Studies on Permeability of Self-Healing Built-In Bacteria Concrete

Srinivasa Reddy V, Jyothi Kumar K S, Seshagiri Rao M V, Sasikala Ch

Abstract: ***Permeability is the most crucial internal factor in concrete durability. The durability of a concrete is closely related to its permeability. The permeability dictates the rate at which aggressive agents can penetrate to attack the concrete and the steel reinforcement. Water penetrability is defined as the degree to which a material permits the transport gases, liquids or ionic species through it. Water can be harmful for concrete, because of its ability to leach calcium hydroxide from the cement paste, to carry harmful dissolved species such as chlorides or acids into the concrete, to form ice in large pores in the paste, and to cause leaching of compounds from the concrete. Water absorption, sorptivity and water permeability measurement are some methods to determine the water penetrability of concrete. A triaxial cell permeability apparatus and method for determining water permeability of concrete are presented in this paper. This method utilizes Darcy's Law for steady flow so as to relate water permeability to the rate of water flow under a pressure head. The major drawbacks commonly encountered in triaxial cell permeability apparatus are addressed by evaluating the water permeability as per as per German standard DIN 1048(Part 5):1991 specifications and MORT&H (Ministry of Road Transport & Highways) 4th Revision specifications. Test results indicated that bacterial concrete is highly impermeable than normal concrete. Permeability measurement techniques and durability modeling are based on the Darcy equation for permeability based on measurement of flow rate, and the Valetta equation for permeability based on measurement of penetration depth and time. Bacteria built-in concrete works on the phenomenon of microbiologically induced calcite precipitation. Calcite crystals formed, due to microbial activities of bacteria Bacillus subtilus JC3, seals the cracks and pores in concrete and enhances the strength and durability of concrete by making concrete impermeable to transport different fluids or gases, like water, chlorides, sulfates or oxygen.***

Keywords: ***Water Permeability, Durability, Bacterial Concrete, DIN 1048, IS 3085:196.***

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I. INTRODUCTION

Permeability of concrete is a complex field of study, since concrete is a heterogeneous blend of materials. Furthermore the concrete properties change with age. One of the main characteristics influencing the durability of concrete is its impermeability to the ingress of water, oxygen, carbon dioxide, chloride, sulphate and other potentially deleterious substances. Several researches refer and attest the great importance of the water molecule on the concrete structure, especially during early stages it is cause for the cement hydration and consequent hardness of the concrete. However, the presence of water after the hardness of the concrete and after the reduction, or the ceasing of the hydration reactions, may cause the deterioration of the concrete or of the steel bar present in the structure. The water take action as a direct agent (lixiviation) or transporting noxious substances, such as chloride ions, sulfate ions and acid, or components that can activate and propel many chemical reactions that speed up the degradation process of the matrix, proportioning this way a substantial reduction of the durability and the service life of the concrete and reinforced concrete structures. Some authors emphasize that the permeability of the water is the most important factor to estimate the durability under the most diverse conditions of service of a structure. The permeability regulates the speed of aggressive water penetration into the concrete besides controlling the movement of the water during the ice-thaw process. In recent years with rapid improvements in properties of high performance concrete, low water permeability of a concrete has become more pronounced so as to mitigate the problems and to improve its resistance to the permeation of water and other solutions, viz. freeze-thaw deterioration, sulfate/other chemical attack and corrosion of embedded reinforcing bars due to chloride-ion penetration. Thus, from this perspective on the durability of the concrete structure, it is worth noting that the water permeability of the concrete structure indeed needs to be assessed properly. The importance of durability of concrete structures with regard to permeability has been extensively discussed over a few decades. In spite of the great interest in concrete permeability, there is no standard method for a permeability test other than indirect methods for instance the British Initial Surface Absorption Test (ISAT) (BS 1881) and the Rapid Chloride Permeability Test (AASHTO T 277). Furthermore, these two methods do not directly measure permeability of concrete. There being presently no standard test methods for permeability test,

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each laboratory has developed its own methods with different configurations, fluids, sample preparations, operating procedures and limitations. This makes comparison of results impossible in most cases. Moreover, there are several drawbacks in these current test methods which Janssen identified for instance stringent sample size requirements, small quantity of flow, leakage around the sample, disturbances in experimental results due to the presence entrapped air in the specimen and dissolved air in the water, the cost of the apparatus and the difficulty of test. While many studies have coped with the problem of leakage and proposed the method of sealing the specimen, some researchers proposed a high pressure triaxial cell to increase the quantity of flow and the accuracy of measurement. However, from the economical viewpoint, these triaxial cells are expensive apparatus and the expense of apparatus comes into consideration. For a porous material like concrete, permeability depends on porosity and pore characteristics such as pore size, orientation, connectivity, and size variation. A set-up, developed on the principle of Darcy's equation, was used for measuring permeability.

