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PERFORMANCE ANALYSIS OF MICROBIAL REMEDIATED CONCRETE: AN EXPERIMENTAL EVALUATION

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Abstract: Due to its durability, strength, and cost-effectiveness compared to other building materials, concrete is the most widely used engineering material in construction. However, concrete's primary drawback is its low tensile strength, making it susceptible to the formation and propagation of micro-cracks, which weaken structures. These tensile stresses can arise from various factors such as chemical reactions, plastic shrinkage, or tensile loading. The increased tendency for cracking makes concrete more vulnerable to damaging environmental elements, further reducing its strength. These cracks allow harmful substances to infiltrate, potentially leading to chemical degradation of the concrete and corrosion of steel reinforcements. This corrosion exacerbates the damage, diminishing the integrity and rigidity of concrete structures. The deterioration of reinforced concrete results in substantial maintenance expenses for both the concrete and the reinforcement. This study aims to develop self-healing concrete that can independently repair cracks caused by various factors, thus minimizing the need for external detection and repair of internal damage.

Keywords: Strength, Durability, micro-cracks, Self- healing

1. Introductin

Self-healing concrete is engineered to enhance the material's density and minimize crack formation and propagation. This results in more durable structural concrete that demands less maintenance [1]. Various methods are used to retard fracture expansion and bridge gaps, thus extending the lifespan of concrete structures. Traditionally, many of these methods have relied on expensive and often toxic materials like epoxy systems [2] [3], acrylic resins, and silicone-based polymers, which are not always compatible with concrete [6] [5].

Recent advancements have introduced bio concrete, or bio-influenced self-healing concrete [4], as a promising alternative for mitigating fracture propagation. Bio concrete utilizes microbial activity to produce mineral compounds that facilitate the healing of fissures [8]. This autonomous healing leads to fewer cracks in the concrete over time [9] [7], increasing its durability and reducing the need for maintenance [10].

Bio mineralization, a natural and environmentally friendly process [11], contributes to the self-healing properties by enhancing the compressive strength of damaged concrete [13]. The generation of calcium carbonate, central to the self-healing process, is influenced by factors such as the pH of the concrete [12], the presence of dissolved inorganic carbon, calcium ions throughout the mixture, and nucleation sites [15].

The effectiveness of bio concrete depends on the types and concentrations of bacteria used, curing methods [16], and the materials employed to integrate the bacteria into the concrete. For optimal performance, bacteria and an organic mineral precursor are incorporated into the concrete during mixing, rather than being applied externally. Among various bacteria capable of self-healing concrete, "Bacillus subtilis" is notably effective. Its inclusion through specific incorporation techniques is crucial for achieving desired self-healing properties [15].

It's also essential to consider methods that impact the extent of fracture healing, which in turn affects concrete strength. Self-healing concrete typically refers to a material's ability to naturally or automatically fill cracks [14] [17]. This mimics the natural crack-sealing process by producing limestone with the aid of microbes and calcium carbonate [19]. In practical applications, self-healing concrete is created by embedding bacteria and calcium carbonate into the concrete matrix in the form of fibers or capsules [21]. When a crack forms, these capsules rupture, exposing the bacteria to air and water [20]. The bacteria then metabolize calcium carbonate to create limestone, sealing the crack. These bacteria, often sourced from soil or water, can withstand compressive forces well, though they are less effective against tensile forces [23].

The presence of cracks reduces concrete durability by allowing the easy ingress of gases and liquids, which may contain harmful substances. If micro-cracks reach steel reinforcements [21], both the concrete and the steel can suffer significant damage. Therefore, controlling crack width and ensuring timely repairs are essential. Self-healing concrete can extend the service life of structures, enhancing durability and sustainability [18]. This is achieved through different techniques, including autogenous self-healing, capsule-based self-healing, vascular self-healing, electro deposition self-healing, microbiological self-healing, and methods involving embedded shape memory alloys (SMAs).

Bacterial self-healing concrete aims to repair cracks and restore water tightness [22]. This type, often dubbed "Bacterial Concrete," contains bacteria that continuously precipitate calcite. It utilizes strains of Bacillus bacteria, calcium lactate, and essential nutrients like nitrogen and phosphorus, which are mixed into the concrete. These components can remain dormant for up to 200 years within the concrete. When a concrete structure cracks and moisture enters, the bacterial spores activate upon contact with water and nutrients. The bacteria produce calcium lactate, which is then converted to insoluble limestone, sealing the crack as it hardens.

To ensure the self-healing agent is not triggered prematurely during concrete mixing, the bacterial spores and calcium lactate-based nutrients are contained within separate expanded clay pellets (2-4 mm wide). The bacteria activate only when water reaches these pellets, initiating the self-healing process.

