Effects of the concentration of various bacillus family bacteria on the strength and durability properties of concrete: A Review

Arun Kumar Parashar1*, Ankur Gupta1
1Assistant Professor, Department of Civil Engineering, GLA University, Mathura, India

*corresponding author- Email Id: arun.parashar@gla.ac.in

Abstract. It is almost impossible to avoid the development of cracks on the surface of the concrete even after using the best quality material and workmanship. These cracks may result into the degradation of concrete in terms of its strength and durability. Therefore it becomes utmost important to seal these cracks so that the devastating effects of the degrading agencies that may enter into the concrete through these cracks can be reduced or eliminated. This paper presents a review on the effects of the concentration of various bacillus family bacteria on the strength and durability properties of concrete. The bacteria with a concentration of 10⁰ CFU to 10⁸ has been considered in this review. This paper also outlines the self- healing ability of different bacillus family bacteria. Self- healing refers to the cracks in concrete, through addition of the bacillus family bacteria to the concrete mix and checks the impacts of bacillus family bacteria on the strength and durability properties of the concrete.

Keywords: Bacterial concrete, bacteria concentration, bacillus family bacteria, strength, durability.

1. Introduction

One of the most used material in construction industry is concrete [1]. Concrete is strong in compression and weak in tension so cracks are developed on the surface of concrete[2]. Micro cracking is unavoidable on the surface of concrete that can enhance the permeability and can reduce the life span and weakens the concrete[3][4]. This problem of cracking is also very much prominent in cement mortars [5]–[7]. Early age cracking of concrete structures is due to humidity fluctuations and temperature thereby making space that allows the harmful degrading agencies to enter into the concrete which tend to degrade the strength and durability of concrete gradually over time [8]. Many research works have tried to overcome the development of cracks on the surface of the concrete so as to reduce or eliminate its effect on the concrete by using various approaches[5], [9]–[12]. Autogenous healing is one such approach in which formation of calcium carbonate take place that helps in sealing of the cracks[13]. Positive results of calcite precipitation based methods have led to several researches on the use of bacteria in concrete. A variety of microorganisms have been used to improve the strength and durability properties of cement concrete[14]. Bacillus family bacteria are the most useful microbial mineral approach to improve the mechanical and durability properties of concrete by producing calcite precipitation to fill the void and pores present in the concrete[14]–[17]. E.Madhavi et
al. (2016) have shown that the mechanical properties of the fly ash and GGBS based concrete gets improved when a bacteria has been used in a concentration of $10^6$ cell/ml [18]. Sanjay et al. (2016) have studies the adaptability of the bacteria in nutrient broth medium and urea medium and the improvement in strength in both the mediums. It was reported that the bacteria is more adaptable in nutrient broth medium than urea medium and also developed better results in the nutrient broth medium [19].

In this study, investigation has been done to study the effect of bacillus family bacteria like subtilis, megaterium, sporosarcina pasteurii, sphaericus on the durability and mechanical properties of concrete. The bacteria concentration of up to $10^8$ cells/ml has been considered in the current study.

![Classification of bacteria](image)

**Fig. 1 Classification of bacteria[20]**

### 2. Methods

Biological agents can serve as an excellent means for developing self-healing property in the concrete. A number of bacteria such as bacillus subtilis, bacillus sphaericus, bacillus pasteurii and bacillus megaterium have been utilized by the researchers to study their effect on the mechanical and durability properties of the concrete. The best self-healing system is that which gets triggered immediately after sensing the development of cracks in the concrete. The cracks developed in the existing structures can also be easily repaired or retrofitted by the use of the self-healing technique. The superficial micro-cracks can be easily and efficiently healed with the use of the autogenous healing techniques. Calcium carbonate layer gets formed in the cracks, on addition of bacteria in the concrete, which confirms the calcite precipitation[21], [22]. The high alkalinity of the concrete is maintained by the addition of bacteria[23], [24]. The bond among the ingredients of the concrete such as cement gel, sand and aggregates become stronger due to the bacteria induced calcite precipitation[25]. Additionally, the durability of the concrete also gets improved due to the filling of the voids and micro-cracks. This bacterial precipitation can effectively fill the cracks of width less than 0.2 mm but if the width becomes more than 0.2 mm then the self-healing mechanism becomes ineffective in filling the micro-cracks. In bacteria induced concrete the development of cracks of any size triggers the action of the bacteria from its stage of hibernation. As soon as the calcite precipitation starts the cracks gets filled by the calcium carbonate thereby causing the self-healing of the concrete. Once the cracks gets filled the bacteria again gets back to their hibernate stage. This process gets repeated every time a crack is developed in the concrete. Bacteria perform as a long lasting healers and this mechanism of healing is called as Microbiologically Induced Calcium Carbonate Precipitation (MICP).
3. Effect of Bacteria on concrete properties