A. Standards for Testing the Permeability of Concrete

The various standards for performance tests for waterproof concrete are:

1. BS 1881 : Part 122 : 1983 – water absorption
2. DIN 1048 : Part 5 : 1991 – water penetration
3. ASTM C 642 – permeable voids and water absorption
4. AASHTO – T 277/ASTM C-1202 – Rapid chloride permeability

II. MATERIALS AND MIX PROPORTIONS

A. Materials

1. Ordinary Portland cement of 53 grade conforming to IS 12269:1987 was used.
2. Micro silica Grade 92D conforming to IS: 15388 is used.
3. Chemical admixtures and super plasticizers conforming to IS: 9103 may be used.
4. All coarse and fine aggregates shall conform to IS:383 and shall be tested as per IS:2386 Parts I to VIII. Fine aggregate of Zone II of IS: 383-1970 are preferable.
5. Aerobic alkaliphilic microorganism Bacillus subtilis strain JC3, cultured and grown at JNTUH Biotech Laboratory, is used in this study. The medium composition required for growth of culture is Peptone: 5 g/lt., NaCl: 5 g/lt. and Yeast extract: 3 g/lt.

B. Mix Proportions

Mix proportion of concrete in ordinary grade, standard grade and high strength grade concretes are:

Ordinary grade concrete (M20)	1: 2.27: 3.45: 0.54
Standard grade concrete (M40)	1: 1.73: 2.60: 0.42
High Strength Grade(M60)	1:1.25:2.41:0.26 (Micro Silica - 6% bwc*)
High Strength Grade(M80)	1:1.06:1.96:0.23 (Micro Silica - 10% bwc*)

*bwc-by weight of cement

II. TEST METHODS AND RESULTS

A. Determination of Water Permeability of Concrete as per IS 3085

Concrete water permeability test is conducted as per IS 3085:1965. The permeability tester used was a 3-cell tester comprising of three test cells, a pressure chamber and an air compressor supplying water to the test samples under required pressure. Bacteria treated concrete cylindrical specimens and controlled cylindrical concrete specimens (without bacteria treatment) of diameter 150mm and height 150mm are casted and cured for 28 and 90 days. Then they are loaded in the specially designed cells, and the sealing compound is used to fill the annular space between the specimen and the cell comprised of two parts of resin and one part of wax by volume. The resin was applied smoking hot. All surfaces of the sample except the top one through which water was to be supplied were painted with the hot sealing compound. The specimen was placed centrally in the cell. Short pieces of jute soaked in molten sealing compound were tightly packed in the sides of lower portion of the annular space. The remaining portion of the space was then filled with the compound which was constantly stirred and compacted so as to release any entrapped air. The testing of seal for any leakage was done after allowing the sealing compound to harden for 24 hours. The specimen was subjected to hydrostatic pressure so that water should percolate from above the specimen's top surface and collected in the bottles kept below the cell with funnel arrangements. It is essential that the seal is leak-proof. This may be checked very conveniently by bolting on the top cover plate, inverting the cell and applying an air pressure of 1 to 2 kg/cm^2 from below. A little water poured on the exposed surface of the specimen is used to detect any leaks through the seal which would show up as bubbles along the edge. In case of leaks the specimen shall be taken out and resealed. A constant air pressure of 15 kg/cm^2 is maintained by using air compressor through out the experiment for a given interval of time. The standard test pressure head to be applied to the water should be 10 kg/cm^2 .The quantity of percolate and water collected is measured at periodic intervals. In the beginning, the rate of water intake is larger than the rate of outflow. As the steady state of flow is approached, the two rates tend to become equal and the outflow reaches maximum and stabilizes. With further passage of time both inflow and outflow generally register a gradual drop. Permeability test shall be continued for about 100 hours after the steady state of flow has been reached and the outflow shall be considered as average of all the outflows measured during the period of 100 hours.

