PROPERTIES OF BACTERIAL SILICA FUME CONCRETE

A Thesis submitted by

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In partial fulfillment of the requirement for

the degree of

Master of Engineering

(Structural Engineering)

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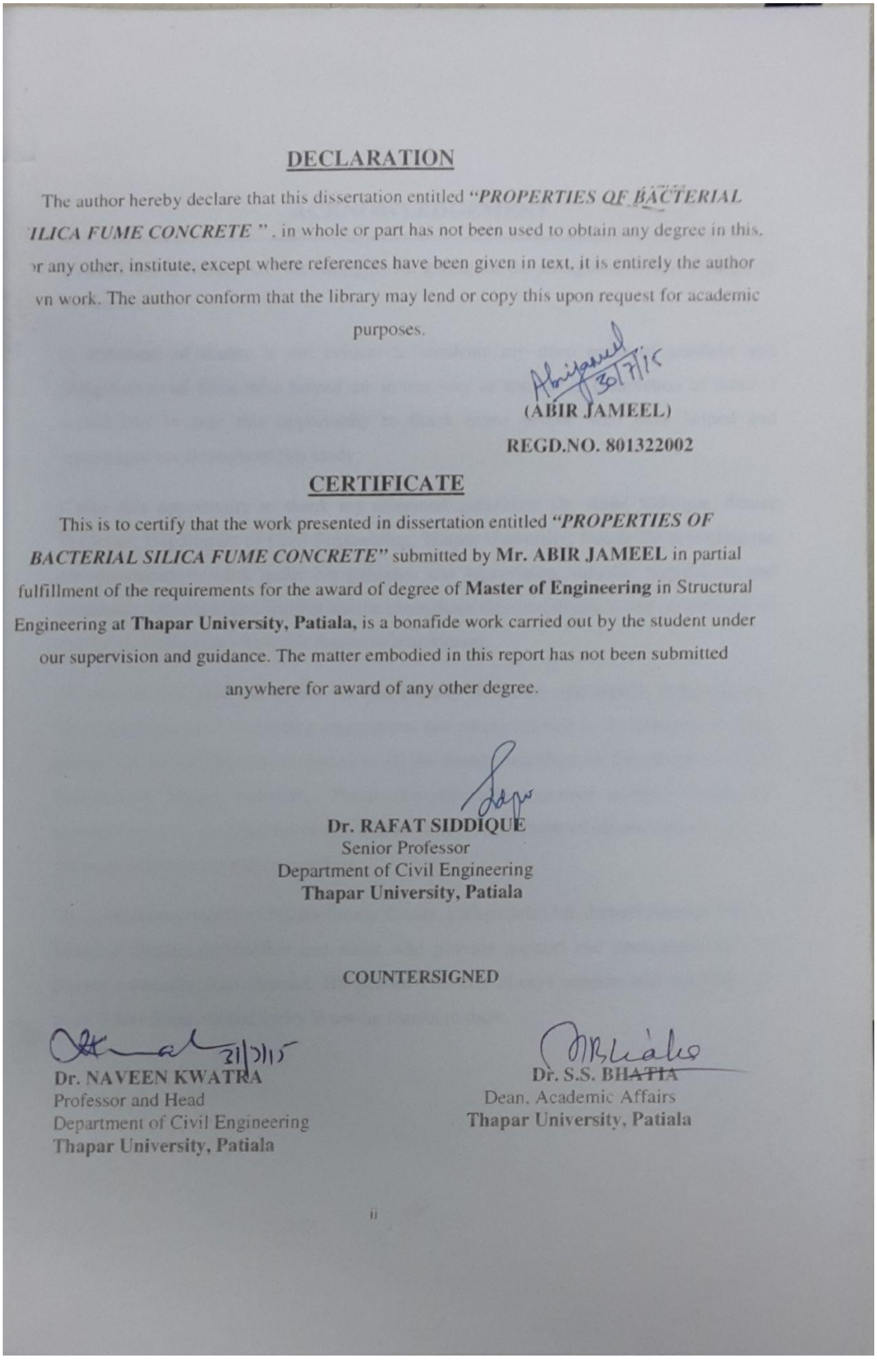
July 2015



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The author hereby declare that this dissertation entitled ***"PROPERTIES OF BACTERIAL ILICA FUME CONCRETE "***, in whole or part has not been used to obtain any degree in this, r any other, institute, except where references have been given in text, it is entirely the author vn work. The author conform that the library may lend or copy this upon request for academic purposes.

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CERTIFICATE

This is to certify that the work presented in dissertation entitled ***"PROPERTIES OF BACTERIAL SILICA FUME CONCRETE"*** submitted by **Mr. ABIR JAMEEL** in partial fulfillment of the requirements for the award of degree of **Master of Engineering** in Structural Engineering at **Thapar University, Patiala,** is a bonafide work carried out by the student under our supervision and guidance. The matter embodied in this report has not been submitted anywhere for award of any other degree.

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ACKNOWLEDGEMENT

I would like to thank GOD the Almighty for giving me the strength to remain on the path to success.

A statement of thanks is not evident to inculcate my deep sense of gratitude and obligation to all those who helped me in one way or another in completion of thesis. I would like to take this opportunity to thank many people who have helped and encouraged me throughout this study.

I take this opportunity to thank my esteemed supervisor Dr. Rafat Siddique, Senior Professor, Department of Civil Engineering, Thapar University, Patiala for providing me an opportunity to work under his guidance and supervision, valuable suggestions and comments, expertise and fruitful advice throughout this investigation and preparation of the thesis. I extend my heartfelt thanks to him forever.

My regards and gratitude to Dr. Naveen kwatra, (Professor and Head), Department of Civil Engineering for providing suggestions and taking interest in the progress of work along with lab facility. Many thanks to all the faculty members of Department of Civil Engineering, Thapar University, Patiala, for providing necessary guidance during my research work. I am thankful to Dr. Kunal Garg, Department of Biotechnology for the constant official help and cooperation.

My most sincere words of thanks for my family, Father (late) Mr. Jameel Ahmad, Mother Shahana Qamar, my brother and sister who provide support and encouragement, my friends especially Rais Ahmad, Bhupendra Pal who always support and motivate my work. I feel fortunate and lucky in owing thanks to them.

Abir Jameel

ABSTRACT

Ingress of harmful chemicals such as Chloride and sulfate may severely damage the structural properties of concrete as well as corrosion of embedded steel which results in failure of concrete structures. The microstructure of concrete has a direct influence on its durability and strength. The durability and strength of concrete can be improved by using a technique which involves bacterial induced calcite precipitation. Bacteria are capable of precipitating calcium carbonate crystals which enhances the microstructural properties of concrete thereby reduction in permeability of concrete.

The premier objective of this work is involved with the use of Ureolytic bacteria in concrete which could make it more durable. The bacteria present in the concrete rapidly sealed freshly formed cracks through calcite production. The bacterial concentration was optimized to 10^5 cfu/ml .In concrete mix, cement was replaced with silica fume in 5% 10% and 15% by weight of cement. The experiments were carried out to estimate the effect of bacteria on the compressive strength, water absorption, porosity, rapid chloride permeability and sorptivity of concrete made with silica fume up to the age of 28 and 56 days. The test result shows that inclusion of bacteria enhanced the compressive strength by 12%, reduced the porosity, water absorption and sorptivity by upto 55% of the silica fume concrete. The improvement in compressive strength was due to deposition of calcite precipitated by bacteria within the pores which was scanned by electron microscopy and characterized by XRD and revealed calcium carbonate precipitation. This precipitation also reduced the chloride permeability in concrete with silica fume. The bacteria improve the impermeability of concrete by improving its pore structure and thereby enhancing the life of concrete structures.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Concrete is a composite material which contains cement, fine aggregate, coarse aggregate and water. Its success lies in its versatility as can be designed to withstand harshest environments while taking on the most inspirational forms. Engineers and scientists are further trying to increase its limits with the help of innovative chemical admixtures and various supplementary cementitious materials (SCMs). Along with the strength, durability of concrete is also an important parameter which affects the type of concrete that is to be used in certain environments. With the use of SCMs the durability of concrete is considerably enhanced, and after the arrival of novel bacterial carbonate precipitation technique we are able to increase the durability of concrete.

In context of durability as with the use of calcite precipitation, the permeability of concrete can be reduced upto a great extent than normal conventional concrete. It is found that bacterial mineral precipitation resulting from metabolic activities of favorable microorganisms in concrete improved the overall behavior of concrete. The process can occur inside or outside the microbial cell. Bacterial activities simply trigger a change in chemistry and pore structure that leads to over saturation and mineral precipitation. Use of these bio mineralogy concepts in concrete leads to potential invention of new material called bacterial concrete.

1.2 SUPPLEMENTARY CEMENTITIOUS MATERIAL

These materials are generally byproducts from refinery processes or natural materials. The use of SCMs in concrete constructions not only prevents these materials to check the pollution but also to enhance the properties of concrete in fresh and hydrated states. The SCMs can be divided in two categories based on their type of reaction, hydraulic and pozzolanic. Hydraulic materials react directly with water to form cementitious compound like ground granulated blast furnace slag (GGBS). Pozzolanic materials do not have any cementitious property but when used with cement or lime react with calcium hydroxide to form products possessing cementitious properties. Silica fume is a byproduct of producing silicon metal or ferrosilicon alloys. One of the most beneficial uses for silica fume is in concrete. Because of its chemical and physical properties, it is a very reactive pozzolana. Concrete containing silica fume can have very high strength and can be very durable (Silica Fume Association, 1987). Silica fume is available as a densified powder or in a water slurry form. Silica fume is also known as micro silica, condensed silica fume, volatilized silica or silica dust. The American concrete institute (ACI) defines silica fume as very fine non crystalline silica produced in electric arc furnaces as a byproduct of production of elemental silicon or alloys containing silicon.

1.3 SILICA FUME

1.3.1 Physical Properties

Silica fume is an ultrafine material with spherical particles less than 1 μm in diameter, the average being about 0.15 μm. This makes it approximately 100 times smaller than the average cement particle. The bulk density of silica fume depends on the degree of densification and varies from 130 to 600 kg/m^3. The specific gravity of silica fume is generally in the range of 2.2 to 2.3. Particle size of silica fume is finer than 1μm other properties which are required by IS15388:2003 are as tabulalted in Table 1.1.

Table 1.1 : Specified properties of silica fume according to IS 15388:2003

Property	Value
Particle size (μm)	< 1
Bulk density (kg/m3)	130-600
Specific Gravity	2.22
SiO_2 (percent by mass, min.)	85
Moisture Content (max, %)	3
Loss on ignition (max, %)	4

1.3.2 Chemical Composition

Chemical compositions of silica fume is mainly consists of silicon oxide, calcium oxide and alkali are found in very low amount. Although silica fume and constituent mineral percentage may vary according to the process of alloy refinery and percentage of silica in constituent ferrosilicon alloy from which the silica fume is extracted. Chemical composition of silica fume reported by various authors are followed in Table 1.2.

Table 1.2: Chemical composition of silica fume samples

Oxides	Sandvik and Gjørv (1992)	Titherington and Hooton (2004)	Yazici (2008)
SiO2	92.1	96.65	92.26
Al2O3	0.5	0.23	0.89
Fe2O3	1.4	0.07	1.97
CaO	0.5	0.31	0.49
MgO	0.3	0.04	0.96
K2O	0.7	0.56	1.31
Na2O	0.3	0.15	0.42
SO3	-	0.17	0.33
LOI	2.8	2.27	-

1.4 REACTION MECHANISM OF SILICA FUME

Because of its extreme fineness and very high amorphous silicon dioxide content, silica fume is a very reactive pozzolanic material. As the Portland cement in concrete begins to react chemically, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form additional binder material called calcium silicate hydrate (CSH) which is very similar to the calcium silicate hydrate formed from hydration of Portland cement (Chahal, 2012). It is an additional binder that gives SF concrete its improved properties. Mechanism of silica fume in concrete can be studied basically under three roles:

(i) Pore-size Refinement and Matrix Packing: The presence of silica fume in the Portland cement concrete mixes causes considerable reduction in the volume of large pores at all ages. It basically acts as filler due to its fineness and because of which it fits into spaces between grains in the same way that sand fills the spaces between particles of coarse aggregates and cement grains fill the spaces between fine aggregates grains.

(ii) Reaction with Free-Lime (from hydration of cement): Calcium hydroxide crystals in Portland cement pastes are a source of weakness because cracks can easily propagate through or within these crystals without any significant resistance affecting the strength, durability and other properties of concrete. Silica fume which contains siliceous material reacts with CH resulting in reduction of CH content in addition to increasing strength contributing cementitious products (CSH) which in other words can be termed as Pozzolanic Reaction.

(iii) Cement Paste–Aggregate Interfacial Improvement: In concrete the characteristics of the transition zone between the aggregate particles and cement paste plays a substantial role in the cement-aggregate bond. Silica fume addition impacts the thickness of transition phase in mortars and the degree of the orientation of the CH crystals in it. The thickness compared with mortar containing only ordinary Portland cement decreases and decline in degree of orientation of CH crystals in conversion phase with the addition of silica fume. Hence mechanical properties and durability is improved because of the enhancement in interfacial and bond strength. Mechanism behind is not only connected to chemical creation of CSH (i.e. pozzolanic reaction) at interface, but also to the microstructure reformation (i.e. CH orientation, porosity and transition zone thickness) as well.

1.5 ADVANTAGES OF USING SILICA FUME

Silica fume is added to Portland cement concrete to improve its properties, in particular its compressive strength, bond strength, permeability and abrasion resistance. These improvements occurs from both the mechanical improvements resulting from addition of a very fine powder to the cement paste mix as well as from the pozzolanic reactions between the silica fume and free calcium hydroxide in the paste. Addition of silica fume also reduces the permeability of concrete to chloride ions, which protects the reinforcing steel of concrete from corrosion, especially in chloride-rich environments such as coastal regions and those of humid continental roadways and runways (because of the use of de-icing salts) (Siddique, 2011).

1.6 APPLICATIONS OF SILICA FUME

- High performance concrete (HPC) containing silica fume for highway bridges, parking decks, marine structures and bridge deck overlays.
- High-strength concrete enhanced silica fume for greater design flexibility.
- Silica fume shotcrete for use in rock stabilization, mine tunnel linings, and rehabilitation of deteriorating bridge and marine columns and piles.
- In repair products silica fume is used in a variety of cementitious repair products.

1.7 ROLE OF BACTERIA IN CONCRETE

Bacteria are microscopic organisms, single-celled prokaryotic creatures having different shapes and the sizes. Bacteria are ubiquitous in every habitat on Earth, growing in soil, acidic hot springs, radioactive waste, water, and deep in the Earth's crust, as well as in organic matter and the live bodies of plants and animals. There are typically 40 million bacterial cells in a gram of soil and a million bacterial cells in a milliliter of fresh water. In all, there are approximately five nonillion (5×10^{30}) bacteria on Earth reported by Whitman et al. (1998) forming much of the world's biomass.

There are broadly speaking two different types of cell wall in bacteria, called Gram-positive and Gram-negative. The names originate from the reaction of cells to the Gram strain, a test long-employed for the classification of bacterial species. In the laboratory, bacteria are usually grown using solid or liquid media. Solid growth media such as agar plates are used to isolate pure cultures of a bacterial strain. However, liquid growth media are used when measurement of growth or large volumes of cells are required. Growth in stirred liquid media occurs as an even cell suspension, making the cultures easy to divide and transfer, although isolating single bacteria from liquid media is difficult. The use of selective media (media with specific nutrients added or deficient or with antibiotics added) can help identify specific organisms.

Bacterial growth follows three phases. When a population of bacteria first enters a high-nutrient environment that allows growth, the cells need to adapt to their new environment. The first phase of growth is the lag phase, a period of slow growth when the cells are adapting to the high-nutrient environment and preparing for fast growth. The lag phase has high biosynthesis rates, as proteins necessary for rapid growth are produced. The second phase of growth is the logarithmic phase (log phase), also known as the exponential phase. The log phase is marked by rapid exponential growth. The rate at which cells grow during this phase is known as the growth rate, and the time taken for the cells to double is known as the generation time. During log phase, nutrients are metabolized at maximum speed until one of the nutrients is depleted and starts limiting growth. The final phase of growth is the stationary phase and is caused by depleted nutrients. The cells reduce their metabolic activity and consume non-essential cellular proteins.

1.8 VARIOUS BACTERIA USED IN THE CONCRETE

Following is the list of bacteria those are consistently used by many researchers in the bacterial concrete study.

i) *Sporosarcina pasteurii* (Bang et al., 2001; Ramachandran et al., 2001).

ii) *Bacillus sphaericus* (Van Tittelboom et al., 2010; Wang et al., 2014; De Belie et al., 2009).

iii) *Escherichia coli* (Ghosh et al., 2005).

1.9 BACTERIAL CONCRETE

The concept of bacterial concrete was first introduced by Ramakrishnan et al. (2000) a novel technique is adopted in remediating cracks and fissures in concrete by utilizing microbiologically induced calcite ($CaCO_3$) precipitation. Bacterially induced calcite precipitation is a technique that comes under a broader category of science called Biomineralization. Common bacteria from above list can induce the precipitation of calcite. As a microbial sealant, $CaCO_3$ exhibited its positive potential in selectively consolidating simulated fractures and surface fissures in granites and in the consolidation of sand. Microbiologically induced calcite precipitation is highly desirable because the calcite precipitation induced as a result of microbial activities, is pollution free and natural. The technique can be used to improve the compressive strength and stiffness of cracked concrete specimens. The bacterial concrete makes use of calcite precipitation by bacteria.

