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An Experimental Examination of the Strength Characteristics of Bacterial Self-Healing Concrete for Retrofitting of Rigid Pavement

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Abstract -
Concrete, as the predominant material in global construction, plays a pivotal role in rigid pavement infrastructure. However, the recurring loading conditions experienced by pavements often result in cracks, compromising concrete durability. This research proposes an environmentally friendly solution, introducing self-healing capabilities to concrete through the incorporation of bacteria, specifically Bacillus Subtilis.

Retrofitting of rigid pavements involves upgrading existing structures to enhance performance, durability, and service life. This cost-effective and sustainable process addresses issues such as cracks, deterioration, and wear, aiming to optimize load-bearing capacity and resist environmental and traffic-induced stressors. The study explores the potential use of Calcium Lactate and Bacillus Subtilis in retrofitting, providing valuable insights for improving existing concrete structures.

The research findings reveal that controlled addition of bacteria up to 3% results in notable improvements, with a 6.6% increase in compressive strength and a 6.76% enhancement in split tensile strength compared to conventional concrete. However, an increase to 5% bacteria led to reduced strength, emphasizing the need for a balanced approach in retrofitting projects.

Additionally, the study indicates that incorporating 5% Calcium Lactate enhances split tensile strength by 3.03% but reduces compressive strength by 2.02%. Careful consideration is urged when using Calcium Lactate, especially at higher concentrations, as it can adversely affect different strength parameters.

Notably, combining 5% Calcium Lactate and 3% Bacillus Subtilis shows positive synergistic effects, yielding a 4.71% increase in compressive strength and an 18.41% improvement in split tensile strength. This combination presents a promising strategy for optimizing strength criteria in retrofitting applications.

One of the study's significant findings underscores the potential of bacterial concrete to substantially reduce the need for repairs and maintenance, making it a cost-effective choice for retrofitting rigid pavements. This has critical implications for infrastructure projects, as reduced maintenance requirements translate to long-term cost savings and increased structural durability. this study demonstrates the feasibility of employing Calcium Lactate with Bacillus Subtilis in retrofitting rigid pavements. It emphasizes the importance of optimizing component percentages for specific strength criteria and highlights the cost-effectiveness and long-term benefits of using bacterial concrete in retrofitting applications, contributing to improved performance and durability of rigid pavements.

Key Words: *Rigid Pavements, Retrofitting, Bacterial Concrete, Bacillus Subtilis, Calcium Lactate, Pavement Durability, Compressive Strength, Self-Healing Concrete.*

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I. INTRODUCTION

Concrete, being the most commonly used construction material worldwide, plays a significant role in the construction of rigid pavements. However, the repetitive loading experienced by pavements often leads to the development of cracks. These cracks permit the entry of harmful substances, ultimately reducing the concrete's durability. Consequently, this research introduces an environmentally friendly solution to confer self-healing capabilities upon concrete. This is achieved by employing bacteria as a healing agent.

Retrofitting of rigid pavements refers to the process of upgrading or enhancing existing concrete pavements or road structures to improve their performance, durability, and service life. It involves the repair, reinforcement, or modification of the existing rigid pavement to address issues such as cracks, deterioration, wear and tear, or to meet modern engineering and safety standards. Retrofitting is typically carried out to extend the lifespan of the pavement, optimize its load-bearing capacity, and enhance its resistance to environmental factors, traffic loads, and other stressors. This process is a cost-effective and sustainable approach to maintaining and improving infrastructure while minimizing the need for complete reconstruction or replacement of the pavement.