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Then the coefficient of permeability (k, in m/sec) based on Darcy's law for a falling water head ,which is applicable at steady state flow conditions, can be computed using the following formula.

$$K = \frac{Q}{A \times T \times (H/L)}$$

Where K= Coefficient of permeability in m/sec

Q = Quantity of water collected in milliliters over the entire period of test

T = Time in seconds over which Q is measured = 100x60x60 sec = 360000sec

A = Area of the specimen face in $m^2 = 0.01767\ m^2$

Water pressure=10 $kg/cm^2 = 10^6$ Pa

1Pa of water pressure = 0.0001m of pressure head (water at room temperature)

Pressure Head = 100 m (kept constant through out the test)

H/L = ratio of pressure head to thickness of the specimen both expressed in metre = 100/0.15 = 666.67

Table I: Coefficients of Permeability for controlled and bacteria treated concrete specimens of age 28 days

Grade of Concrete	Type of specimen	Pressure head H (m)	Quantity of water collected (ml)	Coefficient of permeability x 10^{-9} m/sec	% Reduction
M 20	Controlled	100	9822	2.31	-
	Bacteria treated	100	1157	0.27	88
M 40	Controlled	100	7800	1.84	-
	Bacteria treated	100	1039	0.25	86
M 60	Controlled	100	4125	0.97	-
	Bacteria treated	100	1003	0.24	75
M 80	Controlled	100	2850	0.67	-
	Bacteria treated	100	991	0.23	66

Table II: Coefficients of Permeability for controlled and bacteria treated concrete specimens of age 90 days

Grade of Concrete	Type of specimen	Pressure head H (m)	Quantity of water collected (ml)	Coefficient of permeability x 10^{-9} m/sec	% Reduction
M 20	Controlled	100	9114	2.15	-
	Bacteria treated	100	1108	0.26	88
M 40	Controlled	100	7088	1.67	-
	Bacteria treated	100	1017	0.24	86
M 60	Controlled	100	4009	0.95	-
	Bacteria treated	100	992	0.23	75
M 80	Controlled	100	2505	0.59	-
	Bacteria treated	100	980	0.23	61

Table III: Coefficient of water permeability ranges as per IS: 3085-1965

Water Permeability	Very Low	Low	Medium	High
Coefficient of permeability (x 10^{-9} m/sec)	< 0.5	0.5-1.0	1.0-2.0	>2.0

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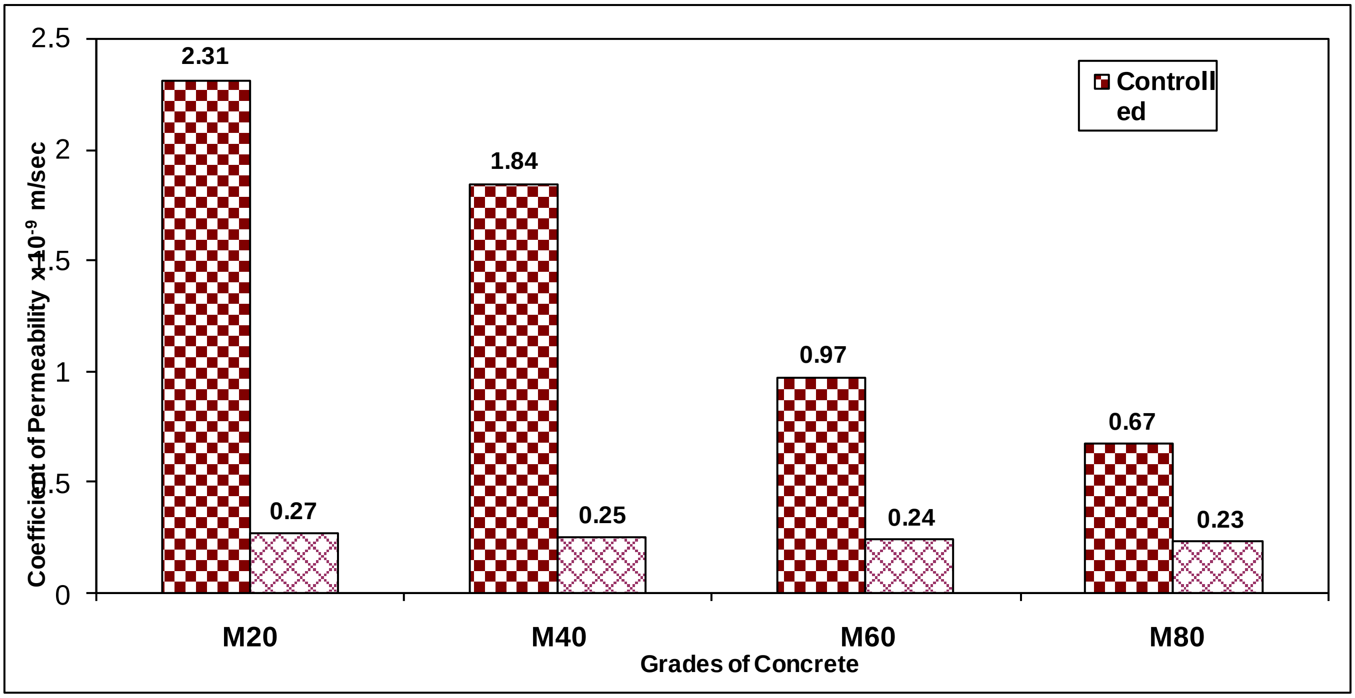

