# PRODUCTION AND OPTIMIZATION OF SELF-HEALING CONCRETE BY USING INDIGENOUS BACTERIA**

**Muhammad Aslam Bhutto[1], Kashif Ahmed[2*] and Muhammad Umar Bin Aamir[2]**

[1]*Department of Civil Engineering, N.E.D. University of Engineering & Technology, Karachi 75270, Pakistan.*
[2]*Department of Chemistry, N.E.D. University of Engineering & Technology, Karachi 75270, Pakistan.*
*Email: kashifahm@neduet.edu.pk

## ABSTRACT

In the construction world, concrete is the most widely used material because of its reliable maintenance and usage along with high fire and water resistivity. However, the major drawback of using concrete is its inefficiency of healing cracks, fishers automatically that typically arises due to lower tensile strength of material as well as due to erosion, salling and popouts etc. The present work targeted to investigate the parameters like compressive strength of bio-concrete, its flexural strength and pullout strength. We used *Bacillus clausii, Bacillus coagulans* and *Lactobacillus reuteri* for our study. The results show higher compressive strength (31.85 %, 37.08 %) of bio-concrete when *Bacillus coagulans* used and tested at 7 and 28 days; higher flexural strength (22.6 %, 23.0 %) in the presence of *Bacillus coagulans* and *Bacillus clausii* after 7 and 28 days of curing while higher pullout strength (51.26 %, 38.25 %) when bio-concrete was incorporated by *Lactobacillus reuteri*. It may be concluded that the use of bacterial strains in the concrete will be advantageous in reducing porosity, reinforcement bar corrosion as well as sealing of cracks to increase service life of structure. It will also improve compressibility and tensile strength to make it a life enriching and elegant construction material.

**Keywords:** Bio-Concrete**,** Bacterial Concrete, self-healing concrete.

## INTRODUCTION

Concrete is one of the most important construction materials in construction industry because of its strength, availability, fire and water resistivity, compatibility, sturdiness and its low price as compared to alternative construction materials like aluminum or bitumen etc. Present consumption of concrete is estimated as 11 billion metric tons per year. However, the only drawback of using concrete as construction material is its inability to heal shallow or small cracks, fishers automatically arises due to the lower tensile strength of concrete material as well as by scaling, Popouts, disintegration, construction errors, erosion etc. As a result it leads to the replacement of structures along with failure in service life (Jonkers *et al.,* 2010; Siddique and Chahal, 2011; Wang *et al.,* 2012).

Over recent decade several studies have been carried out to resolve this problem that includes use of anaerobic and aerobic bacteria microbes along with spectral studies of SEM, EDX and XRD to analyze compositional and micro structural effects, presence of calcite as well as involvement of ureolytic bacteria (Jasira *et al.,* 2016). Mechanical properties and strength characteristics tests were also conducted to seek out the favorable concentration of *B. subtilis* bacterium in self-healing concrete with fly ash as cement replacement (Milan and Sholar, 2018). Moreover another study was about the impact of immobilized microorganism cells with IONs on the potency of bio self-healing concrete with a special stress on compressive strength, drying shrinkage, and crystal characterization (Mostafa *et al.,* 2018). Another study in this regard was based on different researches within the recent years on the employment of microorganism concrete/bio-concrete for the enhancement within the sturdiness, mechanical and permeation aspects of concrete. It contains studies on different bacteria's, their isolation method, newly developed approaches for addition of microorganism in concrete, their effects on compressive strength and water absorption properties of concrete and also the SEM and XRD analysis of concrete containing microorganism (Abhishek *et al.,* 2016). Furthermore a unique research was carried out to investigate effects on self-healing mechanism of concrete by utilizing different active and passive treatments like biomineralization, autogenation of concrete and using spectrophotometry techniques for characterization (Mohamed Alazhari, 2017). Moving forward an elegant research represents that bacterium immobilized in graphite lead nano platelets were effective in samples pre cracked at three and seven days whereas bacteria immobilized in light-weight aggregates were much efficient in samples pre cracked on fourteen and twenty eight days. Additionally, results of compressive strength depict that self-healing concrete created with light-weight mixture incorporating immobilized bacterium had vital improvement in compressive strength of concrete (Wasim and Muhammad, 2016). However still there is a need to establish a comparative and optimization analysis based on spectral behaviors and mechanical characteristics between different types of bacteria

