Hydration Effect of Boric Acid on the Strength of High-Performance Concrete (HPC)

Suriyaprapaksh Rajadesingu¹ and Kantha Deivi Arunachalam*²
Center for Environmental Nuclear Research, Directorate of Research, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamil Nadu, India, 603203
Email: kanthad.arunachalam@gmail.com; Phone: +91-9962211166

Abstract. Boron compounds are commonly used as a cementitious composite material for the attenuation of neutron and gamma radiation in HPC-M40. Boron compounds play a major role in the concrete for radiation shielding properties but addition of boric acid (H₃BO₃) to concrete drastically reduce hardening and strength. Commonly for radiation shielding of high thermal neutron boron based materials used in high purity concrete. In this study, different percentages of boric acid 1, 2, 3, 4 & 5% were added to the high-performance concrete (HPC) and the effects on hydration process and strength were determined. Boron compounds will modify the active sites in the cement material and increase the setting time. The hydration of cement in addition to boric acid in the high-performance concrete has been studied using, X-ray diffraction, Fourier Transfer Infrared Spectrometry (FT-IR) and Field Emission Scanning Electron Microscopy (FESEM). The addition of boric acid concentration into the concrete specimen it is very strength til 60th day of curing. At the end of curing days compressive strength dramatically improved.

1. Introduction
The novelty of this study is to investigate the addition of high percentage of boron compounds to concrete and crisscross the strengthening properties on long time hydration. Cement and concrete are the most common materials in the construction field. Chandramouli et al., [1], especially for the construction of a nuclear power plant. Concrete possesses plenty of positive properties, but mainly cement is used as an essential part of the concrete, representing large environmental burden. Boric acid (BA) is one of the least understood and abundant elements that can be applied in semiconductor field to use in constructions of nuclear installations to prevent gamma and neutron emission during plant operations [2-3]. Addition of boron to the concrete will increase the gamma and neutron attenuation coefficient. Kratochvil J et al., [4]. Boron has virtuous properties so that it can be used in various fields of engineering, military field, radiation shield, textiles industries, metallurgy, building ingredients, aerospace engineering, nuclear power plant and electronics fabrications. One of the easiest ways to add boron compound in concrete is in the form of boric acid and borax, Jang BK et al., [5]. In this investigation, concrete samples were prepared with ordinary Portland cement (P53) by replacing with 1, 2, 3, 4 and 5% of boric acid in the total volume of cement. In this dataset 7, 14, 21, 28, 60, 90, 120 and 150 days compressive strength were calculated using digital compression machine, Rafiee MA et al., [6]. shown in Figure 1.

Concrete is one of easiest method for shield purpose as it is inexpensive and adaptable for any construction design, Ewels C et al., [7]. Different concrete mixtures of various proportions are readily available and have been passed down over generation by builders, Kharita M H et al., [8]. An
important variant of this concrete is M 40 which implies the characteristic compressive strength is 40 N/mm$^2$ and standard ratio for mixing with Course Aggregates, Fine Aggregates, Water and Cement. To reduce the fast moving neutron high scattering cross section materials like hydrogen, iron, and carbon can be used. Hydrogen, iron, and carbon can be applied in concrete aggregates for neutron shielding application of fast-moving electrons, Rajavikraman [9]. Radiations have an adverse effect on concrete as well and it is seen that nuclear radiations may influence the structure and mechanical properties of the materials significantly. Since radiation is present all around us and we are always exposed to environmental radiations from our surroundings in our day to day life [10-11]. But the levels of radiations are of course at a level to which our body has been acquainted with so there is not much harm caused. With the implementation of modern technologies and new sciences in this growing era, we are looking at upside in the incidences of these radiations in our daily life. The high growth in the incorporation of nuclear energy in past decades have made us to find the various modification of the sources to come up with even more breathtaking advancements, Singh V P and Badiger N M [12].

As the growth has increased so has the number of constraints with it. There have been immediate as well as adverse effects coming up with the insertion of these new technologies. These radiations from plants and research centers are having their effect on the community at large, especially people living around these centers, Vega-Carrillo H R [13]. The growing concerns need to be taken care of or have is close by them. There are many types of research undergone which might pose a potential solution to this problem but some of the other restraints have been reported in each.

