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Assessment of Bacterial Concrete Properties Subjected to Wetting and Drying Cycles

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ABSTRACT

Cracking in concrete pavement exhibits a durability problem since the ingress of moisture and harmful chemicals such as sulphates and chlorides into the concrete through the cracks can cause premature matrix degradation and corrosion of embedded steel reinforcement, which may result in the decrement of strength and life. In this work, assessment of the durability of control and bacterial concrete was adopted by subjecting the casted cubes, prisms and cylinder specimens to cycles of wetting and drying. Concrete specimens of various types (cube of 100x100x100 mm, cylinder of 100mm diameter and 200mm height, and prism of 100x100x500 mm) sizes have been prepared in the laboratory, then separated to two sets (with and without bacteria). A soil bacterium named Bacillus subtilis was cultured in the laboratory, the concentration of bacteria cells of B. subtilits in normal saline (NaCl, 9 g/l) suspension was 106 cell/ml. Such bacteria were added to the mixing water. Data was analyzed to assess its impact on

the strength properties (compression, tensile and flexural strength). The depth of penetration of water under pressure in hardened concrete was also determined for control and bacterial concrete. It was noticed that the precipitation of calcite by continuous hydration of cement helps in production of calcium carbonate precipitation with the help of bacteria. It was observed that the bacterial concrete at end of cycles of wetting and drying (60 cycles) exhibits higher compressive, splitting tensile and flexural strength of 25.8%, 22.7% and 22% respectively than that of control concrete. It was concluded that the implementation of the bacteria in the concrete mixture is beneficial to overcome the impact of wetting-drying cycles and can be considered as sustainable and environment friendly solution for durability and resistance to arid climatic condition.

Keywords: Bacteria, durability, concrete, wetting, drying, strength properties

1. INTRODUCTION

Concrete is commonly used for the construction of rigid pavement for airport and major arterials in Iraq. Microcracks usually occur due to various mechanisms such as temperature gradient of thick pavement, repeated loading, shrinkage after casting. Maintenance of cracks of macro size is a routine work, but the problem arises when micro cracks exists, [1, 28, 29]. Cracks tend to expand further and eventually require costly repair. If micro cracks grow and reach the reinforcement, the reinforcement may corrode when it is exposed to water and oxygen and possibly carbon dioxide and chlorides (indirect degradation), [2]. Self-healing of microcracks with the aid of bacteria exhibit large focus recently [3, 4]. It was stated by [5] that Bacterial concrete helps in increase the strength of concrete by the action of calcium precipitation of bacteria and it proves to be cost effective. Bacterial concrete increases compressive strength up to 20% as reported by [6]. The economical dose found by analysis is 10 ml that helped to make bacterial concrete quite economical**.** The cost of bacterial concrete is higher by 7-15% than conventional concrete, [7, 8]. It was stated by [9] that the use of bacterial concrete is one of the eco-friendly techniques for crack healing. This technique uses the calcium precipitate produced by bacterial metabolic activities to heal cracks. Bacterial concrete shows greater strength and durability than normal concrete. A study by [10] had shown that the addition of bacillus Subtilis bacteria showed significant improvement in the compressive, split tensile and flexural strength than the conventional concrete. The strength development of three concrete mixes subjected to many combinations of controlled moist and air-dry environments during the first 27 days was studied by [11]. It was stated that cycled curing (wet and dry) indicates that average moisture variations clearly take place in the samples. It was concluded that surface damage in pavement application could cause early failure due to poor abrasion and weather resistance. The effect of wetting and drying cycles on physical properties of concrete was investigated by [12, 30, 31], the specimens were covered with burlap and spraying them with water three times daily until 28 days and after that they were subjected to alternating wetting and drying cycles. Each cycle consists of placing the specimens for one day at temperature of 80 o C and then they will be cooled to room temperature. They were left in laboratory conditions for 5 days and then subjected to wetting cycle and placed under wet burlap for 6 days. It was concluded that the compressive strength at 90 days (5 cycles) is lower than that of no cycles (at 28 days). Reduction in compressive strength also increases gradually as the cycles increase. Physical salt attack as stated by [13] is caused by the movement of salt solution by capillary action through the concrete and subsequent crystallization through drying. The process is repeated through cycles of wetting and drying. The influencing made in the compressive strength of specimens subjected to wetting and drying cycles to increase the rate of absorption of salts within the period of short time was investigated by [14]. It was concluded that most salt compounds which have damage to concrete are sodium sulfate, and there is a relationship between the rates of decrease in compressive strength and porosity and an increase in concentration. The high solubility of the salt solution increases the penetration of ions into the concrete. Four times reduction in water absorption of bacteria-based fly ash concrete was reported by [15]. Water absorption test at 7-days was conducted as per ASTM C 642, [16]. It was noticed that with the inclusion of bacteria, water absorption capacity of fly ash concretes decreased with the increase in bacteria concentration.

