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Pore structure characterization of bacterial concrete

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Abstract. This work describes an experimental investigation on the impact of calcifying bacteria on permeation properties (such as absorptivity and sorptivity) of bacterial concrete. In order to evaluate the improvement of permeation properties owing to biomineralization in bacterial concrete, tests for sorptivity, porosity, water absorption capacity, and ordinary (M20), standard (M40), and high strength (M60 and M80) grade bacteria were then conducted on the concrete samples treated with the bacteria. The findings demonstrate that the bacterial concrete's porosity, sorptivity, and absorptivity are significantly less than those of the comparable properties of the reference concrete. The addition of Bacillus subtilis JC3 to the concrete notably improves these properties. The chemical study also revealed that bacterial concrete's cement-phase composition contains a sizable amount of calcium precipitate component. Understanding the processes of water transport within pore structure and the interactions between concrete and water require a thorough understanding of porosity. Because a solid contains interconnected channels (pores) that allow water to pass through and promote its transit, water can pass through solids. Concrete's permeability has a significant impact on how long it will last. As a result, the key variables to research in regard to concrete durability are the permeation qualities rather than the mechanical capabilities. Consequently, a great deal of work needs to go into looking into these qualities in the current study.

1 Introduction

Despite being subjected to extreme conditions, reinforced concrete structures are frequently expected to last for extended periods of time with little to no repair or maintenance. Chloride intrusion is one of the main types of environmental attack, causing the reinforcing steel to corrode and thus reducing the structure's strength, serviceability, and aesthetic appeal. This could result in the structure needing to be replaced or repaired early. By employing reasonably impermeable concrete, it is usual practice to stop chlorides from entering the

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structure up to the level of the reinforcing steel bar. Concrete can be penetrated via hydrostatic pressure, diffusion, and capillary absorption of chloride ions. Microbiologically induced calcite precipitation (MICP) has the potential to be used in the repair and preservation of historic materials, buildings, and architectural heritage. A certain amount of empty space is present in the majority of construction materials, both manmade (such as bricks, cement mortar, and concrete) and natural (such as stones). This space is distributed throughout the solid mass as pores, cavities, and fissures of varying sizes and shapes. Porosity, a crucial attribute of building materials that influences their physical qualities (mechanical strength, durability, etc.), is the entire sum of these empty spaces. Understanding the pore structure of building materials is crucial for assessing the level of deterioration, determining the efficacy of surface conservation treatments, and forecasting how the materials would behave when exposed to weathering conditions. An important metric for assessing the behavior of a material when it comes into contact with water is the percentage distribution of pores with varying radii within the substance. The qualities of materials and their viability for building applications are largely determined by the size, distribution, and shape of their pores. Water and the porous structure's interaction is one of the primary reasons of deterioration. Because of the porosity and unfilled spaces created by uneven aggregate grading, insufficient cement paste, insufficient compaction, bleeding, air entraining, if applicable, and insufficient cement hydration, concrete can be thought of as a porous composite material. Like other porous materials, concrete's permeability is measured in terms of permeability, which is the speed at which liquids, such as water, can pass through the material under pressure. Since permeability influences how long concrete will last in harsh settings, it is considered a crucial material attribute for concrete construction. According to Neithalath et al. (2003), the porosity of concrete is not the only factor that determines its permeability; other factors include the tortuosity of the pore channels, pore size and distribution, and porosity.

2 Experimental Programme

2.1 Water Absorption Capacity Test

This test determines the maximum water absorption capacity and the rate of water absorption, in accordance with ASTM C642 (13) "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete." The total amount of water absorbed is proportional to the total open porosity, whereas the distribution of pore sizes mostly determines the process kinetics. A material's maximum amount of water absorbed at room temperature and pressure while saturated is represented as a percentage of the sample's dry mass. The most prevalent method of liquid water movement in concrete, the capillary rise of water, is also measured by this test. The capillary absorption is directly correlated with the pore diameter; the smaller the diameter, the higher the absorption. Sorptivity is the pace at which a sample fills the sample, whereas absorption is a sample's ability to hold water.

2.1.1 Procedure

1. For testing, 100 x 100 x 100 mm concrete cube samples are cast and allowed to cure for 28 days.
2. Before starting the test, wash the samples in the deionized water to remove any powdery debris from the surface. The samples should be dried in an oven set to 60°C

for 24 hours. In the case of treated samples, the comparatively low drying temperature will stop organic materials from degrading.

