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INVESTIGATION OF THE FLEXURAL BEHAVIOR OF BACTERIAL CONCRETE BEAMS

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Abstract

Bacterial self-healing concrete is an eco-friendly and superior treatment technique that has efficient bonding capacity and compatibility with concrete compositions. It is capable of filling deep microcracks and healing the crack autonomously by calcium carbonate precipitating phenomenon which results in sustainable construction materials. The purpose of this research is to investigate the use of microorganisms Bacillus Subtilis to improve the mechanical properties and the efficiency of self-healing of reinforced concrete beams for two types of concrete, reactive powder concrete (RPC), and lightweight self-compacting concrete (LWASCC), by two methods of addition (direct addition, and encapsulation). The experimental program consists of casting six simply supported beams tested under monotonic and repeated loading. Incorporate bacteria and the precursor (calcium lactate) in concrete mixtures show an improvement in compressive strength, splitting, and flexural strength by up to 21.74 %, 10.92 %, 21.21 % by encapsulation method, and 17.7 %, 18.0 %, 20.84 % by direct addition. In addition, there is an enhancement in the first crack load and ultimate load. Microscopical image demonstrated that calcium carbonates had been deposited in the crack up to 1.0 mm width by bacterial activity within 32 days.

Keywords:

Flexural behaviour;
Bacterial concrete beam;
Reactive powder concrete;
Biomineralization;
Self-healing concrete.

1 Introduction

Concrete is considered to be a common composite material for many different kinds of construction, one of concrete's weaknesses is its inability to sustain tensional stress, which can result in the formation of cracks. Micro cracks could damage the reinforcement if they spread and grow to it, in addition to damaging the concrete itself. Monitoring concrete structure cracks and halting their spread has become extremely common these initiatives are crucial for the prompt maintenance, durability, and long-term resilience of concrete buildings and infrastructure. In the past few years, bacterial concrete has been the focus of numerous studies. This new technique can repair the cracks autonomously by bacterial metabolic activity which precipitates calcium carbonate in concrete cracks. Several studies have demonstrated that bacterial spores can remain viable for more than 200 years when exposed to harsh conditions; as a result, they can fulfil the requirements for the required service life of concrete buildings. This new type of smart material is compatible with concrete matrix and environmentally friendly and is able to repair itself which leads to significantly reducing maintenance costs and CO_2 emissions [1-3].

Biomineralization phenomenon represents the precipitation of calcium carbonate crystals by bacterial activity, using microorganisms to construct self-healing concrete has been classified as a biological technique by a number of researchers. Microorganisms are capable to proliferate virtually anywhere, including (soil, water, oil reservoirs, acidic hot springs, and industrial wastes). Several researchers have suggested the use of microorganisms to develop self-healing concrete [4].

Prayuda et al. 2020 [5] discuss the cracks in concrete beams that form as a result of flexural loads and repair the microcracks in the beams using Bacillus subtilis. This type of concrete is commonly referred to as self-healing concrete. The purpose of this investigation was to measure the flexural strength of concrete that has been mended by injecting Bacillus subtillis in the cracks that were generated as a result of static load on the beam with deamination 150x150x600 mm. The beams of normal-strength concrete were tested at 7, 14, 21, and 28 days after being poured. According to the

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findings, the bacteria Bacillus subtilis has the potential to be utilized as a component in the process of repairing microcracks. This is due to the fact that the flexural strength that is generated as a result of the repair is rated as excellent.

Nimafar et al. 2023 [6] Evaluated the effectiveness of two bacteria species on compressive strength, crack healing, and water capillary absorption by exposing a stander concrete cubic 150*150*150 mm specimens to heat at 600 °C and 800 °C. The results of the laboratory study revealed that after 28 days the two microorganisms had a substantial ability to repair both surface and deep cracks by the calcium carbonate deposits and increase compressive strength by 31–93 %. Furthermore, water absorption decreased by about 30%–43%, and capillary water absorption decreased by 15–31 %.

Chen et al. 2022 [7] described biomineralization consider a compatible process with the concrete matrix. Biological self-healing concrete (BSHC) is an environmentally friendly technique. However, the selective bacteria should be capable to survive the harsh condition of concrete including high alkalinity such as bacillus subtilis, which its spores can lie dormant for a period that potentially far exceeds the human lifespan; convincing examples of long-term spore survival have been recorded 500 year [8].

Meera and Subha 2018 [9] studied the assessment of bacteria-based self-healing concrete (Bacillus Subtilis) on strength and durability. It was observed that for cell concentration 10^5 ml/cell the compressive strength of concrete showed a significant increase by 42 %, and there is a considerable increase in split tensile strength at 28 days by 63 %. The results also demonstrated that bacterial concrete has a lower rate of water absorption than conventional concrete.

Shafiei and Mohammadyan 2022 [10] investigated the behavior of bacteria-based self-healing by incorporating bacteria in concrete cubic 50*50*50 mm specimens and using metakaolin as cement replacement under inappropriate environmental conditions. the experimental programs prove that calcium lactate was the appropriate precursor for bacteria to improve the compressive strength of concrete. Also, the presence of bacteria led to the production of C-S-H gel, and the microstructure was denser. Additionally, the cracks were fully crack healing after 28 days, and observations of the samples indicate that bacteria can be alive after 1 year and thus can be supportive to produce durable biofriendly concrete.

The objectives of this work are to investigate the behavior of bacterial concrete beams under repeated loading, study the efficiency of the self-healing process of concrete cracks after re-loading, and the effect of incorporating the non-pathogenic bacteria (bacillus subtilis) into two types of concrete.

2 Experimental programe

1) Preparation of bacteria.
2) Preparation of materials and trail mixes.
3) Study the mechanical properties of concrete (with and without adding bacteria). By casting (18 stander cubes 150x150x150 mm, 18 cylinders 100x200 mm, and 18 prisms 100x100x400 mm).
4) The experimental program involves casting and testing six beams, two of which are bacterial concrete, and the remaining specimens are reference beams that have been tested under monotonic and repeated loading, where two of them were tested monotonically and the other two samples are tested under repeated loading.

The repeated loads were conducted according to the modified load protocol that was recommended by the (FEMA2007) [11] and was utilized in the modeling of the cyclic load (2007). Use only the positive loading (cyclic non-reversed). The abbreviations of this study are listed in Table 1.

Table 1: Abbreviations.