*Dr. Kashif Ahmed; Department of Chemistry, N.E.D. University of Engineering & Technology, Karachi 75270, Pakistan. Phone No: 03012275358; ** Part of manuscript presented in a conference.

and conventional concrete in order to get the most advantageous one so that more optimized conditions could be investigated on that specific bacteria to make this technology a bit more successful and live enriching.

The present study aims to investigate the stability parameters with more emphasis on compressive strength, flexural strength and pullout strength for optimization and comparison of self healing concrete on the basis of different bacterial behaviors with conventional concrete in order to find most beneficial bacterial microbe that provides self healing concrete of opulent performance and efficiency.

## MATERIALS AND METHOD

### Materials and Chemicals

The major chemicals and materials used in this study were portland cement (OPC grade 53), fine aggregates (4.75mm smaller than 0.5 microns), coarse aggregates (20mm greater than 0.5 microns) along with bacteria in their prepared culture media at NED university from microbiology department of FUUAST (Federal Urdu University) that were *Bacillus clausii, Bacillus coagulans* and *Lactobacillus reuteri*. Moreover chemicals used in the culture or media preparation of bacteria were nutrient agar (2-2.5g), heart infusion broth (3.7g), d-glucose (4 g) and peptone (1g).

### Instrumentation Used and Testing's Performed

The instrument used in this research were available in civil department lab of materials which is manual universal testing machine (UH 500 KNI) for compressive, flexural and pullout testing. Moreover bacteria sterilization and incubation was also being done in civil lab by using Autoclave and Incubation machinery. Furthermore slump testing after the preparation of concrete or bio-concrete had also been carried out in order to investigate the accuracy and consistency.

### Preparation of Bacteria Growth Culture in Solid Medium

The culture for bacterial growth had been prepared in solid medium by mixing all of the ingredients mentioned which were 2g nutrient agar and 3.7 g BHI (Heart Infusion Broth) in 100mL water with gentle stirring in a conical flask. Afterwards, the solution was heated till boiling occurs and a gel like substance was formed and then it was transferred to the test tubes and sealed with cap respectively in order to save it from impurities entrapment and then all the test tubes were sterilized to make it safe from contaminations in the autoclave machine where instruments were also sterilized before the start of experimental work. This prepared culture is known as *slant* where bacterial growth is meant to take place after collecting bacterial species inside it (Sri Bhavana *et al.,* 2017, Jonkers *et al.,* 2016, Achal *et al.,* 2013, Chahal *et al.,* 2012, Vashisht and Shukla, 2020).

### Preparation of Liquid Broth

The liquid broth was prepared by dissolving 3.3 g of nutrient agar in 100mL water in a conical flask. Afterwards the mixture was heated till its boiling and then transferred to the test tubes and sealed properly in order to avoid any impurities entrapment. Then it was sterilized in autoclave machine for saving it from impurities and contaminations. After sterilizing bacteria was inoculated inside it and then the prepared broth was incubated for 24 hours at $37^0$C (Sri Bhavana *et al.,* 2017, Gopikumar *et al.,* 2017, Jonkers *et al.,* 2016, Achal *et al.,* 2013, Chahal *et al.,* 2012, Vashisht and Shukla, 2020).