It is a process by which living organisms or bacteria form inorganic solids. Under favorable conditions Bacteria when used in concrete, can continuously precipitate a new highly impermeable calcite layer over the surface of the already existing concrete layer. The precipitated calcite has a coarse crystalline structure that readily adheres to the concrete surface in the form of scales. In addition to the ability to continuously grow upon itself, it is highly insoluble in water. It resists the penetration of harmful agents (chlorides, sulphates, carbon dioxide) into the concrete thereby decreasing the deleterious effects they cause. Due to its inherent ability to precipitate calcite continuously, bacterial concrete can be called as Smart Bio Material for repairing concrete. The MICP comprises a series of complex biochemical reactions. It is selective and its efficiency is affected by the porosity of the medium, the number of cells present and the total volume of nutrient added. The phosphate solution or urea-$CaCl_2$ been found effective as nutrients as reported by Krishnapriya et al. (2015). The bacteria precipitate calcite in the presence of nutrients. The optimum pH for growth of *B. pasteurii* is around 9. The alkaline environment of concrete with pH around 12 is the major hindering factor for the growth of bacteria.

However, *B. pasteurii* has the ability to produce endospores to endure an extreme environment, as found by Ramakrishnan et al. (2000). The microbial modified mortar or concrete has become an important area of research for high-performance construction materials. Ghosh et al. (2005) investigated the effects of incorporating a facultative anaerobic hot spring bacterium on the microstructure of a cement-sand mortar. In a number of recent studies the potential application of bacteria in concrete has been seen, Various researches have reported the improvement of durability properties of concrete (Ramachandran et al., 2001; Rodriguez et al., 2003; De Muynck et al., 2005; Chahal et al., 2012). Increase of Compressive strength properties of concrete and mortar are also reported by Chahal et al. (2012) and Ghosh et al. (2005) respectively, which is the result of calcite precipitation and that is related with the pore size refinement of the matrix.

CHAPTER 2

LITERATURE REVIEW

In this chapter research work related to different Bacterial concrete and other methods employed by researchers to improve hardened properties of concrete are presented. Calcite precipitation activity of bacteria is also presented as reported by various authors.

2.1 REPLACEMENT OF CEMENT WITH SILICA FUME

Study of replacement of cement with silica fume started in later 1970's, with the implementation of tougher environmental laws during the mid-1970s, silicon smelters began to collect the silica fume and search for its applications as earlier it was simply vented in to the atmosphere. The early work done in Norway received most of the attention, since it had shown that Portland cement-based-concretes containing silica fumes had very high strengths and low porosities (Holland, 2005). Since then the research and development of silica fume made it one of the world's most valuable and versatile admixtures for concrete and cementitious products.

2.1.1 Compressive Strength

Yogendran et al. (1991) studied the properties of improving the high strength and some other properties of concrete by incorporating silica fume and super plasticizer. The efficiency of silica fume in improving the properties of concrete and compared at medium and very low water cement ratios was studied. It was also concluded that the optimum replacement of cement by silica fume for high strength concrete in the 28 days compressive strength range of 50 to 70 MPa is seen to be nominally 15 percent for a water cementitious ratio of 0.34. The compressive strength of mixes with a w/c ratio of 0.34 was maximum at 15% silica fume replacement at all ages.

ACI Committee (1987), reported about the physical and chemical properties of silica fume and gives possible application and limitations of its use in concrete. Silica fume, because of its extreme fineness and high silica content, is highly effective pozzolanic material. The main contribution of silica fume to concrete strength development at normal curing temperature takes place from about 3 to 28 days. It was reported that silica fume with high range water reducers has been used to produce very high strength concrete. Compressive strengths of the order of 100 MPa and higher have also been reported.

Dewitler and Mehta (1989) conducted compression experiments on cylinders of size 100 x 200 mm and concluded that the silica fume concrete showed the greatest improvements in strength due to combination of cement hydration and the pozzolanic reaction between 7 and 28 days. Fidjestol (1993) reported about the usage of silica fume in concrete, as reported Norwegian Directorate of Roads requires that concrete for bridges contain upto 5 percent silica fume. The purpose of this requirement is to ensure good compaction of the concrete, high chloride resistance and good strength.

Durekovic (1994) studied the porosity characteristics under the influence of silica fume and super plasticizer. Porosity was investigated in cement pastes with water to solid ratio of 0.28 and cured at normal temperature. Samples with and without superplasticizer admixture were prepared using an OPC in which 0, 5, 10 & 15% of weight was replaced by condensed silica fume (CSF). It was concluded that the most 30 obvious i.e. increase of the median pore size was detected at the age of 3 years in the blend with 15% of CSF.

Wild et al. (1995) has studied the factors influencing strength development of concrete containing silica fume. Experiments were conducted on condensed silica fume concrete with a range of SF content and cured at two temperatures (20^{o}C and 50^{o}C) for period upto 91 days. Strength development and relative strength are considered in relation to temperature, cement hydration and pozzolanic action. It was concluded that at early ages curing temperature has little effect on the strength of the control concrete and at extended curing periods strengths of 50^{o}C cured concrete tend to be less than those of 20^{o}C cured concrete. It was suggested that this loss in strength is due to coarsening of calcium hydroxide crystals particularly at interfacial zones. But curing temperature does however have a very substantial effect on the strength of CSF concrete at early ages principally as a result of the increased rate of reaction of CSF with calcium hydroxide, the ultimate strengths are similar. A continuous increase in relative strength with CSF content at both curing temperatures and the magnitudes of these increases are similar at both temperatures. Zhou et al. (1995) investigated the fracture properties of high strength concrete with varying silica fume content and aggregates. It was studied about the fracture mechanics of high strength concrete with compressive strength in the range of 80 to 115 MPa. Silica fume contents of 10% and 15% cement replacement were used along with 10 mm gravel and 20 mm crushed limestone. It was concluded that increasing the silica fume content from 10% to 15% cement replacement has more effect on compressive strength of concretes with higher water binder ratio.

ACI Committee (1995) reported that the physical and chemical properties of silica fume, effects of silica fume on the properties of fresh and hardened concrete and applications of silica fume in concrete. It was reported that concrete containing silica fume shows significantly reduced bleeding. This effect is caused primarily by the high surface area of the silica fume to be wetted, there is very little free water left in the mixture for bleeding. The static modulus of elasticity of silica fume concrete is apparently similar to that of Portland cement concrete of similar strength. It was also reported that the main contribution of silica fume to concrete strength development at normal curing temperatures takes place from about 3 to 28 days. At 28 days the compressive strength of silica fume concrete is always higher and in some instances significantly also.

Toutanji and Korchi (1995) have investigated the influence of silica fume on the compressive strength of cement paste and mortar. Experiments were conducted to find compressive strengths of silica fume cement paste and mortar were evaluated at various water cementitious ratios. Five different water cementitious ratios 0.22, 0.25, 0.28, 0.31 and 0.34 and two contents of silica fume, 15% and 25% by weight of cement were used. Superplasticizer was used to increase workability. Compression strength was evaluated by testing cubes 51 x 51 x 51mm under servo hydraulic controlled testing machine. From past research they reported that the optimum silica fume content should be 15%. It was concluded that the replacement of cement by silica fume, regardless of w/c ratio, along with the use of a sufficient amount of superplasticizer increases the strength of mortar. Strength increases with increasing silica fume content up to 15% of replacement.

Almusallam et al. (2004) found that the effects of silica fume on compressive strength of concrete made with low quality coarse aggregate (calcareous, dolomitic and quartzitic limestone and steel slag). It was observed that compressive strength increased with age in all the concrete specimens. After 180 days of curing, highest compressive strength was noted in 15% silica fume concrete specimens (54 MPa) followed by those prepared with 10% silica fume (52 MPa), and plain concrete (49 MPa). The higher compressive strength noted in the silica fume cement concrete, compared to plain cement concrete, may be attributed to the reaction of silica fume with calcium hydroxide liberated during the hydration of cement.

2.1.2 Permeation Properties of Silica fume Concrete

Permeability and porosity properties of silica fume concrete reported by various authors have displayed that pore size refinement by addition of silica fume improves the durability properties of silica fume concrete. Igarashi et al. (2005) evaluated the capillary porosity and pore size distribution in high-strength concrete containing 10% silica fume at early ages. It was concluded that silica-fume-containing concretes were found to have fewer coarse pores than ordinary concretes, even at early ages of 12 and 24 h. The threshold diameter at which porosity starts to steeply increase with decreasing pore diameter was smaller in silica-fume-containing concretes than in ordinary concretes at 12 h. This smaller threshold diameter in silica-fume-containing concretes indicated higher packing density of binder grains in these concretes.

Khan (2003) observed that the inclusion of silica fume (0–15% as partial replacement of cement) resulted in more significant reductions in porosity in mixtures. However, the reduction in the porosity was greater when silica fume was incorporated at up to 10% replacement level, beyond which the reduction was marginal or reversed.

Poon et al. (2006) studied the effect of silica fume (5 and 10%) replacement on the porosity of concrete mixtures using MICP, the results showed the decrease in porosity with age due to addition of silica fume.

Cwirzen and Penttala (2005) investigated Capillary water uptake and porosity of non air-entrained concretes having water-to-binder (w/b) ratios of 0.3, 0.35 and 0.42 and different additions of condensed silica, the results from the investigation showed that the concrete having a w/b ratio of 0.3 showed decrease in capillary porosity with silica fume. However for w/b ratios of 0.35 and 0.42, capillary and total porosities appeared to be quite similar.

Rossignolo (2008) studied the effect of silica fume and styrene-butadiene latex (SBR) on the microstructure of the interfacial transition zone (ITZ) between Portland cement pastes and aggregates (basalt). It was observed that the usage of 10% of silica fume, in relation to the cement paste, caused a reduction of 36% in the thickness of the matrix-aggregate ITZ in relation to the control concrete specimens.

Toutanji et al. (1998) reported an investigation on permeability and impact resistance of polypropylene-fiber-reinforced concrete mixtures containing silica fume with variable design proportions, silica fume was used as a replacement by weight of cement. Two silica fume contents were used, 5 and 10%, results showed that the incorporation of polypropylene fibers increased the permeability of conventional concrete. The addition of silica fume improved fiber dispersion in the cementitious matrix, causing a significant reduction in the permeability of the polypropylene fiber reinforced concrete. Moreover, the addition of silica fume was noted to significantly enhance the polypropylene fiber effectiveness in improving the impact resistance of concrete.

Ramezanianpour and Malhotra (1995) reported an investigation in which the performance of slag, fly ash, and silica fume concretes were studied under four different curing regimes. The water-cementitious materials ratio of all the concrete mixtures was kept constant at 0.50, except for the high-volume fly ash concrete mixture, for which the ratio was 0.35. The results indicate that the reduction in the moist-curing period results in lower strengths, higher porosity and more permeable concretes. The strength of the concretes containing fly ash or slag appears to be more sensitive to poor curing that the control concrete, with the sensitivity increasing with the increasing amounts of fly ash or slag in the mixtures. The incorporation of silica fume in the concrete mixtures increased the resistance to chloride ions and produced concretes with very low permeability.

Song et al. (2010) studied deterioration and durability of concrete structures mainly depends on permeability of concrete. Silica fume (SF) as a mineral admixture for high performance concrete produces more discontinues and impermeable pore structure in concrete. The higher permeability reductions with silica fume are due to pore size refinement and matrix densification, reduction in content of $Ca(OH)_2$ and cement paste-aggregate interfacial refinement. During the hydration process the transition interfacial zone is gradually densified due to pozzolanic reaction between silica fume and calcium hydroxide. Based on a microstructure model, a procedure for predicting the permeability of high strength silica fume cement concrete is developed by considering water-to-binder ratio, silica fume replacement ratio and degree of hydration as major influencing factors. Sorptivity or Capillary water absorption characteristics of concrete containing silica fume are studied by various researchers.

Chan and Ji (1998) done experiments on concrete containing oil shale ash and silica fume, sorptivity test results are compared together with oil shale ash and silica fume. Experimental results indicated that oil shale ash is not as effective as silica fume, decreased the water Sorptivity and chloride diffusivity of concrete. Alexander and Magee (1999) Carried out tests to study the effect of GGBS and silica fume towards Sorptivity of concrete and reported that concrete durability is dramatically improved through the use of CSF. Optimum performance was achieved through the use of CSF as a 10% addition by mass to the initial binder content. Study by Tasdemir (2003) also confirmed the enhancement of Sorptivity coefficient and the compressive strength of OPC 42.5 concretes with silica fume. The results obtained indicate that the sorptivity coefficient of concrete decreases as the compressive strength of concrete increases. It is also shown that the sorptivity coefficient of concrete is very sensitive to the curing condition. The effect of curing condition on the sorptivity coefficient of concrete seems to be higher in low-strength concretes.

2.2 BACTERIAL CONCRETE

Ramakrishnan et al. (2001) proposed a novel technique in remediating cracks and fissures in concrete by microbiologically inducing calcite precipitation (MICP). *B. pasteurii*, a common soil bacterium can induce the precipitates of calcite. As a microbial sealant, Calcite exhibited its positive potential in selectively consolidating simulated fractures and surface fissures in granites and in the consolidation of sand. MICP is highly desirable chemical reaction because the calcite precipitation induced is a result of microbial activities. The technique can be used to improve the compressive strength and stiffness of cracked or uncracked concrete specimens.

A durability study on concrete beams treated with bacteria, exposed to alkaline, sulfate and freeze-thaw environments was studied by Ramakrishnan et al. (2001). The effect of different concentrations of bacteria on the durability of concrete was also studied. It was found that all the beams with bacteria performed better than the control beams (without bacteria). The durability performance increased with increase in the concentration of bacteria. Microbial calcite precipitation was quantified by powder X-ray diffraction (XRD) analysis and visualized by scanning electron microscopy (SEM). The unique imaging and microanalysis capabilities of SEM established the presence of calcite precipitation inside cracks, rod shaped bacterial impressions and a new calcite layer on the surface of concrete. This calcite layer improves the impermeability of the specimen, thus increasing its resistance to alkaline, sulfate and freeze-thaw attack.

An alternative technique for the improvement of the durability of concrete is reported by De Muynck et al. (2008). The surface deposition of calcium carbonate crystals decreased the water absorption with 65 to 90% depending on the porosity of the specimens. An increased resistance towards freezing and thawing was also noticed, the results obtained with the biodeposition treatment were similar as those obtained with conventional surface treatments. It was concluded that the surface treatments play an important role in the protection of construction materials from the ingress of water and other deleterious substances. It was reported the effects of bacterial calcite precipitation on parameters affecting the durability of concrete and mortar.

Bacterial deposition of a layer of calcite on the surface of the specimens resulted in a decrease of capillary water uptake and permeability. The type of bacterial culture and medium composition had a profound impact on calcite crystal morphology. The use of pure cultures resulted in a more pronounced decrease in uptake of water. The results obtained with cultures of the species *Sporosarcina pasteurii* were comparable to the ones obtained with conventional water repellents.

A cost effective substrate under submerged fermentation by Alkaliphilic bacteria named *B. subtilis* has been reported by Sanghi et al. (2009) and concluded that high level production of a cellulose free xylanase can be recovered using wheat bran. Later, Sanghi et al. (2010) reported a potentially effective alternative treatment for industrial applications for this characterization of extracellular cellulose-free xylanase was done from a newly alkaliphilic and moderately thermophilic strain of *B.subtilis*.

2.2.1 Compressive Strength

The addition of bacterial cells in mortar cubes showed that there was a significant increase in compressive strength of cubes containing lower concentrations of live cells. Compressive strengths of the cubes containing live or dead cell mass, however, decreased as cell concentrations and curing time increased, suggesting the interference of mortar integrity by biomass as reported by Ramchandran et al. (2001).

Calcite precipitation induced by *B. pasteurii* was studied in two types of portland cement mortar specimens: one prepared from mixing with microorganisms and the other with simulated cracks filled with microbial mixtures. Scanning electron micrographs identified that microbiological calcite precipitation occurred mainly close to the surface areas of the crack, where a dense growth of calcite crystals embedded with cells was observed. Strength improvement of cement sand mortar cube by microbiologically induced calcite precipitation was also reported by Ghosh et al. (2005).

A thermophilic anaerobic microorganism is incorporated at different cell concentrations with the mixing water. The study showed that a 25% increase in 28 days compressive strength of cement mortar was achieved with the addition of about 10^5 cell/ml of mixing water. Scanning electron microscopy proved the strength improvement is due to growth of filler material within the pores of the cement–sand matrix.

The modification in pore size distribution and total pore volume of cement–sand mortar due to such growth is also noted by *E. coli* microorganisms when used in the cement mortar for comparison, but no improvement in strength was observed.