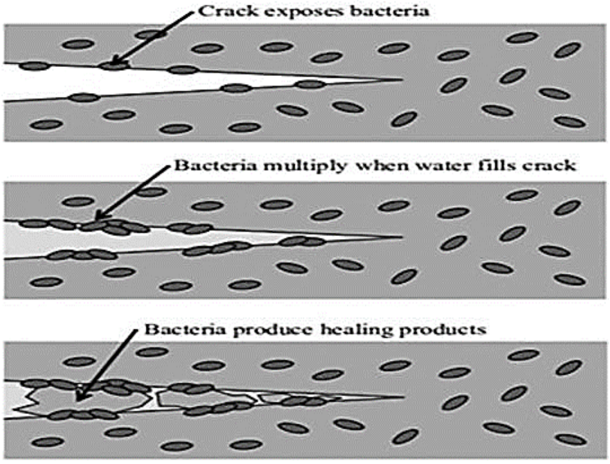
The formation of cracks in structural concrete can result from both internal factors, such as low concrete strength, and external factors, including structural loads, temperature fluctuations, and aging of the structure. These cracks tend to widen due to the absorbent nature of concrete, leading to its deterioration. Timely action is essential when cracks form to prevent them from expanding and diminishing the structural integrity. Traditional crack repair techniques have limitations, including the environmental impact of the materials used and the temporary nature of the remedies.

To address these issues, a microbiologically induced crack healing mechanism has emerged as a reliable solution. Researchers have discovered that certain types of bacteria, when introduced into cementitious composites, can produce calcium carbonate, which can effectively seal these cracks. The process of calcium carbonate precipitation requires a calcium source, with the bacteria acting as mineralization inducers while calcium compounds serve as calcium carbonate precursors and an energy source for the bacteria. To ensure the long-term viability of these bacteria, they need to be in the form of spores, as cracks allow air and water to enter, reactivating the spores. Subsequently, the spores utilize calcium compounds as an energy source and commence the precipitation of calcium carbonate.

In the case of cement concrete roads, the ultimate strength after 90 days is often taken into consideration. This decision is influenced by the fact that only a limited number of commercial vehicles pass over a specific stretch of road within the initial 90-day period. However, the general practice in the industry is to evaluate concrete strengths after 28 days. To address this, the Indian Road Congress (IRC) provides a multiplying factor that can be used to estimate the 90-day strength based on the 28-day strength.

Self-healing concrete is a unique material known for its ability to independently repair cracks through autogenous techniques. This remarkable self-repair capability stems from concrete's inherent durability, enabling it to withstand chemical and physical stresses. As the durability of concrete decreases, the likelihood of crack formation increases. Self-healing concrete possesses the invaluable trait of facilitating the repair of cracks, making it an innovative and important material in construction.

In the face of the prevalent problem of structural cracks, both before and after fracture, various solutions are explored. Among these solutions, Self-Healing or Bacterial Concrete stands out as a corrective process. Self-Healing Concrete has the remarkable capacity to autonomously repair gaps and fissures after solidification, thanks to a bacterial response. This repair process works by subjecting the concrete to repeated dry and wet cycles, enabling the complete sealing of small cracks ranging from 0.05 to 0.1mm in width. This autogenous mending process relies on water infiltrating the cracks like capillaries, hydrating the partially or completely unreacted cement, causing it to expand and cover the crack. However, wider cracks may necessitate additional repair methods.



II. OBJECTIVE OF STUDY

The following tasks were performed to achieve the following objectives of the study.

1. Collected all necessary information and research papers that self-healing concrete and studied them thoroughly.
2. Collect the calcium source from the local vendors' preferably, calcium lactate.
3. Gradation of fine and coarse aggregate was done.
4. Prepared M-30 grade of concrete with varying proportion Bacteria (Bacillus Subtilis).
5. Compressive strength and split tensile strength tests are performed on all mixes and test results are recorded.
6. Conclusion drawn from the test result and scope of study in future. The total work is carried out in mainly three stages.

7. Various tests were performed on different materials that were used in study, in order to determine their properties.
8. Casting of specimens.
9. Testing of specimens and seeing the self-healing property shown by the bacteria.

III. METHODOLOGIES

Typically, concrete structures have a lifespan ranging from 50 to 100 years. However, deterioration can commence as early as one year after construction or within the first ten years. To combat this issue, Bacterial Concrete has emerged as a solution. Bacteria, when combined with a calcium-based nutrient, can remain in a dormant state for approximately 200 years or even longer. Upon the intrusion of water into a crack, these bacteria initiate a healing process by converting calcium lactate into limestone.

After conducting in-depth research on various bacterial groups, "Henk Jonker," the pioneer behind the development of bacterial concrete, determined that the subtilis group of Bacillus Bacteria is the most suitable choice for creating self-healing concrete. In this particular study, "Bacillus Subtilis" with a population of 10^9 per milliliter was utilized. Figure 3.4 provides a visual representation of the bacteria employed in this study for the purpose of self-healing. Furthermore, Table 3.6 presents specific properties of Bacillus subtilis.

