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IMPROVEMENT OF RIGID PAVEMENT PERFORMANCE USING MICROBIAL AGENT

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ABSTRACT

Cracking is the most difficult problem for rigid pavement, not only because it affects the mechanical properties, but also because it affects the road's durability and service life. This paper aims to improve the rigid pavement efficiency, as well as construct a bacterial consortium that can make the concrete to repair itself. A concrete slab with dimensions of 750 x 750 x 200 mm was used in a laboratory case study. *Bacillus flexus* MK-FYT-3 and *Bacillus haynesii* MK-NW-9 were identified using 16s as Bacillus flexus MK-FYT-3 and Bacillus haynesii MK-NW-9, respectively, for the laboratory bio-concrete mixture and deposited to GenBank under accession numbers MN965692 and MN965693. These isolates were able to grow at 60 °C with an optimum temperature of 40 °C, showed an ideal growth at pH of 10, and were capable of producing $CaCO_3$. Under static loading, the bio-concrete slab performed significantly better than the control one.

KEYWORDS: bacterial consortium, cracks, rigid pavement, *Bacillus flexus, Bacillus haynesii.*

تحسين كفاءه الرصف الصلب باستخدام الإضافات الميكروبيولوجيه

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الملخص

تعتبرالشروخ من أصعب المشاكل التى تواجه الرصف الصلب ، ليس فقط لأنه يقلل من الخصائص الميكانيكية ، ولكن أيضًا لأنه يؤثر على متانة الطريق وعمر الخدمة. تهدف هذه الدراسة الى تحسين كفاءة الرصف الصلب ، بالإضافة إلى إنشاء اتحاد بكتيري يمكنه العمل مع الخرسانة لمعالجه نفسها ذاتياً. استخدام بلاطات خرسانية بأبعاد ٧٥٠ × ٧٥٠ × ٢٠٠ مم فى عمل دراسة معملية. كما تم تصنيف وتعريف كلاً من *Bacillus flexus MK-FYT-3* و *Bacillus haynesii MK-NW-9* من قبل GenBank بالأرقام المرجعيه الاتيه MN965692 و MN965693، على التوالى. اثبتت هذه العزلات قدره على النمو عند ٦٠ درجة مئوية مع درجة حرارة مثالية تبلغ ٤٠ درجة مئوية ، وأظهرت نموًا أمثل عند pH 10 ، وكانت قادرة على إنتاج كربونات الكالسيوم $CaCO_3$ أوضحت النتائج تحت الحمل الاستاتيكى، أن البلاطات المعالجه بالبكتيريا تعد أفضل من البلاطات الخرسانيه العاديه.

الكلمات المفتاحية: اتحاد بكتيري ، شروخ ، رصف صلب ، *Bacillus flexus* ، *Bacillus haynesii*.

1. INTRODUCTION

Cracking is denoted as the most challenging problem for the life-cycle performance of concrete pavement [1]. The inner and outer cracks of this pavement will reduce the compressive, tensile, and flexural strength limits of the material. Concrete deterioration is caused by many factors based on suitable partial materials, action factors and provides repeatability to prevent failure. Material degradation is seen as inevitable, and mitigation requires expensive inspection, maintenance, repair, and replacement systems. Hence, poor physical performance remains the single major cause of degradation and failure in the infrastructure systems. Furthermore, the durability of repaired concrete structures remains a major concern since, after 5 years, 20% of all repairs fail, rising to 55% after 10 years [2].

With regard to performance and application, self-healing concrete mechanisms have grown increasingly common in concrete crack repair. The focus should be on sealing efficiency, healing agent compatibility with the concrete matrix, long shelf-life, and eco-friendly viability. The healing agent can be polymeric, inorganic, or biological. The first two types of healing agents have the ability to produce chemical reactions throughout a wide temperature range. which affect the concrete matrix [3]. Self-healing biological agents such as the Bacillus bacteria that precipitate calcium carbonate can recover surface and in deep cracks with a controlled range of temperature by biomineralization [4]. Also, a specific group of alkaline resistant spore forming bacteria collected from (Wadi Natrun, Egypt) was compared with the international ranked (Bacillus DSM497) as a reference mix to develop a type of self-healing for concrete [5].