3. Weigh each sample. Continue the drying process until each sample's mass remains constant, that is, until the difference between two measurements taken two days apart does not exceed 0.1% of the sample's mass.
4. After the samples have dried fully and the constant mass (mo) has been determined, put them in a beaker or container with a base made of glass rods and gradually pour deionized water over them until they are entirely submerged with about 2 cm of water above them.
5. Each sample should be removed from the container at predetermined intervals, quickly blotted of any surface water using a damp cloth, and the mass of the wet samples (mi) and the measurement time should be noted on the data sheet.
6. Samples should be submerged in water once again, and measurements should be made until the weight difference between two measurements taken 24 hours apart is less than 1% of the total amount of water absorbed.

Once the samples have reached constant mass, remove them from the water and dry them once more in an oven set to 60°C. Fill out the data page with this value (md). Carry on with the computations.

a) The amount of water absorbed relative to the mass of the dry sample at each interval is represented as follows:

$$\text{Mass}_i\% = 100 \text{ x } (A_i - B_o)/B_o$$

Where A_i = weight (kg) of the wet sample at time t_i; B_o = weight (kg) of the dry sample

b) Document these values as a function of time on a graph and on a data sheet.

c) Determine the water absorption capacity (WAC) using the recorded data sheet as an example, as follows:

$$\text{Water absorption capacity} = 100 \text{ x } (\text{Mass}_{max} - \text{Mass}_d)/m_d$$

Where Mass_{max} = the sample's mass (kg) at its maximal water absorption

Mass_d = the sample's mass (kg) at the ending of the test following re-drying

The materials' absorption properties determine the duration of the intervals over the first twenty-four hours. Weighing concrete samples is recommended for the first three hours following immersion, and then at progressively longer intervals (15 min, 30 min, 1 hour, etc.). Following that, all samples must be weighed eight hours after the test starts, and then every twenty-four hours until the amount of water absorbed in two consecutive measures does not exceed 1% of the total mass.

2.2 Porosity Test

The purpose of this test was to determine the percentage of poresin the bacterial sample. Saturated weights (Wsat) of the specimens were first measured. After that, bacterial samples were dried in an oven at 105°C until a consistent mass was achieved. After that, the weight of water absorbed (Ww) in grams was computed and translated to cc, which represents the volume of voids in the specimen. At 28, 60, and 90 days of age, the test was performed on 100 x 200 mm size cylinders of bacterial specimen mixtures of ordinary (M20), standard (M40), and high strength (M60) grades of concrete. The volume of voids in a sample of concrete is typically divided by the bulk volume of the sample to estimate its porosity. The measured lengths and diameters of the samples are used to calculate the bulk volume of each sample. Each sample's volume of voids is calculated by deducting its bulk volume from its grain volume, which is the volume of the solid concrete component minus the volume of pores. Using the following formula, porosity (η), or the percentage of interconnected pore space, was finally determined.

$$\eta = (Vol_v/Vol) \times 100 = (Weight_{sat} - Weight_{dry}) \times 100/Vol = Weight_w \times 100/Vol$$

Where, Vol_v = volume of voids in cc= $Weight_{sat}$- $Weight_{dry}$ in grams ;

$$Vol = \text{total volume of specimen in cc} = \pi r^2 h = 3.14 \times 50 \times 50 \times 200 = 1.57 \times 10^6 \text{ mm}^3$$

The following equation was used to find the apparent porosity.

$$\text{Apparent porosity \%} = [(Mass_w - Mass_d)/(Mass_w - Mass_s)] \times 100$$

Where $Mass_w$ = Weight of the saturated specimen (which is retrieved and surface dried after being submerged in water for 48 hours), $Mass_d$ = Weight of the sample following oven-drying and M_s = The specimen's weight when it is suspended in water

The Volume of Permeable Voids (VPV) was calculated according to ASTM C642 using the following formula:

$$\text{Concrete's permeable pore space volume (\%)} = (1 - SG_b / SG_a) \times 100$$

Where

Concrete bulk dry specific gravity (SG_b) = $M_d / (M_w - M_s)$

Concrete apparent specific gravity (SG_a) = $M_d / (M_d - M_s)$

While apparent specific gravity solely takes into account impermeable voids, concrete bulk dry specific gravity takes into account both permeable and impermeable voids.

