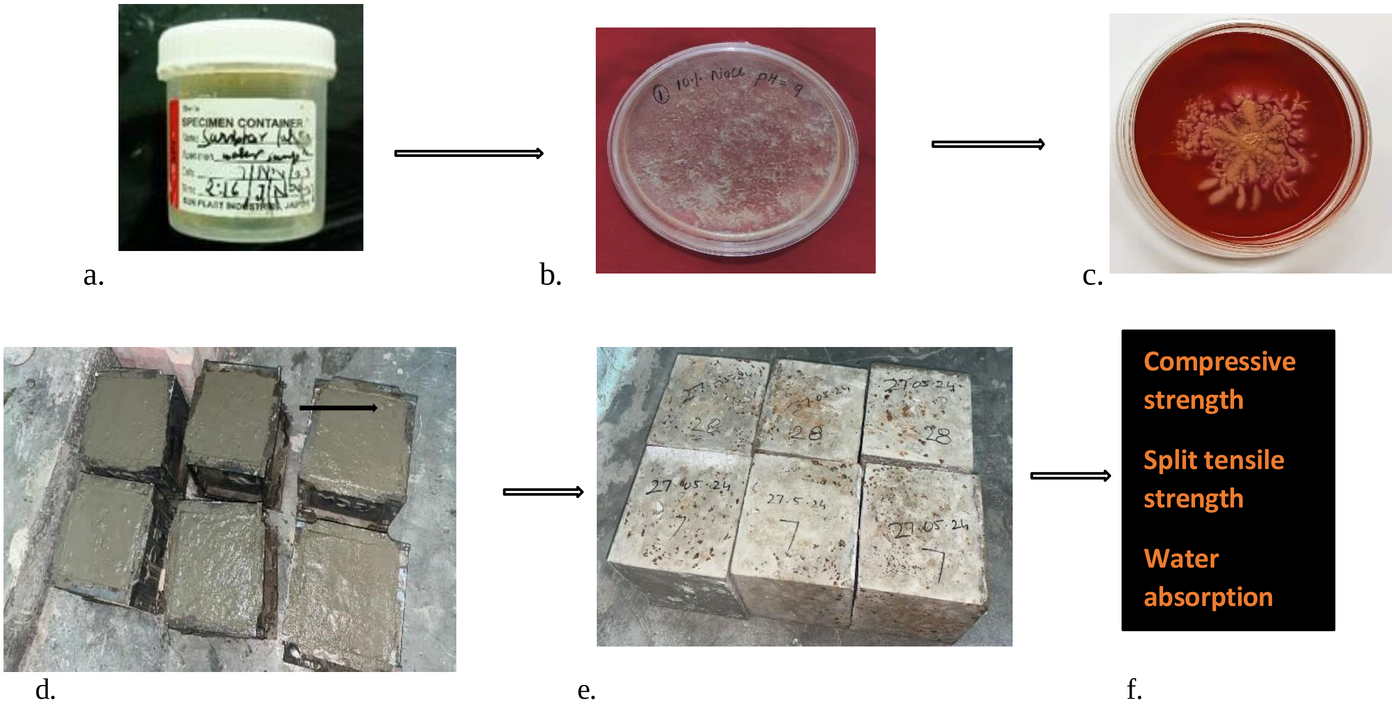

Figure1 a) Soil samples had been collected from sambhar lake b) Isolates grown on 10% NaCl nutrient agar c) Bacterial isolates optimized on B4 medium d) Selected strains used to prepare concrete mixture e) Concrete cubes were incubated for 7 and 28 days f) Various mechanical properties checked.

4. Result & Discussion

4.1 Selection of Strains

In this section when considering the ability to sustain in high pH environments in the initial isolation and screening process, five alkaliphilic bacterial strains were successfully selected for evaluating their potential for mineral precipitation (Fig 1). The 16S rRNA gene sequencing identifies and classifies these at the species level as the following strains viz. *Halomonas salifodinae UJSL1*, *Oceanobacillus kimchii UJSL2, Halobacillus dabanensis UJSL3*, *Halomonas mongoliensis UJSL4*, *Halomonas campaniensis UJSL5*. These bacterial strains mentioned have been submitted to the National Center for Biotechnology Information (NCBI) database for public access and reference. Their critical identifiers will contribute to further research in the field of microbial-induced self-healing concrete and its related studies.