The bacillus family bacteria have been utilized for enhancing the characteristic properties of the concrete in a number of ways. The bacteria have been used in various concentrations up to a maximum of $10^8$ colony forming units (CFU). In most of the cases the mechanical and the durability properties of the concrete got enhanced on introducing bacteria in the concrete. However the properties showed variations with the varying bacteria concentration.

3.1. Effect of Bacillus subtilis bacteria

Bacillus subtilis bacteria have been utilized for improving the properties and durability of the concrete. The bacterial concentration has been used up to $10^8$ cells/ml. Shradha Jena et al. [27] used the various concentrations of bacillus subtilis bacteria at the rate of $10^0$, $10^2$, $10^3$, $10^5$ and $10^6$ cells/ml in the concrete. The results showed that strengths were increased up to $10^5$ cells/ml. The increases in compressive strength were 27.27%, 29.59% and 32% as compared to standard concrete at 7, 14 and 28 days and strength were deceased after the concentration of $10^5$ cell/ml. Use of Bacillus subtilis bacteria in concrete shows the enhancement in strength due to formation of calcite precipitation. Calcium carbonate precipitate filled the voids and heals the cracks presents in concrete. Chereddy Sonali Sri Durga et al. (2019) [28] used the bacillus subtilis bacteria with the concentration of $10^8$ cells/ml and check the impact of micro-organism on the strength and durability properties of the concrete with the help of ultrasonic pulse velocity, flexural strength test, compressive strength test, splitting tensile strength test, and water absorption test. The test results indicate that flexural, compressive and split tensile strength increased by 11%, 22% and 16% as compared to standard concrete at 28 days of testing. The water absorption reduced from 1.28% of standard concrete samples to 0.22% for bacterial mix concrete samples. The ultrasonic pulse velocity test was performed on the concrete specimens by direct transmission at 7, 14 and 28 days after casting. The velocity of the ultrasonic waves gets improved with the increase in time which indicates the improved impermeability of concrete and thereby showing the reduction in crack width due to CaCO$_3$ formation. Nidhi Nain et al. (2019) [29] used the bacillus subtilis bacteria with the concentration of $10^6$ cells/ml and checked the effect of bacteria on the mechanical and durability properties of the concrete. The test results showed an increase in the compressive and split tensile strength at the rate of 14.36% and 25.3% with the use of bacillus subtilis bacteria in concrete as compared to controlled concrete. Bacteria play a positive role not only in increasing the strength of concrete but also in enhancing the durability of concrete by self-

Fig. 2 Bacteria based self-healing concrete[26]
healing of cracks presents in concrete. Farnaz Salmasi et al. [30] used bacillus subtilis bacteria with the concentration of $10^7$ cells/ml and checked the durability properties with the help of chloride penetration test, water absorption, carbonation depth and water penetration depth test. The test results showed a reduction in the chloride penetration, water absorption, carbonation depth and water penetration depth at the rate of 20.5%, 13.1, 27.2% and 44.3% respectively with the use of bacteria in concrete as compared to controlled concrete. Wasim Khaliq [2] used the bacillus subtilis bacteria with the concentration of $3 \times 10^5$ cells/ml and checked the effect of bacteria on the strength and durability properties of the concrete. The maximum increase in compressive strength was found to be 12% in bacterial concrete as compared to controlled concrete. The increase in strength was due to self-healing of concrete by the bacteria.