### Preparation of Concrete or Bio-Concrete

The concrete or bio-concrete was prepared by mixing all of the ingredients which include cement, fine aggregates, coarse aggregates, water and bacteria in certain fixed proportions which were 1:2:4 with the addition of liquid bacteria broth prepared. After the mixing of all of the ingredients in a mixing machine it was transferred to moulds that were 25 cylinders, 4 cubes and 2 beams for each specimen in order to mould the mixture into a desired shape to avoid any deformation in structure. This filling in mould was being done in approximately 3 equal layers and each layer was tamped 25 times with a 5/8 inch diameter tamping rod. Then after compaction of concrete material external surfaces were leveled effectively. Then it was left for 24 h in order to become hardened by getting shape of the mould. After being hardened it was placed in water curing tank in order to let it achieve its maximum properties and strength. After the completion of desired curing time which was 7, 14 and 28 days of curing different mechanical characteristics that were compressive strength, flexural strength, and pullout strength for comparative and optimization analysis (Sri Bhavana *et al.,* 2017, Gopikumar *et al.,* 2017, Jonkers *et al.,* 2016, Achal *et al.,* 2013, Chahal *et al.,* 2012, Vashisht and Shukla, 2020, Alshalif *et al.,* 2019).

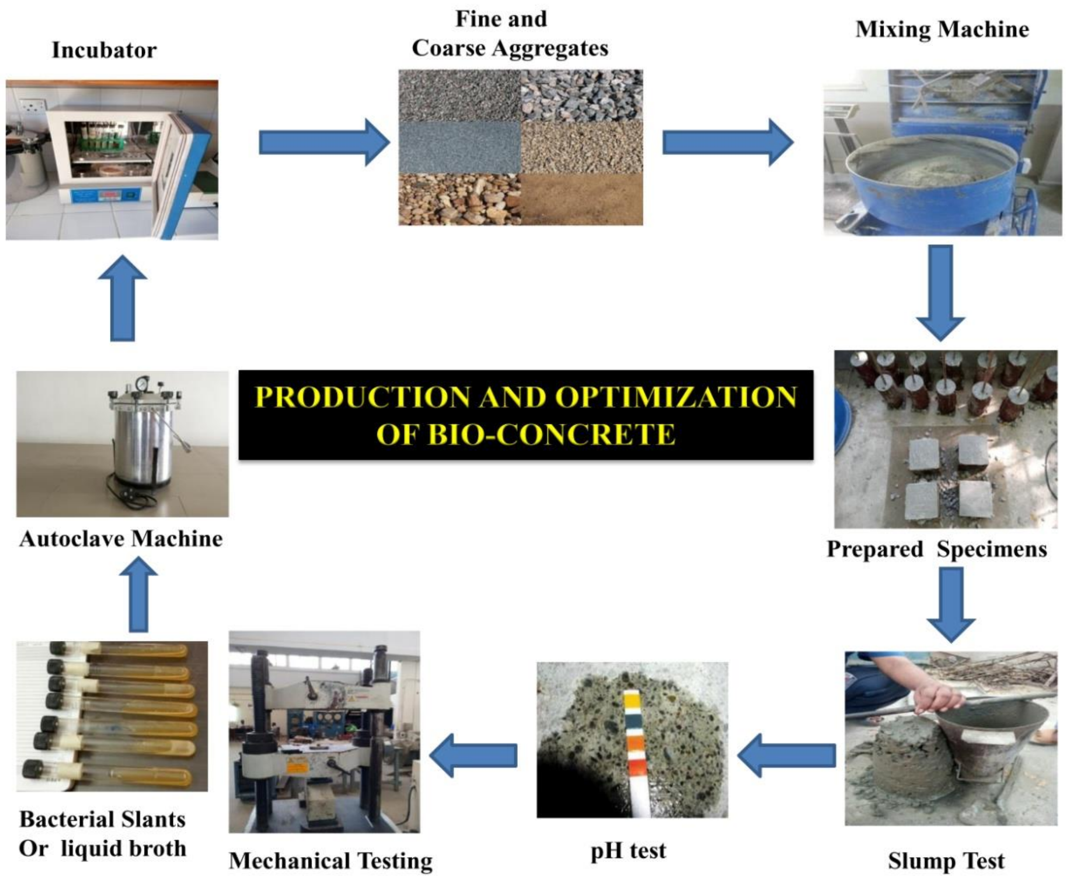


Fig 1. Graphical Abstract Illustration of the Studies carried out elegantly for comparison and optimization of bio-concrete.