Fig 1: Variation of Coefficient of water permeability with Grade of Concrete at 28 days age

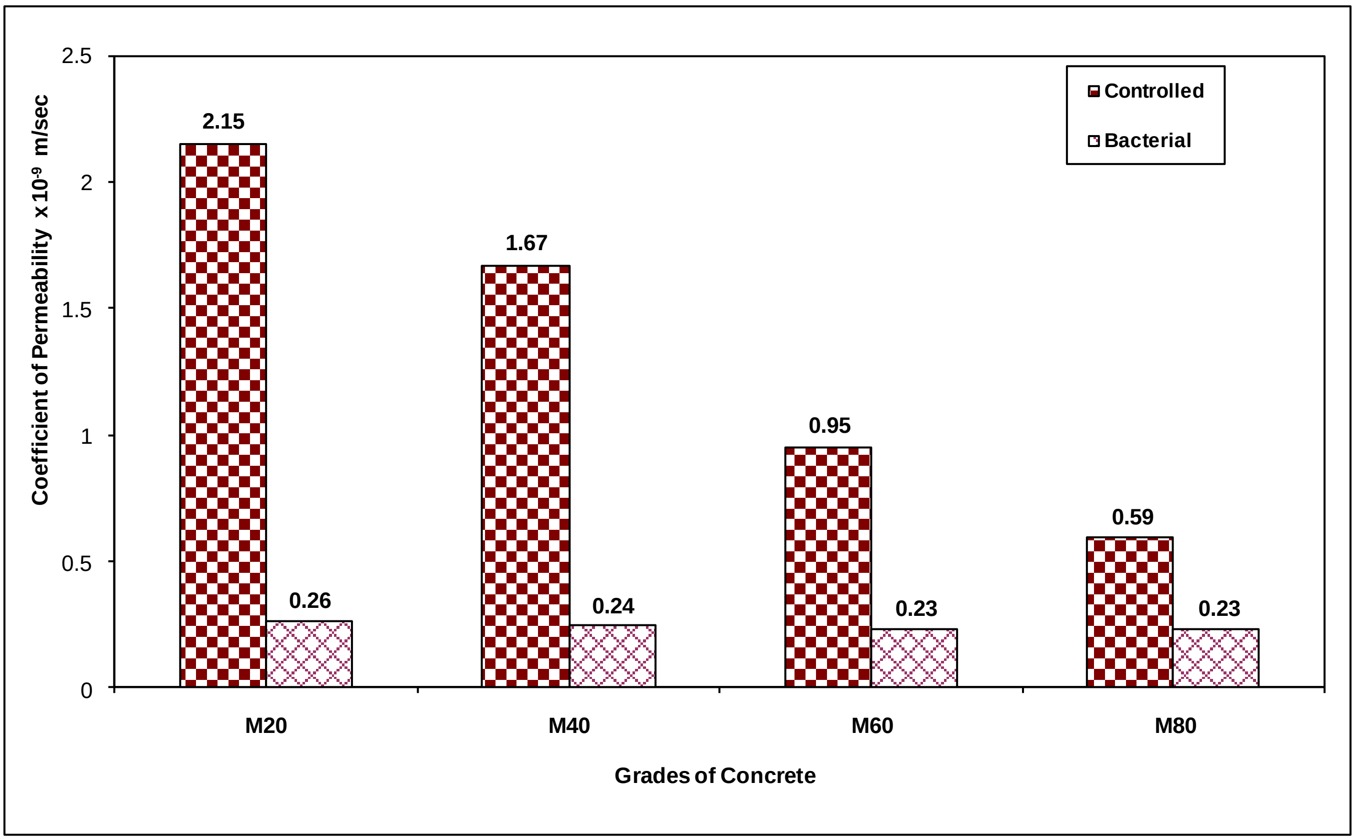

Fig 2: Variation of Coefficient of water permeability with Grade of Concrete at 90 days age