Dry at the University of Michigan used a large-scale application of self-healing in concrete to simulate various situations for bridge elements and pavements in full scale and later field scale studies [6]. In Equador, the first field application took place in 2014 on an existing cracked concrete irrigation canal 3 meters long. Self-healing alkaliphilic bacteria in spore forming added to the concrete mix, and monitored for five months, showed no sign of cracking or deterioration, thus its healing effectiveness could not be determined [7].

1. MATERIALS AND METHODS

1.1. Bacteria Growth Preparation

Soil samples were collected from Wadi Elnatrun region, Egypt, bacterial colonies were isolated and checked for endospore formation. the antagonistic activity of the bacterial isolates was determined, also the isolates were tested for $CaCO_3$ precipitation, finally, blasted on the GenBank to detect and compare the similarity of the isolates with the available sequences on the GenBank database. The concentration of spores in each bacterial isolate was adjusted to be 10^6 CFU/ml and stored at 4 ◦C [8].

1.2. Preparation of Concrete Slabs

1.2.1. Concrete materials

The composition of concrete mixes was characterized by the high content of ordinary Portland cement aiming at the high compactness of the matrix. Portland cement CEM I, 52.5 N, locally available sand that passes via a sieve with pores 4.75 mm and corresponding to zone II of Egyptian standard specifications (ESS) 1109/2002 were used. Dolomite of maximum size 20 mm conforming to ESS 1109/2002 was used as coarse aggregates [9]. The specific gravity of the coarse and fine aggregates was found to be 2.7 and 2.6 respectively.

1.2.2. Mix design and preparation of concrete mixes

Concrete slabs were designed according to ESS and the American Society for Testing and Materials (ASTM) to construct 28-day compressive strength of 40 MPa and to give a slump of 12–38 mm. For concrete mix, the water volume (pH value 7 at zero turbidity) used for the preparation of the control slabs, was 200 L/m^3, whereas for the bio-concrete slabs, 200 ml/L of the total water volume was replaced with Bact-Cal solution, which considered of bacterial spore suspension (1×10^6 CFU/ml) and calcium lactate (252 g/L). the mix proportions are listed in Table1.

Table1: Composition of Concrete Mixes.

Ingredient (Kg/m^3)	Control mixture	Bio-concrete mixture
Cement CEM I/52.5 N	420	420
Water	200	160
W/C ratio	0.48	0.48
Bact-Cal solution	---	40
Coarse aggregate	1265	1265
Fine aggregate	650	650
Fine/Coarse aggregate	0.34	0.34

1.3. Construction of Concrete Pavement Slabs

The laboratory rigid pavement slabs were cast with a size of 750×750×200 mm. Casting, compaction, and finishing were carried out in accordance with standard construction practice as illustrated in Fig.1. For the bio-concrete mixture, a consortium bacterium consisting of mixed cutlers of *Bacillus flexus* MK-FYT-3 and *Bacillus haynesii* MK-NW-9, was added directly to the concrete mix. The nutrient calcium lactate, and yeast extract were dissolved in hot water, and mixed with concrete materials. All samples were covered with burlap and cured with water after 24 h ours of casting [10]; [11].

2. EXPERIMENTAL TESTS

2.1. Static Loading Test

Alani, et al.2014 studied structural behavior and deformation in loaded plain concrete ground-supported slabs that had dimensions of 3000 × 3000 × 150 mm. The plain concrete slab was loaded in the central, the edge and the corner with punching loads [12]. In this study, the static load test was processed. Data was collected in a concrete structural lab. Fig.2, showed the frame setup with a soil bed layer of a 1٢-inch of fine aggregate layer was placed in two lifts, with each lift consolidated by a vibratory compactor to work as a base course stable foundation support for the rigid pavement slabs, which distributes the imposed wheel loads to the subbase layer. The frame used in the test had a 500 KN capacity with a load cell of 450 KN capacity placed under the electrohydraulic jack, located in the Structural Concrete Engineering Laboratory of the Materia Engineering College, Helwan University. Furthermore, it depicted the position of the central applied load, strain gauges were marked, linear variable displacement transducers (LVDTs) were located on the top surface of the slabs in a static loading test. The loading plat was 150×150 mm and placed at the top center of the slab. The strain gauges were placed at the midpoint, the middle edge, and in the corner of the slabs, then connected within the data logging machine. The strain gauge type was PL-60-11-1LJC-F with a gauge length of 60 mm, a gauge resistance of 120 ± 0.50 Ω and a gauge factor of 2.11±1%. LVDTs are used to measure the vertical load deflection in the allocated positions as in the Fig, with an accuracy of $1x10^{-2}$ mm, then connected within the data logging machine. the electrohydraulic Jack was vertically leveled, and the Jack's electrohydraulic pump was also visible.