In the experimental study, we focus on M30 grade concrete, using 43-grade OPC cement. To determine the proportions, the properties of different materials, including natural aggregate, sand, cement, water, and admixtures, are calculated following the mix design procedure outlined in IS 10262-2019. The mix design for this specific blend is as follows:

3.3.1.1 Mix Design in accordance with MORTH standard, IS 10262-2019, and IS 383-2016.

Table 1 Stipulation for Proportioning

1	Mix Design Grade	M30
2	Type of Cement	OPC 43 grade
3	Maximum size of aggregate	20mm
4	Minimum Cement Content as per MORT&H 1700-3A	310Kg/m3
5	Minimum Water Cement Ratio as per MORT&H 1700- 3A	0.45
6	Exposure Condition	severe
7	Degree of Supervision	Good
8	Type of Aggregate	Angular Aggregate
9	Maximum Cement Content as per MORT&H C1.1703.2	540 kg/m3
10	Chemical Admixture Type	Super Plasticizer

Table 2 Data for Materials

1	Cement used	Bangur OPC 43 grade
2	Specific Gravity of Cement	3.15
3	Specific Gravity of Water	1
4	Chemical Admixture	HRJ Flowcon 64-2
5	Specific Gravity of Natural Aggregate	2.91
6	Specific Gravity of Sand	2.62
7	Water Absorption of Natural Aggregate	0.60%
8	Water Absorption of Sand	1.20%
9	Free (surface) Moisture Natural Aggregate	Nil
10	Free (surface) Moisture of sand	Nil
11	Sieve Analysis of Individual Natural Aggregate	Separately done
12	Sieve Analysis of Fine Aggregates	Separately done

Table 3 Mix Calculations

1	Target Mean Strength	38.25
2	Water Cement Ratio	0.5
3	Air Content (%)	1
4	Admixture (Kg)	0.04
5	Water content before admixture (Kg)	191.58
6	Water content after admixture (Kg)	153.264
7	Cement/Cementous matter (Kg/m^3)	306.53

Table 4. Volume Calculations

1	Total Volume (m^3)	1
2	Volume of entrapper air wet concrete (m^3)	0.01
3	Volume of Cement (m^3)	0.097
4	Volume of Water (m^3)	0.153
5	Volume of admixture (m^3)	0.00
6	Volume of all in Aggregate	0.739

Table 5 Weight Calculations

1	Cement (Kg/m^3)	348
2	Water (Kg/m^3)	153
3	Fine Aggregate (Kg/m^3)	697
4	Coarse Aggregate (Kg/m^3)	1347
5	Chemical Admixture (Kg/m^3)	0.04

Table No.5 Mix Proportion

Proportion	
Cement	**1**
Fine Aggregate	**2.02**
Coarse Aggregate	**3.87**

Table 6. Percent of Bacteria added by weight of cement for 1m3

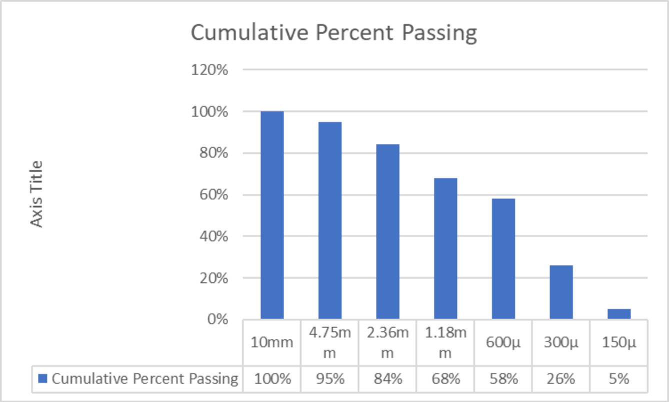
Mix	**% of Calcium Lactate by Weight of Cement**	**Cement (Kg)**	**Sand (Kg)**	**Coarse Aggregate (KG)**	**Calcium Lactate (Kg)**
S1	0%	348	697	1347	0
S4	5%	348	697	1347	17.4
S5	10%	348	697	1347	34.8