Chahal et al. (2012) carried out experiments to evaluate the Influence of *Sporoscarcina pasteurii* bacteria on the compressive strength and rapid chloride permeability of concrete made without and with fly ash. Cement was replaced with three percentages (10, 20 and 30) with fly ash by weight. Three different cell concentration (0, 10^3,10^5,10^7 cfu/ml) of bacteria were used in making the concrete mixes. Their results indicated that inclusion of S. pasteurii in fly ash concrete enhanced the compressive strength, reduced the porosity and permeability of fly ash concrete. Maximum increase (22%) in compressive strength and four-time reduction in water absorption was observed with 10^5 cfu/ml Conc. of bacteria. Usage of bacteria like *S. pasteurii* improves strength and durability of fly ash concrete through self-healing effect.

Krishnapriya et al. (2015) uses three bacteria cells to prepare concrete specimens and to compare with control specimens. These three bacterial strains are *B. megaterium*, *B. licheniformis* and *B. flexus*. They carried out experimental work to evaluate effect on compressive strength and durability properties of concrete, and found that Bacterial concrete specimens cast with *B. megaterium*, *B. licheniformis* and *B. flexus* have increased compressive strengths which amount to 12.1, 10.6 and 6.1% respectively compared to control concrete specimens.

2.2.2 Permeation Properties

Permeability may be defined as the measure of the ability of a material to allow fluids to pass through it. Water absorption is defined as the amount of water absorbed by a material when immersed in water for a stipulated period of time. It is calculated as the ratio of the weight of water absorbed by a material, to the weight of the dry materials. In this section we are presenting here the results obtained by various researches on influence of bacteria on Permeation properties of concrete.

Bacterial deposition of a layer of calcite on the surface of the specimens resulted in a decrease of capillary water uptake and gas permeability (De Muynck et al., 2008). The effects of bacterial carbonate precipitation on the durability of mortar specimens with different porosity. The surface deposition of calcium carbonate crystals decreased the water absorption with 65 to 90% depending on the porosity of the specimens. As a result, the carbonation rate and chloride migration decreased by about 25–30% and 10–40% respectively.

Filling of cracks in the bacterial self-healing concrete proposed by Wiktors and Jonkers (2011) and Wang et al. (2014) became gas and watertight after activation of the bacteria with consumption of the nutrients and crack filling with deposited $CaCO_3$ crystals. Van Tittelboom et al. (2010) noted that the water permeability of damaged specimens containing capsules filled with polymeric healing agent was similar to values obtained for undamaged specimens. Reinhardt and Joss (2003) studied the permeability of self-healing concrete as a function of temperature and crack width and found that the flow rate rises non- linearly in case of an increase of the crack width. The influence of temperature is also well recognizable. The following table compares the test results and theoretical prediction by normalizing the flow rates to the value of 0.08 mm crack width and 20℃.

Achal et al. (2011) studied the water absoption and sorptivity results proved treated mortar cubes absorbed more than three times less water than control cubes as a result of microbial calcite deposition. Microbial deposition of a layer of calcite on the surface of the concrete specimens resulted in substantial decrease of water uptake and permeability compared to control specimens without bacteria. *B. megaterium* was used to Microbially treat the cube specimens. Muynck et al. (2008) and achal et al. (2010) also studied the effect of bacterial precipitation on Sorptivity of concrete/Mortar specimens found a significant decrease in the permeation properties of concrete.

CHAPTER 3

EXPERIMENTAL PROGRAM

In this chapter, the experimental program related to bacteria followed by its isolation and identification, calcite formation, estimation of urease activity and optimization of the bacterial inoculums on the basis of calcite formation. Experimental program related to bacterial concrete, the materials used with their properties, mix proportions, casting of specimens for studying various properties of concrete and methodology adopted for testing of different properties.

The entire experimental program is fulfilled in three steps-

i. Identification and growth of bacteria.
ii. Compressive strength study of concrete with and without bacteria
iii. Durability properties of concrete viz. Rapid chloride permeability test, water absorption/ Porosity and Sorptivity.

3.1 EXPERIMENTAL PROGRAM OF BACTERIA

3.1.1 Isolation and Identification of Bacteria

Alkaliphilic/alkalitolerant bacteria (that tolerate high pH) was isolated from rhizospheric (near to root of plant) soil and from marble sludge. The samples were suspended in sterile saline solution (0.85% NaCl), diluted properly and plated on enrichment medium containing glucose (10 g/l), peptone (10 g/l), yeast extract (5 g/l), KH_2PO_4 (1 g/l), agar (15 g/l) and pH was adjusted to 10.5 with 1 N NaOH.

3.1.2 Urease Activity

For preparation of Urea agar medium, following ingredients were used peptone 1.0 g/l, sodium chloride 5.0g/l, potassium dihydrogen phosphate 2.0g/l, agar 20.0g/l, 0.2% phenol red and distilled water 1000 ml. All the above ingredients were dissolved and the pH was adjusted to 6.8 and autoclaved at 12°C for 15 minutes and cooled later 1g of glucose and steamed for one hour, finally 20% aqueous 100 ml of urea was added and sterilized by filtration and poured into the test tube and slants were prepared. The organisms isolated were streaked on the surface of the media and incubated at 37°C and observed for the change of the color of the media from yellow to pink. The isolate AKKR5 were studied for urease activity.

3.1.3 Morphological Studies of Bacteria

3.1.3.1 Gram Staining

Gram staining method was used to determine the morphology of the bacterial strains. Slide with a bacterial smear was placed on a staining rack. The slide was stained with crystal violet for 1-2 min and then the slide was flooded with Gram's iodine for 1-2 min. decolourization was done by washing the slide slowly with acetone (2-3 seconds). Slide was then thoroughly rinsed with water to remove the acetone. The slide was flooded with safranin counter stain for 2 min and then again washed with water. The excess water was removed and slide was air dried. Finally samples were visualized under microscope. In Gram-positive bacteria, the dark purple crystal violet stain was retained by the thick layer of peptidoglycan and the Gram-negative bacteria, the thin peptidoglycan layer in the periplasm does not retain the dark stain, and the pink safranin counterstain stains the peptidoglycan layer.

3.1.3.2 SEM and XRD Analysis of Bacteria

The morphology and chemical constituents of the bacteria were analyzed with XRD. Samples were completely dried at room temperature, and then Samples were gold coated with a sputter coating Emitech K575 prior to examination. XRD spectra were obtained using an X’Pert PRO diffractometer with a Cu anode (40 kV and 30 mA) and scanning from 5° to 60°. Each bacterial sample was crushed and ground before mounting onto a glass fiber filter using a tubular aerosol suspension chamber (TASC). The components of the sample were identified by comparing them with standards established by the International Center for Diffraction Data. All experiments were performed in triplicate.

3.2 EXPERIMENTAL PROGRAM OF CONCRETE

3.2.1 Materials Used

3.2.1.1 Cement

In this work Ordinary Portland cement of 43 Grade was used for casting cubes and cylinders for all concrete mixes. The cement was of uniform color i.e. grey and was free from any hard lumps. The various tests conducted on cement are initial and final setting time, specific gravity, consistency and compressive strength. Testing of cement was done as per IS: 8112-1989. The various tests results conducted on the cement and composition are listed in Table 3.1 and Table 3.2.

Table 3.1: Physical properties of Ordinary Portland Cement

Physical Properties	Obtained value	Standard Value
Consistency of standard cement paste (%)	28	--
Initial setting time (minutes)	123	Not be less than 30 minutes
Final setting time (minutes)	270	Not be greater than 600 minutes
Specific gravity	3.1	--

3.2.1.2 Fine Aggregate

Natural sand with 4.75 mm maximum size was used as fine aggregate. It was tested as per Indian Standard Specifications IS: 383-1970. Its physical properties and sieve analysis are given in Tables 3.2 and Table 3.3, respectively.

Table 3.2: Physical properties of Fine Aggregate

Characteristics	Value
Specific gravity	2.68
Net water absorption	0.86
Fineness modulus	2.58

Table 3.3: Chemical Composition of Cement using XRF analysis

Chemical Compound	Constituent %
SiO_2	21.25
Al_2O_3	4.74
Fe_2O_3	4.30
CaO	63.49
MgO	1.02
K_2O+ NaO_2	1.08
SO_3	2.92

Table 3.4: Sieve Analysis of Fine Aggregates

Sieve No.	Retained, (gms)	Retained, %	Passing, %	%age Retained cumulative
4.75	10	1	99	1
2.36	60	6	93	7
1.18	200	20	73	27
600	190	19	54	46
300	350	35	19	81
150	150	15	4	96
Pan	40	4	0	100
			Σ % retained = 258	

Fineness Modulus = 258/100 = 2.58.

3.2.1.3 Coarse Aggregate

Crushed stone with maximum 12.5 mm graded aggregates (nominal size) was used. Physical properties and sieve analysis results are given in Tables 3.5 and Table 3.6, respectively.

Table 3.5: Physical Properties of Coarse Aggregates

Properties	Observed values
Maximum size (mm)	12.5
Bulk density (kg/m3)	1650
Specific gravity	2.7
Total water absorption (%)	1.14

Table 3.6: Sieve Analysis of Coarse Aggregates

I.S. Sieve	Weight (gm) Retained	% weight (gm) Retained	Cumulative % weight Retained	% passing
20mm	00	0.0	0.0	100
12.5mm	.97	4.8	4.8	95.2
10mm	642	32.1	36.9	63.1
4.75mm	1184	59.2	96.1	3.9
Pan	77	3.85	100	
		Fineness Modulus = ΣC+500/100 = 6.378		

Table 3.7: Chemical composition of Silica fume by XRF analysis

Compound	% By mass
SiO_2	91.92
Al_2O_3	1.05
Fe_2O_3	1.11
CaO	1.35
MgO	0.61
Na_2O	.6
K_2O	1.73
Loss on Ignition	1.27
Colour	Light grey
Specific Gravity	2.3

3.2.1.4 Properties of Silica fume

Physical and chemical properties of silica fume were analyzed as per IS 15388:2003. Silica fume is composed primarily of pure silica in non-crystalline form. Chemical properties of silica fume include very high content of amorphous silicon dioxide. Small amounts of iron, magnesium, and alkali oxides were also found. Physical and chemical properties results are given in Tables 3.7.

3.2.2 Design of Concrete Mix

The compressive strength of concrete is considered as the strength and index of its quality. Therefore the mix design is generally carried out for a particular compressive strength of concrete with adequate workability so that the fresh concrete can be properly mixed, placed and compacted. The proportions for the mix were calculated adopting the requirements of water as specified in IS: 10262-1982.

The proportioning of concrete mixes consists of three interrelated steps.

(i) Selection of suitable materials and ingredients-cement, supplementary cementing materials, water, coarse and fine aggregates.

(ii) Determination of the relative quantities of these materials in order to produce a concrete that has desired strength and durability.

(iii) Careful quality control of every phase of the concrete making process. In the present study Mix Design for M20 (Design value at the age of 28 days) grade concrete is done according to IS: 10262-1982.

M20 design mix

Data

Characteristic strength at 28 days = 20 N/mm^2

Maximum size of aggregate = 12.5mm

Type of exposure = Mild

Concrete use = Concrete structure

Ingredients of M20 concrete mix are given in Table 3.8.

Table 3.8: Mix Proportion M20 Concrete

Unit of Batch	**Water (kg)**	**Cement (kg)**	**F.A. (kg)**	**C.A. (kg)**
Cubic meter content	195	390	569	1165
Ratio of ingredients	0.5	1	1.45	2.98

F.A: denotes fine aggregates; C.A: denotes coarse aggregates

Mix Composition

The concrete mixes were designed with constant cement, fine aggregate, coarse aggregate. Control concrete mixture was designed as per IS 10262-1982 to have 28-days compressive strength of 20 MPa. Then cement was partially replaced with 5% and 10% and 15% silica fume by weight of cement with Constant concentration of bacterial culture, 10^5 cfu of water. The detailed description of all mixes is given in Table 3.9 (without Bacteria and with Bacteria).

For these mix proportions, required quantities of materials were weighed. The mixing procedure adopted was as follows:

1. The cement, fly ash and silica fume were dry mixed in a tray for about 15 minutes to obtain a uniform color.
2. Weighed quantities of coarse aggregates and sand were then mixed in dry state in drum type mechanical mixer.
3. The mix of cement, fly ash and silica fume was added to the mix of coarse aggregates and sand and these were mixed thoroughly for a homogeneous mix.
4. Water and bacterial culture was then added.
5. All the moulds were properly oiled before casting the specimens. The casting immediately followed mixing, after carrying out the tests for fresh properties. The top surface of the specimens was scraped to remove excess material and achieve smooth finish. The specimens were removed from moulds after 24 hours and cured in water till testing or as per requirement of the test. After required period

of curing i.e. 28 and 56 days, the specimens were taken out of the curing tank and their surfaces were wiped.

Table 3.9: Concrete mix proportions with silica fume (with and without Bacteria)

Mixture No.	**Control (SF0)**	**SF5**	**SF10**	**SF15**
Cement (kg/m^3)	390	370.5	351	331.5
Natural sand (kg/m^3)	568.70	568.70	568.70	568.70
Silica fume (%)	0	5	10	15
Silica fume (kg/m^3)	-	19.5	39	58.5
Coarse aggregate	1164.12	1164.12	1164.12	1164.12
W/C ratio	.5	.5	.5	.5
Water (kg/m^3)	185	185	185	185
Slump (mm)	90	80	70	73

(SF: Silica fume replacement) *bacterial concrete specimens were casted having similar mix proportions and mix no. designated to be BSF0, BSF5, BSF10 and BSF15.

3.2.3 Preparation of Test Specimens

Concrete cubes were prepared with constant concentrations of bacterial cells (10^5cfu/ml) which is decided from the previous work done by the authors suggest that optimum cell concentration dosage is 10^5 cfu/ml. The cell concentration was determined from the bacterial growth curve made by observing optical density at 600 nm. Control concrete cubes were cast with and without the addition of bacteria. All the experiments were performed in triplicates.

3.2.4 Testing Procedure for Concrete

Following tests were performed on hardened concrete

i. Compressive strength (IS: 516 –1959)
ii. Water absorption and Porosity (ASTM C 642– 13)
iii. Rapid chloride permeability Test (ASTM C 1202– 12)
iv. Sorptivity test (ASTM C 1585 – 13)
v. Scanning electron microscopy (SEM) analysis of matrix for calcite precipitate and microstructure.

vi. X- Ray Diffraction (XRD) analysis for characterization of calcite precipitation in Matrix.

The specimen test results were determined at the age of 28 and 56 days, with each specimen in triplicates.

3.2.4.1 Compressive Strength

For each set three standard cubes were cast to determine 28 days and 56 days compressive strength after curing. Cubes were cast and compacted on a vibration machine. After de-molding, all specimens were cured in water at room temperature for compression testing until 28 and 56 days. Cube specimens of size 150 mm were cast for compressive strength as per Indian standard specifications IS: 516–1959.

3.2.4.2 Water Absorption and Porosity

The water absorption and porosity test was conducted as per ASTM C 642–13 in order to determine the increase in resistance towards water penetration in concrete. The cube moulds of 150 mm were prepared both with and without bacteria and silica fume replacement. The concrete specimens were cured for 28 days and 56 days. After curing, the specimens were oven dried at 110°C in oven for 24 hours after removing from oven specimens are allowed to cool in dry air to about 20-25°C and weighed. Then the specimens were immersed in water at approximately 21°C for 48 hours and saturated mass after immersion was calculated. Then the specimens were placed in suitable receptacle, covered with tap water and were boiled for 5 hours, further the saturated mass after boiling was calculated. Apparent mass of boiled specimens are then calculated by suspending it in steel wire basket.

The total porosity (P) measurements are based on Archimedes Principle. The total porosity can be calculated from water saturated surface dry mass (m_{sat}), mass susupended in water (m_{water}) and oven dry mass (m_{dry}) :

$$P\ (\%) = (m_{sat} - m_{dry} / m_{sat} - m_{water}) \times 100$$

Water absorption (%) is calculated as = [(B – A)/A] x 100

Where:

B: mass of surface-dry sample in air after immersion.

A: mass of oven-dried sample in air.

3.2.4.3 Rapid Chloride Permeability Test

Corrosion is mainly caused by the ingress of chloride ions into concrete disturbing the original passivity present. Rapid chloride permeability test (RCPT) has been developed as a quick test able to measure the rate of transport of chloride ions in concrete. One of the main characteristics influencing the durability of concrete is its permeability to the ingress of chloride. The chloride ion present in the concrete can have harmful affect on concrete as well as on the reinforcement. Swelling of concrete due to chloride ion penetration is 2 to 2.5 times larger than that observed with water penetration. So this test covers the experimental evaluation of electrical conductance of concrete to provide rapid indication of concrete resistance against chloride ion penetration.

Six hour test reading are observed to determine the permeability of the samples. Procedure for conducting test is as follows:

The cylinders (100 × 200 mm) thickness with and without bacterial culture were cast and allowed to cure. Specimens were placed in the vacuum dessicator bowl, the setup of the vacuum pump, dessicator with stopcock, vacuum gauge and valve and the deaerated water container after the water has filled the desiccators. The vacuum was maintained in the desiccators bowl for 3 hours. The deaerated water was allowed to flow into the dessicator, so that it completely covers the specimens and no air was allowed to enter. Again the vacuum was maintained for another one hour. Then the specimens were left to soak in the container water for another 18 hours. The specimens were removed from the dessicator, dried and placed in gasket. The liquids (3% NaCl and 0.3 N NaOH solutions) were filled in the two cells. Power supply was set to 60V, and final current reading was recorded after 6h of testing procedure.

