Development of a Bio-Based Self-Healing and Night-Visible Sustainable Road System for Indian Infrastructure

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***Abstract*— Hardened pavements can form cracks with time, which weakens them and increases life cycle costs. Reduced visibility during darkness can also pose risks to road users. In this study, we introduce an idea of bio-based self-healing concrete with photo- luminescent surface which can increase the durability of pavements and improve night- time visibility. Bacteria including Bacillus subtilis and Sporosarcina pasteurii promote the formation of calcium carbonate to seal small cracks when moisture penetrates grout. The system proposed the expansion of pavement**

***Keywords*— Self-healing concrete, MICP, Bacillus subtilis, Sporosarcina pasteurii, photoluminescent pavement, crack repair, night visibility, sustainable roads.**

I. INTRODUCTION

Roads form – road infrastructure is an important aspect of a country as it helps with economic growth and public safety. New roads can make transportation, trade and daily travel much more efficient.

But lots of roads in India are riddled with cracks, potholes and surface degradation that pose a significant danger to motorists and pedestrians. Reports from the Government of India say over 9,438 deaths were reported as a result of pothole accidents between the years 2020 to 2024.In 2020, pothole accidents killed approximately 1,555 people.In 2024, this number climbed to approximately 2,385 fatalities — a troubling leap in pavement- related incidents.

The number of road accidents in India stood at around 4, 64,029 in 2023 with resulting deaths amounted to 1,73,826 and injury figures reached over 4.47 lakh. These figures reflect the severity of road safety issues in the country. Poor road surface maintenance is one of the leading causes for these accidents. In the same way small cracks in pavement become large potholes if they are not fixed on time. There are numerous number of accidents because of poorly maintained roads and delays in major repairs. Another significant safety issue is nighttime poor visibility. Most accidents happen between 6 PM and 9 PM, when road edges, potholes, and paints are difficult for drivers to perceive. Drivers might have issues identifying road defects in dim places. And this makes skids, crashes and cars being pushed into ditches more likely.

II. LITERATURE REVIEW

Researchers have been pushed to undertake new work concerning the next generation of flexible pavements due to the growing demand for durable and sustainable ground transportation infrastructure. Conventional concrete pavements are prone to small cracks formed by shrinkage or temperature changes and continuous traffic loads. Over time, the water that enters past these cracks and chemicals shorten the service life of pavement by weakening its structure. To solve this challenge, researchers have come up with a bio-based self-healing concrete technology that utilizes bacteria to biologically heal cracks formed in the concrete matrix.

Bacillus subtitles, Sporosarcina pasteurii, Bacillus sphaericus and Bacillus magisterium were the most commonly studied bacterial species for self-healing concrete [18–23]. Concrete is alkaline, so when these bacteria are in dormant form they can survive within that material. When the bacteria senses cracks and moisture from the atmospheric environment enters, they get activated and forms Calcium Carbonate ($CaCO_3$) through microbially induced calcium carbonate precipitation (MICP). The calcite deposited about, over time, can fill the cracks and make for a more durable structure. Scientific research investigation (Henk M. Jonkers) revealed that bacterial concrete can repair the cracks approximately 0.5 mm and also decrease the permeability of water in enormous amounts which eventually increases its lifespan. Traffic safety in night-time is an important issue of the transport system. Conventional street illumination is dependent on electricity and necessitates recurrent upkeep. Recently researchers sought photo- luminescent materials that store sunlight in the day and emit it light into the night. Such materials, for instance strontium aluminate phosphors can float for hours without electricity and have been applied to road markings [57] pedestrian-lane and experimental glow-in-the-dark surface roads to improve visibility (Matsuzawa et al., 1996). Even though self-healing concrete and photo-luminescent road technologies have individually been investigated among various studies, they had never been implemented together in a pavement system. This is still a nascent research

area in India. Thus, further studies need to be conducted to create bio-based self-healing concrete with night-visible luminescent materials in conjunction with road construction for enhanced durability and road safety (Jonkers, 2011; Wang et al., 2014).

Problem statement

So traditional lighting is not possible on every road due to high installation costs. While bio-based self-healing concrete and phosphorescent materials is explored in several countries, the composite utilization of these materials in the road construction sector remains minimal within India. Hence developing an eco-friendly highway system which would able to cure small fractures by itself and helps enhance the vision at night without consuming streetlight power.