4.2 Compressive Strength Test

The Compressive Strength Test results (table 1) provides a holistic understanding of the effectiveness of different bacterial strains and their role in enhancing the structural integrity of concrete. The M20 Conventional Concrete (CUBE-7) served as the control sample, displayed a compressive strength of 20.86 N/mm² after 7 days and 25.6 N/mm² after 28 days, with a 4.74%

increase in strength over time. This is taken as the base for making comparisons of the performances of concrete incorporating bacterial strains.

Table 1: Cube Test- Compressive Strength Test

Cube	Incorporated bacterial Strain	Comprehensive Strength (after 7 days) (N/mm^2)	Comprehensive Strength (after 28 days) (N/mm^2)	% Increase in Comprehensive Strength
CUBE-1	*Halomonassalifodinae UJSL1*	26.2	31.47	5.27
CUBE-2	*Oceanobacilluskimchii UJSL2*	24.32	33.43	9.11
CUBE-3	*Halobacillusdabanensis UJSL3*	24.25	32.24	7.99
CUBE-4	*Halomonasmongoliensis UJSL4*	23.76	32.13	8.37
CUBE-5	*Halomonascampaniensis UJSL5*	24.12	33.26	9.14
CUBE-6	Bacterial Consortium	27.28	35.2	7.92
CUBE-7	M 20 (Conventional Concrete)	20.86	25.6	4.74

The Concrete cubes treated along with the bacterial strains showed notable improvements in compressive strength compared to the control. Among the individual bacterial strains, *Oceanobacillus kimchii* UJSL2 (CUBE-2) demonstrated the highest increase in compressive strength, achieving 33.43 N/mm² after 28 days, which represents a 9.11% increase. This indicates that *Oceanobacillus kimchii* has a strong capacity for bio-mineralization, effectively contributing to the self-healing process and enhancing the mechanical properties of the concrete.

*Halomonascampaniensis*UJSL5 (CUBE-5) has also been noticed to exhibit a significant increase showcasing a compressive strength of 33.26 N/mm² and a 9.14% improvement, slightly outperforming *Oceanobacillus kimchii*. This suggests that *Halomonas campaniensis* is highly effective in reinforcing concrete structures, possibly due to its robust mineral precipitation abilities.

The bacterial consortium (CUBE-6) illustrated superior performance, with the highest compressive strength of 35.2 N/mm² after 28 days, resulting in a 7.92% increase in strength. Although the percentage increase is slightly lower than that of some individual strains, the absolute strength achieved by the consortium is the highest. This implies a synergistic effect when multiple bacterial strains are combined, leading to more effective self-healing and overall enhancement of the concrete's compressive strength.

Halomonas salifodinae UJSL1 (CUBE-1), *Halobacillus dabanensis* UJSL3 (CUBE-3), and *Halomonas mongoliensis* UJSL4 (CUBE-4) also contributed to strength gains, with percentage increases of 5.27%, 7.99%, and 8.37%, respectively. These results confirm that all selected strains have positive effects on concrete strength, though some strains are more effective than others.

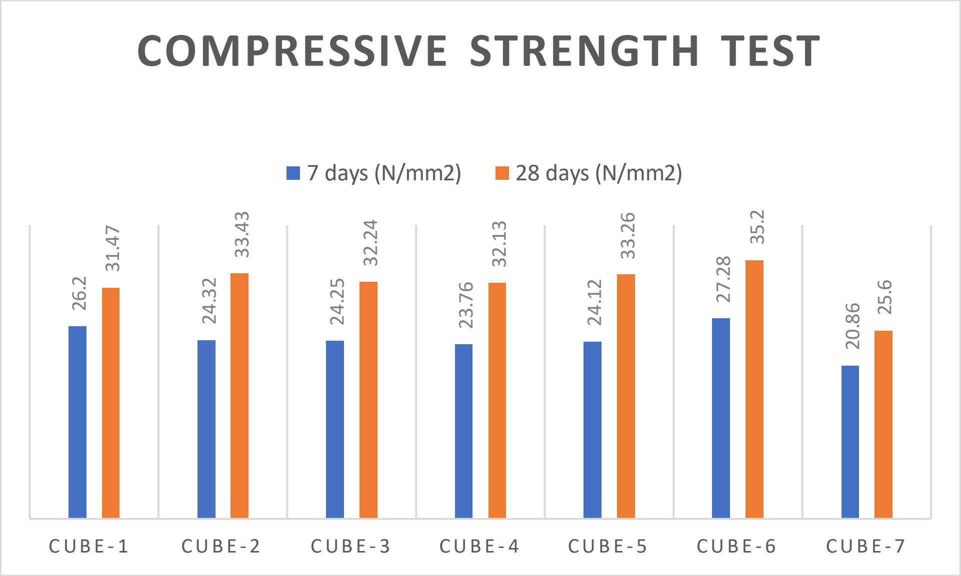

Fig 1:Comparative status of Compressive Strength Test in the bacterial-treated concrete

The summary of the test results can be established (Fig 1) by realizing the high potential of specific alkaliphilic bacteria in enhancing the compressive strength of concrete with promising results from the bacterial consortium. The integration of these bacteria into the concrete mixtures can result in significant advancements in the development of more durable, self-healing construction materials.