3.2.4.4 Sorptivity Test

This test method is used to determine the rate of absorption (sorptivity) of water by hydraulic cement concrete by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time when only one surface of the specimen is exposed to water. The exposed surface of the specimen is immersed in water and water ingress of unsaturated concrete dominated by capillary suction during initial contact with water (ASTM C 1585 -13). 100mm diameter and 50 mm thick concrete disk are prepared as according to ASTM C 1585-04 for conducting the test. Following procedural steps are taken to complete the test.

1. The specimen was dried in oven at about 105°C until constant mass was obtained.

Specimen was cool down to room temperature for 6hr.

2. The side of the specimen was coated with electrician tape to achieve unidirectional flow.
3. The specimen was exposed to water on one face by placing it on slightly raised seat (about 5mm) on a pan filled with water.

The water on the pan was maintained about 5mm above the base of the specimen during the experiment as shown in the figure below. The weight of the specimen was measured at intervals defined by the above mentioned code. The absorption *I* was calculated from the formula :

$$I = \frac{mt}{a \times d}$$

Where:

I = the absorption,

m_t = the change in specimen mass in grams, at the time t (seconds),

a = the exposed area of the specimen, in mm^2, and

d = the density of the water in g/mm^3.

Then the graph of I values was plotted against √t, where t is in seconds. According to ASTM C 1585-13 linear regression analysis using Graph Pad Prism 6.0 of I vs. √t the slope of which gives the value of Sorptivity coefficient that may be related as

$$S_i = I / \sqrt{t}$$

Where:

S_i = Sorptivity Coefficient; rest values are same as above.

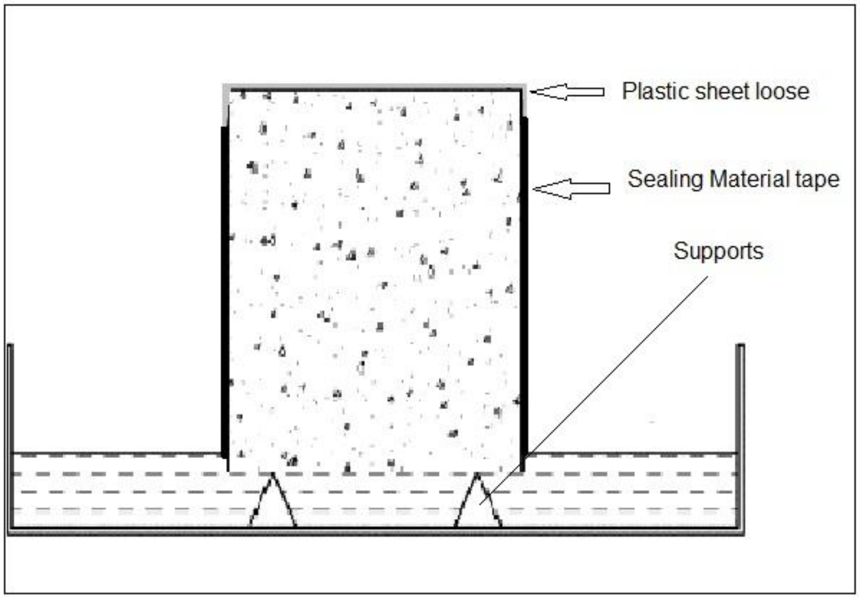

Figure 3.1: Schematic diagram of Capillary absorption test (Sorptivity)

3.2.4.5 Scanning Electron Microscopy

An SEM is essentially a high magnification microscope, which uses a focused scanned electron beam to produce images of the sample, both top-down and, with the necessary sample preparation, cross-sections. The morphology and chemical constituents of the Concrete samples were analyzed with SEM. The Scanning Electron Microscope (SEM) is a powerful instrument which permits the characterization of heterogeneous materials and surfaces. Samples were completely dried at room temperature, then specimens were examined at accelerating voltage range of 20 kV by a SEM (JEOL, JSM 6510 LV).

3.2.4.6 XRD

X-ray diffraction is a non-destructive technique used to determine the elements present in any particular substance. X-ray powder diffraction technique is the most prominent technique used for unraveling the structure of the materials in bulk and thin film forms. XRD spectra were obtained using an X’Pert PRO (PANalytical) diffractometer with a Cu anode (40 kV and 30 mA) and scanning from 5° to 60°. Each sample was crushed and ground before mounting onto a glass fiber filter using a tubular aerosol suspension chamber (TASC). The components of the sample were identified by comparing them with standards established by the International Center for Diffraction Data (ICDD). All experiments were performed in triplicate. X-ray diffraction is based on the fact that, in a mixture, the measured intensity of a diffraction peak is directly proportional to the content of the substance producing it. The samples for X-Ray diffraction analysis were prepared in powdered form. The concrete sample was taken from the inner core of the matrix. For any mineral to be present, all the strong peaks should be present in the XRD graph, else the mineral is not present.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

In this chapter, compressive strength, water absorption, porosity, sorptivity and rapid chloride permeability test of various concrete mixes incorporating 5%, 10%, 15% percentages of silica fume and a constant dosage (10^5 cfu/ml) of calcite precipitating bacteria are discussed. All the tests conducted were in accordance with the methods described in chapter three.

4.2 GROWTH OF BACTERIA

4.2.1 Urease Test

The organisms isolated were streaked on the surface of the media and incubated at 37°C and observed for the change of the color of the media from yellow to pink. The isolate AKKR5 was studied for urease activity. XRD analysis of bacteria precipitate revealed formation of calcite (Figure 4.1).

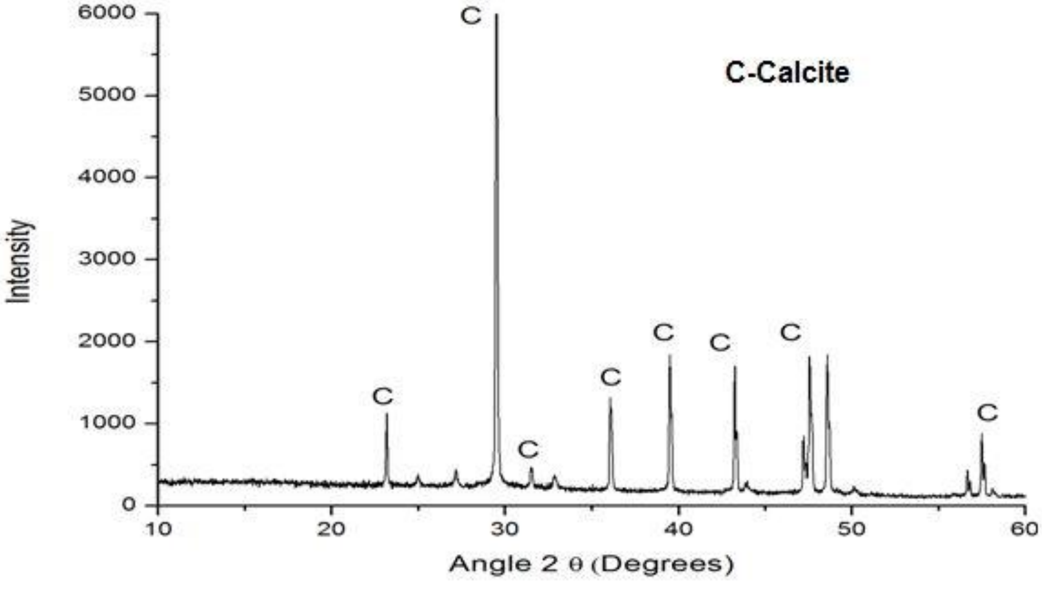

Figure 4.1: XRD analysis of bacterial precipitate

4.3 EFFECT OF SILICA FUME AND BACTERIA ON CONCRETE

4.3.1 Compressive Strength

The objective of this research work is to present the effect of bacteria on the compressive strength of concrete containing silica fume is given in Table 4.1 and shown in Figures 4.2– 4.4. Compressive strength test results shown in Figure 4.2 and Figure 4.3 described the similar pattern of strength development at all ages and comprising of bacterial and control concrete. Silica fume concrete mixtures gained more strength at all ages as compared to the control concrete. 28 days compressive strength of control silica fume specimen with replacement SF5, SF10 and SF15 was 34.84 MPa, 38.72 MPa and 36.63 MPa respectively, while showed compressive strength of 32.85 MPa with increasing SF content (15%) strength starts decreasing but still higher than relative to respective control.

Table 4.1: Compressive strength results of control and bacterial concrete at the age of 28 and 56 days

SF % Replacement	28 Days		56 Days	
	Control (MPa)	Bacterial Concrete (MPa)	Control (MPa)	Bacterial Concrete (MPa)
0	32.85	36.55	36.46	39.01
5	34.84	38.42	38.24	41.43
10	38.72	43.04	41.80	46.85
15	36.63	40.22	40.17	42.38

With the increase in age (28 to 56 days) compressive strength of all mixes are invariably higher as compared to their 28 days compressive strength. This is due to the continuous hydration of cement in concrete indicating the pozzolanic action of silica fume (Dewitler and Mehta, 1989). The 56 days compressive strength of mixes with silica fume replacement level of 5%, 10% and 15% was found to be 5.13%, 17.75%, and 10.04% higher than control specimen of 36.55 MPa. The decrease in SF15 at all ages may be attributed to the fact, that with increase in SF content in matrix free lime (CaO) content from cement reduces, resulted in decreased formation of CSH gel.

Studies on compressive strength with silica fume replacement was carried out by Yogendran et al. (1991); Fidjestol (1993); Wild et al. (1995); Toutonji and Korchi (1995); Sakr (2006); Yunsheng et al. (2008) and it was concluded that concrete mixed with silica fume (10-15%) had the higher compressive strength than control concrete. The strength increment in bacterial concrete specimens (BSF0, BSF5, BSF10) as compared to control concrete (with similar SF replacement) specimens was found to be 11.25%, 10.28%, 11.13%, respectively (Figure 4.2). The increase in strength with the addition of bacteria may be due to deposition of the calcite on surfaces and within the pores of cement sand matrix which plug the pores (Ramachandran et al., 2001; Ramakrishnan et al. 1998; 1999).

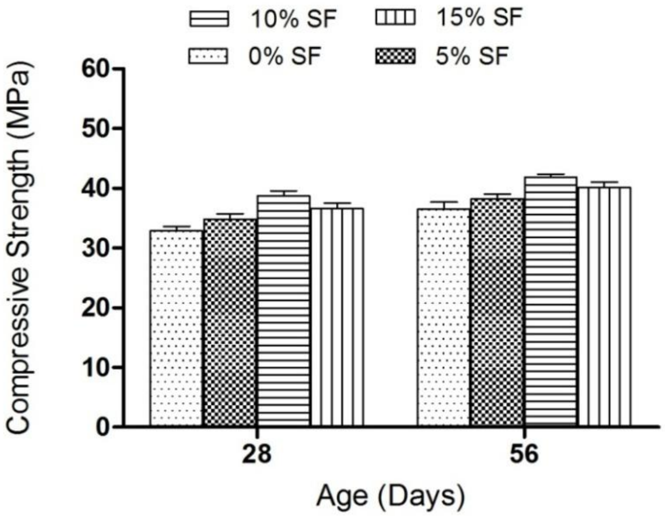

Figure 4.2: Compressive strength of specimens at different age and SF percentage of control concrete

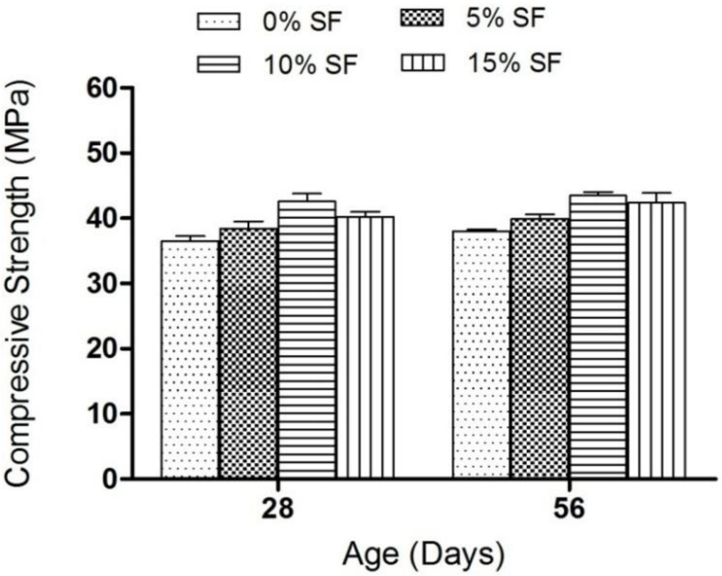

Figure 4.3: Compressive strength of specimens at different age and SF percentage of bacterial concrete

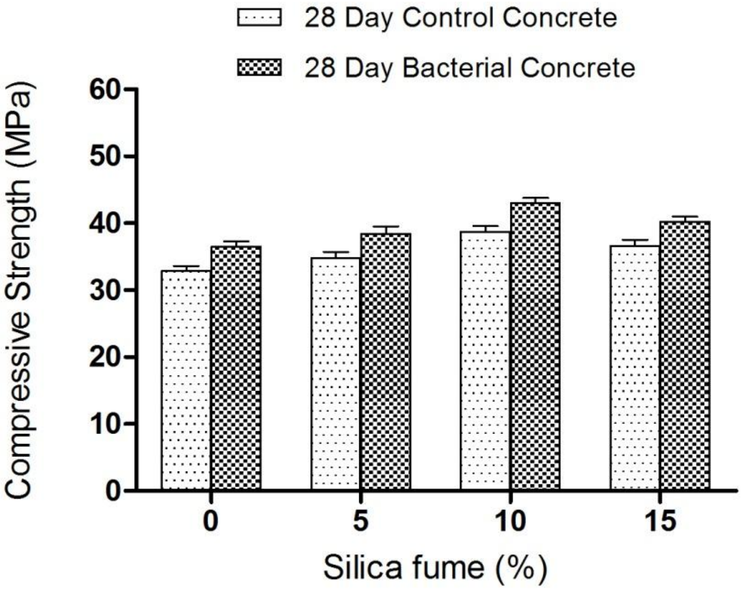

Figure 4.4: Compressive strength of specimens comparing control and bacterial concrete at the age of 28 days

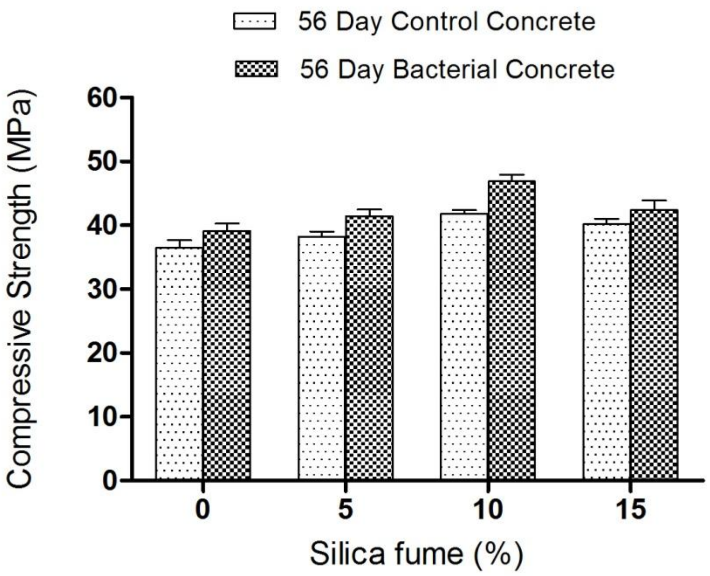

Figure 4.5: Compressive strength of specimens Comparing control and bacterial concrete at the age of 56 days

Ghosh et al. (2006) inferred the improvement in compressive strength due to the deposition of some minute filler material produced by the bacteria that reduce the pore size and modify the microstructure of concrete which is in close agreement to the results obtained in this study. Bacterial precipitated $CaCO_3$ can fill the voids in concrete, decrease porosity, and improve the particle packing efficiency, thereby making concrete dense and increasing the compressive strength as described in the particle packing model (Pei et al., 2013). The maximum increase in compressive strength in BSF10 was found to be 46.85 MPa.

4.3.2 Water Absorption and Porosity

The effect of bacteria on water absorption and porosity of concrete was studied according to ASTM C 642 (2013). Metabolic activities by bacteria led to the precipitation of calcium carbonate. Concrete specimens were tested for water absorption and porosity at the age of 28 and 56 days. The decrease in water absorption and porosity of concrete treated with and without bacteria is given in Table 4.2 and 4.3, respectively. It can be observed from the Table 4.2 that with the inclusion of bacteria, water absorption capacity of control concrete decreased. The presence of bacteria resulted in a significant decrease in the water absorption as compared to control specimens.