1.1 Selection of Bactria

Concrete environments are inhospitable for bacteria due to their high pH, dryness, and scarcity of nutrients. The combined pH of concrete components is around 13, which is generally too alkaline for most living organisms. However, researchers have discovered that specific types of Bacillus bacteria can survive in this highly alkaline setting. These bacteria become active when the concrete starts to crack. The mineral precipitation process initiated by these bacteria reduces the pH of concrete to a more moderate range of 10 to 11.5, necessary for the activation of bacterial spores.

Bacterial Classification

1. Bacteria are single-celled, typically simple organisms that can be classified based on several criteria, including:
2. **Shape**:
   - **Cocci**: Spherical bacteria.
   - **Bacilli**: Rod-shaped bacteria.
   - **Spirilla**: Spiral-shaped bacteria.
3. **Gram Stain**:
   - **Gram-Positive**: Bacteria that retain the crystal violet stain.
   - **Gram-Negative**: Bacteria that do not retain the crystal violet stain and appear red or pink.
4. **Oxygen Requirements**:
   - **Aerobic**: Require oxygen for survival.
   - **Anaerobic**: Do not require oxygen and may even be poisoned by it.
   - **Facultative Anaerobes**: Can survive with or without oxygen.
5. **Metabolic Characteristics**:
   - **Photoautotrophs**: Use light as an energy source and carbon dioxide as a carbon source.
   - **Chemoautotrophs**: Obtain energy by oxidizing inorganic substances.
   - **Heterotrophs**: Depend on organic compounds for both energy and carbon.

Understanding these classifications helps in identifying which bacteria can be used effectively in self-healing concrete. For example, specific strains of Bacillus, known for their resilience to high pH environments [28], are strategically chosen for their ability to precipitate minerals that seal cracks in concrete [25]. This method not only aids in the repair of the material but also enhances its durability.

2 Literature Review

Dr. Henk Jonkers pioneered the development of a bacterial-based concrete that integrates specific Bacillus bacteria with calcium lactate, nitrogen, and phosphorus to create a self-healing agent within the concrete. These components can remain dormant for extended periods until activated by water infiltration. When water penetrates cracks, the bacterial spores germinate and consume the calcium lactate [27], converting it into limestone through an oxygen-consuming process. This conversion seals the cracks and solidifies the surface, enhancing the durability of the reinforced concrete by eliminating oxygen, which reduces corrosion [26].

Thirumalai Chettiar's research on biological concrete explores a unique method for filling cracks and fissures using microbial calcite (CaCO3) precipitation. This falls under the field of study known as biomineralization, specifically focusing on microbiologically induced calcite precipitation (MICP). MICP is a process where living organisms produce inorganic solid minerals. Bacillus pasteurii, a common soil bacterium, has been identified to precipitate calcite effectively.

In related studies, researchers V. Ramakrishnan, R. K. Panchalan, and S. S. Bang examined the use of calcite precipitation induced by Bacillus pasteurii in biological concrete [32]. The microbial action responsible for mineral precipitation is both organic and environmentally friendly [30], making this method particularly advantageous. Researchers assessed the efficacy of this treatment by comparing the strength and stiffness of bacteria-treated fractured specimens to those without bacterial treatment. Experimental research evaluated the recovery of strength in fractured beams remediated with various bacterial concentrations.

The report highlights the endurance of mortar beams treated with bacteria under harsh conditions such as alkaline, sulfate, and freeze-thaw environments. Multiple bacterial concentrations were tested, and the influence of biologically induced mineral precipitation on improving the modulus of rupture, durability, stiffness, and concrete strength was documented using Scanning Electron Microscopy (SEM). The findings indicate that the inclusion of bacteria in concrete enhances its durability, compressive strength, modulus of rupture, and stiffness [31].

3. Methodology

3.1 Cement

Portland cement is the most widely employed type of cement [31], serving as a crucial ingredient in plaster, mortar, and concrete [1]. For the current study, Ordinary Portland Cement (OPC) 43 grade has been used [26] [30]. The specific parameters of the OPC 43 grade cement utilized in this investigation are detailed below:

Table 3.1: Properties of Cement

Properties	Values
Specific Gravity	3.05
Fineness	9%
Standard Consistency	31%
Initial Setting Time	33min
Final Setting Time	600rnin

3.2 Aggregates

Manufactured sand (M Sand) refers to crushed fine aggregate produced from suitable source materials, specifically intended for use in concrete or other specialized products [24]. In contrast, coarse aggregates consist of appropriately sized crushed stones, typically larger than 4.75 mm. The table below outlines the characteristics of M Sand and coarse aggregates [22].

Table 3.2: Properties of Fine Aggregate

Properties	Values
Specific Gravity	2.55
Fineness Modulus	3.6
Bulk Density	1250kg/m^3

Table 3.3: Properties of Coarse Aggregate

Properties	Values
Specific Gravity	2.60
Fineness Modulus	472
Bulk Density	1340kg/rn^3

3.3 Water

Cement paste forms during the hydration process when water is combined with a cementitious material [1]. For our calculations, the specific gravity of this mixture is considered to be 1.