3.2. Bacillus megaterium

Nidhi Nain et al. [29] used the bacillus megaterium bacteria with the concentration of $10^5$ cells/ml and checked the impact of these micro-organisms on the strength and durability properties of the concrete with the help of compressive strength test, split tensile strength test and Energy dispersive spectroscopy test (EDAX). The test results showed an increment in the compressive and split tensile of 22.58% and 18.29% respectively with the use of bacillus megaterium bacteria in concrete as compared to controlled concrete. Bacillus megaterium bacteria play an important role in increasing the strength of concrete as well as in improving the durability characteristics of the concrete. Vighnesh Rameshkumar et al. [31] used metakaolin pozzolan partially replaced by cement and bacillus megaterium bacteria with the concentration of $10^4$ cells/ml and studied the effect of bacteria on the mechanical and durability properties of the concrete. The test results showed the improvement in the strength and durability properties of concrete. The combination of metakaolin and bacillus megaterium bacteria provided the calcium carbonates to the concrete and filled the pores presents in the concrete. Ramin Andalib et al. [32] used the bacillus megaterium bacteria with the concentration ($10^3$, $10^5$ and $10^7$ cells/ml) and checked the strength properties of the concrete. It was found that maximum increase in strength was obtained at $10^3$ cell/ml concentration and after that the concentration was varied from $10 \times 10^3$ cells/ml to $50 \times 10^3$ cells/ml and variation on the strength were observed. The best results were obtained at $30 \times 10^3$ cells/ml concentration. V. Nagarajan et al. [33] used the bacillus megaterium bacteria with the concentration ($10^5$, $10^7$, $10^9$ cells/ml) and checked the strength of bacterial concrete by using of compressive strength, flexural strength and split tensile strength test. The results indicate that flexural, compressive and split tensile strength enhanced up to $10^4$ cells/ml concentration after that strengths started decreasing.

3.3. Bacillus sp.

N. Chahal and R Siddique (2013) [34] presented the method of self-healing in concrete. In this study sporoarcina pasteurii bacterial stain has been used. The conventional cement has been replaced by a combination of 10%, 20% and 30% of fly ash and 5% and 10% of silica fume. This combination was replaced in a medium containing bacterial solution of $10^3$, $10^5$ and $10^7$ cells/ml concentrations. Not only this, the experiment was supplemented by tests regarding porosity and water absorption, compressive strength and chloride permeability test for a period of 91 days. Finally, they resolved that the presence of S. Pasteurii has several positive impacts on concrete like it enhances the compressive strength, reduces the permeability and porosity when used in a combination with silica fume and fly ash concrete. It was also found that the recently formed cracks are sealed due to the presence of the bacteria. P. Ingle et al. (2017) [35] have analyzed the bio concrete in various aspects. They have also performed the qualitative tests like permeability test, compressive strength test etc. The species of bacteria that is used in this experiment is B. Pasteurii. The concentration of bacterial solution used for the production of concrete was $10^3$, $10^5$ and $10^7$ cells/ml. Lastly the observation found out to be the enhancement in strength and durability characteristics of concrete like rise in permeability and compressive strength and reduction in porosity of rice husk concrete. N. Balam [36] have presented
the tests regarding water permeability and rapid chloride, compressive strength and water absorption. They have used bacterial based light weight aggregate concrete (LWAC) with $10^6$ cells/ml bacterial culture of S. pasteurii stain. As a result, they found out that chloride permeability and water absorption reduced by 21.1% and 10.2% respectively. They also observed the enhancement in compressive strength by 20.1% in experimental sample associated with analogous properties in the control ones. They also added, in LWAC sample with bacteria the porosity is less and condensed when compared to the concrete assorted with only bacteria.

Navneet Chahal et al. [37] used the fly ash as the partially replacement (10%, 20%, 30%) with the cement and bacillus sp. bacteria with the concentration of (0, $10^3$, $10^5$, $10^7$) cells/ml and check the strength and durability with the help of Rapid chloride penetration, compressive strength and water absorption test. The test results show the enhancement in the compressive strength up to $10^5$cells/ml after that compressive strength was reduced so $10^5$cells/ml was optimum concentration of bacteria. Optimum reduction in water absorption was obtained at concentration of $10^5$cells/ml.