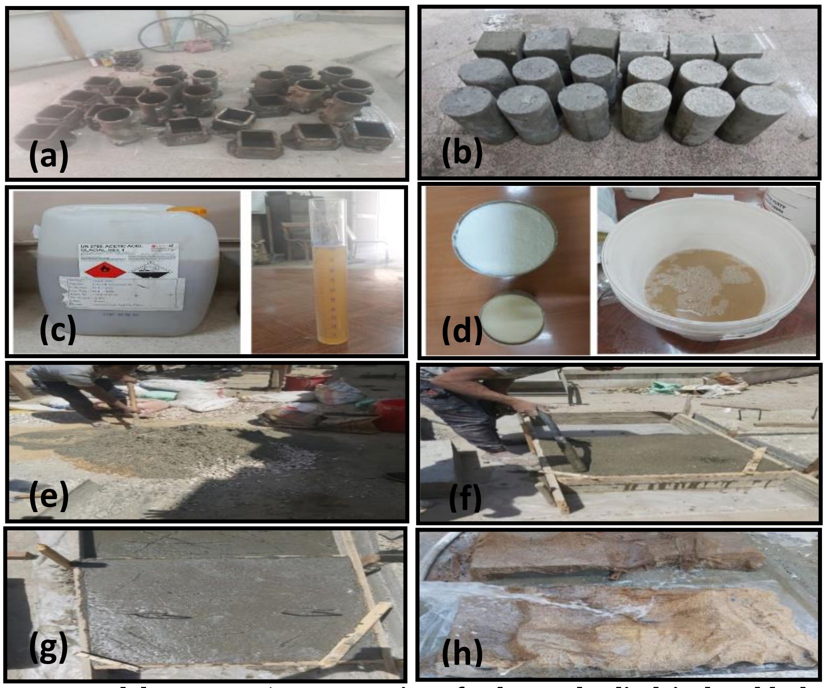

Fig. 1: Casting concrete slabs process (a. preparation of cubes and cylindrical molds, b. casted cubes and cylinders, c. bacterial media, d. calcium lactate, yeast extract and the mixed nutrient with bacterial spores. concrete materials, f. mechanical vibrator, g. finishing slab surface, h. covered slab with burlap and cured with water).