4.3 Split Tensile Strength Test:

The results of the split tensile strength (Table 2)here showed valuable insights related to the impact of incorporating different bacterial strains on the tensile properties of concrete. The M20 Conventional Concrete (CUBE-7) served as the control, with a split tensile strength of 1.86 N/mm² after 7 days and 3.43 N/mm² after 28 days, reflecting a 1.57% increase over time. This control data serves as the baseline to evaluate the performance enhancements provided by the bacterial strains.

Table 2: Cube Test- split tensile strength test

Cube	Incorporated bacterial Strain	Split Tensile Strength (after 7 days) (N/mm^2)	Split Tensile Strength (after 28 days) (N/mm^2)	% Increase in Split Tensile Strength
CUBE-1	*Halomonas salifodinae UJSL1*	2.39	3.62	1.23
CUBE-2	*Oceanobacillus kimchii UJSL2*	2.36	3.57	1.21
CUBE-3	*Halobacillus dabanensis UJSL3*	2.5	3.59	1.09
CUBE-4	*Halomonas mongoliensis UJSL4*	2.41	3.49	1.08
CUBE-5	*Halomonas campaniensis UJSL5*	2.53	3.64	1.11
CUBE-6	Bacterial Consortium	2.68	3.71	1.03
CUBE-7	M 20 (Conventional Concrete)	1.86	3.43	1.57

The bacterial consortium (CUBE-6) have shown the highest split tensile strength after 28 days, achieving 3.71 N/mm². However, this was associated with a relatively modest percentage increase of 1.03%. The results suggest that while the consortium enhances tensile strength, the improvement over time is less pronounced compared to the control. This could indicate that while the consortium effectively contributes to initial strength development, its impact on tensile strength stabilization over time is not as significant.

When considering the individual strains of *Halomonas salifodinae* UJSL1 (CUBE-1) and *Oceanobacilluskimchii*UJSL2 (CUBE-2), there is an exhibition of strong performances with tensile strengths of 3.62 N/mm² and 3.57 N/mm² after 28 days, respectively is seen. These strains showed a 1.23% and 1.21% increase in tensile strength, slightly above the control. It suggests that their consistent contribution to enhancing concrete tensile propertiesis considerable.

On the other hand, taking into account *Halobacillus dabanensis* UJSL3 (CUBE-3) and *Halomona smongoliensis* UJSL4 (CUBE-4) presented lower percentage increases of 1.09% and 1.08%, respectively. Despite showing a somewhat lower percentage improvement, these strains still achieved tensile strengths that are higher than the control, indicating their efficacy in contributing to the structural integrity of concrete.

Halomonas campaniensis UJSL5 (CUBE-5) showed a notable split tensile strength of 3.64 N/mm² after 28 days, with a percentage increase of 1.11%. This shows that *Halomonas campaniensis* is effective in improving the tensile strength of concrete as well as in maintaining a consistent enhancement over time.