FEMA2007	Federal Emergency Management Agency
B.subtilis	Bacillus subtilis
BSHC	Bacteria self-healing concrete
EC	Expanded clay
MICP	Microbially-Induced-Calcite-Precipitation (Biomineralization)
LWASCC	Lightweight aggregate self-compacting concrete
LWASCCB	Bacterial Lightweight aggregate self-compacting concrete
RPC	Reactive powder concrete
RPCB	Bacterial Reactive powder concrete
ITZ	Ideal transition zone

2.1 Materials

The material materials used in this study are:

Ordinary Portland cement R42.5 was used in this study, in accordance with Iraqi standard specifications No. 5/2019 [12].

Structural lightweight aggregate expanded clay (EC) type (LECA) was used in this study with a maximum size of 8 mm.

Water used in mixes and for specimen curing satisfied the requirements for drinking water.

Densified silica fume in grey powder appearance was used in the present study as a pozzolanic material, with a surface area of 21 m^2/g, satisfying ASTM C1240 [13] requirement.

Steel fibers with dimensions of 0.2-0.25 mm in diameter and 12-14 mm in length were used in this study. Table 2 shows the details of steel fiber characteristics according to the datasheet certified by the manufacturer. Fig. 1 explains the visual representations of micro steel fibers. Fibers were employed in some mixtures at a volume fraction of 1.5 %.

The superior plasticizer HRWD used in this work was hyperplast PCE 600, which complies with the requirements of BS EN 934-2 [14] and ASTM C494 [15].

Silica sand has been utilized in the mix of reactive powder concrete (RPC) with a maximum particle size of 0.5 mm.

Calcium lactate $C_6H_{10}CaO_6$. It is a powder that is white in color and has an efflorescent smell, Table 3 shows the physical properties of calcium lactate. Fig. 2 shows the calcium lactate used.

The sand used throughout the present study is “natural river sand” with a maximum size of 4.75 mm havening a 2.76 fineness modulus, and conformed to fine aggregate grading zone II, satisfying Iraqi standard specifications No. 45/1984 [16].

Table 2: Properties of steel fiber used.

Property	Value
Description	Straight
Length [mm]	12-14
Diameter [mm]	0.2-0.25
Density [kg/m^3]	7800
Tensile strength [MPa]	2850
Aspect ratio [L/D]	60-56



Fig. 1: Steel fiber used.

Table 3: Physical properties of calcium lactate used.

Property	Value
Density [kg/m^3]	1494
Solubility in water [g/100ml]	7.8
Oder	Effloresce
Solubility in water [g/100 ml]	Very soluble in ethanol
Molar mass [g/ml]	218.22
Melting point ºC	240

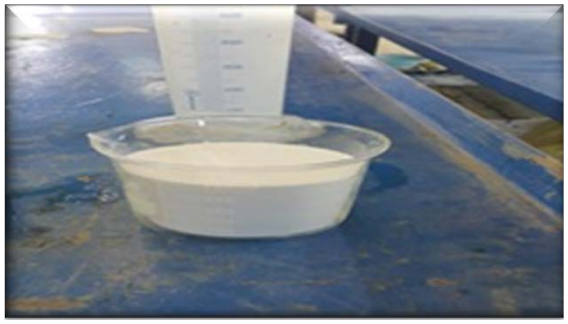


Fig. 2: Calcium lactate used.

2.2 Description and details of bacteria

2.2.1 Preparation of bacterial isolates

5 gm of soil sample was taken and dissolved in 25 ml of distilled water in a sterilized glass and mixed by using a magnetic stirrer for 65 ºC/10 minutes. A drop was taken and cultured in nutrient agar media, finally incubated at a temperature of 37 °C for 24 hours. The bacterial isolate was diagnosed and the gene was. determined by conducting genetic analysis using PCR thermocycler. The genetic analysis showed that the bacterial strain was Bacillus Subtilis and the gene sequence was 539 bp. Also, the isolates were subjected to microscopic examination using Gram stain to identify the shape, and arrangement of the bacteria. As shown in Fig. 3.

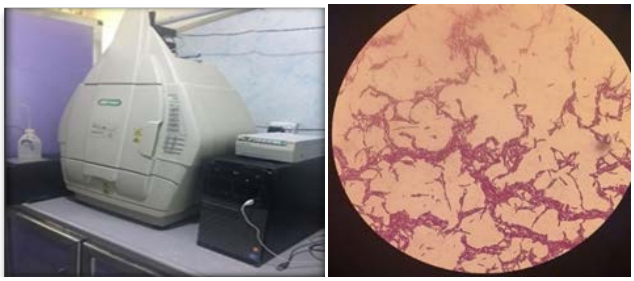


Fig. 3: PCR thermocycler (left), and microscopically examination (right).

2.2.2 Evaluation of bacterial concentration

The assessment of bacterial concentration is performed by Standard MacFarland tubs. The preparation is included two parts: a) dissolved 1 gm of Barium Chloride in 100 ml distilled water, and b) added 1 ml of conc. H_2SO_4 to 99 ml of distilled water, then mixed 0.3 ml of solution a) with 9.7 ml of solution b) and put in sterilized test tubes and used for comparative bacterial counting. The comparative bacterial counting is compared in two ways, the first with the concentration values of McFarland standers and the second with a visual examination. The bacterial concentration was determined by a spectrophotometer device. As shown in Fig. 4.



Fig. 4: Spectrophotometer device.

2.3 Concrete mixes design

Two types of concrete were used in preparing the specimen. Lightweight aggregate self-compacting concrete (LWASCC), and reactive powder concrete (RPC) have been studied to accomplish the hardened properties of bacterial concrete. The percentage of calcium precursor (calcium lactate) added to mixtures containing bacteria was 10 % of cement weight. The bacterial solution was added 100 ml to each 1000 ml of mixing water. Table 4 shows the mixes used.

Table 4: Mixtures used.

Mix	Cement [kg/m³]	Sand [kg/m³]	*w/b*	Bacterial concentration [cell/ml]	HRWD % w. of binder	Steel fiber [kg/m³]	Silica fume w.of cement %	LWA [kg/m³]	Compressive strength
LWASCC	500	750	0.3	-	1.5	-	10	500	46
LWASCCB	500	750	0.3	$6*10^8$	1.5	-	10	500	56
RPC	900	900	0.22	-	1.5	117	20	-	113
RPCB	900	900	0.22	$6*10^8$	1.5	117	20	-	133

2.4 Mixing and casting

The specimens were mixed by using a rotary concrete mixer with a capacity of 0.05 m^3. The mixing procedure was as follows:

Silica fume and cement were mixed together for a few minutes before being added to the aggregate.