Table 4.2: Water absorption test results of control and bacterial concrete at the age of 28 and 56 days

SF % Replacement	28 Days		56 Days	
	Control (%)	Bacterial Concrete (%)	Control (%)	Bacterial Concrete (%)
0	2.29	1.22	2.17	1.08
5	1.84	1.07	1.81	0.86
10	1.64	0.85	1.60	0.74
15	1.75	.99	1.76	0.79

Increase of durability performance of the bacterial concrete is due to bacterial calcite precipitation was held responsible for the durability performance (Ramakrishnan et al., 2001). Once the pores are sealed water ingress was reduced leads to a significant decrease in permeability of concrete. Water absorption capacity of concrete was high in case of control where bacteria were not added. Bacteria resulted in lower water absorption when compared to the control specimens of concrete. It can be seen from Table 4.2 and Figure 4.6 decrease in water absorption of silica fume concrete without bacteria (Control) was 17.04%, 27.38% and 24.82%, respectively in SF5, SF10 and SF15 at the age of 28 days, and further water absorption reduction from 28 days to 56 days was marginal. Bacteria played a significant role in decreasing the water absorption of silica fume concrete which decreased with the addition of bacteria cell concentration (which is kept constant) 10^5 cfu/ml. Trend of decrease in water absorption with the addition of bacteria up to 10% SF replacement was found to be similar at the age of 28 days as well as 56 days cured specimens.

Percentage decrease in the water absorption of bacterial concrete at the age of 28 days were 41.84%, 48.47% and 43.53% for BSF5, BSF10, BSF15 respectively as compared to their respective control. At the age of 56 days bacterial behave in the same manner as that of 28 days specimens with a percentage reduction in water absorption 52.75%, 53.95% and 55.21% in BSF5, BSF10 and BSF15 specimens respectively, with respect to control.

The maximum decrease in the water absorption capacity was found to be 0.74% for 56 days bacterial concrete with 10% silica fume (BSF10) replacement. This decrease in the water absorption may be related with the precipitated crystals of calcite which increases the durability of concrete as discussed by Van Tittelboom et al. (2010). Pei et al. (2013) observed that water absorption decreased significantly in the presence of *B. subtilis* by 2.47% and 1.64% on average at the age of 7 and 28 days.

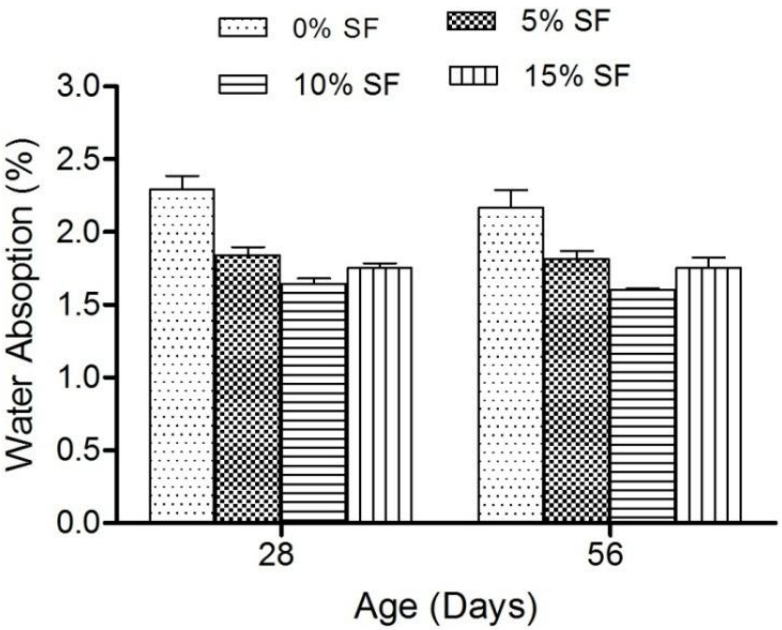

Figure 4.6: Water absorption of specimens at diffrent age and SF percentage of control concrete

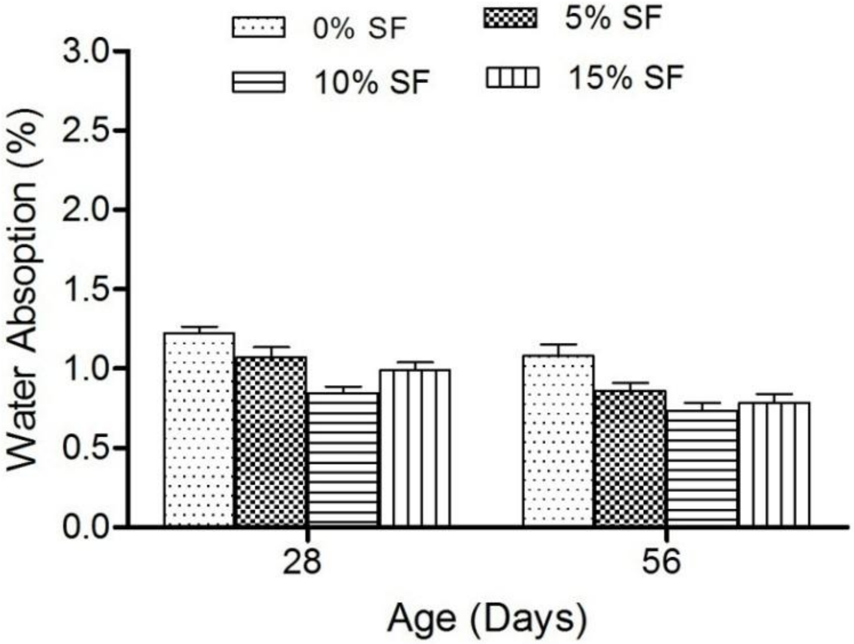

Figure 4.7: Water absorption of specimens at different age and SF percentage of bacterial concrete

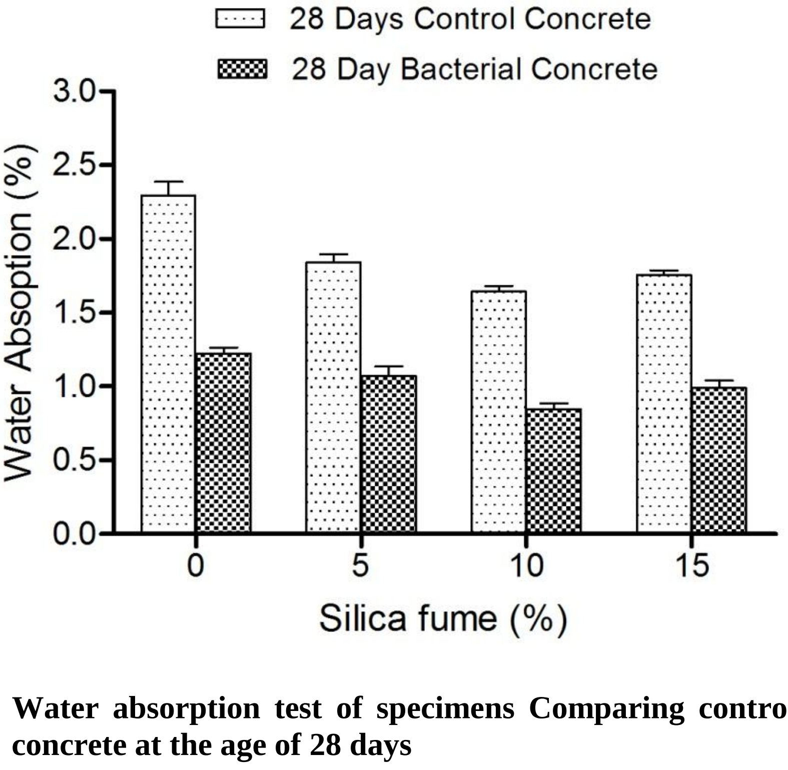

Figure 4.8: Water absorption test of specimens Comparing control and bacterial concrete at the age of 28 days

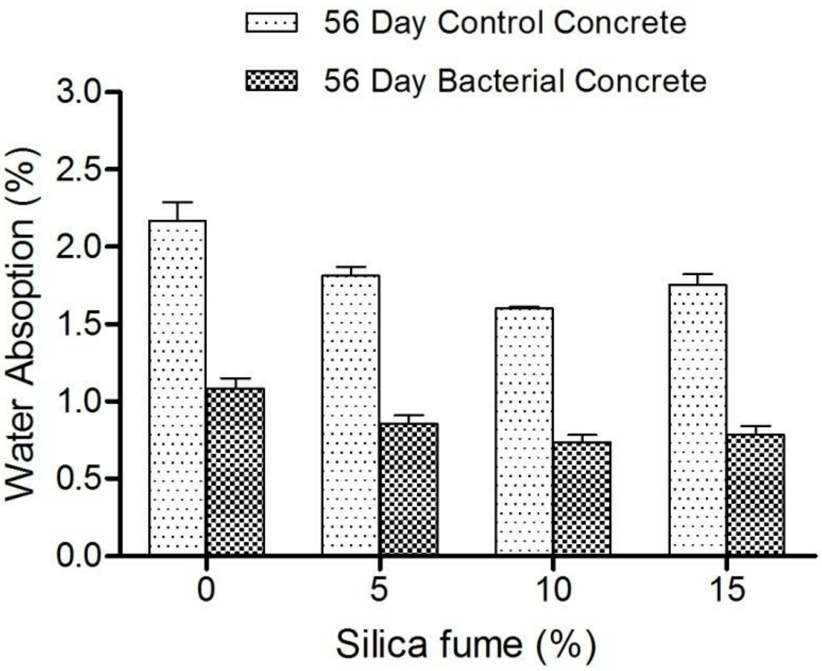

Figure 4.9: Water absorption of test specimens comparing control and bacterial concrete at the age of 56 days

Porosity results of the control and bacterial concrete are provided in Table 4.3. The presence of bacteria resulted in significant reduction of water uptake when compared to control concrete without bacteria. The decrease in porosity of concrete treated with bacteria was due to deposition of calcium crystals on the surface which further resulted in decrease of the permeation properties.

It is seen from the Table 4.3 and Figure 4.10 that reduction in porosity of silica fume concrete was 17.04%, 27.38% and 24.82% with 5% (SF5), 10% (SF10), and 15% (SF15) silica fume content respectively at the age of 28 days, and further porosity decreased up to 10% SF content at the age of 56 days. From Figure 4.12 and 4.13 it was observed that the reduction in porosity of bacterial concrete specimens in both 28 days and 56 days was about 50−55 % as compared to the specimens of control concrete at respective age. In BSF10 at the age 56 days porosity was found to be 1.99%. These results are in accordance with the De Muynck et al. (2008) where 65-90% reduction in water absorption and porosity was noticed in bacterial concrete. The water permeability was decreased by about 68% bacterial specimens while in non bacterial specimen reduction water permeability was reduced from 15-55% (Wang et al., 2014).

Table 4.3: Porosity test results of control and bacterial concrete at the age of 28 and 56 days

SF % Replacement	28 Days		56 Days	
	Control (%)	Bacterial Concrete (%)	Control (%)	Bacterial Concrete (%)
0	6.77	3.07	5.95	2.80
5	5.62	2.67	5.13	2.33
10	4.92	2.36	4.67	1.99
15	5.09	2.41	4.79	2.17

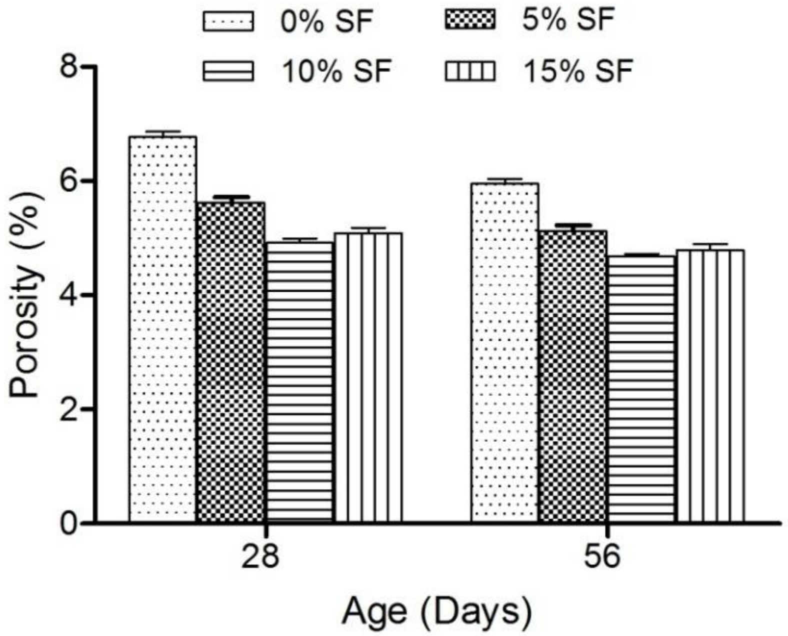

Figure 4.10: Porosity test of specimens at different age and SF percentage of control concrete

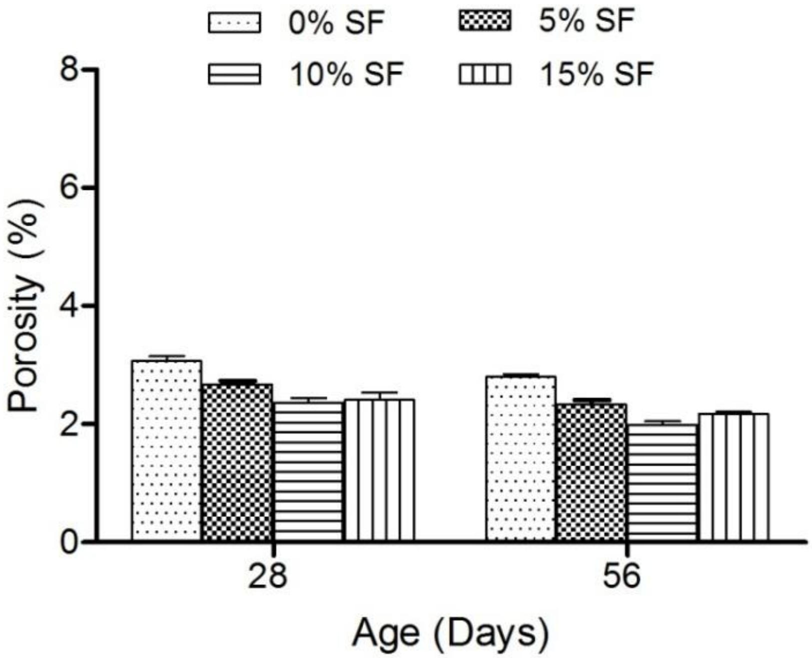

Figure 4.11: Porosity test of specimens at different age and SF percentage of bacterial concrete

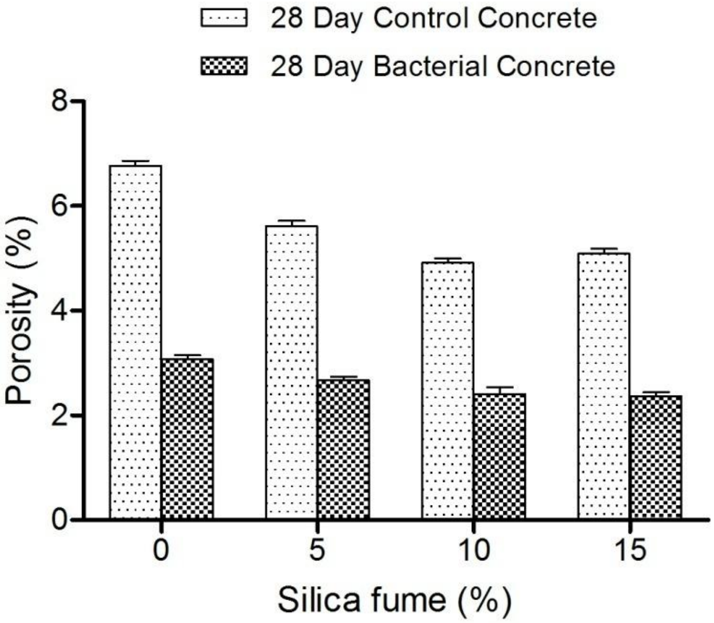

Figure 4.12: Porosity test of specimens comparing control and bacterial concrete at the age of 28 days

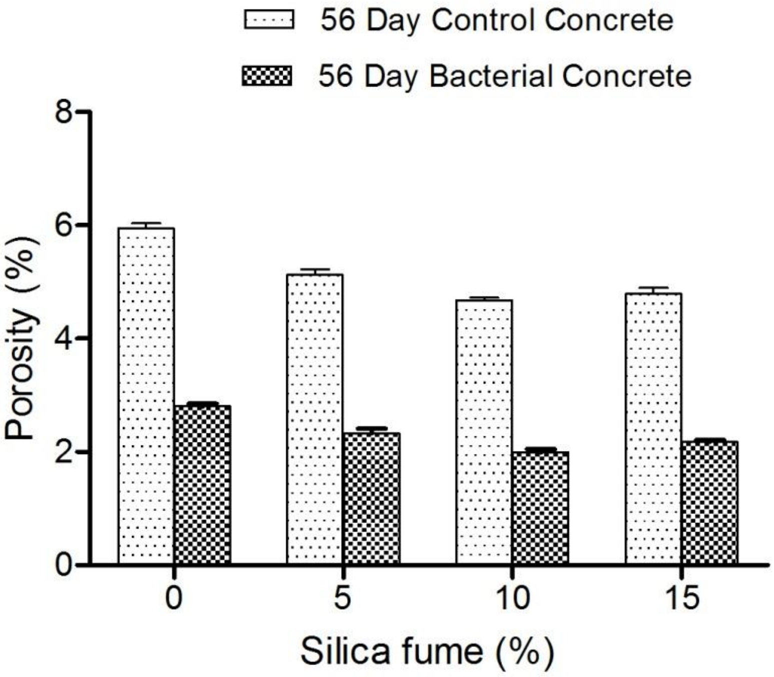

Figure 4.13: Porosity test of specimens comparing control and bacterial concrete at the age of 56 days

4.3.3 Rapid Chloride Permeability Test

The ability of concrete to resist the permeation of chloride ions is an important parameter in determining the durability of concrete structures. The test of the mixes for rapid chloride penetration test was performed at two different ages (28 and 56 days) for bacterial as well as control concrete. Summary of average results of the effect of bacteria on the rapid chloride permeability of concrete at the age of 28 and 56 days is given in Table 4.4. It was observed that trend decrease or increase in RCPT value for all mixes is similar (Figures 4.14–4.17).