3.4 Bacillus Megaterium

Bacillus megaterium is a rod-shaped, Gram-positive bacterium that is predominantly aerobic and capable of forming spores. This bacterium is notable for its large size, with cells reaching up to 4 micrometers in length and 1.5 micrometers in diameter. The cells often form pairs and chains, connected by polysaccharides on their cell walls, which allow them to interact and cooperate.

Bacillus megaterium thrives best at temperatures ranging from 30°C to 45°C, though some strains isolated from a geothermal lake in Antarctica have been found to grow at temperatures as high as 63°C. As an endophyte, Bacillus megaterium holds potential as a biocontrol agent for plant diseases. Additionally, certain strains of Bacillus megaterium have demonstrated the ability to fix nitrogen.

Fig 2: Bacillus Megaterium under microscope

Bacillus megaterium has long been a significant bacterium in industrial applications. It produces a wide range of enzymes, such as amylases utilized in the baking industry and glucose dehydrogenase used in blood glucose testing. Additionally, it synthesizes penicillin amidase, which is essential for the production of synthetic penicillin. This bacterium also generates several amino acid dehydrogenases and enzymes involved in the modification of corticosteroids. Beyond enzymes, Bacillus megaterium is instrumental in producing biologically active compounds with fungicidal and antiviral properties, as well as pyruvate, vitamin B12, and other valuable substances. Furthermore, it produces cyclic lipopeptides, including members of the surfactin, iturin, and fengycin families, which are also produced by many other Bacillus species and are known for their beneficial chemical properties.

3.5 Preparation of Bacterial Concrete

Two ways of manufacturing Bacterial Concrete

a) By direct application

b) By encapsulation in lightweight concrete

Direct Application Method

In the direct application method, bacteria and calcium lactate are introduced directly into the concrete mix. The inclusion of these microorganisms and calcium lactate does not alter the standard properties of the concrete. When the causes of cracks in a structure are evident, the bacteria are exposed to environmental conditions. In the presence of water, these bacteria metabolize calcium lactate, their food source, and produce limestone, which helps seal the cracks. To facilitate this process, treated clay pellets containing bacteria and calcium lactate are added to the concrete mix. Typically, about 6% of clay pellets are incorporated to create bacterial concrete.

4. Results & Discussions

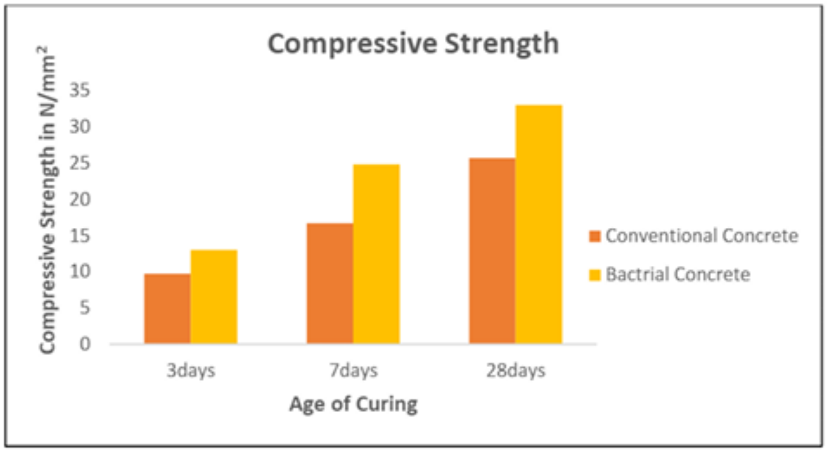

Fig 4: Variation of Strength for Conventional & Bacterial Concrete

The graph above illustrates the variations in compressive strength values at 3, 7, and 28 days of curing. Observations indicate that compressive strength values increase linearly with the curing period. After 28 days of curing, the compressive strength of bacterial concrete is 0.77 times higher than that of conventional concrete.

6. Conclusions:

Following a 28-day curing period, the average compressive strength of microbiological concrete surpasses that of traditional concrete by a factor of 0.77.

- The potential for self-repairing concrete offers a sustainable solution to reduce the significant CO2 emissions associated with conventional concrete production.
- With mining, transportation, and concrete manufacturing collectively accounting for a substantial portion of energy consumption and CO2 emissions, self-healing concrete holds promise in cutting maintenance expenses, prolonging structural longevity, and curbing the demand for additional concrete production and consequent CO2 output.
- Bacterial concrete has emerged as a superior alternative to many conventional methods, owing to its eco-friendly nature and practical application.

- Looking ahead, this innovative concrete technology is poised to underpin the construction of alternative, high-quality structures that are cost-effective and environmentally sustainable.

- The utilization of microbial concrete has the potential to streamline construction processes and introduce novel construction methodologies. Since Bacillus bacteria pose no threat to human health, they can be effectively deployed in construction practices.

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