3.4. Bacillus sphaericus

B. Madhu Sudana Reddy et al. [38] used the bacillus sphaericus bacteria with the concentration ($10^6$, $10^3$, $10^1$cells/ml) and found that $10^3$cells/ml concentration gave the best result of strengths. This is due to calcium carbonate precipitation and better packing of pores in the concrete. The test results of strength, on M20 grade of concrete at the concentration of $0,10^3,10^5,10^7$ cells/ml of bacteria, in compression were determined as 27MPa, 32.4MPa, 35.5MPa and 31.6MPa respectively, in flexure were found as 3.71MPa, 3.92MPa, 5.21MPa and 4.52MPa respectively and in tension were determined as 3.78MPa, 4.23MPa, 4.52MPa and 4.28MPa respectively. Prince Akash Nagar et al.[39] used the bacillus sphaericus bacteria with the concentration of $10^6$cells/ml and calcined clay (10%, 15% and 20%) with the replacement of cement and checked the strength and durability properties of concrete using compressive strength test and water absorption test. The test result showed that strength was decreased with increasing proportions of calcined clay. Compressive strength were approx. decreased by 3.88%, 7.38% and 17.17% and water absorption was also decreased by 16.84%, 8.42% and 5.41% at replacement of 10%, 15% and 20% respectively with the calcined clay as compared to standard concrete. The bacillus sphaericus bacteria were then mixed in calcined clay concrete and the compressive strength increased by 21%, 24% and 24% and water absorption was decreased by 30.97%, 14.52% and 11.14% at 10%, 15% and 20% replacement of cement with Calcined clay. Jagannathan et al. (2018)[40] used the bacillus sphaericus and pasteurii bacteria and fly ash as a replacement of cement at the rate of 10%, 20% and 30% by weight of cement and found that the mechanical properties of the concrete got enhanced. Compressive, flexural and split tensile strength were increased by 10.82%, 5.25% and 29% respectively as compared to standard concrete. Gavimath et al. [41] used bacillus sphaericus bacteria as a self-healing agent in concrete mix. The compression strength was found to be enhanced by 31.05%, 45.98%, and 31.80% after 3, 7 & 28 days respectively. The strength of split tensile was also enhanced by 14.10%, 13.90% and 19.01% at 3, 7 & 28 days of testing respectively.

3.5. Miscellaneous bacteria

Nasrin Karimi et al. (2019)[42] used different types of fiber with the concentration $10^7$ cells/ml of bacillus subtilis bacteria. Bacterial culture was used as a replacement of water in the concrete mix and in a surface treatment gel. The bacteria-incorporated samples, with the highest decrement of 63.88%, 27.51% and 39.84%were recorded for water absorption, carbonation depths and chloride ions respectively. Thus, the use of micro-organisms in the concrete mix and its curing in the calcium lactate-urea solution have shown the capabilities of filling the voids in concrete which tends to decrease porosity in fiber-reinforced samples. H. Ling et al.[43] presented the effect of bacteria on self-healing of cracks in concrete by using chloride test. In addition to this, method of electro migration was used which resulted in hardened transmission of chloride. They witnessed the self-healing
capability of bacteria which can be used in healing the cracks. Bacteria can suspend the chloride transmission in cracks and hence can take protective impacts for reinforced concrete elements. The experiment also reflects a greater way of applying microbial self-healing technique in real time constructions. R. Siddique et al.[44] have presented effect of bio concrete in various concentrations. The study was conducted by replacing cement in concrete with 5%, 10% and 15% silica fume and at 10⁵ cells/ml bacterial concentration. Around 10-12% improvement in compressive strength in a period of 28 days was observed. The authors concluded that the properties of bacterial concrete are way better when compared to that of concrete without bacteria. The result includes reduction in chloride permeability, water absorption and porosity due to the presence of bacteria in concrete. Siddique et al.[45] have observed the effects on bacterial concrete when treated with 10%, 20% and 30% of CBFD in the place of cement. The concentration of bacterial solution was taken as 10⁵ cells/ml. The test regarding properties of bacterial concrete was performed after 28 and 56 days of curing. The strength and the durability properties of the concrete were found to be enhanced by the use of bacterial solution and CBFD as a replacement of cement.

Table 1 below presents the effect of the different bacteria concentrations on the strength and water absorption properties of the concrete.