## RESULTS AND DISCUSSION

### Compressive Strength:

The values and graphical representation of compressive strength for conventional concrete and bacterial concrete are mentioned in Table 1, Table 2, Fig 2 and Fig. 3. The specimens for testing were prepared by using cylindrical moulds with and without the bacterium inside as 100mmx100mmx100mm and 100mm diameter with 200mm height according to ASTM C39/39M. Compressive strength was investigated by the formula FC= P/A where P was the ultimate load and A was the loaded area observed after the demouldation and curing of conventional and bacterial concrete moulds where planes surfaces were in contact of compression testing machine and subjected to load. It was observed that the compressive strengths of bacterial concrete in case of *Bacillus coagulans* at 7 and 28 days of curing were notably higher than those of other bacterial and conventional concrete specimens containing higher increment around 31.85% & 37.08%. It may be because microorganism self-healing concrete has higher deposition on the cell wall surfaces due to the presence of microorganisms which accelerates higher $CaCO_3$ precipitation as well as in the pores of cement sand matrix that plug the pores inside mortar (Santosh *et al.,* 2017; Wasim and Muhammad, 2016). Furthermore the extra cellular cultural growth of microorganisms will contribute mostly in the strength of cement mortar with greater incubation periods and hence strength is higher at 7 and 28 days of curing also compressive strength expresses excellent correlation with days of curing if correlation coefficient R2 has higher values and that occurs conveniently in bacterial concrete specimens tested. A similar study has also been estimated by Ashok Verma *et al.* (2018). However our study shows comparison and optimization between three bacterial species based concrete and conventional concrete that makes it novel and unique and the results clearly indicate that *Bacillus Coagulans* provides higher compressive strengths in comparison with other specimens tested and this is what makes this study more elegant.

Table 1. Compressive Strength of Bacterial and Conventional Concrete.

| **Name of Bacteria** | **7 days maximum strength(KN)** | | | **Average Strength (KN)** | **28 days maximum strength(KN)** | | | **Average Strength(KN)** |
|---|---|---|---|---|---|---|---|---|
| Control | 30.2500 | 71.1406 | 56.2187 | 52.5364 | 72.0781 | 79.5156 | | 75.79685 |
| *Bacillus clausii* | 74.2343 | 84.0156 | 72.8281 | 77.026 | 81.0312 | 81.7968 | 82.8593 | 81.8597 |
| *Bacillus coagulans* | 56.1250 | 123.171 | 81.0468 | 86.7809 | 136.828 | 146.609 | 67.5937 | 117.0102 |
| *Lactobacillus reuteri* | 56.9687 | 45.9218 | 65.4062 | 56.0989 | 80.1562 | 40.0468 | 78.0625 | 66.0885 |

Table 2. % Compressive Strength.

| **Name of test** | **Name of specimen** | **Total 7 days strength (KN)** | **% Strength** | **Total 28 days strength (KN)** | **% Strength** |
|---|---|---|---|---|---|
| COMPRESSIVE STRENGTH | Control | 817.3268 | 19.3% | 946.5772 | 16% |
| | *Bacillus clausii* | | 28.3% | | 25.95% |
| | *Bacillus coagulans* | | 31.85% | | 37.08% |
| | *Lactobacillus reuteri* | | 20.59% | | 20.95% |

Comparative chart of compressive strength test results of conventional and bacterial concrete according to days of curing with % of curing at 7th and 28th days.