The dry ingredients were mixed together until they have homogeneity before adding water. The aggregate was used in a saturated surface dry condition (SSD).

1/3 quantity of water was added and mixed for 1min after that the other 1/3 quantity of water was mixed with superplasticizer in the same volumetric flask and added gradually to avoid the liquidity of the mixture. Finally, the last quantity of water was mixed with the bacterial solution and added to the mixture, and was mixed until the mixture became homogeneous in color and texture. Before mixing, the remaining concrete from the previous batch was cleaned off a damp cloth was used to wipe the pan and blades of the mixer before placing the material.

The steel fiber was added gradually and slowly so that it doesn't agglomerate in a specific part of the mixture finally, all component was mixed for sufficient time. The concrete was placed directly in the molds.

The specimens have been covered with Jnvas sheets to prevent the evaporation of water. After 24 hours, beams and other specimens have been stripped from their molds and submerged in a curing basin. Fig. 5 demonstrates the materials, mixing, and casting.



Fig. 5: Mixing and casting. Material preparation, mixing, and casting.

2.5 Design beams and their details

Six reinforced concretes simply supported beams were constructed and tested with a two-point loads system with a cross-section of 100x150 mm, span length of 1100 mm, and longitudinal reinforcement of 2Ø6 mm, the shear reinforcement for the tested beams Ø4 mm @ 56 mm c/c. Each specimen is designed to fail under flexure. The beam was designed according to ACI 318-19 [17]. Three samples of each bar have been subjected to tensile tests the results were consistent in Table 5. Fig. 6 reflects the geometry of the beam sample used in the present study.

Table 5: Test results of the steel bars used.

Nominal bar diameter [mm]	Measured diameter [mm]	Area [mm^2]	Elongation %	Yield tensile stress [MPa] Fy	Ultimate tensile stress [MPa] Fu	Limits to ASTM A496/A496M		Modulus of elasticity [GPa]
						Fy	Fu	
4	4.10	12.56	10	565	800	515	585	200
6	6.15	28.27	12	520	602	515	585	200

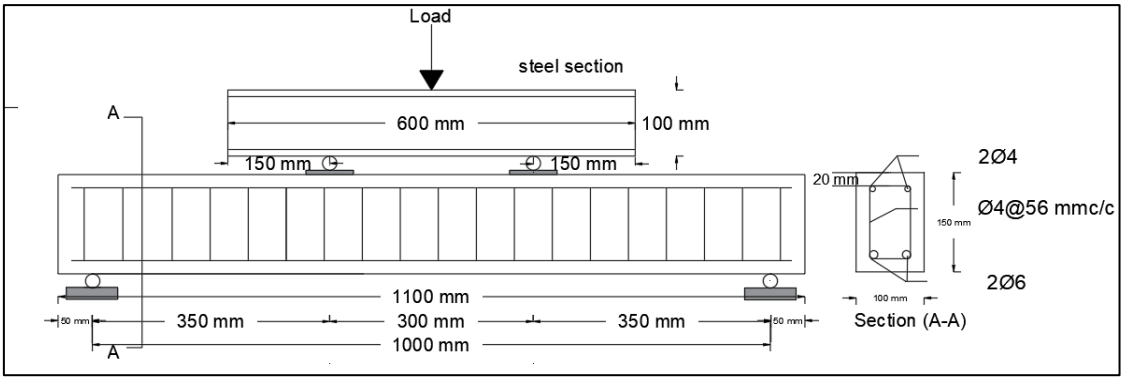


Fig. 6: Design beams and their details.

2.6 Preparing samples

All beams were tested using the hydraulic testing machine (displacement control) with a maximum capacity of 2,000 kN under monotonic and repeated loading. The reference beams were painted with white color to facilitate the detection of the first crack, make crack patterns more visible, and detect the propagation of cracks. The bacterial beam has not been painted; rather, it has been left in its natural concrete color so that the healing process can be monitored more clearly. The beams were labelled and the location of the support point and loading point. Beam specimens were placed at the testing machine and adjusted so that the centreline, supports, and load arms were fixed at their locations, as shown in Fig. 7.



Fig. 7: Beams testing (left), and beams preparing (right).

2.7 Testing procedure

Loading procedure by application of a two-point load. The samples were examined according to FEMA 2007. So that the reference beams were subjected to a monotonous load to the point of failure to determine the ultimate load and ultimate displacement on the basis of which the other reference beam would be subjected to a repeated load. The bacterial beams were tested under repeated loading into two-stage.

The first stage was until cracks were generated which were 0.1, 0.2, and 0.3 to 1.0 mm wide. After that, the loading was stopped, and for the next four weeks, they were subjected to alternating periods of wetness and dryness. The second stage tested the bacterial beams to repeated loads to failure and thus was performed after the beams had completed the self-healing process (after all cracks that formed as a result of the repeated loads in the 1st stage were 100 % self-healing).

3 Experimental results and discussions

3.1 Results of mechanical properties of mixes

3.1.1 Fresh properties

3.1.1.1 Workability for LWASCC

The workability test of self-compacting concrete should be based on the European SCC recommendation EFNARC 2002. The following tests were carried outflow, V-shape, and L-shape as listed in Table 6. Fig. 8 shows the slump flow, and L-box tests.

Table 6: Test results of fresh properties for LWASCC.

Characteristic	Preferred test methods	Result		Unit	Specification limits
		LWASCC	LWASCCB		
Flow ability	Slump-flow test	680	700	[mm]	650-800
Viscosity (assessed by the rate of flow)	V-funnel test	10.2	8.0	[Sec]	6-12
Passing ability	L-box test	0.89	0.92	%	0.8-1



Fig. 8: Slump flow test (left), and L-box test (right).

3.1.1.2 Consistency (flow table)

The flow table was used to test the consistency of Reactive Powder Concrete (RPC). Fig. 9 illustrates the consistency test of RPC. The test was carried out in accordance with the requirements of Standard ASTM-C1437-20. The values of (flow table) are listed in Table 7. The test result was conducted according to the following equation.

$$Flow = \frac{D-100}{100} \quad (1)$$

Table 7: Test result for flow table for RPC mixes.

No.	Concrete type	Flow table value [mm]
1	RPC	100
2	RPCB	110



Fig. 9: Consistency test of RPC.

