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A Review of Flexural Strength on Self-Healing Concrete using Bacillus as Self-Healing Agent

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Abstract: Concrete is the most widely utilized construction material in the world. Hence, construction industry development required to improve on material to ensure the concrete high functionality. Cracks in concrete are very common either macro or micro cracks. The cracks will affect the durability of concrete especially on important structure such as beam. Objective of this study is to study the effect on the flexural strength of self-healing concrete and study the performance of bacteria on self-healing concrete with different bacteria concentration. Introduction bacteria into concrete received a lot of interest. Bacteria will aid in mineral precipitation of pores and tiny cavity areas. Bacillus is a type of bacteria that can produce calcium carbonate ($CaCo_3$) to enhance the concrete characteristic. Bacillus family bacteria and flexural strength of concrete is the limitation of this study. Method of this study is using systematic review. This study shows that adding bacteria with or without nutrients, has a negative impact on the mechanical qualities of concrete. However, some studies show opposite result. As a result, the effect of bacterial and nutrient input on concrete will vary depending in how they are incorporated. The addition of bacteria could potentially improve its flexural strength.

Keywords: Self-Healing Concrete, Bacillus , Cracks

1. Introduction

Concrete is derived from the Latin word "concretus", which meaning compound. It is a heterogenous composite material made up of cement, coarse aggregate, fine aggregate and water that was utilized by the ancient Romans in the construction of walls and roof [1]. Concrete is the most widely utilized construction materials in the world. Unfortunately, concrete is vulnerable to a wide range of damages, all which end in cracks. Intrinsic self-healing that is popular in new age concrete. This sort of healing however does not match the concrete durability requirements [1].

The invention of self-healing concrete has completely changed. It enables people to develop structure without having to worry about destruction or extensive maintenance. Incorporation of bacterial self-healing agent in concrete mixtures changes the microstructure of the material, which is reflected in

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its mechanical properties. Self-healing concrete play an important role as an early preventive approach from the formation of crack becoming crucial.

Aim of this study to study the effect on flexural strength of self-healing concrete with incorporating of different type of bacteria and study the performance of bacteria supplied in a concrete mixed with different concentration. Amount of bacteria concentration added affect the increasing and decreasing the value of self-healing concrete and different type of bacteria give different performance.

2. Literature review

2.1 Concrete

Concrete is a structural material made up of solid, chemically inert particles combined with cement and water. Different varieties of concrete were available in market to meet the design criteria and specifications. Some type of concrete such as lightweight concrete and bio concrete may help to preserve environment. Bio concrete is a concrete that use bacteria $CaCO_3$ precipitation as a friendly and cost-effective solution. It produces limestone biologically to mend cracks that occur on the surface of concrete structures [2].

2.2 Classification

2.2.1 Autogenous self-healing

According to RILEM's definition, autogenous self-healing is a process in which a material's injury is repaired using only its original components. To put it another way, the ability of concrete and other cementitious materials to self-heal is only conceivable because of their chemical makeup and under suitable climatic conditions. Since the beginning of the nineteenth century, this phenomenon has been examined. The French Academy of Science discovered the mending of cracks in water retention structures, culverts and pipes 1836. Following that, several studies recognized the presence of autogenous healing products in concrete cracks and attempted to validate their physiochemical basis [3].

2.2.2 Autonomous self-healing

One of the first uses of bacteria to seal cracks in concrete. Many research efforts have focused on the use of bacteria modified mortars that can be used externally for concrete restoration. The use of microorganisms for self-healing concrete has recently been investigated [3].

2.3 Cracks

Temperature cracks, shrinkage cracks, settlement cracks, load cracks and construction cracks are the most common type of cracks in concrete structures. Shrinkage stress surpassing concrete ultimate tensile strength because of high temperature or high wind forces causes plastic shrinkage cracks. Cracks have different features depending on the loads they are subjected. Cracks produced by central tension penetrate the cross-section of a member and are perpendicular to the stress direction. Oblique compression failure or shear compression failure can occur in the shear area, resulting the oblique cracks along the beam end and abdomen [4].

2.4 Bacteria

2.4.1 Bacillus pasturii

Sporosarcina pasteurii was the old name for bacillus pasturii. Bacillus pasturii has been proposed as a potentially useful organic improvement material [5].

2.4.2 Bacillus subtilis

Bacillus subtilis is an obligate aerobe bacterium that is used as a mosquito larvicide. It produces endospores that are spherical in shape. Bacillus subtilis is a gram-positive rod-shaped bacterium that form chains of medium sized, smooth colonies with an entire border [5].