Table 7. Percent of Calcium Lactate added as Calcium Source for Bacteria for

Mix	**% of Calcium Lactate by Weight of Cement**	**Cement (Kg)**	**Sand (Kg)**	**Coarse Aggregate (KG)**	**Calcium Lactate (Kg)**
S1	0%	348	697	1347	0
S4	5%	348	697	1347	17.4
S5	10%	348	697	1347	34.8

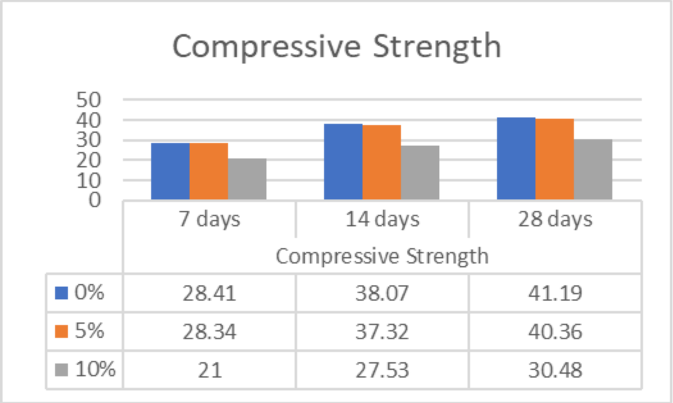
IV. RESULTS

This section provides a comprehensive compilation of test results covering a wide spectrum of materials, including cement, sand, aggregate, bacteria, and others. Moreover, the test results for both fresh and hardened concrete are incorporated within this report.



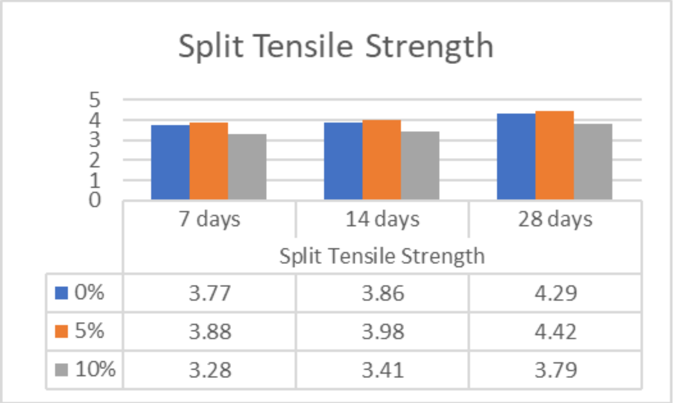
	10mm	4.75mm	2.36mm	1.18mm	600µ	300µ	150µ
■ Cumulative Percent Passing	100%	95%	84%	68%	58%	26%	5%

Figure No.1 Grading of fine aggregate as per sieve analysis



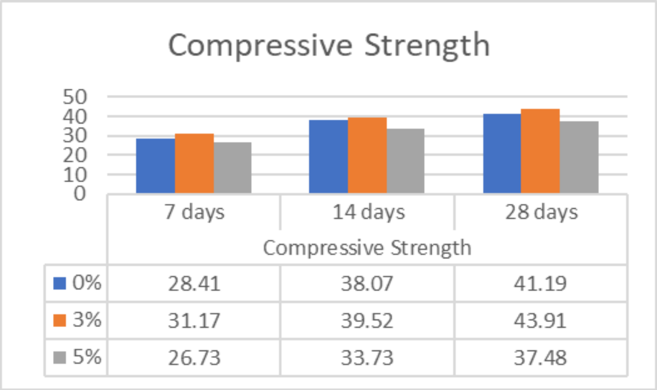
	7 days	14 days	28 days
■ 0%	28.41	38.07	41.19
■ 5%	28.34	37.32	40.36
■ 10%	21	27.53	30.48

Figure No.2 7 Days, 14 days and 28 days Compressive Strength at varying percentage of Calcium Lactate



	7 days	14 days	28 days
■ 0%	3.77	3.86	4.29
■ 5%	3.88	3.98	4.42
■ 10%	3.28	3.41	3.79