3.1.2 Hardened properties

3.1.2.1 Compressive strength *fcu*

Compressive strength tests were performed on standard cubes 150*150*150 mm after 7 and 28 days and using the average of three cast cubes per specimen. The test was determined according to BS. 1881: Part 116: 1983 [18]. A hydraulic universal digital compression testing machine of 3000 kN capacity. The results for all the mixtures are listed in Table 8, Fig. 10, and Fig. 11. The failure pattern of the concrete mixes that were used are shown in Fig. 12.

Table 8: Test result of compressive strength.

Specimen	Control	*fcu* [MPa]		Standard deviation [MPa]	
		7 days	28 days	7 days	28 days
Control	LWASSC	33.7	46.0	2.12	2.84
Bacterial concrete	LWASSCB	37.5	56.0	1.8	1.0
Control	RPC	110	113	3.71	3.59
Bacterial concrete	RPCB	125.8	133	1.95	2.05

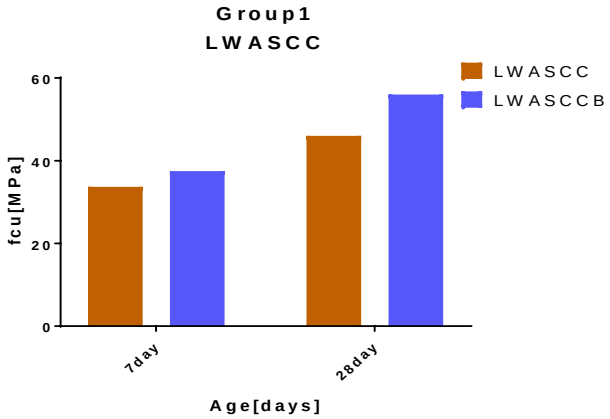


Fig. 10: Compressive strength at 7 and 28 days for control and bacterial concrete.

As seen in Fig. 10, specimens remediated with bacteria LWASCCB exhibit higher compressive strengths at all their curing ages than the control, in which the percentage of increase was 11.28 % at 7

days and 21.74 at 28 days. Reactive powder concert (RPC) has improved in compressive strength by direct incorporation of bacteria about 14.36 % at 7 days17. 7% at 28.

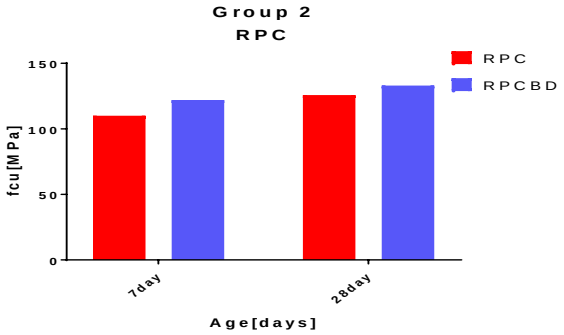


Fig. 11: Compressive strength at 7 and 28 days for control and bacterial concrete.

The increase in compressive strength in all previous mixtures was due to the filling and plug of the pores and the generating of bio-calcium carbonate crystals as a product of bacterial metabolic activity inside the concrete, the deposition of calcite in the pores of concrete led to a decrease in ITZ and thus improves the microstructure, and increase concrete density. Bacteria can also boost the degree of the cement hydration reactions by raising C-S-H gel chain length which in turn increases the strength of the concrete [19].



LWASCC LWASCCB RPC RPCB

Fig. 12: The mode of failure for concrete cubes 150x150x150 mm^3 were tested for compressive strength.

3.1.2.2 Splitting tensile strength *ft*

The splitting tensile strength utilized in this study was evaluated by testing three standard cylinders of 100 mm diameter, and 200 mm length by the ASTM C496/C496M -17[20] specification. The results of splitting tensile strength are listed in Table 9 and Fig. 13 and Fig. 14. The failure pattern of the concrete mixes that were used are shown in Fig. 15.

Table 9: Splitting tensile strength results.

Specimen	Control	*ft* at 28 days [MPa]	Standard deviation [MPa]
Control	LWASSC	2.93	1.4
Bacterial concrete	LWASSCB	3.25	1.25
Control	RPC	13.9	2.8
Bacterial concrete	RPCB	16.4	2.87

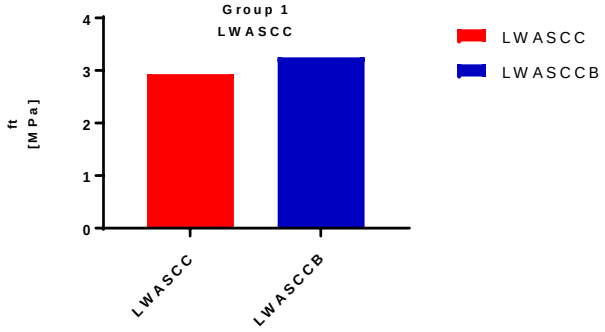


Fig. 13: Splitting tensile strength at 28 days for control and bacterial concrete.

In lightweight aggregate self-compacting concrete, the percentage was 10.92 %, as shown in Fig. 13.

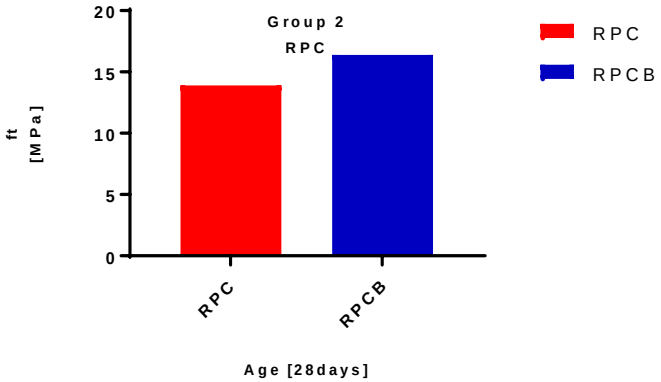
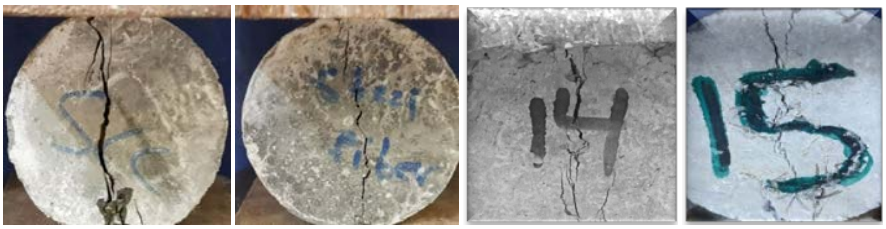


Fig. 14: Splitting tensile strength at 28 days for control and bacterial concrete.