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Fig 3: Water Permeability Test Apparatus

B. Determination of Water Permeability of Concrete as per DIN 1048

The Darcy's Law can be applied only for steady state flows. It has been observed by many investigators that steady state flow conditions could not be achieved in concrete mixes having low permeability even after subjecting the test samples to pressures as high as 3.5 MPa for a test period extending up to several weeks. In such cases, some investigators have used the Depth of Penetration to determine the water permeability of concrete. In our present study, for high strength grade concrete (M60 and M80) steady state conditions could not be achieved before 72 hours, so water permeability test, on controlled and bacteria induced specimens, as per German standard DIN 1048(Part 5):1991 specifications and MORT&H (Ministry of Road transport & Highways) 4th Revision Cl.1716.5 is carried out on 150mm cylindrical specimens. This test gives a measure of the resistance of concrete against the penetration of water exerting pressure. It shall normally be carried out when the age of the concrete is 28 to 35 days. For this test, controlled and bacteria treated specimens are casted and placed inside the permeability cell at age 28 days, the water is introduced on the top of the cell and the pressure of 0.5 N/mm^2 is applied in way to force the water to penetrate through the sample. The measurement of the permeability is carried out by a method based on water penetration depth after 96 hrs. Water with a colour indicator is used, which helps to determine the border of penetration depth. If water penetrates through to the underside of the specimen, the test may be terminated and the specimen rejected as failed. The mean of the maximum depth of penetration from three specimens thus tested shall be taken as the test result.

To measure the water coefficient by penetration, Valenta's law can be applied if the material is less permeable.

$$k = \frac{D^2 V}{2 H T}$$

Where, k= Water permeability coefficient (m/s)
D= depth of penetration (m)
V= Volume of voids filled by water in the penetrated zone
H= Applied pressure (1 bar = 10m)
T= Time to penetrate to depth D (s)

Table IV: Depth of Penetration for controlled and bacteria treated concrete specimens of age 28 days

Grade of Concrete	**Type of specimen**	**Depth of Water Penetration (mm)**	**Requirement as per MORT&H 4th Revision Clause 1716.5**
M 20	Controlled	23	25mm (Maximum permissible limit)
	Bacteria treated	5	
M 40	Controlled	17	
	Bacteria treated	4	
M 60	Controlled	9	
	Bacteria treated	2	
M 80	Controlled	5	
	Bacteria treated	1	

Table V: Permeability ranges according to standard DIN 1048 (Part 5):1991

Permeability as per to DIN 1048 standard	**Low**	**Medium**	**High**
Penetration depth after 96 hrs	Less than 30 mm	30-60 mm	Greater than 60 mm

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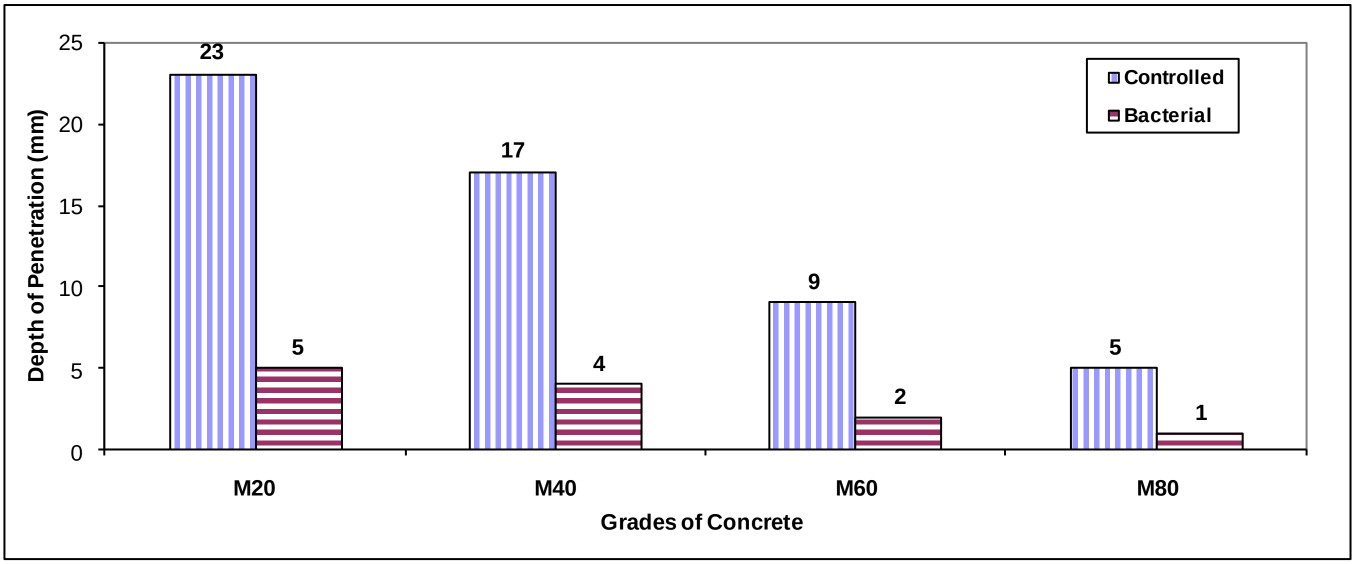