2.3 ASTM C1585 Sorptivity Test

The capillary forces that the pore structure exerts to attract fluids into the material's body are measured by a property called sorptivity. It offers a relative measurement that combines the diameter and quantity of pores in a pore. Although the flow can be considered in any geometry theoretically, in practice it is too mathematically difficult to be useful outside of one-dimensional flow circumstances. All you need for a low-tech, straightforward method of determining a sample's sorptivity in the lab is a shallow tub of water, a scale, and a stopwatch. The cylindrical specimens, measuring 100 x 50 mm, are preconditioned to a specific moisture level using either air drying or oven drying for seven days at 50°C. The suction face and the face across from it were left unsealed, but the sides of the concrete sample were sealed, usually with sealant or electrician's tape. At time 0, the sample's initial mass is taken and submerged in water to a depth of 5 to 10 mm. Up until the final reading, the process was performed successively at different intervals of 15, 30, 60, 120, 24 and 72 hours. Plotting is done between the square root of the elapsed time (−t) and the increase in mass per unit area over the density of water (I). The sorptivity (k) is the slope of the line that best fits these locations, omitting the origin. As seen in Fig. 1, cylindrical concrete specimens were positioned on a filtered support (sponge) with the water level 10±1 mm above the inflow face. It is possible to say the following about one-dimensional flow [Hall, 1989]:

$$I = k \times \sqrt{t}$$

Where k is sorptivity coefficient and I = W/(A x d)

W = the amount of water absorbed in kg

A= the cross-section of the specimen that was in contact with water (m^2)

d= density of the medium in which the specimen was dipped (1000 kg/m^3 in case medium is water)

The rate of water absorption, sorptivity (k), is the slope of I- $\sqrt{t}$ graph ($m / min^{1/2}$ or $kg/ m^2 / \sqrt{min}$).

The relationship between cumulative water absorption (kg/m2) and square root of exposure time (t 0.5) deviates from linearity during the first few minutes due to small initial surface tension and buoyancy effects. Therefore, only the portion of the curves for the exposure period from 15 minutes to 72 hours, where the curves were continuously linear, was used to calculate the sorptivity coefficient. Sorptivity provides a measure of the nominal pore radius and number of pores, whereas volume of permeable voids (VPV) is a measure of voids.

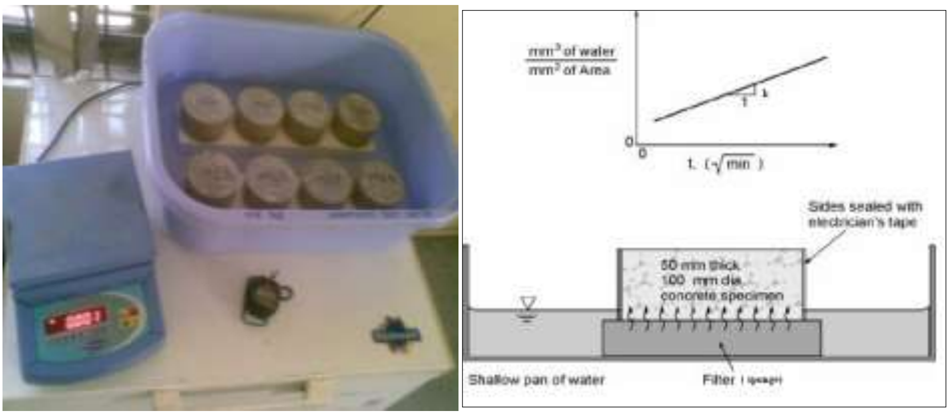


Fig 1. Experimental Setup for Sorptivity Test

3 Test Results

The following table 1 presents the elemental composition of reference concrete and bacterial concrete samples

Table 1. Elemental Composition of Reference Concrete and Bacterial Concrete samples