Fig. 14 shows that the splitting tensile strength of RPC increased by 18.0 % by adding the cultured bacteria to the concrete mixture.

As was previously mentioned, for the compressive strength, the observed improvement in split tensile strength is mainly attributed to the metabolic activities of bacteria, which lead to the deposition of calcite crystals in the pore. As a consequence of this, the microstructure of the concrete was enhanced, and the strength increased.



LWASCC LWASCCB RPC RPCB

Fig. 15: The mode of failure of splitting tensile strength for concrete mixtures.

3.1.2.3 Flexural strength *fr*

The flexural strength test was carried out on concrete prisms with dimensions of 100*100*400 mm, and a span of 300 mm. These concrete prisms were cast by the specification provided by ASTM C78/C78M-22 [21]. The results of flexural strength are listed in Table 10, Fig. 16, and Fig.17. The failure pattern of the concrete mixes that were used are shown in Fig. 18, and Fig. 19.

Table 10: Flexural strength results.

Specimen	Control	*fr* at 28 days [MPa]	Standard deviation [MPa]
Control	LWASSC	3.3	1.5
Bacterial concrete	LWASSCB	4.0	1.02
Control	RPC	19	2.5
Bacterial concrete	RPCB	22.96	2.94

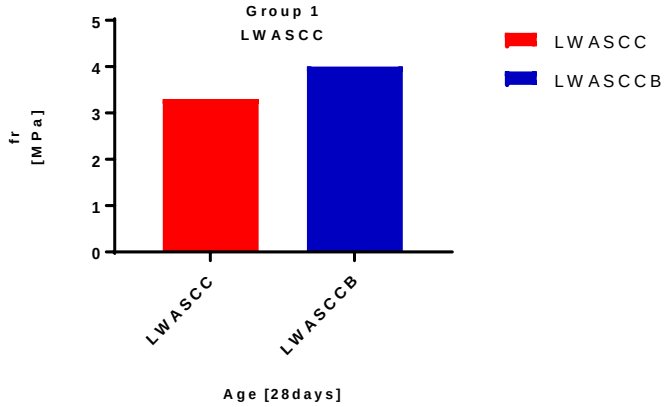


Fig.16: Flexural strength at 28 days for control and bacterial concrete.

The result of flexural tensile strength in bacterial lightweight concrete LWASCCB plotted in Fig. 16 was increased about 21.21 %. Fig. 17 explains that in the reactive powder concrete in which the bacterial suspension was added directly the percentage of increase was 20.84 %.

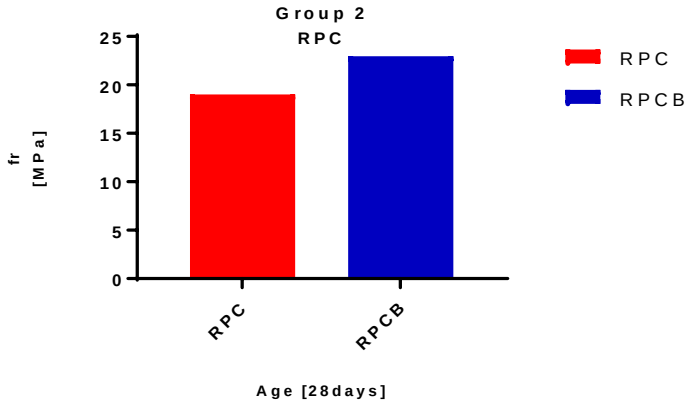


Fig. 17: Flexural strength at 28 days for control and bacterial concrete.

The result of flexural tensile strength in bacterial lightweight concrete LWASCCB plotted in Fig. 16 was increased about 21.21 %. Fig. 17 explains that in the reactive powder concrete in which the bacterial suspension was added directly the percentage of increase was 20.8 %. The improvement of concrete strengths (compressive strength, splitting tensile strength, flexural strength) was achieved by using non-pathogenic bacteria B. subtilis in the concrete which makes the concrete matrix more strength.

Incorporated bacteria in concrete will produce glue or gel. The glue is a natural adhesive material and it is very strong. Using this glue will seal the crack and fill pores in the concrete matrix. Thus, bacteria produce calcium carbonate, filamentous to act as reinforcing fiber, and levans glue which acts as a binding agent. The calcium carbonate and levans glue combined with filamentous cells make hardening to strengthen the surrounding concrete [19].



LWASCC LWASCCB

Fig. 18: The mode of failure of splitting tensile strength for concrete mixtures.



RPC RPCB

Fig. 19: The mode of failure of splitting tensile strength for concrete mixtures.

3.2 Flexural test results of beams

The beams in this study were divided into two groups (Lightweight self-compacting concrete, and reactive powder concrete). Table 11 demonstrates the results of flexural tests for beams included first crack load *Pcr* midspan deflection at crack load Δcr and ultimate load *Pu* midspan deflection at ultimate load Δu.

Table 11: Flexural test results of beams.

Group no.	Concrete type	Beam symbol	*Pcr* [kN]	*Δcr* [mm]	No of cycle	*Pu* [kN]	*Δu* [mm]	No of cycle	Test type
G.1	LWASCC	BM5	13.48	1.39	-	20.3	9.12	-	Monotonic
		BR13	11.52	1.0	8	19.32	9.86	47	Repeated
		BR14	14.72	1.11	13	21.23	10	49	Repeated
G.2	RPC	BM6	23.5	0.8	-	34.0	6.0	-	Monotonic
		BR15	22.3	1.2	22	33.2	7.6	51	Repeated
		BR16	26.0	1.3	23	34.5	7.89	52	Repeated

3.2.1 Behaviour of beams tested under monotonic loading

Tow reference beams from each group were tested monotonically to failure, and the results of flexural tests for beams included first crack load *Pcr* midspan deflection at crack load Δcr ultimate load *Pu* midspan deflection at ultimate load Δu, stiffness at cracking load *Kcr*, and stiffness at ultimate load *Kav* are illustrated in Table 12.

Table 12: Flexural test results of beams.

Concrete type	Beam symbol	*Pcr* [kN]	*Δcr* [mm]	*Pu* [kN]	*Δu* [mm]	*Kcr*	*Kav*	*Pcr/Pu* [%]
LWASCC	BM5	13.48	1.39	20.3	9.12	9.7	2.2	66.40
RPC	BM6	23.5	0.8	34.0	6.0	29.4	5.7	69.11

The beam is exposed to load the load-deflection curve begins linearly with a constant slope. After cracking has occurred the response between load and deflection takes on a nonlinear form with a variable slope. As shown in Fig. 20.