Radiation shielding properties have been tested for various materials and Boron has been proven to be an effective element. Concrete is another inexpensive material for radiation shielding but the drawback is the thickness which is very difficult to achieve and labor intensive so the inexpensiveness is hampered. The mixing of Boron in the form of various compounds has proven to be effective at very low thickness for the shielding properties but there are also limitations to those views, the most prevalent of them being the loss of strength. We are trying to increase not only the strength of the concrete but also the attenuation of the radiation. Radiations emitted by elements are of various types depending on the nature and the atomic size and the isotope of the element. The rays emitted include: (i) Alpha (ii) Beta (iii) Gamma and (iv) Neutron, which has specific ionizing properties and capabilities which might be harmful to humans. It also used for low dose for the cancer there is uncertainty about the effect, İçelli Orhan Mann [14]. The study conducted in 1984 &1994 concluded that the average monthly dose exceed the threshold value of 0.1 mSv to 2.4 mSv, Auvinen A [15]. This has been overcome in modern days with the advancements of science and technologies but the question about the protectiveness of the people in and around the nuclear plant still remains a question of dispute. Various studies have shown the various penetration levels and the blocking effect of various materials towards these Irradiations and a conclusion has been drawn that: i) Alpha rays blocked by Material like paper or our bare skin so there is no harmful effect in low doses. ii) Beta Rays can be prevented by the use of an aluminum foil and being lightweight they can penetrate the skin. iii) Gamma Rays have an electromagnetic spectrum passing through every object except thick lead > 1 cm[16-17].

Being the 5 elements laying very close to carbon the properties of this element is often related to that of carbon. But there is more than meets the eye. Though being the second strongest element after carbon in diamond, the property of it to increase the neutron shielding of M40 concrete and slow down the secondary captured gamma-rays, Pomaro B [18]. The boron isotope has a high capture tenacity at B-10 for thermal neutrons so boron widely used for gamma and neutron shielding and if is more effective compare than other elements to capture thermal neutrons. There are three ways in which the boron can be added in M40 concrete for effective shielding to suppress gamma rays emission, Xu S [19].

1. As aggregates: there are boron-containing aggregates which can be used in concrete for radiation attenuation. Some of boron compounds as listed by American standard for addition as additive for the radiation attenuation, Kharita M H [20].

2. Using boron as a cement mixture.
3. Addition of compound in water as soluble compounds for their uniform distribution [8].

Addition of boron compounds to the cement the hydration process may include

- When the hydration process occur calcium oxide (CaO) reacted with water (H₂O) and started produce calcium hydroxide (Ca[OH]₂).
- In this reaction water in molecules quickly converts to alkaline solution. Absorptions of calcium cations (Ca²⁺) and hydroxide anions (OH⁻) in alkaline solution increase and B(OH)₃ rapidly dissolves. B(OH)₃ ions in mixture react with OH⁻ ions and they form the tetra hydroxyl-borate (B[OH]₄⁻) compound. Finally Ca⁺ cations react with B(OH)₄⁻

\[
\text{Ca}^{2+} + 2[B(OH)4^-] + 2\text{H}_2\text{O} \leftrightarrow \text{Ca}[B(OH)4]_{2.2}\text{H}_2\text{O} \tag{1}
\]

The precipitated calcium di borate (CBH₆) compound somewhat or fully covers the surface of cement materials. Hydration reaction of cement particulates partially or fully covered with an impermeable CBH₆ layer either completely stops or fairly retards. This is the reason for the hydration and also formation of flash setting. The slowdown effect of boron is seen in Binici H [21]. The slowdown or fast up effect can be changed by using suitable fast up/retarder additives. In this experiment boron were mixed with the water for casting M40 concrete shown in Figure 3.

2. Materials and Methods

2.1. Concrete Design Mix

The HPC - M40 grade and ordinary Portland cement P53, were obtained from Chettinad Cement (Pvt.) Company, India. 12 mm coarse aggregates were used after sieved manually and the concrete grade and design mix coarse aggregates size varied. To reduce chloride contamination river sand wash added as a fine aggregate and distilled water was used for the preparation of concrete to avoid other contaminations. Table 1 & 2 shows the composition and properties of Portland P53& H₃BO₃.