Reference Specimen				Bacterial Specimen			
Element	Element Percentage	Compound	Compound Percentage	Element	Element Percentage	Compound	Compound Percentage
Na	0.32	Na_2O	0.44	Na	0.54	Na_2O	0.72
Mg	0.05	MgO	0	Mg	0.65	MgO	1.03
Al	7.12	Al_2O_3	13.51	Al	0.27	Al_2O_3	0.44
Si	25.91	SiO_2	59.62	Si	1.05	SiO_2	2.25
S	0	SO_3	0	S	0	SO_3	0
Cl	0.22			Cl	0		0
K	15.22	K_2O	18.42	K	0	K_2O	0
Ca	8.42	CaO	10.73	Ca	69.37	CaO	92.76
Fe	0.33	Fe_2O_3	0.44	Fe	0	Fe_2O_3	0
O	42.54			O	29.28		

Table 2. Water Absorption at different time intervals of Reference and bacterial concrete for different grades

Measurement Intervals t_i (min)	Reference Concrete							
	M20		M40		M60		M80	
	m_o= 2.49 kg		m_o= 2.51 kg		m_o= 2.59 kg		m_o= 2.63 kg	
	m_i(kg)	M_i(%)	m_i(kg)	M_i(%)	m_i(kg)	M_i(%)	m_i(kg)	M_i(%)
0	2.491	0.001	2.519	0.001	2.599	0.001	2.655	0.001
15	2.512	0.802	2.558	1.592	2.618	0.772	2.664	0.382
30	2.593	4.023	2.567	1.993	2.627	1.163	2.673	0.753
60	2.604	4.424	2.586	2.794	2.636	1.544	2.672	0.754
90	2.615	4.825	2.585	2.795	2.645	1.935	2.671	0.755
180	2.626	5.226	2.584	2.796	2.644	1.936	2.674	0.756
480	2.627	5.227	2.583	2.797	2.643	1.937	2.673	0.757
1440	2.638	5.628	2.582	2.798	2.642	1.938	2.672	0.758
2880	2.639	5.629	2.581	2.799	2.641	1.939	2.671	0.759

Measurement Intervals t_i (min)	Bacterial Concrete							
	M20		M40		M60		M80	
	m_o= 2.51 kg		m_o= 2.53 kg		m_o= 2.60 kg		m_o= 2.64 kg	
	m_i(kg)	M_i(%)	m_i(kg)	M_i(%)	m_i(kg)	M_i(%)	m_i(kg)	M_i(%)
0	2.511	0.00	2.531	0.001	2.609	0.001	2.643	0.002
15	2.522	0.404	2.542	0.402	2.617	0.382	2.652	0.383
30	2.543	1.207	2.553	0.793	2.626	0.773	2.654	0.384
60	2.564	1.996	2.554	0.794	2.622	0.774	2.655	0.385
90	2.585	2.795	2.564	1.195	2.621	0.776	2.656	0.388
180	2.586	2.794	2.563	1.196	2.624	0.777	2.657	0.389
480	2.587	2.793	2.562	1.197	2.623	0.778	2.658	0.383
1440	2.588	2.792	2.561	1.198	2.622	0.779	2.652	0.385
2880	2.589	2.791	2.567	1.199	2.621	0.772	2.654	0.384