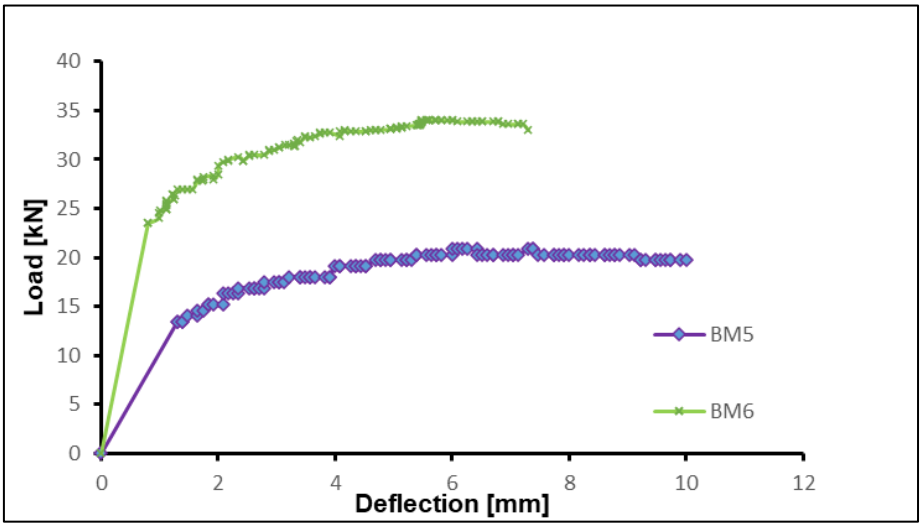


Fig. 20: Comparison of load-deflection curves between concrete types.

As can be seen from Fig. 20, in the reactive powder concrete beam BM6, there was a considerable increase in the first crack and ultimate loads as compared with the Lightweight self-compacting Concrete beam BM5 where the percentage of increase was equal to 74.33 %, and 67.48 % respectively, while there was a decrease in the first crack and ultimate deflection by 42.4 % and 34.21 % respectively as compared with beam BM5. In the first stage (modulus of rapture zone) presence of steel fiber has a significant positive effect on the first crack (delay cracks propagation). And this led to an increase in the first crack loading. For the post-peak zone, the presence of steel fiber in addition to the under-reinforcement rebar become more under-reinforcement and led to 67.48 % more than BM5. The response of the RPC beam BM6 is considerably steeper than BM1. In practice, fibers are essential for RPC beams to overcome brittleness due to their ability to control cracking. The decrease in mid-span deflection of the reactive powder concrete beam BM6 is caused by the improved flexural stiffness of the beam specimens, which consequently decreased beam deformation.

3.2.2 Behaviour of beams tested under repeated loading

3.2.2.1 References beams

Tow reference beams from each group were tested under repeated loading to failure. Table 13 presents the comparison effect between the concrete beams under consideration. Load-deflection curves for beams are shown in Fig. 21 and Fig. 22.

$$D^1 = \frac{Ni}{ni} \tag{2}$$

Where:
Ni - no of cycles at cracking load,
ni - no of cycles at ultimate load.

Table 13: Flexural test results of beams.

Concrete type	Beam symbol	*Pcr* [kN]	*Δcr* [mm]	No of cycle	*Pu* [kN]	*Δu* [mm]	No of cycle	D^1	*Pcr/Pu* [%]
LWASCC	BR13	11.52	1.0	8	19.3	9.86	47	0.17	59.6
RPC	BR15	22.3	1.2	22	33.2	7.6	51	0.43	67.2

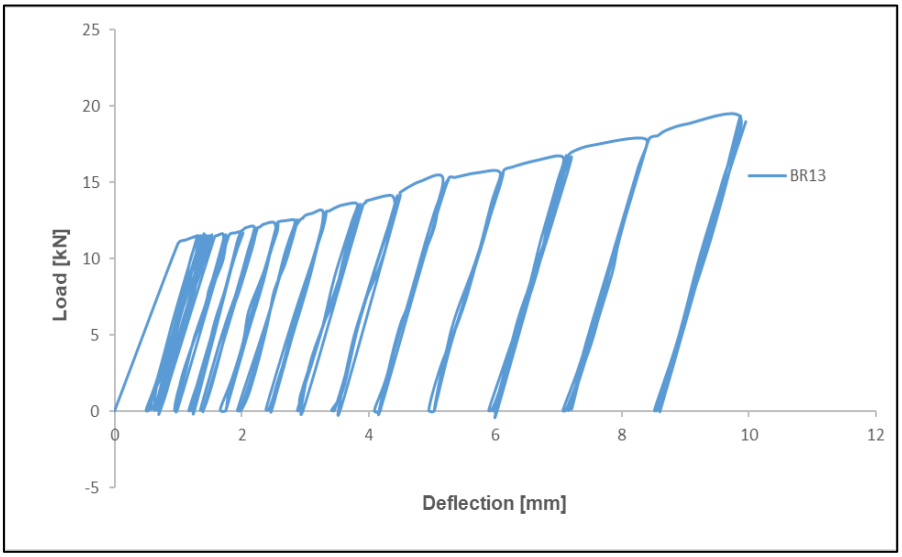


Fig. 21: Load-deflection curve of beam BR13 under repeated loads.

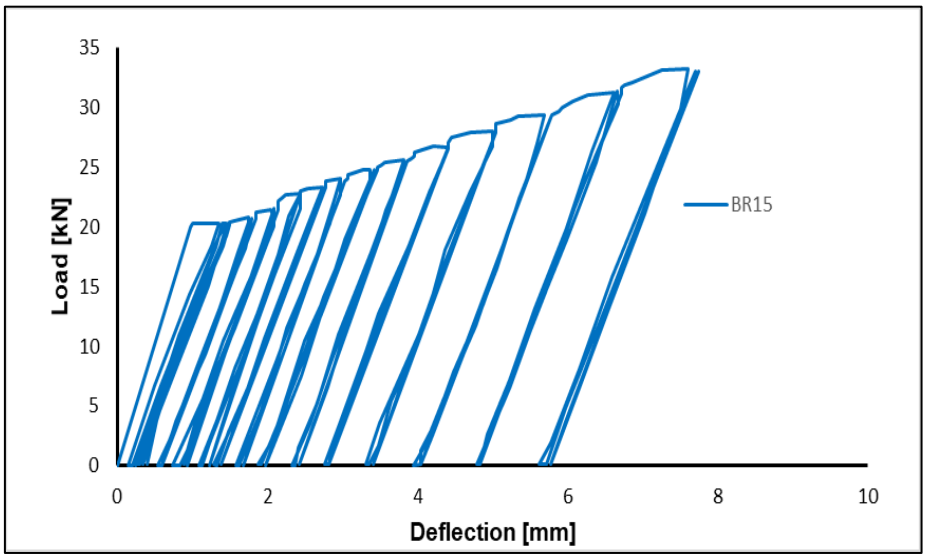


Fig. 22: Load-deflection curve of beam BR15 under repeated loads.