Table: 1 Effect of Bacteria concentration on strength and water absorption properties of concrete

| Type of Bacteria | Bacteria Conc. (cells/ml) | Strength | Water Absorption | References |
|------------------|---------------------------|----------|------------------|------------|
| Bacteria Subtilis | 10⁰, 10¹, 10², 10³, 10⁴, 10⁵ | Strength increased up to 10⁵ cells/ml bacterial concentration then it started decreasing. | Water absorption decreased with the use of bacillus subtilis at 10³ and 10⁴ cells/ml. | [27][28][29][30] |
| Bacillus megaterium bacteria | 10⁰, 10¹, 10², 10³, 10⁴, 10⁵ | Flexural, Compressive and split tensile strength increased up to 10⁴ cells/ml concentration and beyond that strength started decreasing. | Water absorption of bacterial concrete was decreased as compared to standard concrete. | [29][31][32][33][34][35][36] |
| Bacillus sp. bacteria | 10⁰, 10¹, 10², 10³, 10⁴, 10⁵ | Compressive strength increased up to 10³ cells/ml and after that it started decreasing | Reduced permeability and water absorption when used in a combination with silica fume and fly ash concrete. Maximum reduction at 10⁵ cells/ml. | [34][37][35][36][38][39][40][41] |
| Bacillus sphaericus bacteria | 10⁰, 10¹, 10², 10³, 10⁴, 10⁵ | 10⁵ cells/ml concentration gave the best strengths. Calcined clay concrete at 10⁵ cells/ml concentration showed improved strength. | Water absorption of concretes was reduced using the bacteria in concrete. | |

4. Conclusions

Based on the investigation of the effect of bacillus family bacteria like subtilis, sporosarcina pasteurii, megaterium, sphaericus on the mechanical properties and durability of concrete with the concentration ranging from 10⁰ cells/ml to 10⁵ cells/ml, following conclusions can be made:

1. The use of bacteria in concrete reduced the water permeability by filing of void.
2. Mechanical properties of concrete enhance with the use of bacteria in concrete.
3. Durability of concrete increased with the help of self-healing process of bacteria in concrete.
4. Bacteria are also helpful in repairing cracks present in concrete.
5. Bacterial concentration 10⁵ cells/ml gave most significant results as compared to other bacterial concentration.
References

[1] K. Vijay, M. Murmu, and S. V. Deo, “Bacteria based self healing concrete – A review,” Constr. Build. Mater., vol. 152, pp. 1008–1014, 2017.

[2] W. Khaliq and M. B. Ehsan, “Crack healing in concrete using various bio influenced self-healing techniques,” Constr. Build. Mater., vol. 102, pp. 349–357, 2016.

[3] A. K. Parashar, N. Gupta, K. Kishore, and P. A. Nagar, “An experimental investigation on mechanical properties of calcined clay concrete embedded with bacillus subtilis,” Mater. Today Proc., Sep. 2020.

[4] P. Kumar Tiwari, P. Sharma, N. Sharma, M. Verma, and Rohitash, “An experimental investigation on metakaoline GGBS based concrete with recycled coarse aggregate,” Mater. Today Proc., no. xxxx, 2020.

[5] P. Sharma, N. Sharma, P. Singh, M. Verma, and H. S. Purihar, “Examine the effect of setting time and compressive strength of cement mortar paste using inimidodiacetic acid,” Mater. Today Proc., vol. 32, no. xxxx, pp. 878–881, 2020.

[6] M. Verma, N. Sharma, P. Sharma, and P. Singh, “Evaluate the Effect in Terms of Setting Time and Compressive Strength of Oleic Acid as an Admixture in Cement,” Test Eng. Manag., vol. May-June, no. 12422, pp. 12422–12427, 2020.

[7] M. Verma, N. Sharma, P. Sharma, and P. Singh, “Evaluate the Effect in Terms of Setting Time and Compressive Strength of Oleic Acid as an Admixture in Cement,” Test Eng. Manag., vol. May-June, no. 23116, pp. 12422–12427, 2020.

[8] E. Tziviloglou, V. Wiktor, H. M. Jonkers, and E. Schlangen, “Bacteria-based self-healing concrete to increase liquid tightness of cracks,” Constr. Build. Mater., vol. 122, pp. 118–125, 2016.