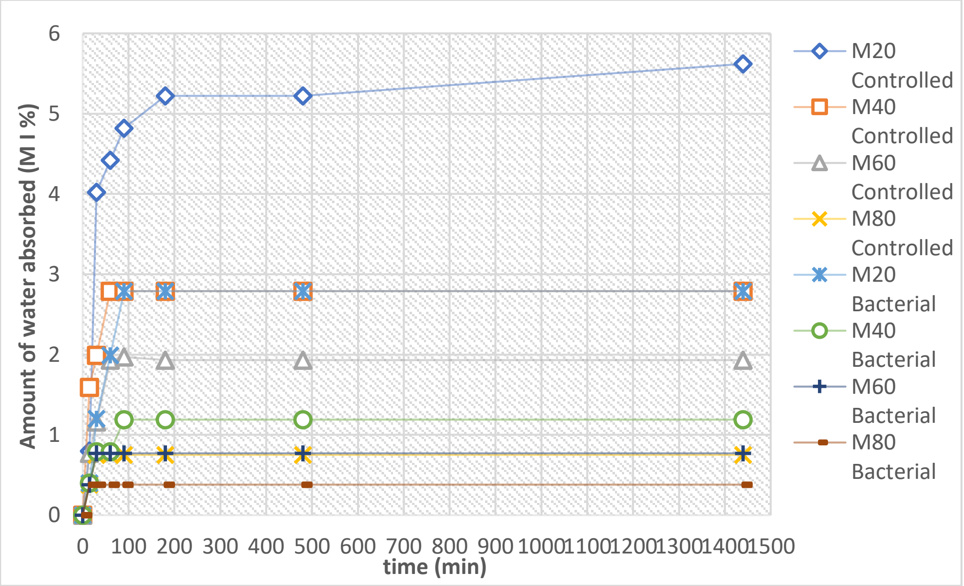


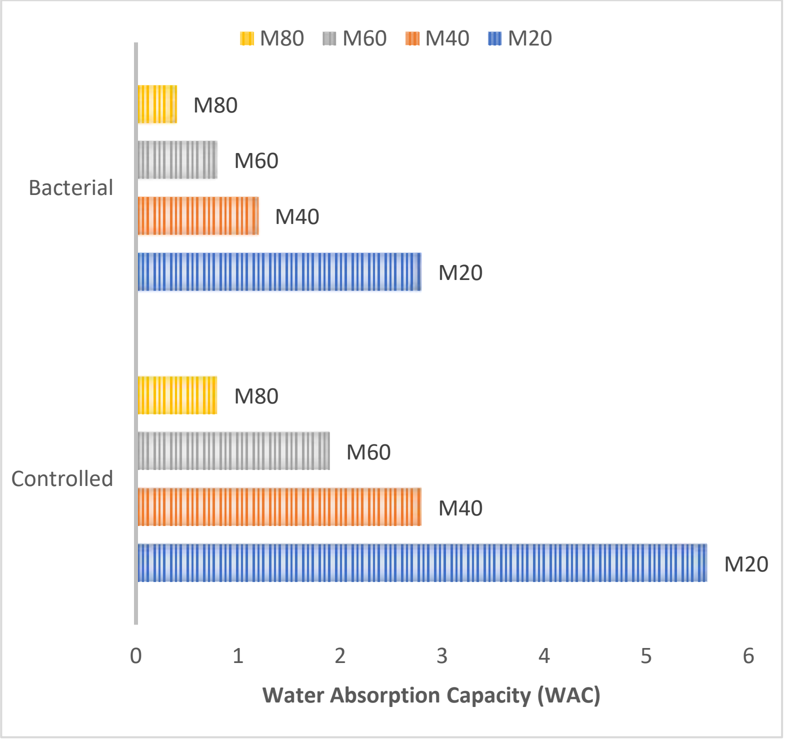
Fig. 2. Plot showing amount of water absorption with time for different grades of controlled and bacterial specimens

Table 3. Water Absorption Capacity (WAC), Volume of Permeable Voids and Apparent porosity of controlled and bacterial concrete specimens for different grades

	Reference Concrete				Bacterial Concrete			
	M20	M40	M60	M80	M20	M40	M60	M80
m_{max} (kg)	2.631	2.581	2.641	2.671	2.582	2.561	2.622	2.651
m_d (kg)	2.492	2.512	2.592	2.632	2.513	2.532	2.602	2.641
m_s (kg)	1.493	1.453	1.503	1.513	1.464	1.463	1.503	1.512
Water Absorption Capacity (WAC) (%)	5.61	2.84	1.92	0.84	2.82	1.21	0.84	0.41
VPV	14	7	5	4	7	3	2	1
Apparent porosity (%)	11.41	5.51	3.81	1.41	5.72	2.11	1.12	0.51

Table 4. Durability Classification as per ASTM C642

Classification	Volume of Permeable Voids (VPV) (% by volume)	Water Absorption Capacity (% by weight)
Excellent	<14	<5
Good	14-16	5-6
Normal	16-17	6-7
Marginal	17-19	7-8
Bad	>19	>8