3.2.2.2 Bacterial concrete beams

Two bacterial concrete beams from each group were tested under repeated loading to failure. After all cracks are self-healing Table 14 presents the comparison effect between the concrete beams under consideration. Load-deflection curves for beams are shown in Fig. 23 and Fig. 24.

Table 8: Flexural test results of beams

Concrete type	Beam symbol	*Pcr* [kN]	*Δcr* [mm]	No of cycle	*Pu* [kN]	*Δu* [mm]	No of cycle	D^1	*Pcr/Pu* [%]
LWASCCB	BR14	14.72	1.11	13	21.23	10.0	49	0.26	69.33
RPCB	BR16	26.0	1.3	23	34.5	7.89	52	0.44	75.36

From the observation of the results in the table above, there is an improvement in each of the cracking load and ultimate load incisions in the bacterial concrete beams used in this study. Where the bacterial lightweight aggregate concrete LWASCCB achieves the highest percentage of increase. Where it was increased by 27.77 %, and 10 % at the first crack and ultimate load respectively as compared with the reference beam BR13. As in Fig. 23. While the percentages of increase in bacterial reactive powder concrete RPCB were about 16.59 % at the first crack load, and 3.91 % at the ultimate load respectively. As compared to the reference beams BR15. As can be seen in Fig. 24. Both the load-

bearing capacity and deflection were enhanced due to the healing of microcracks and the filling of pores in the concrete matrix caused by bacterial precipitation of calcite.

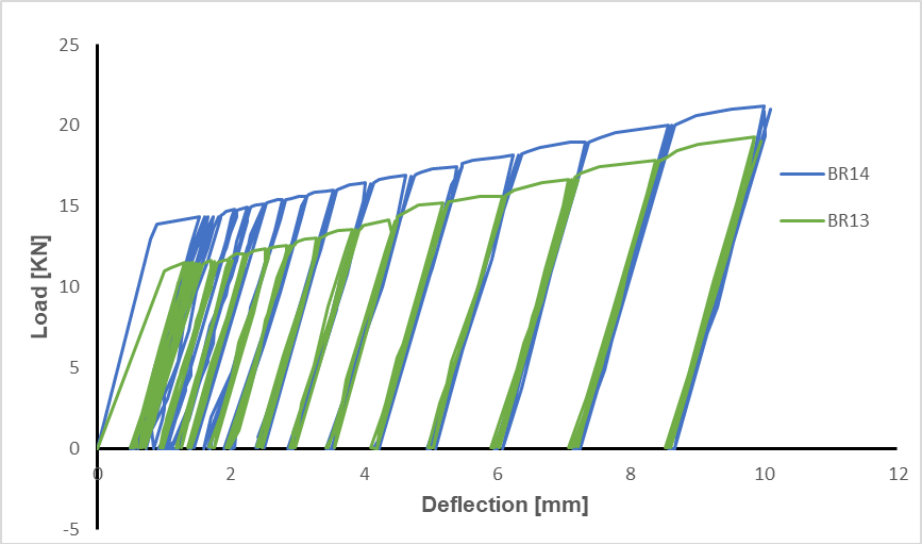


Fig. 23: Load-deflection curves for beams BR13 and BR14.

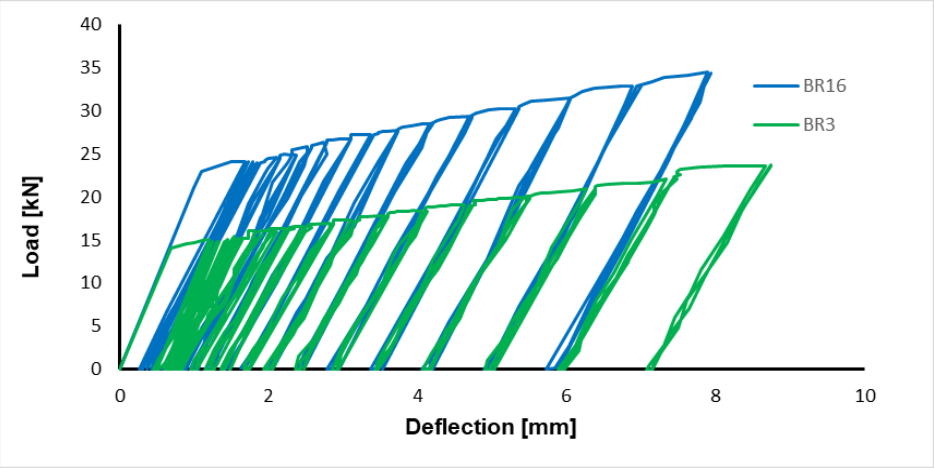


Fig. 24: Load-deflection curves for beams BR15 and BR16.

4 Evaluating the cracks healing efficiency of bacterial concrete beam

From the microscopic inspections, it can be evidently seen that all the cracks of the samples have calcium carbonate crystals precipitated by bacterial activity at the end of the self-healing process in a time-dependent manner. As demonstrated in Fig. 25 and Fig. 26.