[9] R. Siddique, E. K. Singh, P. Kumal, M. Singh, V. Cornalidesi, and A. Rajor, “Properties of bacterial rice husk ash concrete,” Constr. Build. Mater., 2016.

[10] A. Gupta, N. Gupta, A. Shukla, R. Goyal, and S. Kumar, “Utilization of recycled aggregate, plastic, glass waste and coconut shells in concrete - A review,” IOP Conf. Ser. Mater. Sci. Eng., vol. 804, no. 1, 2020.

[11] N. Gupta, A. Gupta, K. K. Saxena, A. Shukla, and S. K. Goyal, “Mechanical and durability properties of geopolymer concrete composite at varying superplasticizer dosage,” Mater. Today Proc., no. xxxx, 2020.

[12] S. Praveenkumar and G. Sankararamanian, “Mechanical and durability properties of bagasse ash-blended high-performance concrete,” SN Appl. Sci., vol. 1, no. 12, pp. 1–7, 2019.

[13] S. Gupta, S. D. Pang, and H. W. Kua, “Autonomous healing in concrete by bio-based healing agents – A review,” Constr. Build. Mater., vol. 146, pp. 419–428, 2017.

[14] W. De Muynck, D. Debrouwer, N. De Belie, and W. Verstraete, “Bacterial carbonate precipitation improves the durability of cementitious materials,” Cem. Concr. Res., vol. 38, no. 7, pp. 1005–1014, 2008.

[15] S. A. Kadapure, G. S. Kulkarni, and K. B. Prakash, “Study on properties of bacteria-embedded fly ash concrete,” Asian J. Civ. Eng., vol. 20, no. 5, pp. 627–636, 2019.

[16] J. Wang, K. Van Tittelboom, N. De Belie, and W. Verstraete, “Use of silica gel or polyurethane immobilized bacteria for self-healing concrete,” Elsevier Ltd. 2012.

[17] T. Shanmuga Priya, N. Ramesh, A. Agarwal, S. Bhusnur, and K. Chaudhary, “Strength and durability characteristics of concrete made by micronized biomass silica and Bacteria-Bacillus sphaericus,” Constr. Build. Mater., vol. 226, pp. 827–838, 2019.

[18] E. Madhavi and T. Divya Bhavana, “Strength Properties of a Bacterial Concrete with Flyash and GGBS,” Int. J. Eng. Res., vol. V5, no. 02, pp. 546–548, 2016.

[19] N. Singla, S. K. Sharma, and J. S. Rattan, “An Experimental Investigation on Properties of High Strength Bacterial Concrete (Bacillus Subtilis),” pp. 381–385, 2016.

[20] K. Pappupreethi, R. Ammakunnoth, and P. Magudeaswaran, “Bacterial concrete: A review,” Int. J. Civ. Eng. Technol., vol. 8, no. 2, pp. 588–594, 2017.

[21] R. Pei, J. Liu, S. Wang, and M. Yang, “Use of bacterial cell walls to improve the mechanical performance of concrete,” Cem. Concrr. Compos., 2013.

[22] H. M. Jonkers, A. Thijssen, G. Muzyer, O. Copuroglu, and E. Schlangen, “Application of bacteria as self-healing agent for the development of sustainable concrete,” Ecol. Eng., 2010.

[23] R. Siddique and N. K. Chahal, “Effect of ureolytic bacteria on concrete properties,” Construction and Building Materials, 2011.

[24] Y. Ç. Erşan, F. B. Da Silva, N. Boon, W. Verstraete, and N. De Belie, “Screening of bacteria and concrete compatible protection materials,” Constr. Build. Mater., 2015.

[25] N. K. Dhami, M. S. Reddy, and A. Mukherjee, “Improvement in strength properties of ash bricks by bacterial calcite,” Ecol. Eng., 2012.

[26] K. Vijay, M. Murmu, and S. V. Deo, “Bacteria based self healing concrete – A review,” Constr. Build. Mater., vol. 152, no. October, pp. 1008–1014, 2017.

[27] S. Jena, B. Basa, K. C. Panda, and N. K. Sahoo, “Impact of Bacillus subtilis bacterium on the properties of concrete,” Mater. Today Proc., no. xxxx, 2020.