**Pullout Strength**

The graphical representation and increment in values of pullout strength in comparison of conventional concrete with those of bacterial concrete are mentioned in Table 3, Table 4, Fig 4 and Fig. 5. The specimens for testing were prepared by using cylindrical moulds along with 26th inch steel rods in the centre with and without the bacteria inside as 100mm × 200mm steel (650mm 0r 26’’ long steel rods according to ASTM C 900). It was observed that *Lactobacillus reuteri* based bacterial concrete specimens contains notably higher pullout strengths then other bacterial based specimens and conventional concrete around 51.26% and 38.25% at both 7 and 28 days of curing. This is due to the fact that the ratio of compression and pullout strength varies directly with the increment in the degree and age of compression which needs to be maintained constant for the accurate and effective results as studied by Malhotra (1975). Furthermore not major work has been carried out on the pullout efficiency of conventional and bacterial concrete but till now it has been declared that it measures the pullout of a specific steel rod from the specimen by cracking it hence it pulls out in the form of cone approximately 45 degrees in shape by a special tension ram of the equipment mentioned above and same happened in our study also accompanied by Malhotra (1980). Moreover, it has also been observed that there is correlations exist between the pullout strength and compressive strength of concrete cured at standard conditions. However our study shows comparison and optimization of three bacterial based concrete specimens with each other and with conventional concrete and the results clearly indicate that *Lactobacillus reuteri* based bacterial concrete specimen shows higher pullout strength than those of conventional concrete and other bacterial based concrete specimens tested which makes this study more scintillating and ethereal.

Table 3. Pullout Strength of Bacterial and Conventional Concrete.

| **Name of Bacteria** | **7 days maximum strength(KN)** | | | **Average Strength (KN)** | **28 days maximum strength(KN)** | | **Average Strength (KN)** |
|---|---|---|---|---|---|---|---|
| Control | 15.5781 | 19.1093 | 18.0937 | 17.5937 | 12.1562 | 24.5468 | 18.3515 |
| *Bacillus clausii* | 11.1406 | 16.8125 | 18.0000 | 15.3177 | 12.8125 | 30.0937 | 21.4531 |
| *Bacillus coagulans* | 18.3281 | 13.6406 | 15.9063 | 15.9583 | 18.4687 | 27.1875 | 22.8281 |
| *Lactobacillus reuteri* | 119.921 | 14.8125 | 19.4682 | 51.4006 | 34.0781 | 43.5312 | 38.80465 |

Table 4. % Pullout Strength.

| Name of test | Name of specimen | Total 7 days strength (KN) | % Strength | Total 28 days strength (KN) | % Strength |
|---|---|---|---|---|---|
| PULLOUT STRENGTH | Control | 300.8114 | 17.55 | 202.8747 | 18.09 |
| | *Bacillus clausii* | | 15.28 | | 21.15 |
| | *Bacillus coagulans* | | 15.92 | | 22.50 |
| | *Lactobacillus reuteri* | | 51.26 | | 38.25 |

Comparative chart of % of pullout strength test results of conventional and bacterial concrete according to 7 and 28 days of curing.

**Flexural Strength**

Table 5, Table 6, Fig 6, Fig 7, Fig 8 and Fig 9 shows the results of flexural strength test for both conventional and bacteria based concrete. Flexural strength was also investigated according to ASTM C78/78M by using the formula Flexural strength, $f_b$= P x l / ($bd^2$) where P was the load applied, l was the length and b and d were the cross section dimensions of the specimens after the demouldation and curing of conventional and bacterial concrete where specimens for testing were prepared by using cubical moulds as prism beam 2 feet×6’’×8’’with and without the bacterium inside. Amazingly it was observed that the flexural strength results of *Bacillus coagulans* and *Bacillus clausii* based bacterial concrete at 7 and 28 days were notably higher than those of conventional concrete and other bacterial concrete specimens tested at 7 and 28 days of curing containing 22.6% and 23.1%higher increment. It may be because flexural strength increases with increase in compressive strength and the age of specimens to be tested (Ahmed *et al*., 2016; Nagarajan *et al*., 2017). Furthermore flexural strength could show decrease with the increment in compressibility at the same age of concrete specimens while percentage of flexural strength slows down with the increment in sturdiness of concrete specimens. Moving forward similar results has also been projected by Santosh *et al.* (2017), Mohanasundharam *et al.* (2014). However our study shows comparison and optimization of three bacterial based concrete specimens with each other and with conventional concrete and the results clearly indicate that *Bacillus coagulans* and *Bacillus clausii* based bacterial concrete specimens’ shows higher flexural strength than those of conventional concrete and other bacterial based concrete specimens tested which makes this study bit more convenient and enriching.