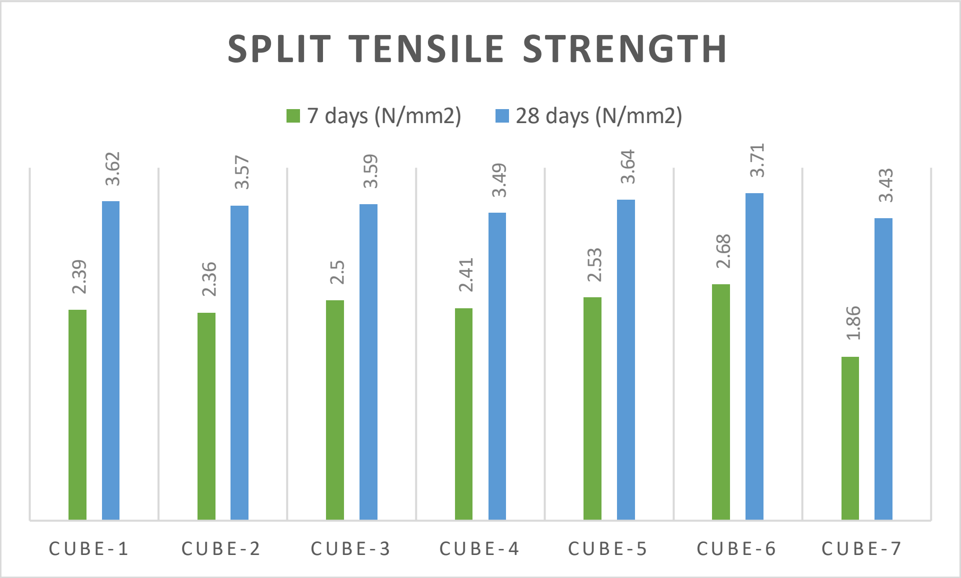

Fig 2: Comparative status of Split Tensile Strength in the bacterial-treated concrete

The results generated from this test (Fig 2) in the study reveal the positive influence of the selected bacterial strains on the split tensile strength of concrete. The degree of impact can be argued to vary from time to time. The control sample considered still generated a relatively high percentage increase, suggesting conventional concrete continual strength gain over time. However, the bacterial strains, particularly the consortium and *Halomonas salifodinae*, significantly contribute to tensile strength. This makes them valuable additions for enhancing the durability and resilience of concrete structures.

4.4 Water Absorption Test:

In terms of the Water Absorption Test, there are crucial insights found around the ability of bacterial strains to enhance the durability of concrete by reducing its porosity and water absorption capacity. The M20 Conventional Concrete (CUBE-7) served as the control sample, with water absorption values of 1.89% after 7 days and 1.83% after 28 days, resulting in a 3.17%

decrease in water absorption over time (Table 3). This baseline helps assess the effectiveness of the bacterial strains in reducing water permeability.

Table 3: Cube Test- Water Absorption Test

Cube	Incorporated Strain	Water Absorption (after 7 days) (%)	Water Absorption (after 28 days) (%)	% decrease in water absorption
CUBE-1	*Halomonas salifodinae UJSL1*	1.75	1.67	4.57
CUBE-2	*Oceanobacillus kimchii UJSL2*	1.69	1.61	4.73
CUBE-3	*Halobacillus dabanensis UJSL3*	1.72	1.64	4.65
CUBE-4	*Halomonas mongoliensis UJSL4*	1.68	1.65	1.78
CUBE-5	*Halomonas campaniensis UJSL5*	1.61	1.58	1.86
CUBE-6	Bacterial Consortium	1.54	1.43	7.14
CUBE-7	M 20 (Conventional Concrete)	1.89	1.83	3.17

Among the bacterial-treated concrete samples, the Bacterial Consortium (CUBE-6) showed the most significant reduction in water absorption, with values decreasing from 1.54% after 7 days to 1.43% after 28 days, representing a 7.14% decrease. This result here leads to the inclination that the combination of multiple bacterial strains is highly effective in minimizing the porosity of the concrete. It thereby causes an enhancement in its resistance to water penetration. The reduced water absorption also suggests improved self-healing capabilities, as the bio-mineralization process likely filled micro-cracks and voids more effectively.

Oceanobacillus kimchii UJSL2 (CUBE-2) also demonstrated strong performance, with a water absorption decrease of 4.73%. This indicates that *Oceanobacillus kimchii* is particularly efficient in reducing water permeability, likely due to its robust mineral precipitation activity, which helps seal micro-cracks and reduce porosity. *Halomonas salifodinae* UJSL1 (CUBE-1) and *Halobacillus dabanensis* UJSL3 (CUBE-3) showed similar reductions in water absorption, with decreases of 4.57% and 4.65%, respectively. These strains also contribute effectively to reducing concrete porosity, thereby improving the material's overall durability and water resistance.

Halomonas mongoliensis UJSL4 (CUBE-4) and *Halomonas campaniensis* UJSL5 (CUBE-5) exhibited lower reductions in water absorption, with decreases of 1.78% and 1.86%, respectively. While these strains still enhanced the concrete's resistance to water absorption, their impact was less pronounced compared to other strains.