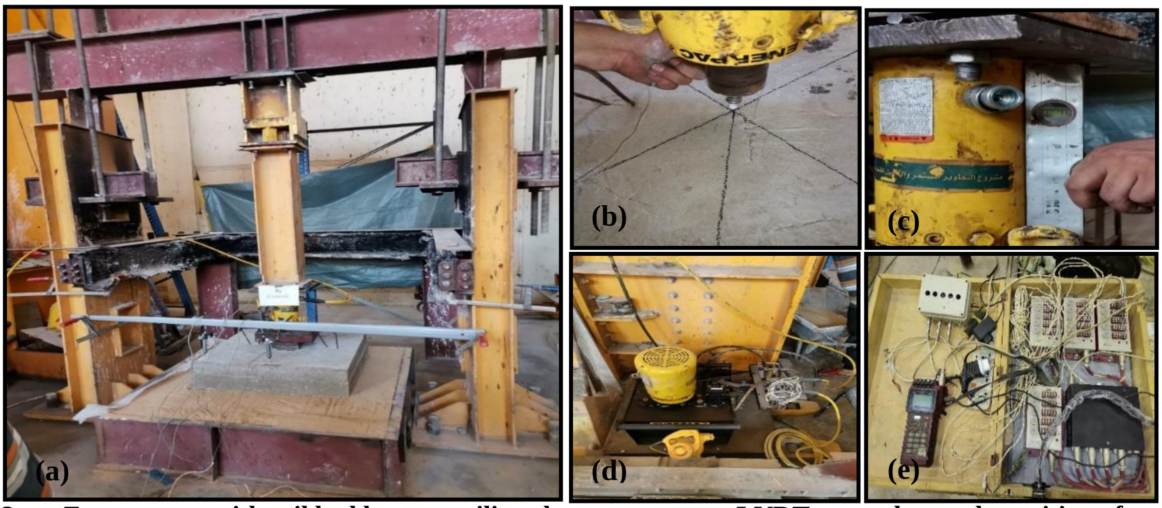

Fig.2: a. Frame setup with soil bed layer, auxiliary beam to support LVDTs transducers, b. position of central applied load, c. electrohydraulic Jack vertically leveled, d. electrohydraulic pump of the Jack, e. data logging machine.

2.1.1. Failure shape under the static load during test

A loading test was conducted on the control and the bio-concrete slabs, until failure, as shown in Fig.3.

Fig.3: the crack failure pattern A.the control slab, B. the bio-concrete slab.

2.2. Cost efficient of using Bacterial Consortium on rigid pavement

Sustainability of the road network and pavement development has become a major concern. In addition to the major attention towards pavement projects and economic growth, the value of pavement projects is very massive, where not only the construction's initial cost, but the maintenance cost also need consideration [13].

Life cycle cost analysis (LCCA) is basically a method based on principles of economic analysis to evaluate the overall long-term economic efficiency between competing alternative investment options [14]. In this phase of work, it was identified the scope for the current life cycle cost of rigid pavement according to AASHTO [15].

3. RESULTS

3.1. Slabs Loading Test Results

Rigid pavement does not flex under loading as in flexible pavement, and the load carrying capacity increases because of the rigidity at high modulus of elasticity of the slab. Westergaard is widely regarded as the pioneer in providing logical loading analysis of rigid pavements. The concrete slab is assumed to be a homogeneous, thin elastic plate resting on a dense liquid foundation, and subjected to flexural stresses. Westergaard developed the closed-form formulae for the wheel load stresses as the stress (bending tension) σi and the deflection δi at interior of a rigid slab denoted in equations 1 and 2 [16]:

$$\sigma i = \frac{3(1+\mu)P}{2\pi h2}\left(\ln\frac{l}{b} + 0.6159\right) \text{------------------------} \quad (1)$$

$$\delta i = \frac{P}{8Kl\text{^}2}\left\{1 + \frac{1}{2\pi}\left[\ln\left(\frac{a}{2l}\right) - 0.673\right]\left(\frac{a}{l}\right)\text{^}2\right\} \text{------------------------} (2)$$

where: μ is the Poisson coefficient, P is the load applied (KN), h is the slab thickness (m), K is the soil reaction modulus (N/mm^3), a is the equivalent radius of the wheel contact with the surface (m), l is the radius of relative stiffness (m).

3.1.1. Load vs deflection of the conventional concrete and the bio-concrete

Data was collected and recorded for the control and the bio-concrete rigid pavement slab. The proportion relationship between load vs deflection under static loading was illustrated in Fig.4.

The results showed that the first crack was noted at a load of 130.70 KN (50% of ultimate load) and at a load of 193.5 KN (60% of ultimate load) for the control slab and bio-concrete slab, respectively.