2.4.3 Bacillus sphaericus

Lysinibacillus sphaericus (formerly known as Bacillus sphaericus) could create safe endospores that are resistant to high temperatures, synthetic substances and intense light and can last for long periods of time [5].

3. Methodology

A systematic review aims to find, evaluate and synthesize the best available evidence on a given research question to provide accurate and evidence-based solutions. The knowledge can be paired with professional judgement to make decisions on how to deliver interventions or make changes in policy, developing the discipline and providing information for future practice and study. Systematic review is the best way to combine the results of multiple studies that looking into the same questions. Phases that included in systematic reviews is formulation of the topic or problem, identification and critical evaluation of existing evidence, synthesis of the findings and drawing of relevant conclusions.

3.1 Methods

Case study is a type of a research approach commonly used in the humanities. The effect of bacillus incorporation into concrete influence the flexural strength is investigated. This study will employ qualitative analysis, which aids in the discovery of various data sources.

3.2 Flexural strength

Flexure tests are commonly performed to assess a material’s flexural modulus or strength. A flexure test is less expensive than a tensile test and the result differ slightly. The material is laid horizontally over two points of contact and the force is applied to the top of the material until the sample fails. The flexural strength of that sample is represented by the greatest recorded force.

4. Results and Discussion

4.1 Flexural Strength

Jena *et al*. [6] investigated the flexural strength of concrete incorporation with Bacillus Subtilis. The inclusion of bacterial cells enhances the strength of the concrete specimen and the maximal flexural strength are attained at a cell concentration of 10^5 cell/ml, after which it drops. The best results are obtained at 10^5 cells/ml, because when cell concentration reaches this amount, strength begins to deteriorate. After 7, 14 and 28 days, the percentile improvement in strength of concrete with 10^5 cells/ml is 37.93%, 34.37% and 29.14% respectively compared to control concrete. In the presence of 10^6 cells/ml cell concentration, strength increases by 31.03%, 21.87% and 18.57% percent after 7,14 and 28 days respectively. Addition of Bacillus Subtilis bacterium species increase the concrete strength because of its ability to generate calcite precipitate. Calcium carbonate precipitate clogs pores in concrete and repairs cracks resulting in increased strength.

Harshali *et al.* [7] performed experimental study to evaluate the strength in comparison of conventional concrete and bio-concrete using Bacillus Sphaericus and Protius Vulgaris. Bacillus Sphaericus and Protius Vulgaris combination with sand as filling material in artificially formed cuts in cement mortar that was cured in urea and $CaCl_2$ medium to fill voids in fresh concrete and plug artificially in cracked cement mortar. The flexural strength of bio concrete has increased by 5.18 percent after 28th days performed the flexural strength test. The value of conventional concrete and bio concrete is 3.55 MPa and 3.73 MPa respectively.

Madhu Sudhana Reddy and Revathi [8] conducted an experimental study of flexural strength of concrete to create a long-lasting cement concrete by using different quantities of Bacillus Sphaericus in crack filling and biomineralization to improve strength. In comparison to the bacterial proportions of 10,000 cells/ml and 10^7 cells/ml, the percentage rise in strength of concrete with cracks for bacterial mixed and flexural strength of prisms with crack for 100,000 cells/ml bacterial dosage was found to be optimal. Bacillus Sphaericus bacteria will precipitate less calcium carbonate at lower concentrations of 10^3 cells/ml, and at higher concentrations of 10^7 cells/ml, the voids may be completely filled by Bacillus Sphaericus cells, as evidenced by SEM analysis, resulting in less nutrients passing through for calcium carbonate precipitation. As a result, 10^5 cell/ml was discovered to be optimum concentration for a considerable improvement in strength. In comparison to reference specimens, it is also discovered that the durability of concrete with bacteria rises.

Durga *et al.* [9] conduct mechanical and durability test to compute the rate of self-healing concrete. The concrete samples were tested for flexural strength after 7 and 28 days of curing. The flexural strength of bacterial mix specimens is 5.96 MPa, increased from 5.08 MPa in regular concrete samples. The excretion of urease enzyme of biomaterial increases the flexural strength of bacterial mix specimens by 11% after 28 days of curing.