Based on the above literature survey, the number of prior works reported about the behavior of concrete or bacterial concrete that was subjected to laboratory cycles of wetting and drying and its effect on the mechanical performance of concrete was very rare and scattered. This investigation will be focused on assessment of the durability of bacterial concrete in terms of wetting and drying cycles and the permeation properties which affect the durability.

2. MATERIALS AND METHODS

2.1. Portland Cement

The Iraqi Ordinary Portland cement (Type 1) with a commercial name of (Tasluga) was implemented throughout this investigation. Table 1 exhibit the chemical composition of cement, while Table 2 presents the physical properties of cement.

Table 1 Chemical composition of cement

Oxide	% by Weight	Limit of Iraqi Specification, [17]
CaO	61.28	--------
SiO2	18.372	--------
Al2O3	3.58	--------
Fe2O3	5.02	--------
MgO	1.39	< 5.0
SO3	2.02	< 2.80
C_3A	0.988	--------
LI2B4O7	6:1	--------
Loss on ignition	2.85	≤ 4.0
Insoluble residue	1.07	< 1.5
Lime saturated Factor	1.0148	≥ 0.66 ≤ 1.02

Table 2 Physical properties of cement

Physical Properties	Test Result	Limits of Iraqi Specification
Specific surface area, Blain's method m^2/kg	394	≥ 230
Soundness, Autoclave's Method, %	0.03	< 0.8
Setting time, Vicat's method Initial setting hr: min Final setting hr: min	 2:15 3:30	 ≥ 45 min ≤ 10 hours
Compressive strength 3 days N/mm^2 7 days N/mm^2	 20.7 26.1	 ≥ 15 ≥ 23

2.2. Coarse Aggregate

Crushed gravel with a nominal size of (19mm) brought from Nibaee region was implemented in this work. The gravel was separated into different sizes by sieve then recombined to match the grading requirements according to Iraqi specification (IQS 45) [18]. The aggregate was flushed by water. Later, it was air dried. The physical properties of coarse aggregate are shown in Table 3.

Table 3 Physical properties of coarse aggregate

Properties	Results	Specification
Bulk Specific gravity	2.63	ASTM C127-01, [16]
Absorption, %	1.167	ASTM C127-0, [16]
Clay content	0.06	IQS No. 45-84, [18]

2.3. Fine Aggregate

Fine aggregate (passing sieve No.4) was brought from Al-Ukhaider region and used in this work. The physical properties of fine aggregate are shown in Table 4. plate 1 demonstrate the preparation of aggregates for testing.The combined aggregate gradation implemented is presented in Fig.1.

Table 4 Physical properties of fine aggregate

Properties	Results
Fineness modulus	2.5
Specific gravity	2.6
Absorption, %	0.85

Plate 1 Preparation of aggregates for testing

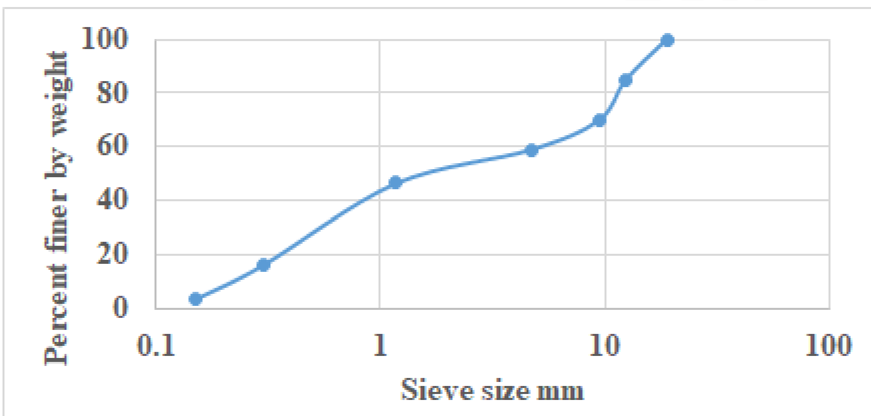

Figure 1 Combined gradation of aggregate

2.4. Water

The water used in mixes was drinking water of Baghdad area. This water was also used for curing.