Table 5. Flexural Strength and Beam Deflection of Bacterial and Conventional Concrete.

| Name of specimen | 7 Days Maximum Load (KN) | 28 Days Maximum Load (KN) |
|---|---|---|
| *Control* | 11.0937/12.1718 | 16.7187/13.5000 |
| *Bacillus clausii* | 14.0156 | 19.2968 |
| *Bacillus coagulans* | 14.6093 | 16.9843 |
| *Lactobacillus reuteri* | 12.6875 | 16.7500 |

| Control Load (KN) | 7 days testing Specimen 1 Def (MM) | Control Load (KN) | 7days testing Specimen 2 Def (MM) | Control Load (KN) | 28 days testing Specimen 1 Def (MM) | Control Load (KN) | 28 days testing specimen 2 Def (MM) |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0.01 | 1 | 0 | 1 | 0 |
| 2 | 0.02 | 2 | 0.03 | 2 | 0.01 | 2 | 0.05 |
| 3 | 0.05 | 3 | 0.06 | 3 | 0.05 | 3 | 0.09 |
| 4 | 0.06 | 4 | 0.09 | 4 | 0.07 | 4 | 0.14 |
| 5 | 0.08 | 5 | 0.11 | 5 | 0.1 | 5 | 0.18 |
| 6 | 0.09 | 6 | 0.14 | 6 | 0.13 | 6 | 0.21 |
| 7 | 0.11 | 7 | 0.16 | 7 | 0.15 | 7 | 0.24 |
| 8 | 0.13 | 8 | 0.19 | 8 | 0.19 | 8 | 0.26 |
| 9 | 0.15 | 9 | 0.2 | 9 | 0.2 | 9 | 0.3 |
| 10 | 0.18 | 10 | 0.22 | 10 | 0.21 | 10 | 0.32 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 11 | 0.20 | 11 | 0.25 | 11 | 0.23 | 11 | 0.35 |
| | | | | 12 | 0.26 | 12 | 0.37 |
| | | | | 13 | 0.29 | 13 | 0.39 |
| | | | | 14 | 0.3 | | |
| | | | | 15 | 0.32 | | |
| | | | | 16 | 0.35 | | |

| ***Bacillus clausii*** **Load (KN)** | **7 days testing Specimen 1 Def (MM)** | ***Bacillus clausii*** **Load (KN)** | **28days testing Specimen 2 Def (MM)** | ***Bacillus coagulan*** **Load (KN)** | **7 days testing Specimen 1 Def (MM)** | ***Bacillus coagulan*** **Load (KN)** | **28 days testing specimen 2 Def (MM)** |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 1 | 0.01 | 1 | 0.01 |
| 2 | 0 | 2 | 0.01 | 2 | 0.09 | 2 | 0.09 |
| 3 | 0 | 3 | 0.07 | 3 | 0.14 | 3 | 0.1 |
| 4 | 0 | 4 | 0.09 | 4 | 0.19 | 4 | 0.11 |
| 5 | 0 | 5 | 0.11 | 5 | 0.21 | 5 | 0.14 |
| 6 | 0.01 | 6 | 0.12 | 6 | 0.26 | 6 | 0.17 |
| 7 | 0.03 | 7 | 0.14 | 7 | 0.3 | 7 | 0.18 |
| 8 | 0.05 | 8 | 0.19 | 8 | 0.35 | 8 | 0.21 |
| 9 | 0.09 | 9 | 0.2 | 9 | 0.39 | 9 | 0.25 |
| 10 | 0.11 | 10 | 0.21 | 10 | 0.42 | 10 | 0.26 |
| 11 | 0.12 | 11 | 0.24 | 11 | 0.45 | 11 | 0.29 |
| 12 | 0.14 | 12 | 0.26 | 12 | 0.5 | 12 | 0.3 |
| 13 | 0.3 | 13 | 0.29 | 13 | 0.52 | 13 | 0.31 |
| 14 | 0.6 | 14 | 0.31 | 14 | 0.6 | 14 | 0.32 |
| | | 15 | 0.39 | | | 15 | 0.34 |
| | | 16 | 0.4 | | | 16 | 0.36 |
| | | 17 | 0.41 | | | | |
| | | 18 | 0.42 | | | | |
| | | 19 | 0.44 | | | | |