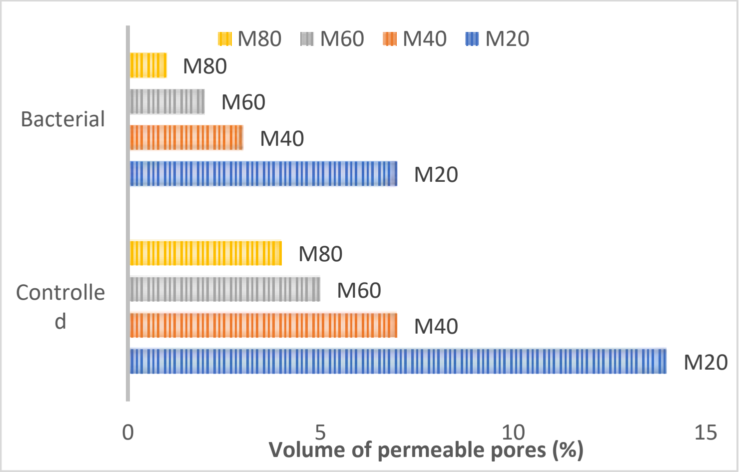


Fig. 3. Water absorption Capacity and volume of permeable pore space of controlled and bacterial concrete

Table 5. The gain in mass per unit area over the density of water 'I' (m) at regular intervals of time't' (min)

Reference Concrete							
M20		M40		M60		M80	
I x 10^{-3}(m)	t(min)	I x 10^{-3}(m)	t(min)	I x 10^{-3}(m)	t(min)	I x 10^{-3}(m)	t(min)
0	0	0	0	0	0	0	0
0.0005	15	0.0004	15	0.0003	15	0.0002	15
0.0007	30	0.0005	30	0.0004	30	0.0003	30
0.001	60	0.0007	60	0.0005	60	0.0004	60
0.0014	120	0.001	120	0.0008	120	0.0006	120
0.0019	240	0.0014	240	0.0011	240	0.0009	240
0.0024	360	0.0017	360	0.0013	360	0.001	360
0.0047	1440	0.0035	1440	0.0027	1440	0.0021	1440
0.0067	2880	0.0049	2880	0.0038	2880	0.003	2880
0.0082	4320	0.006	4320	0.00437	4320	0.0036	4320

Bacterial Concrete							
M20		M40		M60		M80	
I x 10^{-3}(m)	t(min)	I x 10^{-3}(m)	t(min)	I x 10^{-3}(m)	t(min)	I x 10^{-3}(m)	t(min)
0	0	0	0	0	0	0	0
0.00045	15	0.0003	15	0.0002	15	0.0002	15
0.00055	30	0.0004	30	0.0003	30	0.0003	30
0.00075	60	0.0005	60	0.0005	60	0.0004	60
0.001	120	0.0008	120	0.0007	120	0.0006	120
0.00145	240	0.0011	240	0.001	240	0.0008	240
0.00175	360	0.0013	360	0.0012	360	0.001	360
0.00355	1440	0.0027	1440	0.0024	1440	0.0019	1440
0.00495	2880	0.0038	2880	0.0033	2880	0.0027	2880
0.00635	4320	0.0047	4320	0.0041	4320	0.0034	4320