2.5. Nutrients

Nutrients are the main energy sources for bacteria, it is very important to provide proper and enough nutrient for calcite producing bacteria. a suitable mineral substrate is to be provided along with bacteria during casting. Calcium lactate is also known as calcium salt and the chemical formula is $C_6H_{10}CaO_6$. It looks like white powder and it possesses efflorescent odor. Calcium lactate was selected for the present study as a calcium source, Table 5 show a Physical properties of calcium lactate. Bacteria use urea as a source of nitrogen, where urease hydrolyses urea releasing two ammonium molecules and carbonate ions. Therefore, urea is selected as the nitrogen source for the bacteria.

Table 5 Physical properties of calcium lactate

Chemical formula	$C_6H_{10}CaO_6$
Appearance	White powder
Density	1494 kg/m^3
Solubility in water	7.8 g/100 ml
Odor	Efflorescent

Solubility	Very soluble in ethanol
Molar mass	218.22 g/mol

2.6. Nutrient agar

Nutrient Agar is a general purpose, nutrient medium used for the cultivation of microbes supporting growth of a wide range of non-fastidious organisms. Nutrient agar is popular because it can grow a variety of types of bacteria and fungi, and contains many nutrients needed for the bacterial growth. Table 6 shows the Composition of Nutrient agar.

Table 6 Composition of Nutrient agar

Composition	Notes
0.5% Peptone	It is an enzymatic digest of animal protein. Peptone is the principal source of organic nitrogen for the growing bacteria.
0.3% beef extract/yeast extract	It is the water-soluble substances which aid in bacterial growth, such as vitamins, carbohydrates, organic nitrogen compounds and salts.
1.5% agar	It is the solidifying agent.
0.5% NaCl	The presence of sodium chloride in nutrient agar maintains a salt concentration in the medium that is like the cytoplasm of the microorganisms.
Distilled water	Water is essential for the growth of and reproduction of micro-organisms and provides the medium through which various nutrients can be transported.

2.7. Test Methodology

The methodology implemented in this investigation consists of three steps, in the first step, Culture and growth of bacteria (Bacillus subtilis) in the laboratory was conducted, the details of this step is published elsewhere, [10]. In the second step, preparation of concrete specimens (cubes, cylinder and beams) was conducted. In the third step, after curing of the specimens for 28 days, specimens were subjected to 30 and 60 Wetting-Drying cycles then the strength properties of concrete specimens were evaluated.

2.8. Preparation of Control Concrete Mixture

Concrete mixture was designed as per ACI 211.1, [19] method, such mixture is usually used for rigid pavement in order to get the suitable compressive strength of 30Mpa at 28 days. The mix proportion is (1:1.5:3.75) with 0.45 water cement ratio.The design mixture and proportions of concrete are given in Table 7.

Table 7 Materials and proportions for mixture concrete

Material	Weight
Cement	373kg/m^3
Water	178 kg/m^3
Coarse aggregate	1080 kg/m^3
Fine aggregate	644 kg/m^3

2.9. Preparation of Bacterial Concrete Materials

In the mixing process of bacterial concrete, the bacterial concentration of 106 cell/ml of water was added to the water during the process of mixing, nutrients (calcium lactate of 2% of cement mass) were firstly dissolved in part of the mixing water and part of the mixing water was replaced by bacterial suspension.

2.10. Durability in Terms of Wetting and Drying Cycles

The specimens of three cubes &three cylinder and 3 prisms from each type of mixture (control and bacterial concrete) were subjected to cycles of wetting and drying in the light of many research works, [2, 20, 21]. The cycles are started by placing the specimens in the oven at temperature 70˚C for 24 hr. Then, it is removed from oven and it is immersed in water for 24 hours at 28˚C. The alternate immersion and drying of specimens are repeated for 60 cycles. After each cycle specimens were subjected to visual examination to detect any expected defects. drying of specimens is shown in Plate 2.