| ***Lactobacillus reuteri*** **Load (KN)** | **7 days testing Specimen 1 Def (MM)** | ***Lactobacillus reuteri*** **Load (KN)** | **28 days testing Specimen 2 Def (MM)** |
|---|---|---|---|
| 1 | 0 | 1 | 0 |
| 2 | 0.02 | 2 | 0 |
| 3 | 0.06 | 3 | 0 |
| 4 | 0.09 | 4 | 0.01 |
| 5 | 0.13 | 5 | 0.07 |
| 6 | 0.16 | 6 | 0.09 |
| 7 | 0.18 | 7 | 0.11 |
| 8 | 0.2 | 8 | 0.14 |
| 9 | 0.25 | 9 | 0.19 |
| 10 | 0.29 | 10 | 0.2 |
| 11 | 0.32 | 11 | 0.21 |
| 12 | 0.36 | 12 | 0.24 |
| | | 13 | 0.26 |
| | | 14 | 0.28 |
| | | 15 | 0.29 |
| | | 16 | 0.31 |

Table 6. % Flexural Strength.

| **Total Strength(KN)** | **% Strength** | **Total Strength(KN)** | **% Strength** |
|---|---|---|---|
| 64.5779 | 18 | 83.2228 | 18.2 |
| | 21.7 | | 23.1 |
| | 22.6 | | 20.4 |
| | 19.6 | | 20.1 |

Comparative chart of % of flexural strength test results of conventional and bacterial concrete according to days of curing.

## CONCLUSION

This study has been carried out for comparative and optimization analysis of bacterial based concrete specimens with those of conventional concrete. In this study three bacterial species were used namely *Bacillus clausii*, *Bacillus coagulans* and *Lactobacillus reuteri* as well as preparation of nutrient broth and bacterial cultural growth media was also conducted. The estimated results shown 31.85 % and 37.08% higher compressive strength of *Bacillus coagulans* based bacterial concrete specimens along with 22.6% and 23.1 % increment for *Bacillus coagulans* and *Bacillus clausii* in flexural and pullout strength of *Lactobacillus reuteri* based bacterial concrete specimens were 51.26 % and 38.25 % at 7 and 28 days of curing. In these studies, the target was to find the bacterial specie that provides higher efficiency and consistency of self-healing concrete by enhancing its mechanical characteristics and structural durability and all the bacteria used had been estimated as the most advantageous bacterial species based concrete specimens tested till now.

## REFERENCES

Abhishek T., P. Akshay and S. Khushpreet (2016). Bacterial concrete and effect of different bacteria on the strength and water absorption characteristics of concrete: a review. *Int. J. Civ. Eng. Tech.,* 7: 43-56.

Ashok Varma, B. and G.Chandra Sekhar (2018). Study on strength and durability properties of bio-concrete. *Int. J. Eng. Tech.,* 7 (2.1): 11-14.

Ahmed, M., M. Javed and M. Abul Salam (2016). A study of factors affecting the flexural tensile strength of concrete. *J. K. Sa. Uni. Eng. Sci.,* 28: 147-156.

Achal, V., A. Mukerjee, and M.S. Reddy (2013). Biogenic treatment improves the durability and remediates the cracks of concrete structures. *J. Cons. Bui. Mat.,* 48: 1-5.

Alshalif, A.F., M.I. Juki, N. Othman, A.A Al-Gheethi and F.S. Khalid (2019). Improvement of mechanical properties of bio-concrete using Enterococcus faecalis and Bacillus cereus. *Envoi. Eng. Res*., 24(4): (2019) 630-637.