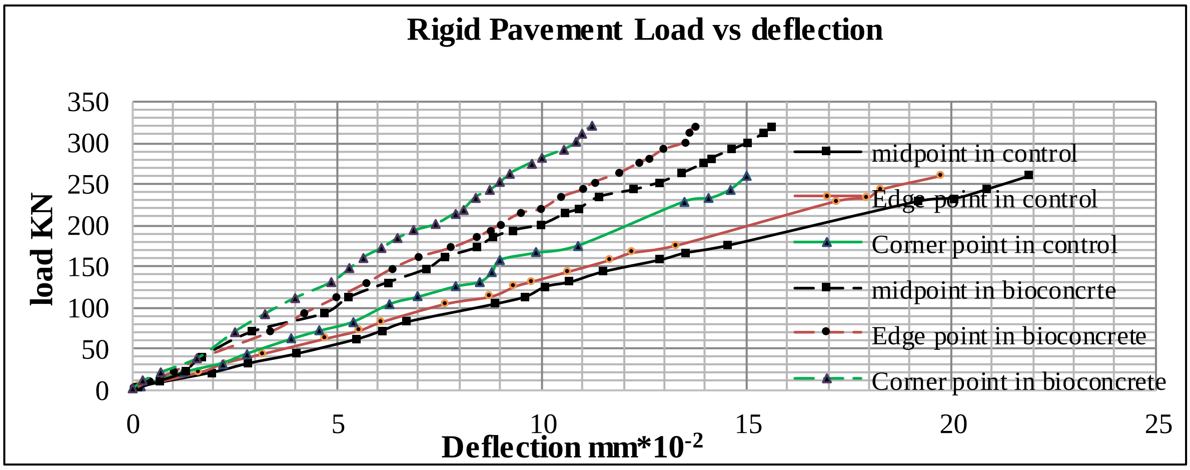

Fig. 4: Load vs deflection of the conventional concrete and the bio-concrete loading test results.

3.1.2. Load vs strain of the conventional concrete and the bio-concrete

Data was collected and recorded for the control and the bio-concrete rigid pavement slab. The proportion relationship between load vs strain was calculated and illustrated in Fig.5. The center region suspended to strain more than at the edge with significant reduction in the bio-concrete slab less than control slab, also the edge and the corner regions for both the control slab and the bio-concrete slab had less than 5% strain and 1% strain respectively.

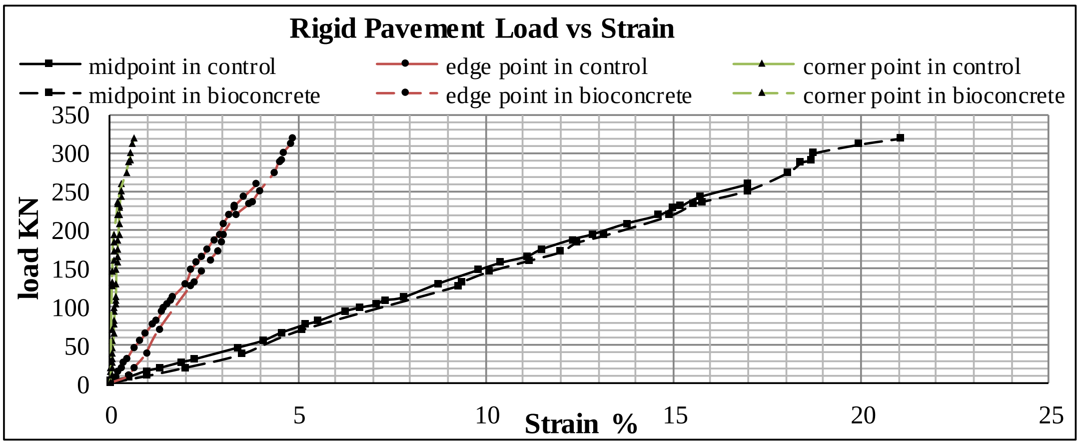

Fig.5: Load vs strain curve of the conventional concrete and the bio-concrete loading test results.

3.2. Cost Efficient of Using Bacterial Consortium on Rigid Pavement Results

The initial construction cost for the control and the bio-concrete rigid pavement was analyzed for one kilometer long of a road with 10 m width with airport thickness of 20 cm as in the following Table 2, and Table 3.

Table 2: Material Quantity and Initial Cost of Construction Control Rigid Pavement.

Constituent (Kg/m3)	Control quantity	Cost/ m^3	Airport slab cost/kilometer
Cement CEM I	420	380	760,000
Water	200	3.60	7,200
Coarse aggregate	1265	540	1,080,000
Fine aggregate	650	130	260,000
Total initial cost			**2,107,200**

The cost of self-healing nutrient growth was estimated to be 390 L.E. Each litter of bacteria media solution production needed 13 grammes of nutrient growth. To investigate the effect of self-healing in closure cracks for more than one cycle in order to gain sustainable repair for road pavement, $1m^3$ of concrete mix required the replacement of 20 L of water with bacteria media solution.