| Table 1. Chemical composition and physical properties of P53 cement (Portland cement). |
|-----------------------------------|-----------------|-----------------|
| Chemical composition of P53 cement (%) | Physical properties P53 cement |
| CaO | 61.69 | Specific gravity |
| SiO₂ | 19.8 | Retained on 45 μm (%) |
| Al₂O₃ | 5.59 | |
| Fe₂O₃ | 3.21 | |
| MgO | 1.34 | |
| SO₃ | 3.89 | |
| K₂O | 1.79 | |
| Na₂O | 0.19 | |
| Loss on ignition | 2.5 | |

| Table 2. Chemical composition and physical characteristics of H₃BO₃. |
|-------------------------------------|-----------------|-----------------|
| Chemical composition (%) | Physical characteristics |
| Assay | 99.5 | Molecular Weight |
| Cl | 0.0002 | pH (4% aq. Sol.) |
| SO₄ | 0.001 | Boiling Point |
| Fe | 0.0002 | Melting Point |
| Pb | 0.0005 | Solubility |
| Cu | 0.0002 | Density |
2.2. Mix Proportions

The design mix proportions of grade-M40 concrete was prepared by the addition of 1, 2, 3, 4, and 5% of boric acid to replace to the total weight of the cement content. The most important criteria for the concrete are the strength imparted ~40 N/mm$^2$ which is the standard required for the heavy mechanisms carried out in the plant. This experiment is done after many trial and errors. Triplet concrete cubes were casted for the compressive strength properties Figure 4. Design mix proposition of the M40 concrete by weight of the specimen (Wt. %) is given in table 3. following the M40 concrete design mix ratio of 1:1.65:2.9:0.4. (Cement: Fine Agg.: Course Agg.: Water (lit.))

The equation for the calculation of cement is given by:

$$\text{Cement quantity} = 400 \left(\frac{\text{amount of cement}}{\text{m}^3}\right) \times \text{Specimen Dimension} \times \text{No. of cubes} \times \text{Wastage}$$

(2)

| Parameter | Boric acid | Cement | Fine aggregate | Coarse aggregate | Water |
|-----------|------------|--------|----------------|------------------|-------|
| Control   | -          | 1.66   | 2.73           | 4.84             | 0.664 |
| BA 1%     | 0.0166     | 1.6434 | 2.73           | 4.84             | 0.664 |
| BA 2%     | 0.0332     | 1.6268 | 2.73           | 4.84             | 0.664 |
| BA 3%     | 0.0498     | 1.6102 | 2.73           | 4.84             | 0.664 |
| BA 4%     | 0.0664     | 1.5936 | 2.73           | 4.84             | 0.664 |
| BA 5%     | 0.083      | 1.577  | 2.73           | 4.84             | 0.664 |

2.3. Casting and Curing

The method of design mix for the HPC-M40 grade concrete is comparable to conventional concrete. The mixing procedure of this concrete materials were kept in the 56 dm$^3$.

The concrete mixture was added with coarse aggregate (12mm) and different percentage of BA and dissolved in distilled water.100 × 100 × 100 mm cubic steel molds were used for the concrete specimens. After a couple of minute the steel molds were removed from the vibrator and kept at room temperature for curing in the laboratory condition for 48 h. The concrete specimens were de-molded and kept for curing by immersing the water until testing. The higher concentration of BA cubes were de-molded after 96 h due to the hydration and not required for water curing.

2.4. Setting Time Experiment

The setting times of the flexible material with and without boron were analyzed and calculated using Vicat needle apparatus (Model: ASTM C 187-191) as shown in Figure 2. Vicat needle was used to study the effect of addition of different percentage of boron. Different percentage BA with the initial and final sitting time of boron results are shown in Figure 3. The addition of boron at different percentage 1-5 showed that there was an initial increased setting time and which got delayed later.
Figure 1. Digital Compression testing machine.

Figure 2. Vicat needle apparatus.
3. Characterization

3.1. XRD Analysis

The structural properties of Boric acid nanoparticles were studied using X-ray powder diffraction (XRD) analysis. The powder XRD patterns of the Boric acid nanoparticles were determined using Bruker D8 advance X-ray diffractometer which uses Cu-Kα radiation of wavelength $\lambda \sim 1.5415 \text{ Å}$, at the scanning speed of 0.02°/s with the Bragg angle 2θ over a range of 5° to 100° at room temperature [23-24].

3.2. FT-IR Analysis

The functional properties of the Boric acid particles were determined using Perkin-Elmer FTIR spectrometer. FT-IR analysis was carried out using Cary 660 FT-IR, Agilent Technology. The samples were prepared as a pellet using potassium bromide in the ratio of 1:10 and analyzed by KBr pellet technique and scanned in the range of 4000-400 cm$^{-1}$ with a resolution of ±4 cm$^{-1}$ [24-26].