III. OBJECTIVES OF THE STUDY

To examine the potential role of bio-based self-healing concrete in autonomously repairing fine cracks on road surfaces. To study the utilization of photo-luminescent materials that potentially enhance road visibility at night without needing electricity. To develop how these two technologies can bring road durability and safety. Applications of this sustainable road technology for future road construction in India.

IV. MATERIAL AND METHODOLOGY

The components used in this research are Ordinary Portland Cement (OPC), fine aggregates, coarse aggregates, and portable water for synchronization of concrete. Bio-inspired bacteria were introduced into the concrete, giving the pavement self-healing capability, allowing small stress fractures in the pavement to be repaired. Moreover, construction utilized photo-luminescent material based on strontium aluminate, which enables the road surface to absorb sunlight during daytime and illuminating visible light at nighttime.

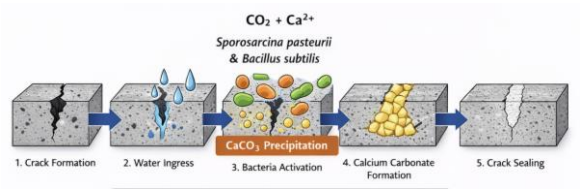

Fig. 1. Mechanism of Bacterial Self- Healing in Concrete

As shown in Figure 1, bacterial activation results in calcium carbonate precipitation which seals the crack. Molds were prepared and the concrete specimens were cast using a standard mix design. Cracking was then introduced to the cured concrete in a controlled manner, facilitating the observation of its self-healing behavior. Each group of concrete specimens had a surface layer embedded with photo-luminescent material. The experimental evaluation of the developed material was then monitored for crack healing efficiency as well as visibility in darkness by replicating laboratory conditions.

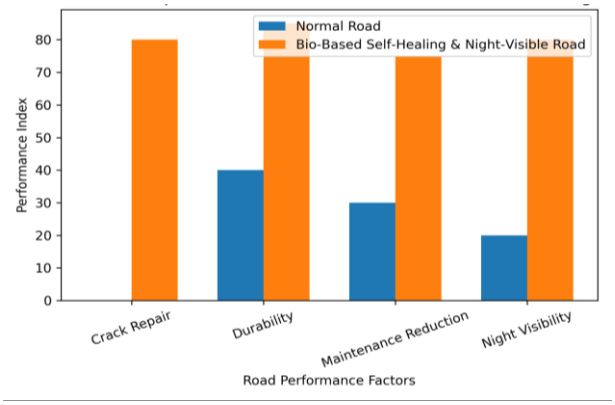

Fig. 2. Graph showing performance comparison: Conversational road vs. Bio- Based self-healing road

TABLE 1. Materials Used

Material
Ordinary Portland Cement (OPC)
Fine Aggregate (Sand)
Coarse Aggregate
Water
Bio-based Bacteria
Strontium Aluminate (Photo-luminescent material)

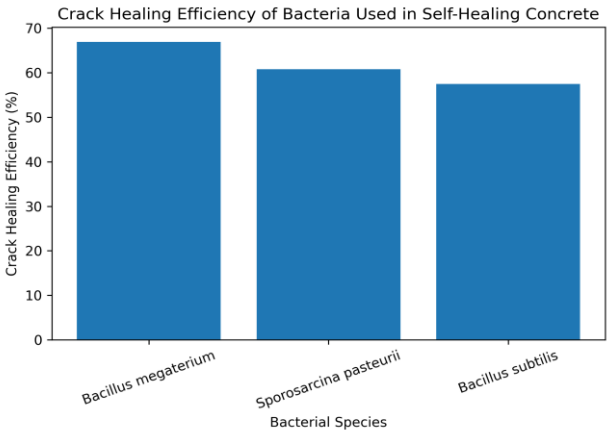

Fig. 3. Showing crack healing efficiency of bacteria uses in self-healing concrete