Figure No. 3 7 days, 14 days and 28 days Compressive Strength at varying percentage of Calcium Lactate



	7 days	14 days	28 days
■ 0%	28.41	38.07	41.19
■ 3%	31.17	39.52	43.91
■ 5%	26.73	33.73	37.48

Figure No.4. Compressive Strength Test Results of Concrete by adding Bacteria

In the formulation of concrete involving the combination of Bacillus Subtilis bacteria and Calcium Lactate, we determined the optimal percentages based on prior mixes. Our findings revealed that a 3% bacteria content resulted in the highest strength, and similarly, a 5% Calcium Lactate content produced the maximum strength. Consequently, a blend was prepared using 5% Calcium Lactate and 3% Bacillus Subtilis bacteria.

The results of the Compressive Strength test are presented.

Here are the key discussions based on the obtained results:

i. The utilization of Bacillus Subtilis bacteria at 3% content level yields superior outcomes in both compressive and split tensile strength.

ii. The inclusion of 3% bacteria leads to a notable 9.71% increase in compressive strength at 7 days and a 6.60% enhancement at 28 days.

iii. The addition of 3% bacteria results in a 5.31% boost in split tensile strength at 7 days and a 6.76% improvement at 28 days.

iv. Incorporating 5% bacteria causes a decrease in both compressive and tensile strength of concrete, with reductions of 9.01% and 1.86%, respectively.

v. The combination of bacteria and calcium lactate produces promising results. Adding calcium lactate with bacteria is aimed at determining the optimum calcium source required for bacteria, which is found to be 5% of calcium lactate for every 3% of bacteria.

vi. The introduction of both calcium lactate and bacteria leads to an increase in both tensile and compressive strength. Compressive strength improves by 6.58% at 7 days and 4.71% at 28 days.

vii. When both calcium lactate and bacteria are added, split tensile strength demonstrates substantial improvements, with a 16.98% increase at 7 days and an 18.41% increase at 28 days.

V. CONCLUSIONS

The findings of this study offer valuable insights into the potential use of Calcium Lactate and Bacillus Subtilis in the retrofitting of rigid pavements. These conclusions are particularly relevant for enhancing the performance of existing concrete structures.

1. The addition of bacteria up to 3% resulted in notable improvements, including a 6.6% increase in compressive strength and a 6.76% enhancement in split tensile strength when compared to conventional concrete. This indicates that a controlled addition of bacteria can positively impact the mechanical properties of the concrete. However, it's crucial to note that an increase in the bacteria percentage to 5% led to a decrease in strength. Therefore, a balanced approach is essential to optimize the benefits of bacterial concrete in retrofitting projects.
2. The study also revealed that the addition of 5% Calcium Lactate reduced compressive strength by 2.02%, but it increased split tensile strength by 3.03% when compared to conventional concrete. However, the results indicated that when the Calcium Lactate content was increased to 10%, it had an adverse effect on both compressive and split tensile strength. These findings emphasize the need for careful consideration when incorporating Calcium Lactate into concrete mixtures for retrofitting, with an awareness of its potential impact on different strength parameters.
3. Interestingly, combining Calcium Lactate and Bacteria at specific levels (5% and 3%, respectively) showed positive effects. This combination led to a 4.71% increase in compressive strength and a remarkable 18.41% improvement in split tensile strength. These results suggest that there is a synergistic effect when using Calcium Lactate and Bacillus Subtilis together in the retrofitting of rigid pavements.
4. Perhaps one of the most significant findings of this study is the potential for bacterial concrete to significantly reduce the need for repairs and maintenance, ultimately making it a more cost-effective choice for retrofitting rigid pavements. This is a critical consideration for infrastructure projects, as reduced maintenance requirements can result in long-term cost savings and increased structural durability.

In conclusion, this study demonstrates the feasibility of employing Calcium Lactate in conjunction with Bacillus Subtilis in the retrofitting of rigid pavements. It highlights the importance of carefully optimizing the percentages of these components to meet specific strength criteria. Additionally, the study underscores the cost-effectiveness and long-term benefits of using bacterial concrete for retrofitting applications, which can have a positive impact on the overall performance and durability of rigid pavements.

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