Fig 4: Depth of penetration for various grades of Concrete at 90 days age

IV. DISCUSSIONS

There were no signs of physical water transmission through high strength grades (M60 and M80) of bacteria induced concrete specimens, under 100 meters water head for first 72 hrs. Because the water permeability in these concretes was very low under the testing pressure, so water penetration depth in measured by splitting the concrete samples at the end of 24 hrs using methylene blue indicator.

It was found that significantly lower water permeability is observed in bacteria induced specimens than controlled specimens under 100m water head. Reduction in water permeability of specimens treated with bacteria is nearly 88%, 86%, 75% and 66% in M20, M40, M60 and M80 grade concretes respectively, of age 28days. Similarly, reduction in water permeability of specimens treated with bacteria is nearly 88%, 86%, 75% and 61% in M20, M40, M60 and M80 grades of concrete respectively, at 90days age. Zero water penetration in water permeability tests under 100m water head is observed during first 72 hrs of test period in M60 and M80. Water permeability in bacteria induced specimens decreased by nearly 79% in all the grades of concrete.

DIN 1048 recognizes that a water penetration of 50 mm or less represents a concrete that is medium permeable and water penetration of 30 mm or less is less permeable and is usually specified for severe exposure conditions.

The values of water permeability are low in M60 and M80 high strength grade concrete due to pore refinement and which is more pronounced in bacteria built-in concrete due to plugging of pores with calcite mineral precipitates.

The depth of water penetration measured in bacteria induced specimens when tested in DIN 1048 water permeability tests corresponds to the "very low permeability". Depth of penetration is reduced in bacteria built-in specimens by nearly 76% in all the grades of concrete. The decrease in the coefficient of water permeability in the bacterial specimens is due to formation of calcite ($CaCO_3$) layer on the surface and inside the pores.

The coefficient of permeability in controlled concrete decreases as the grade of concrete increases from M20 to M80 due to C-S-H gel formation from pozzolanic reaction between SiO2 and $Ca(OH)_2$ .The decrease is pronounced in higher grades ,M60 and M80, due to addition of Silica fume. Similar pattern of decrease in depth of penetration of water is observed in high grade concreteinduced with bacteria thus resulted in reduction in the porosity of the concrete and subsequently the pores.

From this analysis, it clearly understood that bacteria based concrete is highly impermeable against water, which enhances both the strength and durability properties of concrete.

V. CONCLUSIONS

Based on laboratory investigations, the following findings are accessible:

1. Lower water permeability is attained by bacteria built-in concrete compared to controlled concrete
2. Due to high impermeable nature, Bacterial concrete is a potential self-healing remediation technique for cracks in concrete.
3. In bacterial concrete interconnectivity of pores is disturbed due to plugging of pores with calcite crystals. Since interconnected pores are significant for permeability, the water permeability is decreased in bacteria treated specimens. Thus concrete permeability depends on its pore Structure. Even the best of concrete is not gas-tight or watertight unless the pores are closed.
4. Microbiologically induced calcium carbonate crystals, in the cracks and pores of concrete using built-in bacteria B.subtilus JC3, seals the cracks and pores in hardened concrete thereby making the concrete impermeable.

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This process of self-healing using microorganisms is an innovative method for remediation of cracks in old and new concrete structures.

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