Venkata Siva Rama Prasad & Lakshmi [10] performed experimental study using Bacillus Subtilis bacteria and calcium lactate to arrest fractures in concrete. Bacillus Subtilis bacteria with calcite lactate were utilized in this investigation at varied percentages which are 5%, 10% and 15% for M40 grade concrete. At the ages of 7 and 28 days of cure, the flexural strength was measured. From the experimental work it can be concluded that the flexural strength was good at 10% of bacteria in bacterial concrete mixed. At all ages of curing, adding bacteria to concrete has considerably improved flexural strength**.**

Table 1: Summary of results from previous research on the flexural strength of self-healing concrete

No	Authors	Type of Bacteria	Bacteria Concentration (cell/ml)	Flexural Strength in 7 days (MPa)	Flexural Strength in 14 days (MPa)	Flexural Strength in 21 days (MPa)	Flexural Strength in 28 days (MPa)
1	[6]	Bacillus Subtilis	0	2.9	3.1	Not mention	3.4
			10	3.2	3.4		3.7
			10^2	3.5	3.7		3.8
			10^3	3.7	3.8		4.0
			10^4	3.8	4.0		4.2
			10^5	4.0	4.3		4.5
			10^6	3.8	3.9		4.1
2	[7]	Combination of Protius Vulgaris and Bacillus Sphaericus	10	Not mention	Not mention	Not mention	3.5
			10^5				3.7
3	[8]	Bacillus Subtilis	10	Not mention	Not mention	3.7	Not mention
			10^3			3.9	
			10^5			5.2	
			10^7			4.5	

4	[9]	Bacillus Subtilis	0 10^8	3.8 4.0	Not mention	Not mention	5.08 5.96
5	[10]	Bacillus Subtilis with calcium lactate	10^5 + 0% 10^5 + 5% 10^5 + 10% 10^5 + 15%	3.5 4.3 4.5 4.6	4.2 4.3 4.5 4.7	Not mention	4.2 3.9 4.3 4.4

4.2 Type of bacteria used as self-healing agent

Most of the studies used Bacillus Subtilis as bacteria self-healing agent. Huynh *et al*. [11], Jena *et al.* [6], Madhu Sudhana Reddy and Revathi [8], Durga *et al.* [9] is among the researchers that utilized Bacillus Subtilis. Jonkers *et al.* [12] used Bacillus Pseudofirmus. Krishnapriyaa *et al.* [13] and R. Andalib *et al.* [14] used Bacillus Megaterium. Bacillus Megaterium is another bacillus family that has been found to be effective as a concrete healer. Bacillus bacteria from bacillus family have been widely used as a result of these investigations, demonstrating their ability to resist high alkalinity in concrete. These investigations also reveal that after being stimulated by water, Bacillus family can precipitate $CaCO_3$.

Table 2: Summary type of bacteria used by other researchers

No	Author	Bacteria Type
1	[11]	Bacillus Subtilis
2	[6]	Bacillus Subtilis
3	[7]	Bacillus Subtilis
4	[9]	Bacillus Subtilis
5	[12]	Bacillus Pseudofirmus
6	[13]	Bacillus Megaterium
7	[14]	Bacillus Megaterium

4.3 Bacteria concentration

The effectiveness of sealing is determined not only by the type of bacteria used, but also by the volume of bacteria and nutrients injected to the concrete. It is possible that the amount of bacteria spores absorbed into the concrete will rise. However, nutrients are required to produce $CaCO_3$ after the spore has been activated by water. As shown in the following reaction, the amount of nutrients will restrict the amount of $CaCO_3$ produced.

$$CaC_6H_{10}O_6 + 6O_2 \longrightarrow CaCO_3 + 5CO_2 + 5H_2O \qquad \textit{Eq.1}$$

Wang *et al*. [15] found that the amount of spores incorporated in a 1 m^3. Concrete mixture is within 2% of hydrogels, with each hydrogels containing 10^9spores/ml. in 28 days, this mixture resulted in a healing rate of 80% - 90% for 0.3 mm crack width and 30% - 50% for 0.3mm to 0.7mm crack width. The healing hydrogel also contains nutrients and urea to aid in the precipitation of CaCO3. Bacillus Megaterium was used as the bacterial healer in a study that used 10^5 cell/ml solution in the concrete mix composition. The concrete was made with approximately 186 x 10^5 cell/m^3 of the mixture. Another study from J. Ducasse *et al.* [16] utilized about the same concentration of 10^8 spores/L as Wang *et al*. [15] and found nearly the same healing percentage. According to the study, the bacterial solution of 10^8 spores/L impregnated into Light Weight Aggregate (LWA) restored 69% of its water tightness. Wang *et al.* [15] recorded maximum crack width healed were about 0.18 mm and 0.31 mm. The number of spores impregnated in the overall concrete mixture is equal to 5% of cement.