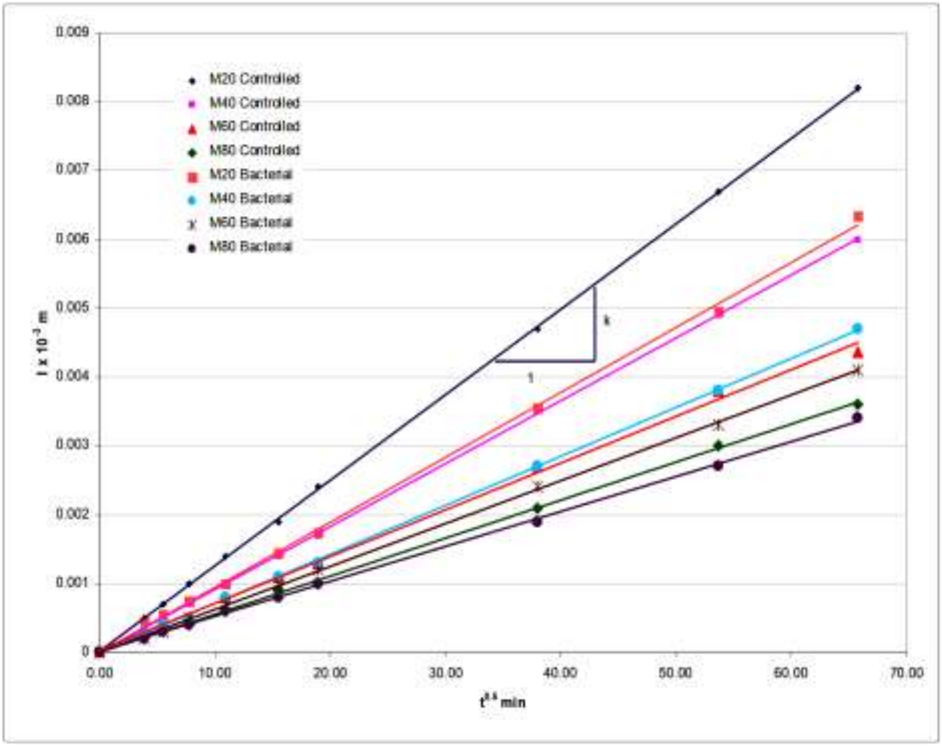


Fig. 4. Plot between I- √t to calculate sorptivity coefficient (k)

Table 6. Sorptivity Coefficients of controlled and bacterial concrete specimens of different grades

	Grade of the Concrete	Sorptivity Coefficient (k) x 10^{-3} m/min$^{0.5}$
Reference Concrete	M20	0.124
	M40	0.092
	M60	0.07
	M80	0.055
Bacterial Concrete	M20	0.091
	M40	0.071
	M60	0.062
	M80	0.051

Table 7. Porosity of Concrete (η) in % of various grades at different ages

	Grade of Concrete	Porosity of Concrete (η)(%)		
		28 days	60 days	90 days
Reference Concrete	M20	3.652	3.443	3.411
	M40	3.221	3.034	2.972
	M60	2.352	2.115	1.963
	M80	2.221	1.986	1.724
Bacterial Concrete	M20	1.092	1.017	0.955
	M40	1.022	0.928	0.886
	M60	0.933	0.889	0.807
	M80	0.874	0.825	0.778

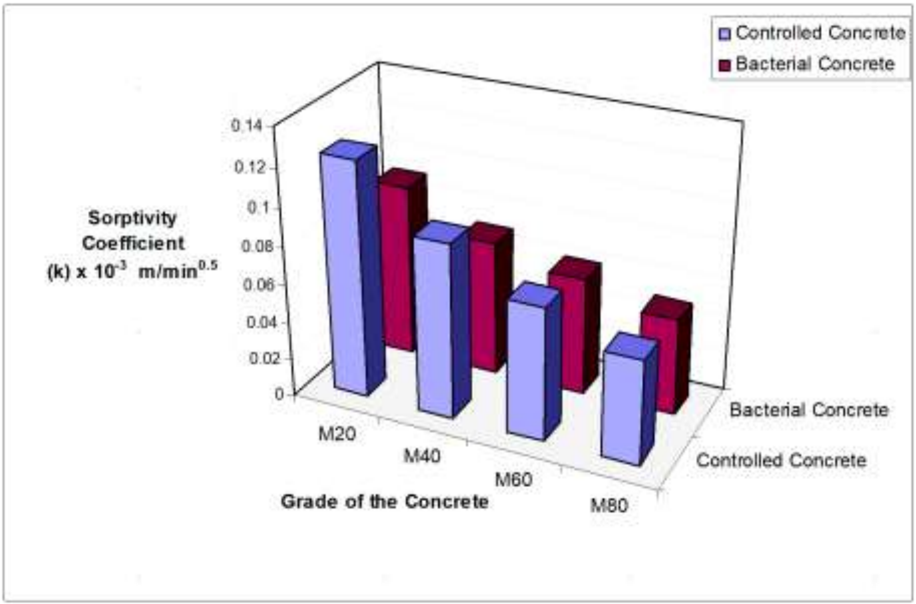


Fig. 5. Variation of sorptivity of reference and bacterial specimens for different grades