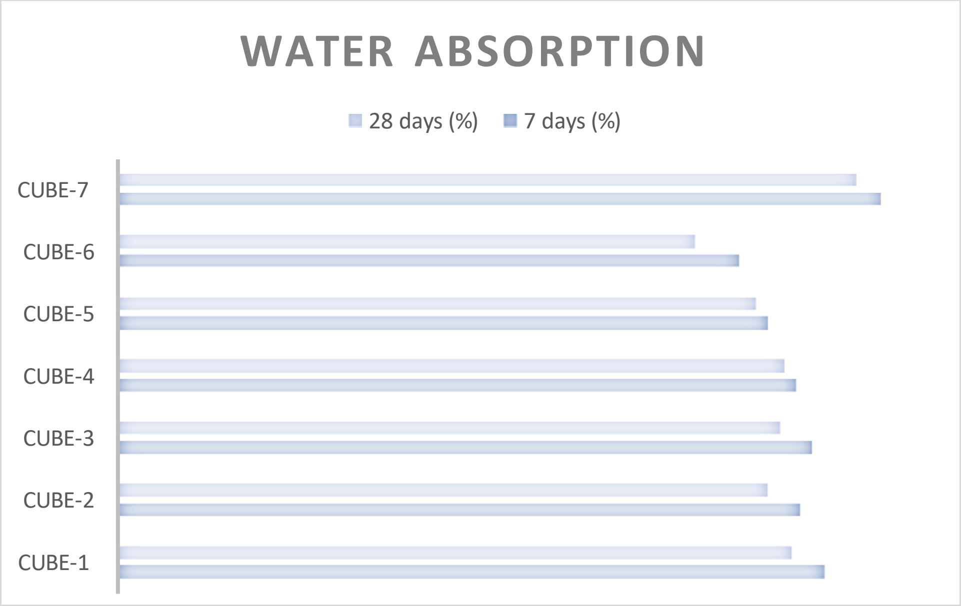

Fig 3: Comparative status of water absorption in the bacterial-treated concrete

In the Water Absorption Test results, the indication towards the bacterial strains contributing to reducing the concrete's water absorption capacity, with the bacterial consortium showing the most significant effect is evident. This reduction in water absorption suggests better levels of durability and self-healing properties, making these bacterial-treated concretes more resistant to environmental factors and potential degradation. The overall decrease in water absorption across all samples highlights the potential of using bacterial strains to produce more durable and resilient concrete structures.

5. Discussion:

The results in the above section through the incorporation of alkaliphilic bacterial strains into concrete demonstrate a significant enhancement in mechanical properties. This can be directly linked to the process of Microbially Induced Carbonate Precipitation (MICP). The results highlighting the increase in compressive strength observed in the bacterial-treated concrete samples can be attributed to the effective precipitation of calcium carbonate within the concrete matrix. Strains like *Oceano bacilluskimchii* UJSL2 and *Halomonas salifodinae* UJSL1, showed substantial improvements in compressive strength, and are likely efficient in MICP. The deposited $CaCO_3$ fills the pores and cracks, leading to a denser and more compact structure. It leads to the enhancement of the concrete's resistance to compressive forces. The bacterial consortium (CUBE-6), which exhibits the highest compressive strength. Similar results have been demonstrated by [12,13] suggesting that the combined metabolic activities of multiple strains can optimize the MICP process, resulting in superior concrete performance.

The enhanced split tensile strength observed in the bacterial-treated samples is also a result of MICP. The precipitation of calcium carbonate at the micro-level contributes to improved bonding between the aggregate particles and the cement matrix[13]. This enhanced bonding is critical for resisting tensile forces, which are typically the weakest point in concrete. The strains *Halomonas salifodinae* UJSL1 and *Oceanobacillus kimchii* UJSL2 showed higher tensile strengths, indicating their potential for promoting effective MICP, which in turn enhances the overall tensile properties of the concrete.

Literature suggests that the bacteria-treated samples lead to a reduction in water absorption fully contribute to the role played by MICP in improving the concrete properties. The calcium carbonate formulated through the process reduces the porosity in the concrete which makes it less permeable to water. This degree in the porosity levels contributes inthe improvement of material resistance and benefits through long-term durability that can lead to the avoidance of freeze-thaw damage and other forms of degradation[14]. The bacterial consortium (CUBE-6), with the highest reduction in water absorption, highlights the effectiveness of MICP in creating a more durable concrete matrix.