4.4 Nutrient type

Bacteria performance outcome also affected by the type of nutrient accompanying the bacteria. Study from Jonkers *et al.* [12] used 0.5% of calcium lactate from the weight of cement in concrete mixture and found to be more viable as a deposition agent than urea. The hydrolysis of urea can produce a large amount of nitrogen, which can lead to corrosion of steel reinforcing. Wang *et al*. [15] study findings showed that 20 – 80 μm sized particles mineralized on the fractured concrete surface. The feasibility of the mineralization process in bacterial self-healing concrete was also demonstrated in a study using bio-reagents comprising urea and calcium nitrate. The study used 0.9 and 1.2 grammes of urea and calcium nitrate respectively. In comparison to Jonkers *et al.* [12], the amount of urea and calcium nitrate used is higher, at about 1.2% of cement content. The greatest crack width sealed was 0.5 mm, resulting in greater crack filling efficiency than the control sample. R. Andalib *et al*. [14] employed a bacterial broth medium culture with 80 g of calcium lactate and 20 g of urea per litre. Study from Tziviloglou *et al.* [17] utilized 200 g/L calcium lactate in the bacterial mixing solution which is the amount is lower than other researchers. Calcium carbonate is formed because of bacterial metabolic conversion of nutrients such as calcium lactate, calcium nitrate and urea. Most studies reveal white particles precipitating on crack surfaces which is consistent with carbonate precipitating bacteria's capacity. A study that immersed broken mortar in calcium lactate and calcium gluconate solution backs this up. Calcium lactate and calcium gluconate boosted the self-healing kinetics of mortar by increasing the availability of calcium and carbonate ions in cracks, according to the findings J. Ducasse *et al*. [16].

Table 3: Summary of nutrient type used by previous researchers

No	Author	Nutrient Type
1	[12]	0.5% calcium lactate
2	[15]	0.9 g urea 1.2 g calcium nitrate
3	[14]	80 g/L calcium lactate 20 g/L urea
4	[17]	200 g/L calcium lactate
5	[16]	Calcium gluconate + mortars Calcium lactate + mortars

4.5 Immobilization of bacteria

Krishnapriyaa *et al*. [13] stated that there has been research that have directly embedded microorganisms with or without nutrition into concrete. One method is use bacterial solution instead of fresh water in the concrete mixture. This method used a bacterial cell rather than a spore, which made the embedding procedure much easier. However, using an active bacterial cell state instead of a dormant spore may result in early calcium source conversion during concrete mixing. Once the concrete has set, the decreased calcium source may reduce the microbial concrete capacity to heal. Despite incorporating active bacteria cells in the concrete, Krishnapriyaa *et al.* [13] found that bacteria concrete precipitated white particles at 70 days of specimen age and that full cracks healing was achieved at 81 days of concrete age. The microstructure of concrete can be enhanced by embedding live bacteria since the bacteria continue to precipitate. It is seen by increasing the compressive strength at 28 days than 7 days. Jonkers *et al*. [12] examined an approach that is nearly identical to this one, but uses bacteria spore inserted into the mortar specimen. After 28 days, the majority of the spores were crushed in concrete. This was due to the hydration process in concrete, which reduced the pore volume and caused the imbedded spores to be crushed. The mineral-forming potential of bacterial cements were lowered. As a result, a protective vehicle is required to keep spores safe inside concrete. According to Tziviloglou *et al*. [17], impregnating light weight aggregate (LWA) with spores, calcium supply and nutrition is one way. The porous LWA will work as a medium for transporting bacteria-based self-healing agents into concrete while protecting it from crushing. The LWA of expanded clay particles has been studied and it has been found to result in ongoing healing activity for 28 to 56 days. However, replacing sand with expanded clay particles resulted in 40% reduction in concrete compressive strength. Wang *et al*. [15] used diatomaceous earth which has pore diameters ranging from 0.1 µm to 0.5 µm. The study discovered that capillary water absorption at cracks implies a high level of healing potential. When compared to concrete with bacterial aggregate, concrete containing bacillus-infused diatomaceous earth reduced absorption by 50%. Chen *et al.* [18] used ceramsite in another study and found a reduction in permeability. This approach made use of the LWA's porous network and followed a basic procedure. Changing the bacteria and calcium source from a solution to a powder is another option. It is identical as a direct method because no protective carrier for bacteria used in this procedure. CERUP was created by Da Silva *et al*. [19] by air drying, filtration and grinding to a particle size of less than 500 µm. The bacteria spore and nutrition were freeze dried by Wang *et al.* [15]. The spore and nutrition were enclosed in hydrogel and injected between glasses, after which they were freeze ground and freeze dried to produce powder. Hydrogel acted as a water retainer to help bacteria convert calcium sources metabolically. This enables self-healing to occur even when water is provided. A realistic situation of concrete would not have an abundance of water unless the structure is immersed. Even under realistic wet-dry cycles, the study found 40% to 90% healing ratios with a maximum repaired width of 0.5 mm. The cycles involve immersing the sample in water for 1 hour and then drying it for 11 hours. In comparison to Tziviloglou *et al.* [17], the amount of water given to the sample was reduced by 22 hours while still getting a comparable outcome. The addition of hydrogel to the concrete, on the other hand, caused the concrete to take longer to harden. As a result, the sample was only demolded after 48 hours in the mold. Hydrogel may have caused a delay in concrete setting by interfering with the development of C-S-H gel. A self-healing agent coating containing hydrogel, spores and nutrition. A self-healing agent coating containing hydrogel, spores and nutrition may be used to overcome the delay effect.