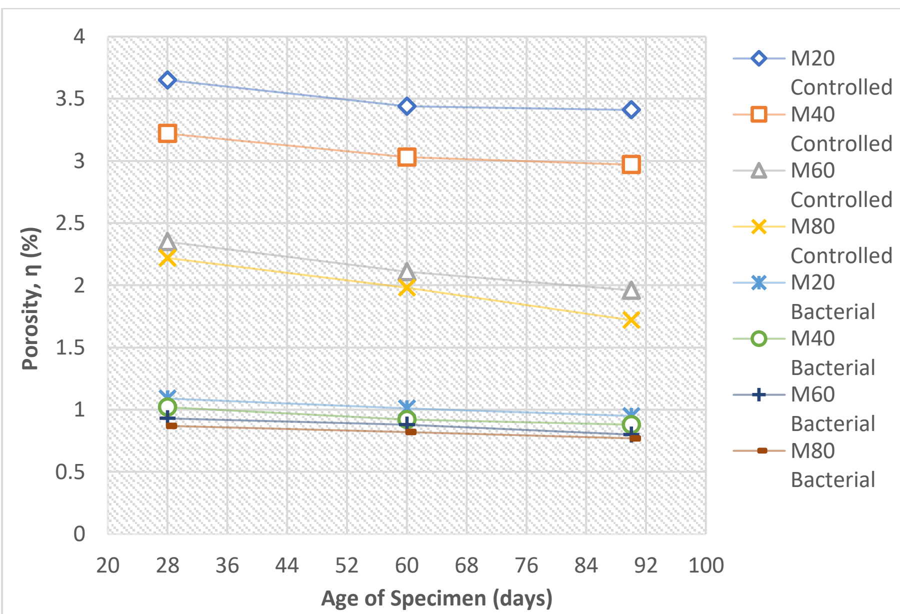


Fig. 6. Variation of porosity with age for different grades of reference and bacterial specimens

4 Discussions

The elemental composition of bacterial concrete is shown in Table 1, where a high calcium oxide content predominates, suggesting the existence of calcium precipitation. The amount of water absorbed over time for various grades of bacterial and reference specimens is displayed in Fig 1. Table 3 displays the apparent porosity, volume of permeable voids, and water absorption capacity (WAC) for various grades of bacterial and reference concrete specimens. Figure 2 displays the volume of permeable pore space and the water absorption capacity for various grades of reference and microbiological concrete. The bacterial concrete specimens exhibit a roughly 50% reduction in their volume of permeable pores (VPV), apparent porosity, and water absorption capacity (WAC). The introduction of bacteria into concrete results in a nearly 70% reduction in porosity in specimens. The relationship between the square root of the elapsed time ($\sqrt{t}$) and the increase in mass per unit area over the density of water (I) is plotted in Table 5. The sorptivity coefficient (k) is the slope of the line that best fits these points. Table 6 shows that sorptivity for concrete specimens treated with bacteria for all grades reduces systematically. When compared to corresponding grades of reference concrete specimens, the sorptivity coefficients of the bacterial concrete specimens are low for all grades. This is because the capillary pores in the bulk paste and at the interfaces between the cement paste and aggregate are reduced due to the filling of the pores by mineral precipitation. Compared to bacterial concrete, reference concrete yields higher sorptivity values.

5 Conclusions

The following findings are based on the experimental research on concrete's sorptivity and water absorption:
1. It was found that when bacteria were introduced into the concrete, the specimens' abilities to absorb water diminished. It is to be predicted that as the curing period increases, the water absorption of the bacterial and reference concretes tends to decrease. As the grades of reference and bacteria-treated concrete specimens were compared, the variations in their water absorption properties grew more pronounced and were noticeably smaller for the bacteria-treated specimens. The present case involves the production of minerals by bacteria that plug the pores of the concrete, modifying the pore structure of the cement-sand matrix. It is well known that pozzolanic reactions, to some extent, contribute to the refinement of the binder capillary porosity, with direct consequences on the improvement of the durability characteristics of the concrete as observed in M60 and M80 grades.
2. It has been demonstrated in the literature that porosity is not the only factor affecting concrete strength; a number of other parameters, including pore size distribution, microcracks, interface, and so on, are also significant determinants of the mechanical properties of concrete.
3. In comparison to control concrete, concrete samples treated with bacteria had decreased sorptivity and porosity values. This indicates that the bacterial concrete takes longer for water to rise through capillary action than the control concrete, proving that the bacterial concrete is less porous. The average pore radius of the concrete was decreased by obstructing the large voids (pore discontinuity) in the hydrated cement paste, which may have resulted from the precipitation of calcite minerals in the pores as a result of B. subtilus's microbial activity. Finer particles of silica fume settling in between cement particles may also have contributed to the high strength grade bacterial concretes.

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