In terms of both compressive and split tensile strength, the tests conducted showed that the bacterial consortium (CUBE-6) outperformed individual strains. It can be interpreted as an indication that the combined action of multiple bacterial species results in a more robust concrete matrix. It can be attributed to more effective bio-mineralization, leading to the improvement of the material's ability to resist compressive forces and an increase in its tensile strength. It is to be noted that, *Oceanobacillus kimchii UJSL2* and *Halomonas salifodinae UJSL1* were consistently among the top performers in both tests. It indicates a direct correlation between improvements in compressive and tensile strengths, suggesting the bacteria's mineral precipitation leads to a denser, more cohesive internal structure that can enhance resistance to both compressive and tensile forces.

Another notable and significant finding from the tests here is that strains that improved compressive and tensile strengths also tended to decrease water absorption. Let's take the example of *Oceanobacillus kimchii UJSL2 and Halomonas salifodinae UJSL1*, which showed notable increases in both compressive and tensile strengths leading to considerable reductions in water absorption (4.73% and 4.57%, respectively). This inverse relationship indicates that the mineralization process facilitated by these bacteria effectively fills pores and micro-cracks, leading to a denser concrete matrix. It indicates the lower levels of porosity increase the strength and limit the ingress of water, which is critical for preventing long-term deterioration and enhancing durability.

The bacterial consortium (CUBE-6) exemplifies this correlation as it exhibited the highest compressive and tensile strengths while also achieving the most significant reduction in water absorption (7.14%). This suggests that the consortium's bio-mineralization process was particularly effective in producing a concrete matrix that is both strong and less permeable to water.Lower water absorption is closely linked to enhanced long-term durability. The reduction in water absorption observed in bacterial-treated samples implies that these concretes are less prone to degradation from freeze-thaw cycles, chemical attack, and other environmental factors. Over time, this would result in concrete that maintains its structural integrity longer than conventional concrete.

The test results also highlight the relationship occurring between water absorption and mechanical strength that is gained over time. As the water absorption process experiences a decrease, the ability to self-heal by the concrete through mineral precipitation experiences and increase. It leads to the filling up of the emerging microcracks while maintaining and even at times increasing the compressive as well as tensile strength over time which can be reflected within 28 days result. For example, the bacterial consortium not only had the lowest water absorption but also showed the highest percentage increase in compressive strength (7.92%) and tensile strength (1.03%).

Literature suggests that consistent improvements along the properties of tensile strength, water absorption and compressive strength highlight the underlying mechanism for these enhancements to be MICP[15]. The bio-mineralization process facilitated by these alkaliphilic bacteria leads to the formation of calcium carbonate within the concrete matrix, which in turn strengthens the material and makes it more resistant to external factors[16]. The bacterial strains employed in this study, particularly when used in a consortium, are highly effective in inducing carbonate precipitation, leading to significant improvements in the concrete's performance. Thus, it is demonstrated that the incorporation of these alkaliphilic bacteria into concrete leverages the process of MICP leads to enhanced levels of mechanical properties and durability. This bio-based approach not only improves the strength of the concrete but also contributes to its self-healing capabilities, making it a promising strategy for developing more resilient and sustainable construction materials.

6. Conclusion

The study here focuses on examining the self-healing role of alkaliphilic bacteria isolated from the Summer Salt Lake in India holds a promising role in enhancing the sustainability of construction technology. By overtaking the natural process of Microbially Induced Calcium Carbonate Precipitation (MICP), the study has shown that the incorporation of specific strains of bacteria—namely *Halomonas salifodinae* UJSL1, *Oceanobacilluskimchii* UJSL2, *Halobacillus dabanensis* UJSL3, *Halomonas mongoliensis* UJSL4, and *Halomonas campaniensis* UJSL5. They can significantly enhance the mechanical properties of concrete, including compressive strength, split tensile strength, and water absorption capacity. The discussion on the analysis indicates that bacterial strains not only contribute to increased strength but can also reduce water permeability. This eventually leads to extending the longevity and durability of the concrete. This biotechnological approach offers an eco-friendly solution to infrastructure development, particularly in regions with harsh environmental conditions, such as those found in India. Moreover, the successful application of MICP through the experiments of this study underscores the potential of using indigenous microbial resources for innovative engineering applications. In terms of economic provisions, the adoption of self-healing concrete can reduce maintenance costs, extend the lifespan of structures, and decrease the environmental footprint associated with cement production. Environmentally, this technology aligns with the global shift towards more sustainable construction practices, offering a viable method to mitigate the impact of climate change on infrastructure. The integration of MICP in concrete not only addresses current challenges in construction durability but also sets the stage for future research and application in various civil engineering domains. The study emphasizes the importance of exploring and utilizing local biological resources, making way for further innovations in sustainable building materials in India and beyond.

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