Chahal, N., R. Siddique and A. Rajor (2012). Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of concrete incorporating silica fume. *J. Cons. Bui .Mat.,* 37: 645-651.

Gopikumar, S., K. Kiruthika, C.R.T. Suriyaprakash and P. Vignesh (2017). Next Generation Low Cost Bio Concrete for Sustainable Building. *Int. J. Eng. Sci. Inv.,* 6: 38-42.

Jonkers, H.M., E. Tziviloglou, V. Wiktor and E. Schlange (2016). Bacteria-based self-healing concrete to increase liquid tightness of cracks. *Cons. Bui. Mat.,* 122: 118–125.

Jonkers, H.M., A. Thijssena, G. Muyzer, O. Copuroglua and E. Schlangen (2010). Application of bacteria as self-healing agent for the development of sustainable concrete. *Eco. Eng.,* 36(2): 230-235.

Jasira, B., K. Ifrah, T. Aditya and S. Khushpreet (2016). Bio Concrete- The Self-Healing Concrete. *Ind. J. Sci. Tec*., 9(47): 1-5. DOI: 10.17485/ijst/2016/v9i47/105252.

Milan, J. and P.G. Sholar (2018). Experimental Study on Strength Characteristics of Self –Healing Concrete with Fly Ash. *Int. J. Eng. Res. Tec.,* 6: 1-4. ISSN: 2278-0181 ETCEA - 2K18 Conference Proceedings.

Mostafa, S., S. Ajit, K.S. Ali, E. Alireza, G. Younes and B. Aydin (2018). Mechanical properties of bio self-healing concrete containing immobilized bacteria with iron oxide nanoparticles. *App. Micro. Biotech.,* 102: 4489–4498.

Mohamed Alazhari, S.A. (2017). *The effect of microbiological agents on the efficiency of bio-based repair systems for concrete.* University of Bath, Somerset and UK, PHD thesis.

Mohanasundharam. C., R. Jeevakkumar and K. Shankar (2014). An Experimental Study on Performance of Bacteria in Concrete. *Int. J. Inn. Res. Comp. Sci. Tec.,* 2: 1-5 ISSN: 2347-5552.

Malhotra, V.M. (1980). Comparison of Pullout Strength of Concrete with Compressive Strength of Cylinders and Cores, Pulse Velocity, and Rebound Number. *J. Proc.,* 77: 161-170.

Malhotra, V.M. (1975). Evaluation of the pull-out test to determine strength of in-situ concrete *Mat. Riaux. Et. Cons.,* 8: 19-31.

Nagarajan, V., T. Karthik Prabhu, M. Gowri Shankar and P. Jagadesh (2017). A Study on the Strength of the Bacterial Concrete Embedded with Bacillus Megaterium. *Int. Res. J. Eng. Tec.*, 4: 1784-1788

Sri Bhavana, R., Polu Raju and S.S. Asadi (2017). Experimental study on bacterial concrete with partial replacement of cement by fly ash. *Int. J. Civ. Eng. Tech.*, 8: 201–209.

Santosh, A.K., S.K. Girish and K.B. Prakash (2017). A Laboratory Investigation on the Production of Sustainable Bacteria-Blended Fly Ash Concrete. *Ar. J. Sci. Eng.*, 42: 1039–1048.

Siddique, R.. and Chahal (2011). Effect of ureolytic bacteria on concrete properties. *Cons. Bui Mat.*, 25(10): 3791-3801.

Vashisht, R.. and A. Shukla (2020). Potential application of bacteria to improve the self-healing and strength of concrete. *J. Bui. Path. Rehab.*, 5: 1-13 https://doi.org/10.1007/s41024-020-0073-5.

Wang, J.V., N.K. De Belie and W. Verstraete (2012). Use of silica gel or polyurethane immobilized bacteria for self-healing concrete. *Cons. Bui. Mat.*, 26(1): 532-540.

Wasim, K. and B. Muhammad (2016). Crack healing in concrete using various bio influenced self-healing techniques. *J. Cons. Bui. Mat.*, 102: 349–357.

(*Accepted for publication October 2022*)