3.3. FESEM Analysis

The size and the surface morphology of the BA samples were analyzed by Field Emission Scanning Electron Microscopy (FESEM). A samples were spread evenly on the sterile carbon tap and analyzed with an quickening voltage of 20 kV using Quanta 200 FESEM. [27-28].

4. Results and Discussion

4.1. Setting time

The initial and final setting times of Portland cement in presence of different percentage of Boric acid are shown in Figure 3. The setting time is directly proportional to the concentration of the BA showing increase in the initial and final setting times with the increase of BA concentration. This clearly showed that BA arrested the hydration of BA and Portland cement.

![Figure 3: Variation of setting time (BA).](image-url)
4.2. Strength properties

The compressive strength of the specimens were calculated in a digital compression machine (Model: Accro Tech AT-125-2) and shown in Figure 1. The addition of different percentages of boron such as 1, 2, 3, 4 & 5 into the concrete increased the compressive strength of the specimens. It was observed that addition of various percentage of boric acid did not improve the strength up to 21st days of curing; whereas after 28th, 90th, 120th and 150th days of curing the strength gradually increased compared to the control. When the curing days reached 150th days, the 2% and 4% of boric acid specimen cubes showed good compressive strength as shown in Figure 5.

Figure 4. M40 Design mix Concrete Specimen.
4.3. XRD Results

The X-ray diffraction pattern has been analyzed using powder X software and compared with the JCPDS No. 30-0199. The X-ray diffraction pattern of Boric acid particles are shown in Figure 5. It was revealed from the diffraction pattern that the samples were polycrystalline in nature and the crystalline nature of the materials were confirmed from the broadness of the peaks. The preferential orientation of Boric acid along (100) plane confirmed the triclinic phase of the sample shown in Figure 6.

The average crystallite size of the Boric acid was calculated using Sherrer’s formula [28].

\[
D = \frac{0.91}{\beta \cos \theta}
\]  
(3.1)

Where \(\lambda\) is the wavelength of the X-radiation used (\(\lambda = 1.54\ \text{Å}\)), \(\beta\) is the full width at half-maximum (FWHM) value in radians and \(\theta\) is the Bragg’s diffraction angle in degree. The calculated mean crystallite size was 39.01 nm. The lattice parameters were calculated as \(a = 7.01\ \text{Å}, b = 7.04\ \text{Å}\) and \(c = 6.58\ \text{Å}\) whereas the values of interplanar spacing were \(\alpha = 92.84^\circ, \beta = 101.06^\circ\) and \(\gamma = 119.68^\circ\). The micro strain was calculated using the formula [29].

\[
\varepsilon = \frac{\beta \cos \theta}{4}
\]  
(3.2)

whose value was \(8.88 \times 10^{-4}\) which confirms the presence of a very small amount of strain in the synthesized samples [31-32].
4.4. FTIR Results

The functional groups present in the boric acid were analyzed using FTIR spectroscopy and the spectrum is shown in Figure 7. The presence of various peaks showed the vibrations of the various functional groups existing in the sample. The presence of a peak at 3205 cm\(^{-1}\) shows the stretching vibrations of the O-H bond [7]. The peaks at 2358 and 2252 cm\(^{-1}\) may be attributed due to the C-H stretching vibrations [32-33]. Since the chemical element consists of boron which is a non-metal, the presence of these vibrations is due to the absorbance of moisture from the atmosphere during the KBr pellet technique. The presence of a peak at 1350 cm\(^{-1}\) is due to the asymmetric stretching vibrations of B-O in BO\(_3\) molecules and the peak at 1184 cm\(^{-1}\) may be due to the out of plane bending vibrations of B-OH. The presence of a peak at 754 cm\(^{-1}\) may be attributed to the vibrations of -OH. The peak at 643 cm\(^{-1}\) represents deformation vibrations of the atoms in B-O bond. Whereas the peak at 538 cm\(^{-1}\) represents the bending vibrations of O-B-O bond [35-37]. Thus the presence of functional groups is confirmed from the FTIR analysis.

![Figure 6. X-ray diffraction of BA.](image)
Figure 7. FTIR spectra of Boric Acid.