Plate 2 Drying of Specimens in oven at 70 °C

2.11. Durability in terms of Surface Absorption (water penetration) Test

Another way to measure the influence of bacteria in the extent of self-healing is by measuring the permeation properties. Penetration of water or chloride ions into concrete can adversely affect its durability. The penetration of water can give rise to corrosion of the steel reinforced bars in concrete. Thus, the rate at which concrete absorbs water or chloride ions of salt water, becomes an important property to be tested. Many techniques are existing and others under development for calculating the permeability of concrete such as determining the depth of penetration of water under pressure in hardened concrete which was carried out according to BS EN 12390, [22]. Essentially, the test characterizes the surface cover of concrete when it is submitted to water pressure, namely rainwater fall. Research has indicated that a concrete which has a low permeability lasts longer without exhibiting signs of distress and deterioration. Therefore, the permeation properties have been used principally for the comparison of the effectiveness of different surface treatments. Two different groups of specimens were prepared (control and bacterial), each group to contain three cubes of size (150 x150 x150) mm and the test started when the specimens are at least 28 days old. The surface of each cube to be exposed to water pressure was roughened with a wire brush. Test arrangement is shown in Plate 3. Each specimen was fitted in the apparatus and a water pressure of (500) kPa was applied for (72) hours using of tap water. During the test, the appearance of the surfaces of the test specimen not exposed to the water pressure was observed to note the presence of water. A watertight seal was provided, made of rubber material. After the pressure has been applied for the specified time, the specimen was removed from the apparatus, the face on which the water pressure was applied was wiped to remove excess water. Plate 4 show Test setup for measuring depth of water penetration. The specimen was break in half using the compressive strength determination machine, perpendicularly to the face on which the water pressure was applied.

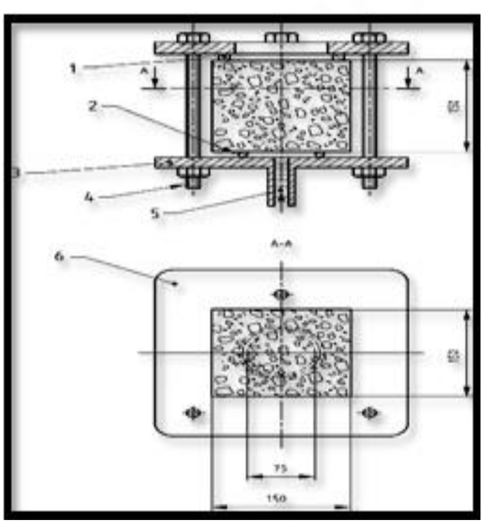

Plate 3 Test Arrangement for Penetration of water

Plate 4 Test setup for penetration of water

3. RESULTS AND DISCUSSION

3.1. Effect of Wetting and Drying Cycles on mechanical properties

As shown in Table 8, the mechanical strength (compressive, splitting tensile, flexural strength) for bacterial concrete performed better than the control concrete (without bacteria) before and after subjecting to cycles of wetting and drying.

Table 8 Test results of compressive, tensile, and flexural strength after wetting and drying cycles

Mixture type	Compressive strength (MPa)			Splitting tensile strength (MPa)			Flexural strength (MPa)		
	Number of cycles after 28 days curing			Number of cycles after 28 days curing			Number of cycles after 28 days curing		
	Zero	30 days	60 days	Zero	30 days	60 days	Zero	30 days	60 days
Control	37.8	36.63	35.3	3.78	3.64	3.45	4.4	4.22	3.95
Bacterial	46.7	46.2	45.5	4.58	4.46	4.41	5.2	5.05	5

The results show that the mix of bacterial concrete exhibit higher compressive and splitting tensile, and flexural strength by 28.89%, 27.8% and 26.58% respectively after 60 cycles of wetting and drying as compared to the control mixture. This effect may be due to the calcite layer which leads to fill the voids and improves the impermeability of the specimen, thus increasing its resistance to the damage caused by wetting and drying process and therefore creating stronger bonds within the concrete matrix and this reduces the effect of wetting and drying process on concrete. Table 9 show the percentage of decrease in strength for cubes and cylinders and prisms with and without bacteria subjected to alternate wetting and drying cycles.