TABLE 2. Materials and Their Functions in Bio-Based Self-Healing Concrete

Material Composition Table

Material	Type	Function in System
Ordinary Portland Cement (OPC)	Binder	Primary cementitious matrix forming the structural framework
Fine Aggregate(River Sand)	Aggregate	Improves workability and structural stability
Coarse Aggregate	Aggregate	Provides strength and load-bearing capacity
Calcium Lactate / Urea	Nutrient Source	Supports bacterial metabolism for $CaCO_3$ precipitation
BacterialSpores	Biological Agent	Enables self-healing through microbially induced calcite formation
Photoluminescent Powder	Functional Additive	Enhances nighttime road visibility

TABLE 3. Bacterial Species Used in the Study

Bacterial Species	Type	Role in Self-Healing Mechanism
Bacillus subtilis	Spore-forming bacteria	Produces calcite crystals to seal micro-cracks
Sporosarcina pasteurii	Ureolytic bacteria	Facilitates rapid calcium carbonate precipitation
Bacillus sphaericus	Alkali-resistant bacteria	Enhances durability and.crack sealing capability
Bacillus megaterium	Mineral-precip itating bacteria	Improves calcite deposition within pores

VII. ADVANTAGES

Lowers road damage

When self-healing concrete heals itself of small cracks, it limits future damage and extends the lifespan of the roadway. Reduction in maintenance costs

Self-healing concrete reduces the amount of time needed to complete scheduled maintenance and repairs on minor cracks in self-healing concrete.Increased visibility at night Photo-luminescent materials absorb light energy during the daytime then emit it at night. As such, they allow drivers to see road delineations more easily at night.Reduction in electricity useStreet lights can be reduced from some areas due to glowing materials; therefore, this allows for reductions in electricity usage.Sustainable building practices

Waste energy is reduced through this technology as well as the effective lifespan of the roadways. Enhances roadway safety Increased visibility and increased structural integrity through higher durability of surfaces allow for a lower accident rate, especially at high speeds (freeways) and when driving through rural areas.

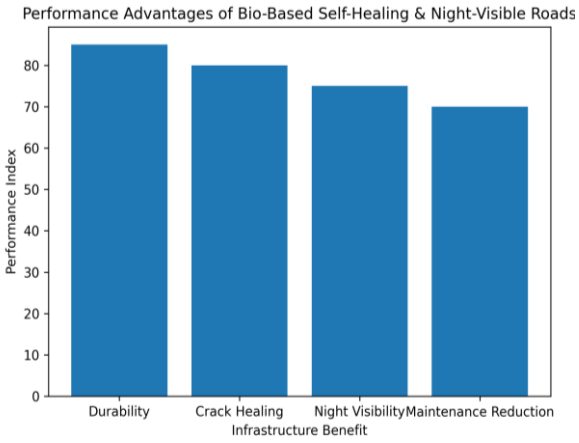

Fig. 4. Performance advantage of Bio-Based self

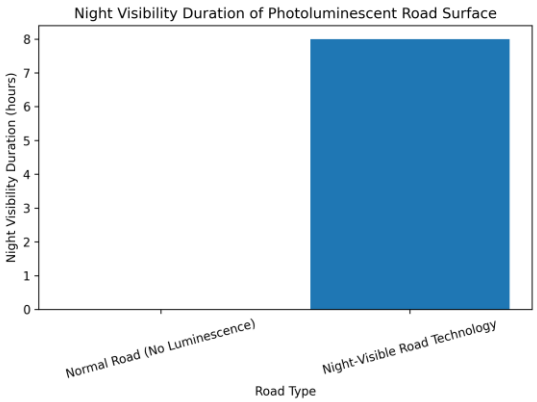

Fig. 5. Night visibility duration of photo luminescent road technology

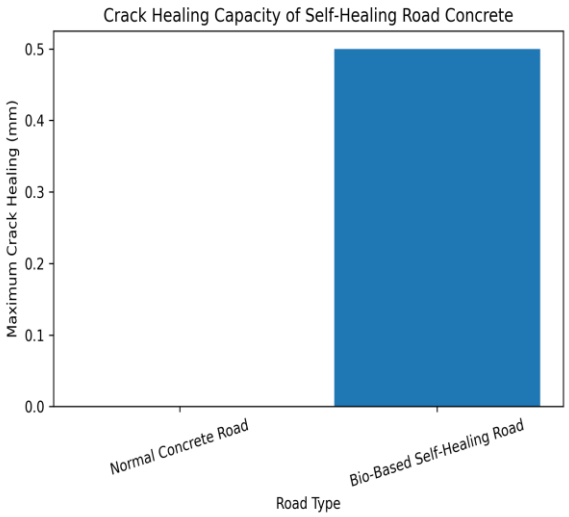

Fig. 6. Comparison normal roads vs. Bio-Based self-healing road

VIII. LIMITATIONS

1. The initial investment for bio-based self-healing concrete and photo-luminescent coatings is substantially higher compared to existing traditional highway construction methods; therefore, the overall impact will be minimal until after initial construction stages of national roads in India have been complete.