When cracks occur in concrete H_2O enters the concrete through those cracks which lead to a decrease in the PH value this in turn activates the bacteria to begin the process of self-healing by precipitating calcium carbonate crystals $CaCO_3$ in the presence of calcium source, which led to fills the voids and seals concrete cracks [23] as shown in the following equation:

$$CaC_6H_{10}O_6 + 6O_2 \xrightarrow{Metabolic\ convertion} CaCO_3 + 5CO_2 + 5H_2O \quad (3)$$

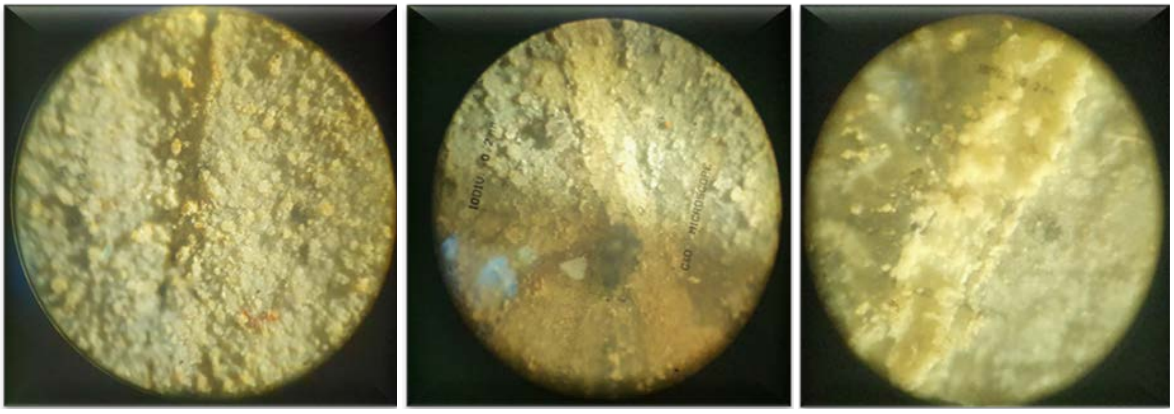
The interaction between the calcium hydroxide produced by the hydration of the cement and the CO_2 produced during bacterial activity causes an increase in $CaCO_3$ precipitation as illustrated in the equation below.

$$5CO_2 + Ca(OH)_2 \rightarrow 5CaCO_3 + 5H_2O \quad (4)$$

The significant rise in the level of mineral deposition in crack surfaces results in efficient self-healing.

Additionally, the water resulting from the chemical reaction above was responsible for the hydration of the unhydrated cement particles, which led to the development of an additional quantity of CSH gel. This, in turn, was also cause a significant increase in the concrete's strength.

Fig. 25, and Fig. 26 display the microscopical examination of the cracks of the samples that have been studied during the self-healing period which shows the stages of self-healing (bottom view).



After 14 days. After 32 days. After 40 days.

Fig. 25: LWASCCB mixture, crack width 1.0 mm.



After 7 days. After 26 days. After 30 days.

Fig. 26: RPCB mixture, crack width 0.6 mm.

5 General behaviour and crack pattern

The crack patterns at the failure stage of all beams are shown in Fig. 27, each beam is designed to fail under flexure, which is identified by the development of cracks in the tensile stress zone, followed by the yielding of steel bars and a shift in the neutral axis toward the compression zone. The following comments characterize the tested beam's overall behaviour.

5.1 General behaviour, crack pattern at failure for beams tested under monotonic load

For the lightweight aggregate self-compacting concrete beam BM5, tension cracks develop in the beam tension zone before progressively extending toward the compression face. Further, there was no sudden failure of the beam. These results agreed with [24].

The RPC beam BM6 suffered the first microcracks in the bottom face between the loading locations, where the beam was subjected to pure bending. Cracks consequently appeared and sparsely distributed microcracks. After the initial cracking, new micro-cracks began to form between the initial cracks as the load continued. The majority of the cracks were expanded toward the upper face without significantly widening. The RPC beam proved the ability to redistribute stresses and undergo multiple cracking before fiber pull-out. These results agreed with [25].

5.2 General behaviour, crack pattern at failure for beams tested under repeated loading

5.2.1 Reference beams

Cracks that were identical to those that occurred during the monotonic test were seen in the specimen during the 8th cycle in beam BR14, and in the 22th cycle in BR16 of stage one of repeated loading. In subsequent cycles, the same cracks that were seen previously were closed during the unloading phase. However, in the next cycle, they began to open during the loading phase, and in subsequent cycles, some new cracks appeared.

5.2.2 Bacterial concrete beams

The bacterial concrete beams were tested in two stages: The first stage was subject the beams to repeated load until cracks formed then the test was stopped and the beams were subjected to wet and dry cycles. After all the cracks self-healing, the beams were tested under repeated loading to failure, the cracks formed in this stage are different from those generated in the first stage.



Fig. 27: Cracks pattern of beams at failure.

6 Conclusion

The following conclusions are drawn from the experimental program that was conducted:

1) The novel methodology which included the incorporation of microorganisms (bacillus subtitles) by the two technics into the concrete mixtures has been proven to enhance the mechanical properties of the concrete (fresh and hardened properties).

2) The workability is improved by adding bacteria and calcium lactate simultaneously, and this is because the calcium lactate acts as a retardant in concrete.

3) The encapsulation technics improved the concrete strength (compressive strength, splitting tensile strength, and modulus of rupture) at 28 days by 21.74 %, 10.92 % and 21.21 % respectively.

4) The direct addition enhanced the concrete strength (compressive strength, splitting tensile strength, and modulus of rupture) at 28 days by 17.7 %, 18.0 %, and 20.84 % respectively.

5) The increase in the strength of bacterial concrete was due to biomineralization by bacteria, which enhances the concrete microstructure by producing calcium carbonate crystal, which in turn works to fill voids inside the concrete. Bacteria can also boost the degree of the cement hydration reactions by raising C-S-H gel chain length which in turn increases the strength of the concrete.

6) Incorporated bacteria in concrete will produce glue or gel. The glue is a natural adhesive material and it is very strong. Using this glue will seal the crack and fill pores in the concrete matrix. Thus, bacteria produce calcium carbonate, filamentous to act as reinforcing fiber, and levans glue which acts as a binding agent. The calcium carbonate and levans glue combined with filamentous cells make hardening to strengthen the surrounding concrete.

7) Incorporation of bacteria in the concrete shows an improvement in the 1st crack loads and ultimate loads as compared with reference beams.

8) The microscopical examination of the cracks of the samples that have been studied during the self-healing period shows the stages of self-healing in which the crack width ranges from 0.1-1.0 mm within a maximum period equal to 32 days.

9) Incorporation of bacteria in concrete mixes led to an increase in the elastic range and fatigue life by increasing the D^1.

10) The cracks generated by reloading take another pathway than the path of cracks in the first stage, where the new cracks deviated from healed cracks, and this indicates that the crystal mineral which precipitated as a consequence of bacterial activity was sufficiently powerful to heal the cracks.

Recommendation for future studies

Tests on frost resistance or resistance to salt for deicing agents on bacterial concrete.

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