Table 9 Percentage of decrease in compressive strength after freezing and thawing cycles

Mixture type	Compressive strength		Splitting tensile strength		Flexural strength	
	% reduction after 30 cycles	% reduction after 60 cycles	% reduction after 30 cycles	% reduction after 60 cycles	% reduction after 30 cycles	% reduction after 60 cycles
Control	3.09	6.6	3.7	8.73	4.09	10.22
Bacterial	1.07	2.57	2.62	3.71	2.88	3.84

The reduction in strength increases with increase in cycles, when compared with that before cycles (at 28 days). This reduction may be due to the microcracks as a result of drying process, also these cracks are weakening the material of concrete, thereby increasing the capability of failure inside the concrete specimens. The bonds between particles of aggregate and paste are weakened and become weaker than that of no cycles. During the drying cycle, the bacteria may generate spores to overcome the drying impact. This may also happen because at each drying period, the rate of hydration will be reduced therefore capillary porosity increase and with increase capillary pore the density decrease, [23]. It is expected that further hydration and moisture content changes during the specimen conditioning regimes may contribute to continuation of strength gain. However, the degree of material damage increases and the extent of self-healing with little or no recovery after wet–dry cycles repair the microstructural damage within these cracked materials, [24]. Similarly, the same effect could have led to an increase in matrix toughness that limits the amount of multiple cracking responsible for tensile ductility, [25]. These results confirm without a doubt that self-healing of bacterial concrete material results not only in sealing of cracks, but also in the enhancement of overall physical properties. This phenomenon serves as a testament to the real possibilities of full recovery of mechanical properties via self-healing within concrete material [24]. Similar findings were reported by [26].

3.2. Effect of bacteria induced self-healing on the depth of water penetration

The depth of water penetration value was calculated as the average of three cubes (15*15*15 cm) for each stage after placing each specimen in the apparatus and apply tap water pressure to the surface of the test specimen from the bottom by 0.5 Mpa for (72) hours. The depth of water penetration is normally used to evaluate the concrete superficial porosity and to educate the role of calcium crystals ($CaCO_3$) (formed from the metabolic reactions of the added bacteria in mixing water for concrete) to surface absorption properties concrete. The first stage was a conventional or normal concrete cube, the second stage was a cube of concrete with a Bacterial solution (Bacillus Subtilis + Nutrients). A comparison of depth of water penetration results between two specimens' groups is discussed in this section. Figure 2 compare the depth of water penetration in concrete cubes for two stages.

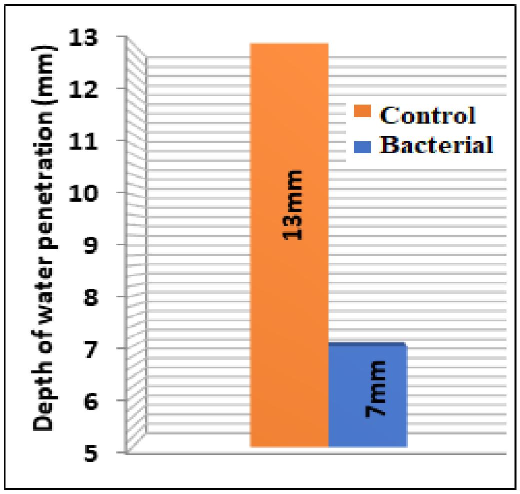

Figure 2 Comparison of depth of water penetration in concrete

It can be seen from the figure above that the depth of water penetration in specimens induced bacteria in mixing were less than control concrete by 85.7%. The deposition of a layer of calcium carbonate crystals on the surface resulted in a decrease of the permeation properties. Therefore, the ingress of harmful substances may be limited. From these experiments, the possible deposition of a layer of carbonate crystals on the surface by bacterial isolate has the potential to improve the resistance of cementitious materials towards degradation processes. Significant decrease of the water uptake for bacterial concrete when compared with control specimens was reported by [27].

4. CONCLUSIONS

Based on the limited testing program, the following conclusions may be drawn

1- The bacterial concrete exhibit higher compressive, tensile, and flexural strength by 28.89%, 27.8% and 26.58% respectively after 60 cycles of wetting and drying than that of control concrete.

2- The depth of water penetration for bacterial concrete was less than control concrete by 85.7%.

3- The presence of bacteria resulted in a significant decrease in the water uptake compared to control specimens.

4- Bacteria can be easily cultured and safely used in enhancing the strength characteristics of concrete.

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