4.5. Field Emission Scanning Electron Microscope

The FESEM analysis of the samples were analysed using Quanta 200 FE-SEM as shown in Figure 8. The FESEM data showed that the BA powder is a poly disperse systems. The analysis of the dispersed composition revealed that 45% of the particles have a size of less than 20 microns [38-39]. The crystals of boric acid particles are combination of the planar layer of their thickness around 100 nm [39].
Figure 8. SEM Images of Boric acid.

5. Conclusion
The effect of addition of boric acid in concrete specimens were studied for its morphology, structure and function. Various technique such as XRD, FESEM & FT-IR were used to study the properties. The crystalline nature of the specimen evidenced the enhancement of the radiation attenuation properties. The existence of BO$_3$ in concrete samples were confirmed by FT-IR and the formation of the uniform sheets like shape was evidenced by FESEM image. The functional group and shape of the boron compounds added HPC concrete proved that the boron mixed HPC concert is best suited for gamma and neutron shielding. Our results also concluded that hydration of specimen will be reduced when its exposed for longer duration of curing by the addition of boric acid Figure 5. Our observations proved the suitability of addition of high percentage of boron in HPC for gamma and neutron attenuation.

6. References
[1] K Chandramouli, R P Srinivasa, S T Seshadri, N Pannirselvam and P Sravana 2010 Rapid Chloride Permeability Test for Durability Studies on Glass Fibre Reinforced Concrete *ARPN J. Eng. Appl. Sci.* **5** 67–71
[2] L Di, C Wang, J Wu, L S Wan and Z K Xu 2011 Progress in boric acid based saccharide sensors *Fenxi Huaxue/ Chinese J. Anal. Chem.* **39** 592–598
[3] D Koupouri and G N Angelopoulos 2015 Effect of boron waste and boric acid addition on the production of low energy belite cement *Cem. Concr. Compos.* **68** 1–8
[4] J Kratochvil, T Opravil and P Diviš 2014 The Effect of Boron and its Compounds on Setting of Portland Cement *Adv. Mater. Res.* **1000** 16–19
[5] B K Jang, J C Lee, J H Kim and C W Chung 2017 Enhancement of thermal neutron shielding of cement mortar by using borosilicate glass powder *Appl. Radiat. Isot.* **123** 1–5
[6] M A Rafiee *et al.* 2013 Hexagonal boron nitride and graphite oxide reinforced multifunctional porous cement composites *Adv. Funct. Mater.* **23** 5624–30
[7] C Ewels, M Glerup and V Krstic 2010 Nitrogen and boron doping in carbon nanotubes *Doped Nanomater Nanodevices* 1–82
[8] M H Kharita, S Yousef and M Alnassar 2011 Review on the addition of boron compounds to radiation shielding concrete *Prog. Nucl. Energy* **53** 207–11
[9] Rajavikraman R S 2013 Novel Method for Radiation Shielding Using Nano-Concrete Composite *Int. Jol of Mat. Sci. and Eng.* **1** 23–26
[10] R Küçer and N Küçer 2015 Neutron Shielding Properties of Concretes Containing Boron Carbide and Ferro – Boron *Procedia - Soc. Behav. Sci.* **195** 1752–56
[11] E Schlangen, H Jonkers, S Qian, and Garcia 2010 Recent advances on self healing of concrete *Proc. Fract. Mech. Concr. Concr. Struct.* **7** 291–98
[12] V P Singh and N M Badiger 2014 Gamma ray and neutron shielding properties of some alloy materials *Ann. Nucl. Energy* **64** 301–10
[13] H R Vega Carrillo, V M Hernández-Dávila, T. Rivera-Montalvo and A. Sánchez 2012 Characterization of a $^{239}$PuBe Isotopic Neutron Source *Proc. ISSSD 2012* **1** 64–69
[14] İçelli Orhan Mann, Kulwinder Singh Yałçın, Zeynel Orak, Salim Karakaya and Vatan Karakaya 2013 Investigation of shielding properties of some boron compounds **55** 341-350
[15] A Auvinen, E Pukkanen, H Hyvänen, M Hakama, and T Rytömaa 2002 Cancer incidence among Finnish nuclear reactor workers *J. Occup. Environ. Med.* **44** 634–38