RCPT test results shown in Figure 4.14 and 4.15 described the similar pattern of strength development in control and bacterial concrete. Silica fume concrete mixture showed lesser permeability at all ages as compared to the control concrete (SF0). Chloride permeability in 5% (SF5), 10% (SF10) and 15% (SF15) was 1229, 840 and 1132 coulombs respectively as compared to 2525 coulombs of control mixture (SF0).

Table 4.4: RCPT test results of control and bacterial concrete at the age of 28 and 56 days

SF % Replacement	28 Days		56 Days	
	Control (coulombs)	Bacterial Concrete (coulombs)	Control (coulombs)	Bacterial Concrete (coulombs)
SF0	2525	2159	1985	1729
SF5	1537	1338	1229	1107
SF10	960	783	840	746
SF15	1185	984	1132	950

In SF15, permeability starts increasing but still lower than relative to respective control (SF0) at the age of both 28 and 56 days. The large decrease in the permeability with time in the above concretes was due to the change in the pore structure of the hydrated cementitious system with the use of SF (Ramezanianpour and Malhotra, 1995; Shi, 2004; Khan, 2003). With the increase in age it was found that permeability of all mixes are invariably lower at the age of 56 days as compared to 28 days permeability and this was due to the continuous hydration of cement in concrete. The 56 days permeability of mixes with silica fume replacement level of 5%, 10% and 15% was found to be 38.10%, 57.69%, and 43% lower than control specimen of 1985 coulombs at similar age.

When permeability of bacterial concrete was compared to control concrete (Figure. 4.15 and 4.16) the decrease in permeability was 12%, 18% and 16% for SF5, SF10 and SF15 respectively at the age of 28 days. The results obtained are in good agreement with Chahal et al. (2012) as it was suggested that bacterial calcite deposition reduced the chloride permeability of bacterial concrete as compared to control concrete. Lowest permeability was observed in bacterial concrete with 10% silica fume replacement at 28 days age of concrete specimen of 783 coulombs. At 56 days when compared to bacterial concrete the decrement in permeability was from 1985 coulombs to 746 coulombs. There was an increase in permeability of BSF15 concrete relative to BSF10 but still the bacterial concrete mixes have much lower permeability than control mix (950 coulombs).

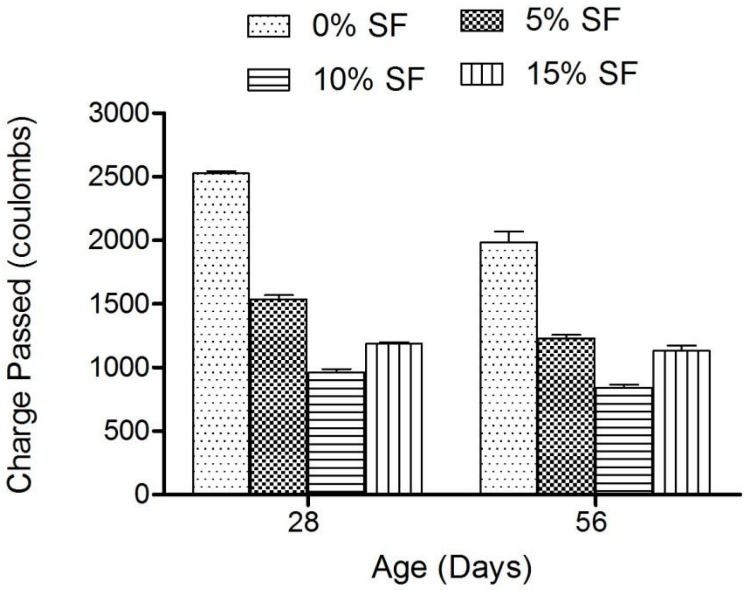

Figure 4.14: RCPT test of specimens at different age and SF percentage of control concrete

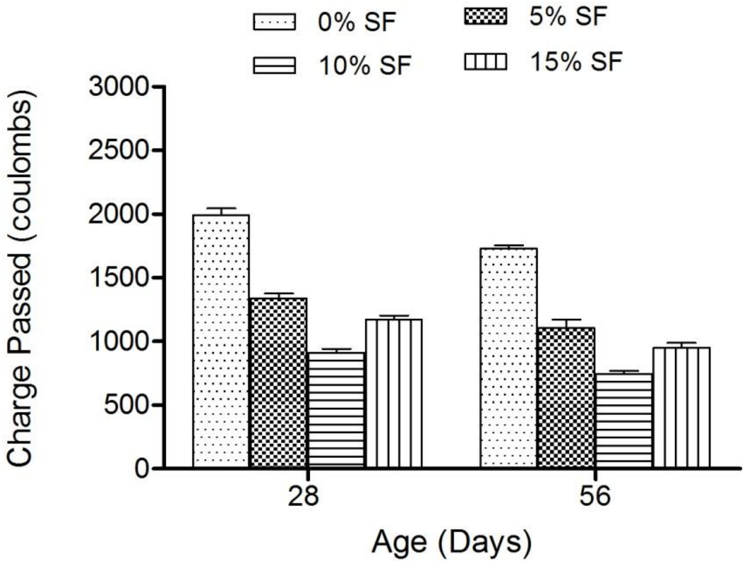

Figure 4.15: RCPT test of specimens at different age and SF percentage of bacterial concrete

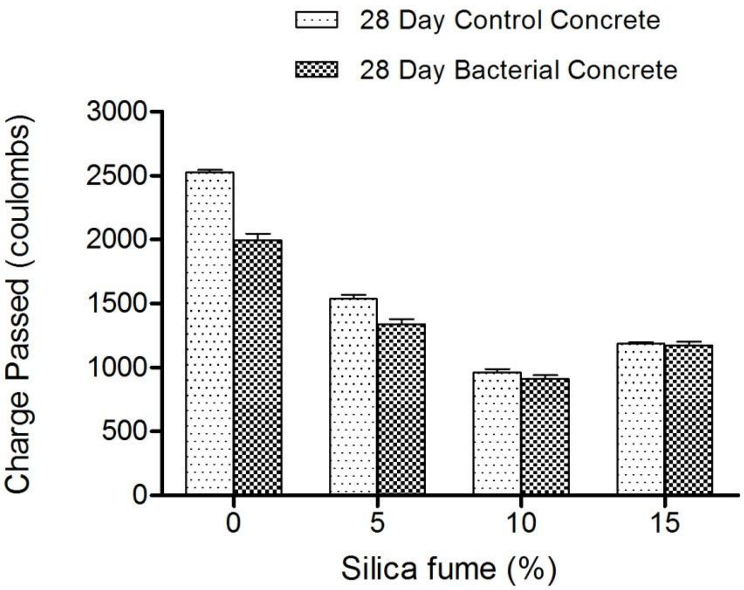

Figure 4.16: **RCPT test of specimens comparing control and bacterial concrete at the age of 28 days**

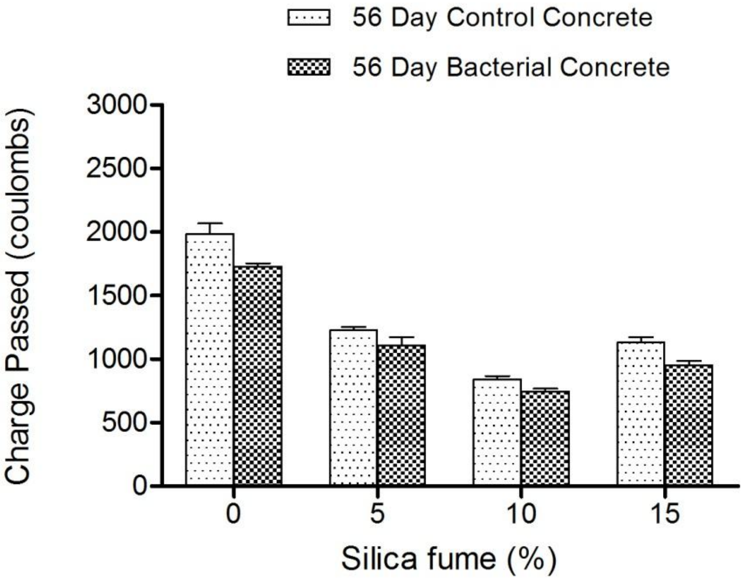

Figure 4.17: **RCPT test of specimens comparing control and bacterial concrete at the age of 56 days**

4.3.4 Sorptivity

Sorptivity is defined as the rate of movement of a waterfront through a porous material under capillary action explained by Kelham (1988). The test was done in accordance to the ASTM C 1585–13. From Table 4.5 and Figure 4.17–4.20 it is seen that capillary water uptake results were significantly influenced with the addition of bacteria , 50– 70% reduction in sorptivity coefficient of specimens were observed both at 28 and 56 days. The minimum water capillary uptake was observed in BSF10 (0.0021 mm /√s) at the age of 56 days. This is because after the addition of the bacteria the microstructure of the mortar specimens was changed, therefore the water transport properties of the specimen decreased (Wang et al., 2014).

Mortar cubes treated with bacteria and a calcium source showed significantly less water absorption compared to untreated specimens (De Muynck et al., 2008) which was attributed to the presence of biological precipitated calcite. Other researchers also reported up to 50% decrease in capillary water uptake and durability properties such as chloride migration test and water absorption (Tiano et al., 1999; Nemati and Voordouw, 2003; Whiffinn, 2004).

Reduction in sorptivity in SF10 was due to formation of dense microstructure due to pozzolanic reaction of silica fume. A 10% addition of SF by mass of the binder content caused the greatest improvement in performance, with an index of 3.42 mm/√h obtained. Index values less than 6.0 mm/√h have been reported to represent excellent concrete performance (Alexander and Magee, 1999) which showed that results of this report are in accordance with the literature present. Results from Chan and Ji (1998) also confirmed that addition of silica fume to concrete reduced sorptivity.

Table 4.5: Sorptivity test results of control and bacterial concrete at the age of 28 and 56 days

SF % Replacement	28 Days		56 Days	
	Control (mm/√s)	Bacterial Concrete (mm/√s)	Control (mm/√s)	Bacterial Concrete (mm/√s)
0	0.0094	0.00425	0.0053	0.0026
5	0.0074	0.0032	0.0048	0.0023
10	0.0070	0.0048	0.0034	0.0021
15	0.0100	0.0023	0.0038	0.0025

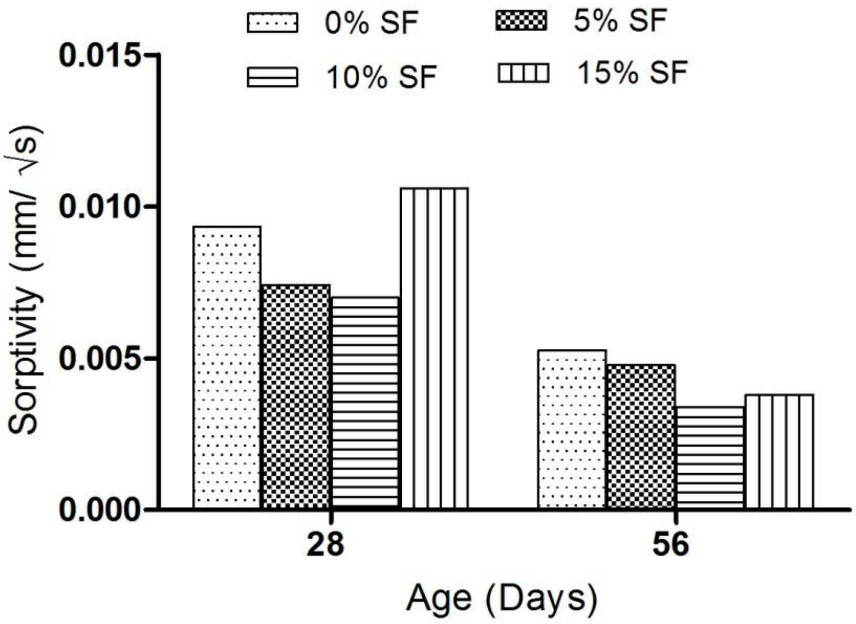

Figure 4.18: Sorptivity test of specimens at different age and SF percentage of control concrete

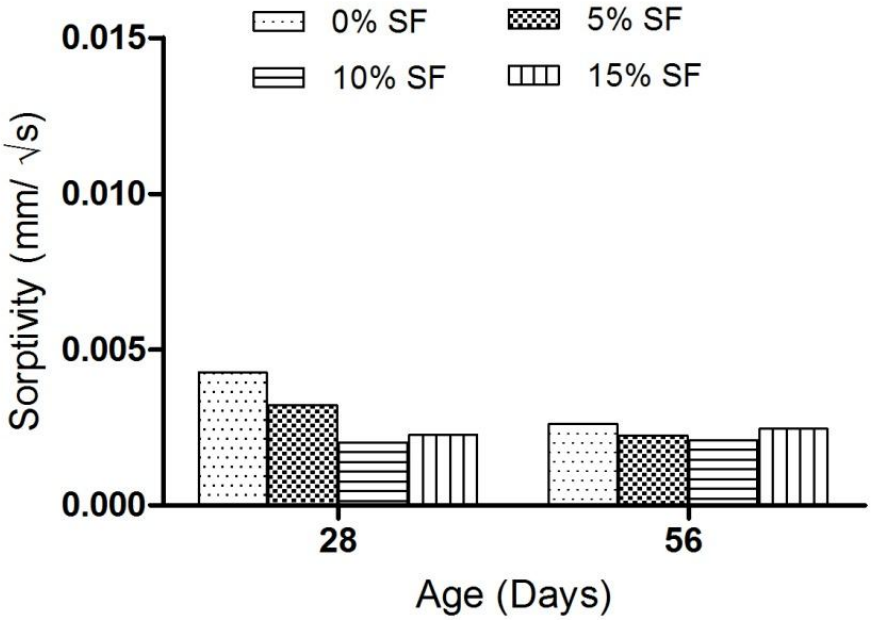

Figure 4.19: Sorptivity test of specimens at different age and SF percentage of bacterial concrete

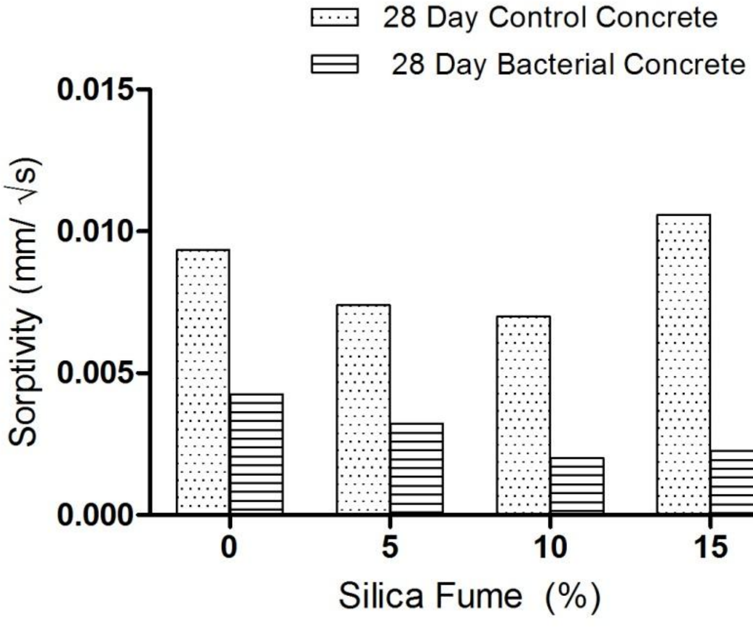

Figure 4.20: Sorptivity test of specimens comparing control and bacterial concrete at the age of 28 days