4.6 Crack remediation

Visually monitoring the diameter of mended crack or the decrease in penetration rate of cracked concrete is how autogenous healing is performed. At 28 days of age, cracks were produced and then healed in full water immersion or a wet-dry cycle. In comparison to full water immersion, the wet-dry cycle involves alternating exposure of the cracked area to water, which closely simulates the actual condition of the concrete structure. Overall, bacterial self-healing concrete had a healed width of 0.45 mm to 0.54 mm. Under full water immersion, Da Silva *et al*. [19] found a maximum width of 0.45 mm healed. In concrete, the highest width healed was achieved utilizing LWA incorporating Bacillus Subtilis. The maximum width that has healed is around 0.53 mm. Bacterial concrete was able to heal a maximum crack width of 0.5 mm after a shorter period of immersion. However, due to a lack of water exposure, the proportion of healing after 28 days was in the 40% to 90% range. A longer cycle may result in a higher proportion. Tziviloglou *et al.* [17] utilized an 11-hour longer immersion time for the specimen than Wang *et al*. [15] but did not achieve 100% crack healing. However, the following a 56-day wet-dry cycle, the sample had almost completely healed in term of water tightness. This suggests that water exposure to the crack location affects the bacterial concrete's ability to repair. This has been demonstrated by studies that have successfully repaired apparent cracks by increasing the amount of water exposed to the specimen. After 81 days of full immersion, Krishnapriya *et al*. [13] found that apparent cracks in bacterial concrete had healed completely. The reduction of water permeability over time has also been used to measure crack healing performance. After 49 days of healing, a combination of ceramsite, brewer yeast and Bacillus Mucilagionous in concrete was able to reduce water permeability coefficient from 7.9 – 8.3 x 10^{-5} m/s to 0.8 x 10^{-7} m/s. the reduction is over 100% which is consistent with Tziviloglou *et al*. [17], who reported a 96% water tightness recovery after 56 days. Even though the two studies used different methods to determine permeability, the results show that bacterial concrete has the ability to self-heal cracks. According to Wang *et al*. [15], the water permeability of bacterial concrete fell by 68% which is consistent with Chen *et al*. [18] findings. After

28 days of recovery and 1 hour of water immersion every 12-hour cycle, this result was accomplished. The water second ingredients of hydrogel in the self-healing agent component contributes to this.

Conclusion

As conclusion, this study is based on the objective of this study which are to summarize the flexural strength of concrete on different type of bacteria in bacillus family and to study the properties of self-healing concrete incorporation with bacillus family based on previous research. It can be said that the objective of this study is achieved as the result of flexural strength of self-healing concrete been analyzed from previous chapter. Flexural strength of self-healing concrete shows an increment than conventional concrete. Effect of incorporation of bacteria into concrete can be decided as a crucial component in increasing the concrete strength. However, the performance of concrete not only depend on the type of bacteria but also the optimal concentration of bacteria as the more the bacteria concentration, it will decrease the flexural strength. The optimal concentration of bacteria is on 10^5 cell/ml. Overall, the utilization of bacteria in concrete is a good way to increase the flexural strength of self-healing concrete. Next, on bacteria of self-healing concrete production procedures have been researched and performance has been measured. Any bacteria that capable metabolically convert calcium sources to calcium carbonate can be utilized to make autogenous healing concrete. To maintain concrete self-healing ability during its lifetime, it is critical to provide protection to bacteria in the concrete mix. When compared to conventional concrete, self-healing concrete may totally heal cracks on its own.

For future research, study focused on the curing day that should be consistent, bacteria type should be various and concentration followed by previous study.

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