[16] Jozwiak-Niedzwiedzka, Daria Brandt, Andrzej M 2013 The influence of ionizing radiation on microstructure and properties of concrete shields - a review *Cement Wapno Beton* **4** 216-35
[17] Vega-Carrillo *et al.*, 2007 Water-extended polyester neutron shield for a $^{252}$Cf neutron source *Rad. Prot. Dos.* **126** 269-73
[18] B Pomaro 2016 A Review on Radiation Damage in Concrete for Nuclear Facilities: From Experiments to Modeling *Model. Simul. Eng.* **16** 1–10.
[19] S Xu, M Bourham, and A Rabiei 2010 A novel ultra-light structure for radiation shielding Mater. Des. 31 2140–46
[20] M H Kharita, S Yousef and M AlNassar 2011 Review on the addition of boron compounds to radiation shielding concrete Prog. Nucl. Energy 53 207–11
[21] H Binici, O Aksogan, A H Sevinc and A. Kucukonder 2014 Mechanical and radioactivity shielding performances of mortars made with colemanite, barite, ground basaltic pumice and ground blast furnace slag Constr. Build. Mater. 50 177–83.
[22] X Jiao et al., 2011 Synthesis of boron suboxide from boron and boric acid under mild pressure and temperature conditions Mater. Res. Bull. 46 786–89
[23] A Sudoh, H Konno, H Habazaki and H Kiyono 2007 Synthesis of boron carbide microcrystals from saccharides and boric acid Tanso 2007 8–12.
[24] E. Yilmaz et al., 2016 Gamma ray and neutron shielding properties of some concrete materials Annals of Nuclear Energy. 38 2204-2212
[25] A Şahin and I Ar 2015 Synthesis, characterization and fuel cell performance tests of boric acid and boron phosphate doped, sulphonated and phosphonated poly(vinyl alcohol) based composite membranes J. Power Sources 288 426–33
[26] P Singh, B Singh, M Kumar and A Kumar 2014 One step reduction of Boric Acid to boron carbide nanoparticles Ceram. Int. 40 15331–334
[27] S Ding, S Zheng, M Xie, L Peng, X Guo and W. Ding 2011 One-pot synthesis of boron-doped mesoporous carbon with boric acid as a multifunction reagent Microporous Mesoporous Mater. 142 609–13
[28] J L Watts, P C Talbot, J A Alarco and I D R Mackinnon 2016 Morphology control in high yield boron carbide 0–1.
[29] M Ponnar, C Thangamani, P Monisha, S S Gomathi and K Pushpanathan 2018 Influence of Ce doping on CuO nanoparticles synthesized by microwave irradiation method Appl. Surf. Sci. 1–12.
[30] L. Duclaux 2002 Review of the doping of carbon nanotubes (multi walled and single-walled) J. Carbon., 40 1751–64
[31] B U Yoo, H H Nersisyan, H Y Ryu, J S Lee and J H Lee Structural and thermal properties of boron nanoparticles synthesized from B_2O_3+3Mg+kNaCl mixture Combust. Flame, 161 3222–28
[32] C Xiong and W Tu 2014 Synthesis of water-dispersible boron nitride nanoparticles Eur. J. Inorg. Chem. 19 3010–15
[33] G R Bhimanapati, N R Glavin and J A Robinson 2016 2D Boron Nitride: Synthesis and Applications Semiconductors and Semimetals 95 101-47
[34] I Akkurt, H Akyildirim, B Mavi, S Kilincarslan and C Basyigit 2010 Gamma-ray shielding properties of concrete including barite at different energies Prog. Nucl. Energy, 52 620–23
[35] Y Zhou, R Sun, Z Zhang, W Fan, D Zhou and C Sheng 2016 Preparation of boron nitride fiber by organic precursor method Results Phys. 10–13
[36] Suriyapprakash R and Kantha D. Arunachalam 2019 Single step pulverization effect of Borax decahydrate and Boric acid - a comparison IOP. Mater. Res. Express 6 94009.
[37] V Achal, A Mukerjee and M Sudhakara Reddy 2013 Biogenic treatment improves the durability and remediates the cracks of concrete structures Constr. Build. Mater. 48 1–5
[38] C Karthik and P Rama Mohan Rao 2016 Properties of bacterial-based self-healing concrete - A review Int. J. ChemTech Res. 9 182–88
[39] P M Visakh, O B Nazarenko, Y A Amelkovich and T V Melnikova 2015 Thermal properties of epoxy composites filled with boric acid IOP Conf. Ser. Mater. Sci. Eng. 81 012-095