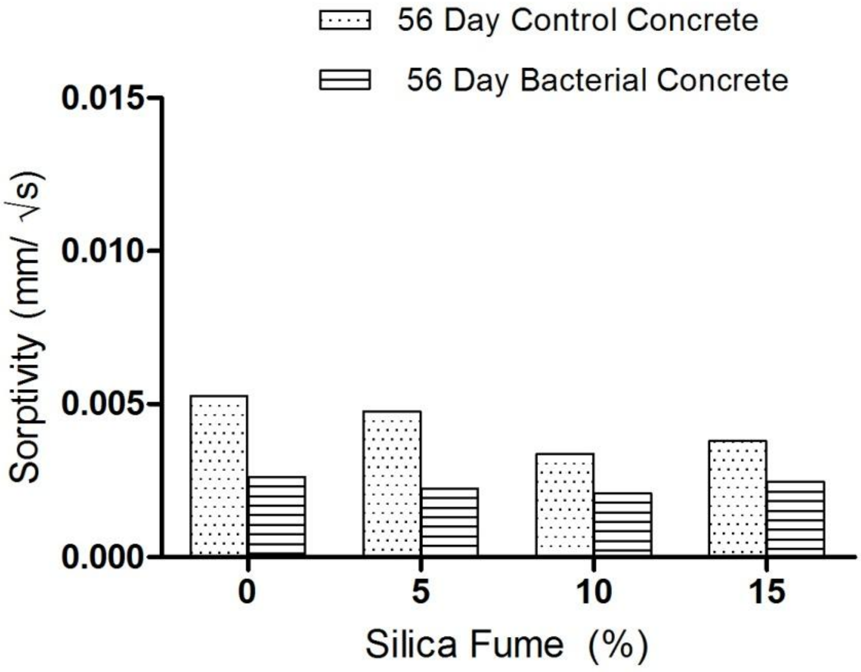

Figure 4.21: Sorptivity test of specimens comparing control and bacterial concrete at the age of 56 days

4.3.5 SEM Analysis of Concrete

The concrete specimens (extracted from core of concrete cube) treated with bacteria and control were analyzed using this technique, and SEM pictures are shown in Figures 4.22−4.25. The identification of different phases present on SEM micrographs were studied from the literature present (Nochaiya et al., 2010; Hewlett, 2003; Yazici, 2007). The SEM analysis revealed the presence of distinct calcite crystals in the concrete samples. The presence of crystalline calcite associated with bacteria shows that bacteria served as pore filler sites during precipitation process (Zhang et al., 2015). The SEM analysis of control (SF0) and bacterial treated control (BSF0), and also with SF (5%, 10% and 15%) containing control concrete and bacterial concrete were carried out using JEOL, JSM 6510 LV. In SF0 concrete the SEM image shows the formation of calcium silicate hydrate (CSH) and the hydration reaction formed dense structure resulted in increased compressive strength, pores were also visible with portlandite (CH) formation. In case of bacterial concrete the precipitation of calcite (C) was visible in pores due to which increase in strength and permeation properties may be defined. In Figure 4.23 with 5% SF replacement the formation of CH crystals were less as compared to control because of the pozzolanic reaction of silica available from SF replacement, hence more of CSH gel formation can be seen with more dense matrix, it can be seen that CH is still observable, but to a lesser extent than in the mix without SF. This is due to the pozzolanic reaction that occurred between silica fume and CH, thereby led to reduction in CH (Nochaiya et al., 2010). In BSF5 calcite precipitation in voids and on surface are visible.

SEM micrograph of SF10 specimens (Figure 4.24a) were found to have much dense microstructure of concrete with CSH formation with negligible amount of CH and very small pores but the number of voids and their size in the mix has significantly reduced .In bacterial specimen (Figure 4.24b) calcite precipitation were clearly seen which shows densification of paste aggregate matrix resulted in decreased porosity and gain in strength (Ghosh et al., 2005; De Muynck et al., 2008; Pei et al., 2013). Wider voids are visible due to decrease of the cement content in the matrix of SF15 and BSF15 specimens which resulted in increase in the permeability and decrease in strength of concrete.

4.3.6 XRD Analysis of Bacterial Concrete

X-ray diffraction (XRD) analysis of concrete specimens with or without bacterial SF replacement shows peaks of quartz (Q), calcium silicate hydrate (CSH), calcite (C), Larnite (L) and ettringite (E) minerals, depicted in Figures 4.26 – 4.29. The powder crystal X-ray analysis of the samples with and without bacteria shows that there were some extra peaks in the XRD spectra of the bacteria treated samples, which are absent in the control samples such as precipitation of bacteria which shows higher amount of calcite in case of bacterial concrete. XRD analysis was compared with the literature present (Zhang et al., 2015; De Muynck et al., 2008; Pei et al., 2013).

The increase in CSH and calcite content at SF10 replacement suggest the reason for increase in the strength and permeation properties of the specimens. In BSF10/SF10 XRD analysis revealed the formation of ettringites however the intensity is less as compared to BSF15/SF15, still increase in strength may be explained by crystal growth theory that not all the ettringite formed causes expansion leading to reduction in strength since a portion of the ettringite will be deposited in available voids and cracks, so only the excess will cause expansion (Halaweh, 2006), as found in case of 15% (BSF15/SF15) increase in etrringites are clearly visible in XRD data. Thus, we can say that in BSF15/SF15 expansive ettringites are responsible for decrease in strength of the specimens.

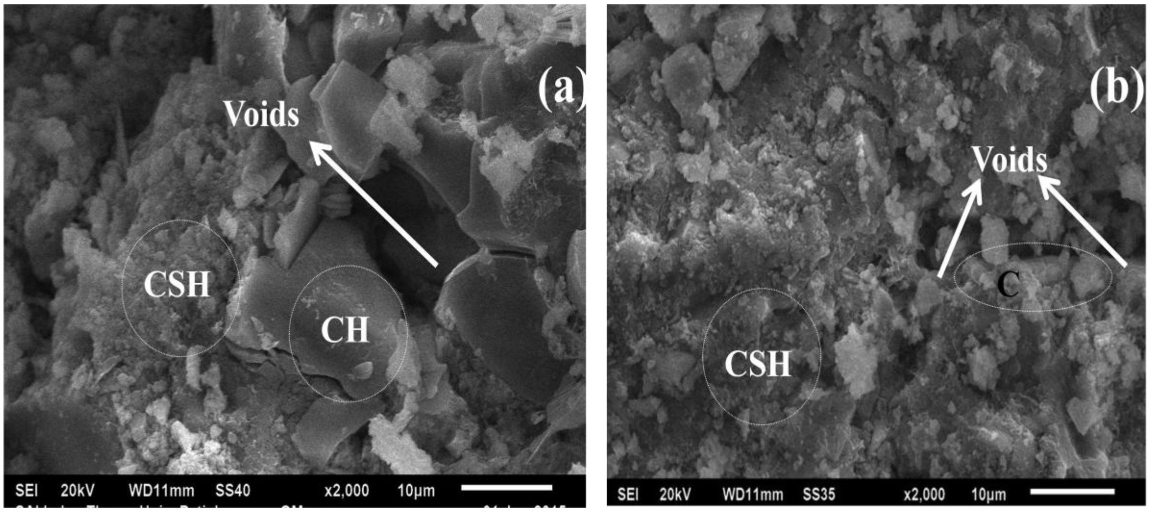

Figure 4.22: SEM micrograph showing (a) Control concrete (SF0) (b) Bacterial concrete (BSF0)

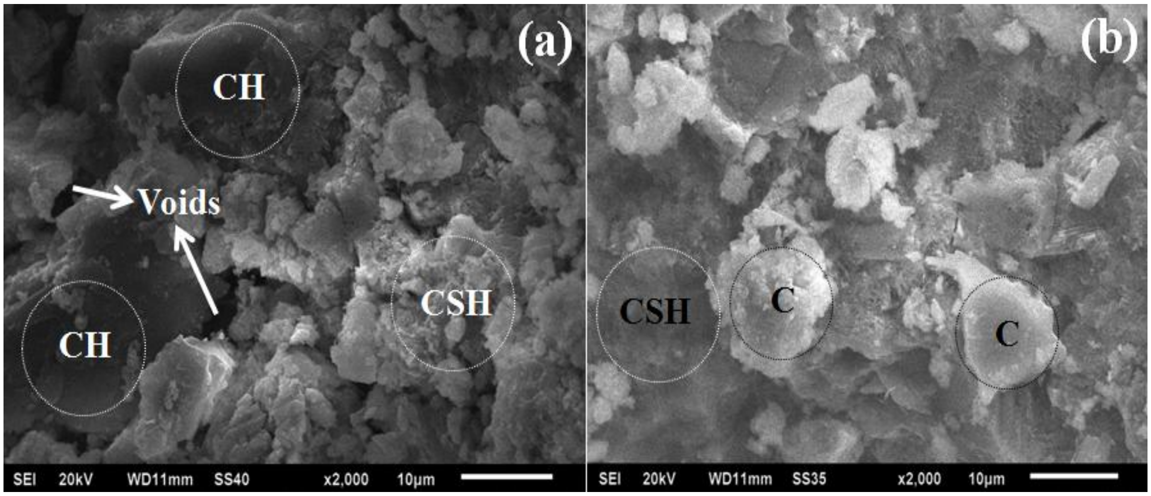

Figure 4.23: SEM micrograph showing (a) control concrete (SF5) (b) bacterial concrete (BSF5)

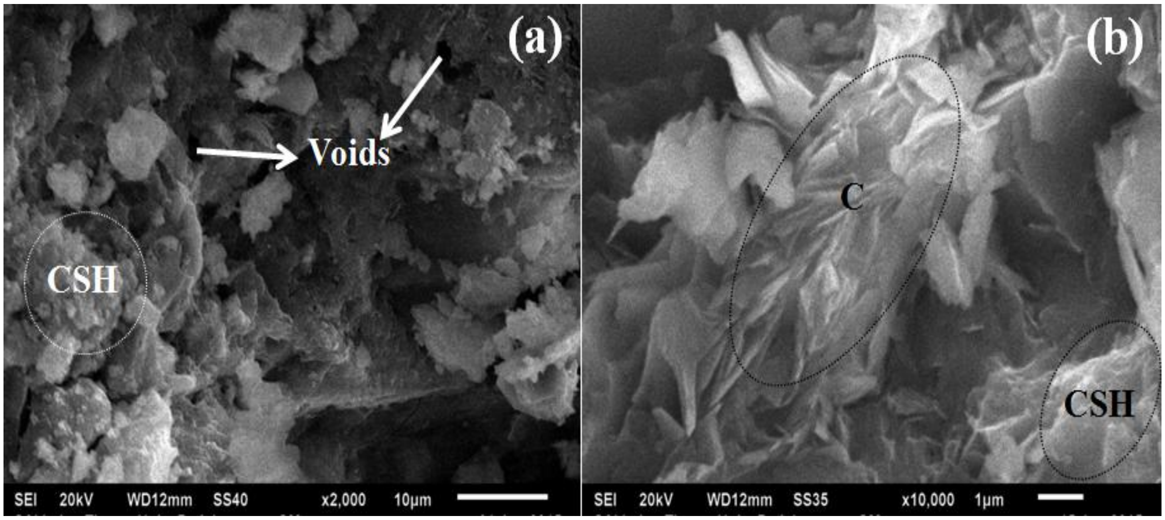

Figure 4.24: SEM micrograph showing (a) control concrete (SF10) (b) bacterial concrete (BSF10)

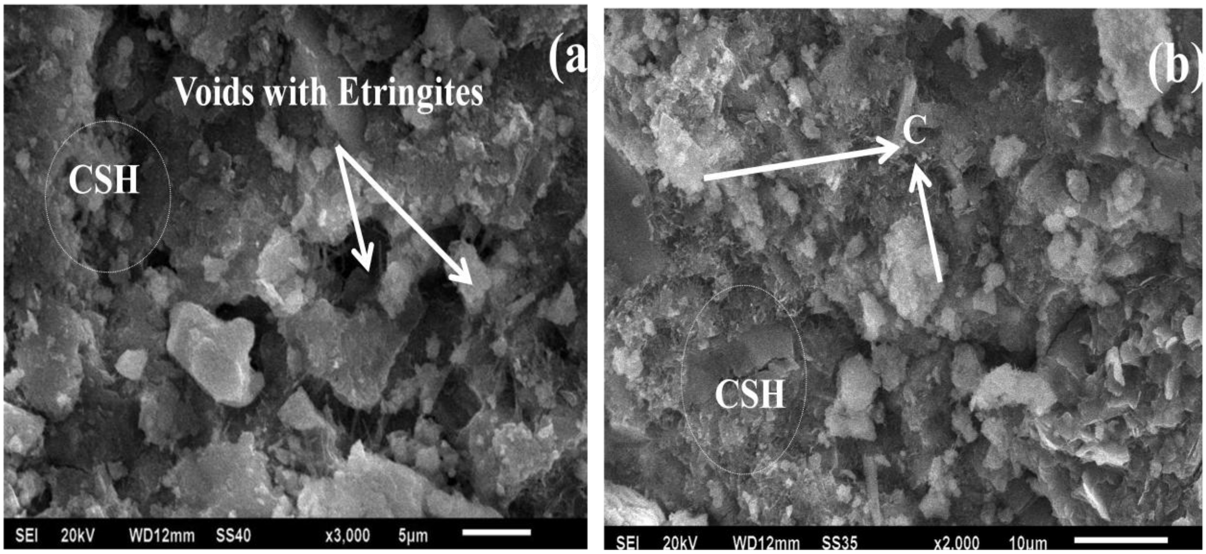

Figure 4.25: SEM micrograph showing (a) control concrete (SF15) (b) bacterial concrete (BSF15)

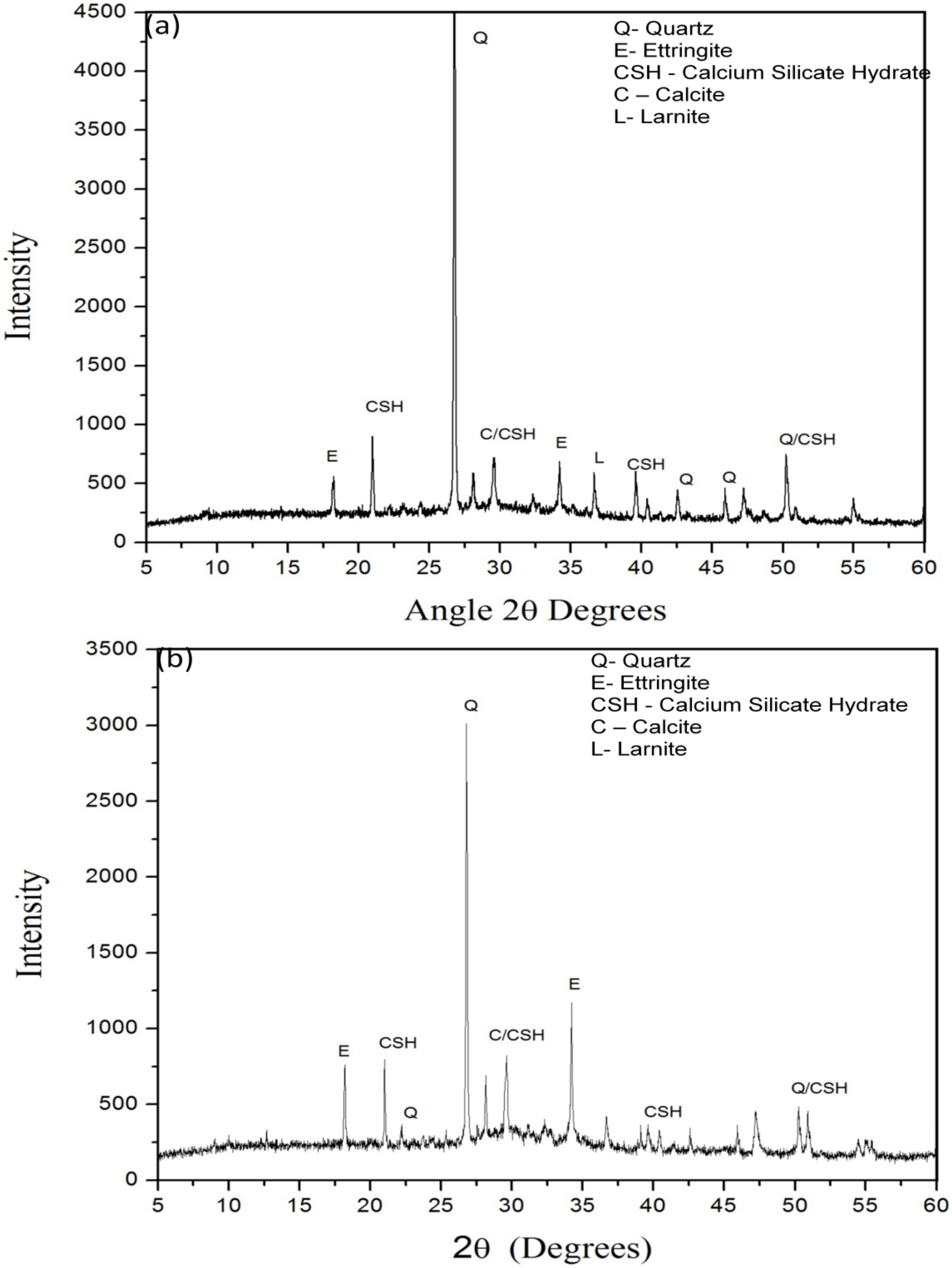

Figure 4.26: XRD analysis of (a) control concrete (SF0) (b) bacterial Concrete (BSF0)