[28] C. S. S. Durga, N. Ruben, M. S. R. Chand, and C. Venkatesh, “Performance studies on rate of self healing in bio concrete,” Mater. Today Proc., vol. 27, no. xxxx, pp. 158–162, 2020.
[29] N. Nain, R. Surabhi, N. V. Yathish, V. Krishnamurthy, T. Deepa, and S. Tharannum, “Enhancement in strength parameters of concrete by application of Bacillus bacteria,” Constr. Build. Mater., vol. 202, pp. 904–908, 2019.

[30] F. Salmasi and D. Mostofinejad, “Investigating the effects of bacterial activity on compressive strength and durability of natural lightweight aggregate concrete reinforced with steel fibers,” Constr. Build. Mater., vol. 251, p. 119032, 2020.

[31] V. Ramesh Kumar, S. Prabhath Ranjan Kumar, V. Poornima, R. Venkatasubramani, and V. Sreevidya, “Improvements in mechanical and durability parameters of bio-engineered concrete with metakaolin as a partial substitute for cement,” Eur. J. Environ. Civ. Eng., vol. 0, no. 0, pp. 1–14, 2020.

[32] R. Andalib et al., “Optimum concentration of Bacillus megaterium for strengthening structural concrete,” Constr. Build. Mater., vol. 118, pp. 180–193, 2016.

[33] V. Nagarajan, T. K. Prabhu, M. G. Shankar, and P. Jagadesha, “A Study on the Strength of the Bacterial Concrete Embedded with Bacillus Megaterium,” Int. Res. J. Eng. Technol., vol. 4, no. 12, pp. 1784–1788, 2017.

[34] N. Chahal and R. Siddique, “Permeation properties of concrete made with fly ash and silica fume: Influence of ureolytic bacteria,” Constr. Build. Mater., 2012.

[35] P. P. K. Ingle, P. V. S. Bhagat, P. P. M. Shrestha, and P. R. D. Potdar, “Effect of Bacteria on Partial Replacement of Cement with Rice Husk Ash,” no. March, pp. 3–8, 2017.

[36] N. Hosseini Balam, D. Mostofinejad, and M. Eftekhari, “Effects of bacterial remediation on compressive strength, water absorption, and chloride permeability of lightweight aggregate concrete,” Constr. Build. Mater., 2017.

[37] N. Chahal, R. Siddique, and A. Rajor, “Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of fly ash concrete,” Constr. Build. Mater., 2012.

[38] B. Madhu Sudana Reddy and D. Revathi, “An experimental study on effect of Bacillus sphaericus bacteria in crack filling and strength enhancement of concrete,” in Materials Today: Proceedings, 2019.

[39] P. A. N. Agar, N. Gupta, K. Kishore, and A. K. Parashar, “Coupled effect of B. Sphaericus bacteria and calcined clay mineral on OPC concrete,” Mater. Today Proc., no. xxxx, 2020.

[40] P. Jagannathan, K. S. Satya Narayanan, K. D. Arunachalam, and S. K. Annamalai, “Studies on the mechanical properties of bacterial concrete with two bacterial species,” Mater. Today Proc., vol. 5, no. 2, pp. 8875–8879, 2018.

[41] A. Gandhimathi, D. Suji, and B. Elayarajah, “Bacterial concrete: Development of concrete to increase the compressive and split-tensile strength using bacillus sphaericus,” Int. J. Appl. Eng. Res., vol. 10, no. 3, pp. 7125–7132, 2015.

[42] N. Karimi and D. Mostofinejad, “Bacillus subtilis bacteria used in fiber reinforced concrete and their effects on concrete penetrability,” Constr. Build. Mater., vol. 230, p. 117051, 2020.

[43] H. Ling and C. Qian, “Effects of self-healing cracks in bacterial concrete on the transmission of chloride during electromigration,” Constr. Build. Mater., 2017.

[44] R. Siddique et al., “Effect of bacteria on strength, permeation characteristics and micro-structure of silica fume concrete,” Constr. Build. Mater., 2017.

[45] R. Siddique et al., “Influence of bacteria on compressive strength and permeation properties of concrete made with cement baghouse filter dust,” Constr. Build. Mater., 2016.