2. Extreme summer temperatures can negatively affect the viability of the bacteria contained in self-healing concrete and may therefore result in diminished efficiencies of photo-luminescent materials over extended periods of time.

3. During heavy monsoon rains, the continuous flow of water and the accumulation of dirt and mud on road surfaces can negatively affect the glow of photo-luminescent materials. These conditions may also cause a reduction in long-term performance of the self-healing properties of the concrete

4. In some colder areas of northern India, the very low winter temperatures can significantly reduce the bacterial activity within self-healing concrete, thereby reducing the self-healing efficiency of the concrete

5. Country of India does not have an Infrastructure that Tests Materials There is still a great deal of testing on self-healing concrete and luminescent road materials being done at laboratory level or as experimental tests, and no large scale field tests of these materials being conducted throughout the country of India over long term periods in various climatic and traffic conditions.

IX. FUTER SCOPE

Bio-based concrete with the ability to heal itself and photo luminescent (i.e., light-emitting) road surfaces are technologies that can have a profound effect on the future design and construction of pavements in India. Currently, the use of bacteria in concrete to develop the ability to self-heal is still in its infancy. Future research continues to improve the functionality of these bacteria, particularly with regards to their ability to survive and effectively perform their/self-healing function under the various environmental conditions encountered in India, such as: hot summer temperatures; heavy (monsoon) rainfall; and cold winter temperatures. Development of better photo luminescent (light-emitting) materials is another area that requires further investigation. With new photo luminescent materials that have improved durability and longevity, brighter and longer-lasting light will be emitted by the new materials, therefore improving nighttime driver visibility on road surfaces. Potential use of the technology will become available for research trials in real world settings, like highways, rural roads, or smart city development. These studies will give researchers information about the long term durability of the technology when exposed to traffic loads and climatic conditions.

Future improvements and the larger roll-out of the new technology may result in India's development of safer, sustainable, and energy efficient roads.

X. RESULT

Based on the study's findings, bio-based self-healing concrete is an option for reducing the development of small cracks and minor fractures on pavement surfaces. Decreases in the amount of cracking observed on the concrete samples over time occurred because the bacteria induced the formation of calcium carbonate that fills cracks. Evidence of the same phenomenon occurring in terms of biological concrete was documented through the studies completed by Jonkers (2011) who indicated that the bacteria based concrete would effectively self-heal up to specified dimensions as well as improve the overall durability of concrete structure.

Photo-luminescent materials were applied to the surface layer for a material that would (after exposure to sunlight) glow brightly with visible light. The material would collect sunlight as a power source when exposed to sunlight during daylight hours, emitting light for hours after (in darkness) improving visibility in the absence of electricity.

Matsuzawa et al. (1996) also indicated that long-lasting phosphorescence could be produced via long-lasting alkaline earth phosphors (strontium aluminate) with the ability to produce luminescence of great brightness.

Based on this data set, the combination of self-healing concrete and photo-luminescent materials demonstrated significant potential with respect to both durability and visibility (at night). Therefore, the combination of Self-healing concrete and photo-

luminescent materials could lead to the development of safer and more sustainable road systems, particularly in areas deficient in street lighting.

XI. CONCLUSION

The eye is used for the bio-based self- healing concrete and photo-luminescent material, which supports sustainable roads. The outcomes demonstrate that self-healing concrete can restore small fractures in the road surface, resulting in greater durability and work life of pavements. Simultaneously, photo-luminescent materials can enhance night-time visibility by emitting light without consuming electricity.

Using these two technologies together can help make roads safer and more environmentally friendly. In India, this technology is still new and not widely used yet, but it has good potential for future road construction. More research and practical testing are needed to understand how well it works over a long period of time.

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