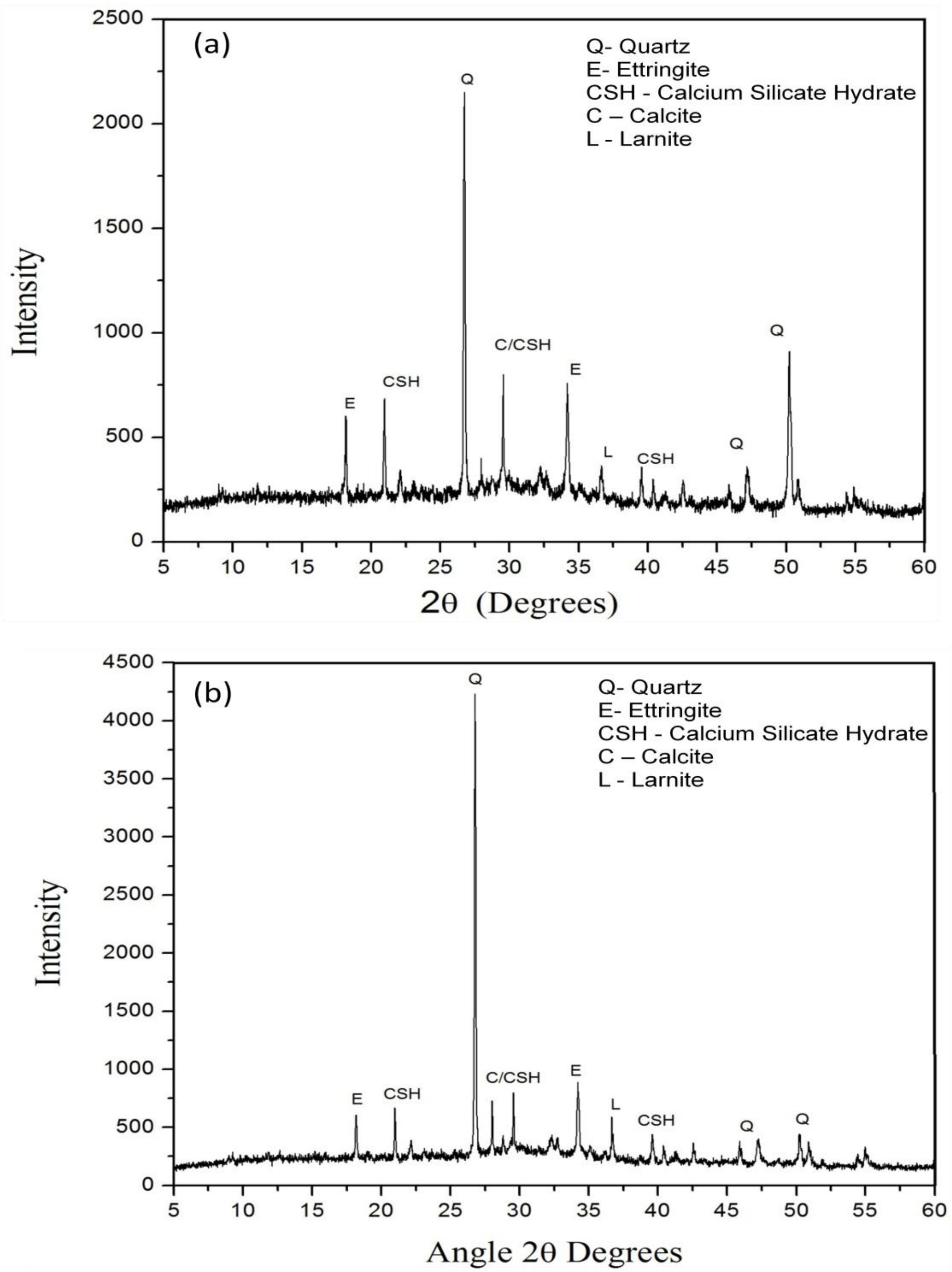

Figure 4.27: XRD analysis of (a) control concrete (SF5) (b) bacterial Concrete (BSF5)

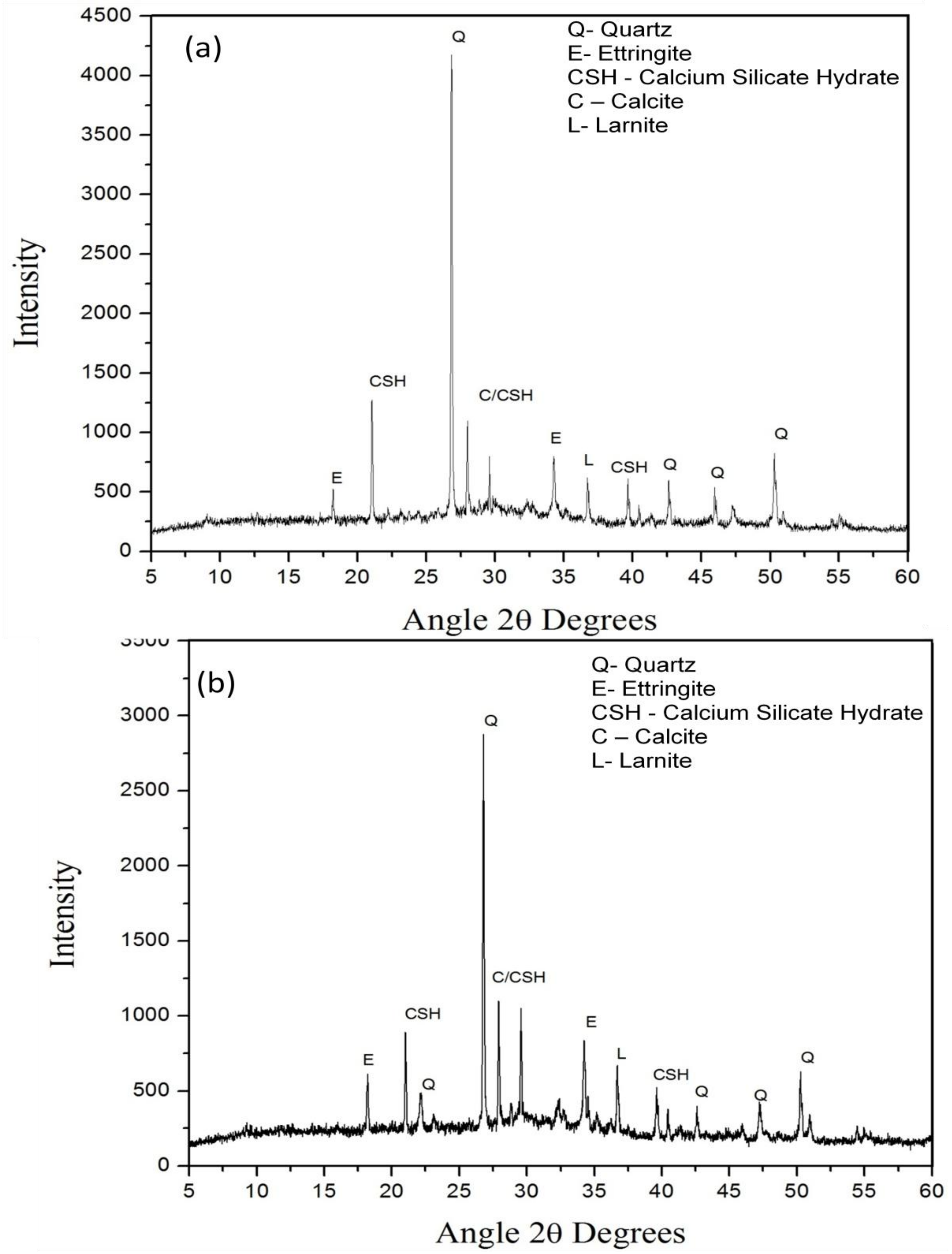

Figure 4.28: XRD analysis of (a) control concrete (SF10) (b) bacterial Concrete (BSF10)

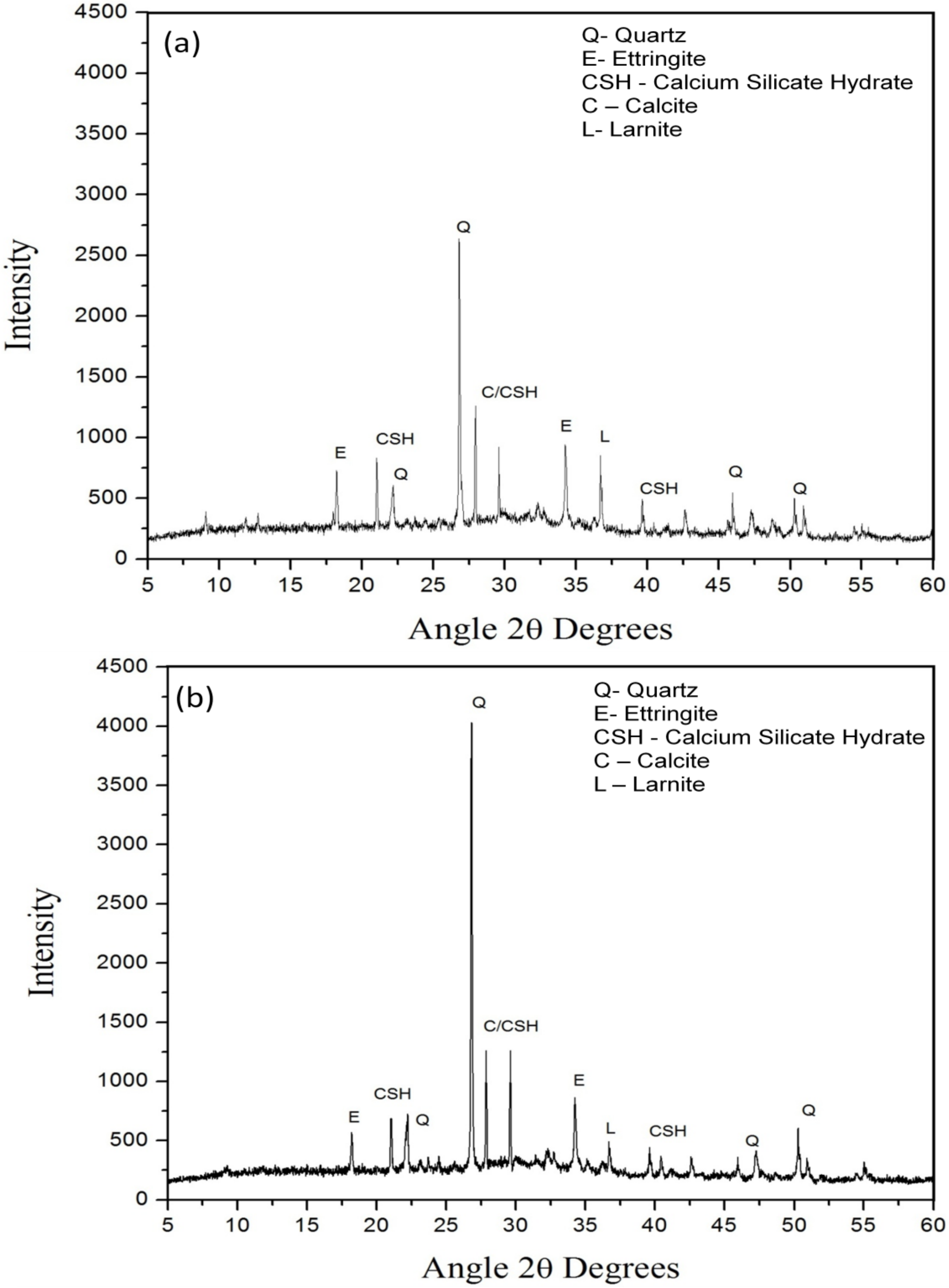

Figure 4.29: XRD analysis of (a) control concrete (SF15) (b) bacterial Concrete (BSF15)

CHAPTER 5

CONCLUSION

5.1 GENERAL

The present work investigated influence of bacteria on the permeation properties of concrete containing supplementary cementing material. The supplementary cementing material used was silica fume which replaced cement partially by percentage of its weight. The presence of bacteria played significant role on permeation properties of concrete. The properties studied were on M20 grade of concrete. On the basis of the results from the present study, following conclusions are drawn.

5.1.1 Compressive Strength

i. Compressive strengths for all concrete mixtures were designed for M20 grade. The compressive strengths observed for 28 days and 56 days with bacterial addition of concrete mixes were found to be more than 32 MPa.

ii. The maximum compressive strength after 56 days was observed for a mixture with 10% silica fume which had bacteria cell concentration 10^5 cfu/ml which is about 12% more than the control specimen with same silica fume replacement.

iii. Compressive strength in all cases increased with increase in age for all mixtures with or without bacteria. However, the rate of compressive strength increase was higher in case of mixtures with bacteria than mixtures without bacteria.

iv. From the above it has been concluded that the improvement in compressive strength was due to deposition of calcite on the bacteria cell surfaces within the pores which was scanned by electron microscopy and confirmed by XRD which revealed calcium carbonate precipitation.

5.1.2 Water Absorption

i. Water absorption was assessed for all concrete mixtures. It was found that water absorption was less in mixtures with bacteria addition as compared to the mixtures without bacteria. This indicates that it may be due to the calcite precipitation action of bacteria and addition of silica fume as filler and pozzolanic material.

ii. The minimum water absorption after 56 days was found for mixtures with constant bacterial concentration of 10^5 cfu/ml. The absorption of water was 48–55 % reduced in water absorption at 28 and 56 days respectively with 10^5 cfu/ml of bacteria which could in turn increase durability of concrete structures. It may be concluded that reduction in water absorption was result of presence of Silica fume in concrete and optimum doze of bacteria.

5.1.3 Porosity

i. Water porosity was assessed for all concrete mixtures. It was found that water porosity was less in mixtures where bacteria were added as compared to the mixtures without bacteria. This indicates that the pores of the concrete may be reduced in number or may have been blocked, which was the result of calcite precipitation by bacteria.

ii. The reduction in porosity of bacterial concrete specimens was found to be 50–55% less as compared to non bacterial control concrete specimens.

iii. The minimum water porosity at the age of 56 days was observed for a mixture with 10% silica fume which had 10^5 cfu/ml bacterial concentration. It may be concluded that reduction in water porosity was result of presence of silica fume and optimum dosage of bacteria.

iv. Water porosity in all cases decreased with increase in age for all mixtures with or without bacteria. However, the rate of water porosity decrease was higher in case of mixtures with bacteria than mixtures without bacteria.

5.1.4 Rapid Chloride Permeability Test

i. Chloride permeability resistance was assessed for all concrete mixtures. It was found that chloride permeability resistance was less in mixtures where bacteria was added as compared to the mixtures without bacteria which indicates resistance to the flow through the voids of concrete as a result of reduction in their number or blockage.

ii. The minimum RCPT value (Coulombs) was for the 10% silica fume for bacterial concentration of 10^5 cfu/ml. The value reduced nearly 12% in BSF10 as compared to SF10 without bacteria at the age of 56.

iii. RCPT values in all cases decreased with increase in age for all mixtures with or without bacteria. However, the rate of chloride penetration decrease was much higher in case of mixtures with bacteria than mixtures without bacteria.

5.1.5 Sorptivity

i. Sorptivity was assessed for all concrete mixtures. It was found that sorptivity was less in mixtures where bacteria was added as compared to the mixtures without bacteria which indicates resistance to the flow through the voids of concrete as a result of reduction in their pore structure or blockage.

ii. The minimum value of Sorptivity was found for BSF10 at the age of 56 days which is of the value .0021 mm/ √s, less than sorptivity of all the samples tested it may be due to the calcite precipitation action of bacteria and addition of silica fume as filler and pozzolanic material.

iii. Sorptivity values in all cases decreased with increase in age for all mixtures with or without bacteria. However, the rate of capillary water uptake decrease was much lower in case of mixtures with bacteria than mixtures without bacteria.

5.1.6 Scanning Electron Microscope (SEM) Studies

i. The SEM analysis of bacterial concrete revealed distinct calcite crystals embedded with bacteria which indicated that the bacteria served as the nucleation sites for the mineralization process.

ii. From the analysis it was clear and concluded that the bacterial concrete samples show crystalline and dense matrix, where individual crystals could be recognized. The degree of formation of crystals in the matrix of treated samples is heterogeneous. This type of textural setting concludes that the coherence between cement particles and the matrix in micro-scale is enhanced due to preferential crystallization at the concrete–matrix interfaces.

iii. Non expansive ettringite formation in voids which supports the increased compressive strength in 10% silica fume (BSF10) bacterial concrete calcite filler material was also present in the same mix in significant amount.

5.1.7 X-ray Diffraction Studies

i. Microstructure analysis was done using XRD for confirmation of calcite which was present in the form of calcium carbonate at the age of 28 and 56 days. Calcite precipitation was more at the age of 56 days and in all concrete mixes of concrete, calcite was present.

ii. Calcium hydroxide if leached out causes durability problems. But in our research work the presence of CH ($Ca(OH)_2$) is negligible in all concrete mix except control which confirm the maximum consumption of CH in the pozzolanic reaction and non expansive ettringite formation which supports the increased compressive strength in 10% silica fume (BSF10) bacterial concrete.

5.1.8 Scope for Further Studies

The present work is concentrated on ordinary grade (M20) control and bacterial concrete. The same work can be extended to the higher grade concrete. Further the long term effects need to be studied. Also it is recommended to develop the bacterial concrete by using different mineral admixtures like GGBS, metakaolin and waste foundry their combinations and study the compatibility.

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