Table 3: Material Quantity and Initial Cost of Construction Bio-Concrete Rigid Pavement.

Constituent (Kg/m3)	Bio-concrete quantity	Cost/ m^3	Airport slab cost/kilometer
Cement CEM I	420	380	760,000
Water	160	3.24	6,480
Coarse aggregate	1265	540	1,080,000
Fine aggregate	650	130	260,000
Bacterial media solution	20	100	200,000
Calcium lactate	10	100	200,000
Yeast extract	1	30	60,000
Total initial cost			**2,566,480**

The annual maintenance is required to sustain the pavement serviceability of the current pavement projects during their pavement life, which faces many types of damage The Net Present Value (NPV) is described in the following equation formula 3:

$$NPV = \text{Initial cost} + \sum_{j=1}^{n} \left(Future\ costj \left(\frac{1}{(1+i)^n} \right) \right) \text{--} \quad (3)$$

where, n= the numbers of years of future costs incurred over the analysis period; i= discount rate in percentage; future cost considered for maintenance cost and user delay cost.

Table 4: NPV of the Control Rigid Pavement.

Cost activity	Airport cost/kilometer
Initial cost	2,107,200
Annual maintenance	42,144
User delay cost	63,216
Future cost	1,162,090
NPV	**3,269,290**

Table 5: NPV of the Bio-Concrete Rigid Pavement.

Cost activity	Airport cost/kilometer
Initial cost	2,566,480
Annual maintenance	--
User delay cost	--
Future cost	--
NPV	**2,566,480**

The construction initial cost and the maintenance cost between the control and the bio-concrete rigid pavement mixture were illustrated as in Fig.7.

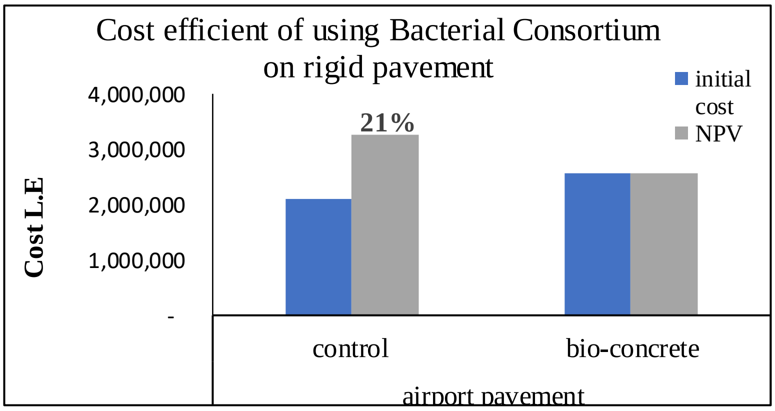

Fig.7: Cost efficient of using bacterial consortium on rigid pavement.

4. DISCUSSION

In our study, the results obtained from the experimental static loading test of the rigid pavement slabs recorded an increased the ultimate load of the bio-concrete slab by 23% more than the control ultimate load. There was also a significant reduction in the vertical deflection of the bio- concrete slab compared to the control slab.

The concrete stiffness increased in the bio-concrete slab more than in the control slab, with a better agreement with the significant increase in the mechanical properties. The results of load vs deflection are similar to the study conducted in the UK on wall panel cracks and monitored for 6 months [17]. Moreover, the strain of the interior loading case at the midpoint of the slab had a very small effect on the corner region of the control and the bio-concrete due to the stiffness of the concrete.

The cracked tensile stress and deflection were calculated according to the experimental ultimate load, giving the values of (4.10 Mpa, 4.53 Mpa) and ($21.9*10^{-2}$ mm, $16.98*10^{-2}$ mm) for the control and the bio-concrete slab pavement, respectively, which is in accordance with The wheel load cracking stress and deflection were calculated according to the Westergaard equation [16]. For aircraft type Boeing 747–400ER in Egypt, airport rigid pavement with a single axle single wheel load of 102 KN gives a value of 3.3 Mpa and 0.56 mm. Fully meeting the static strength requirements with loading test results. The tensile stresses computed for the experimental test are similar to the results of a study that looked into the maximum tensile stresses in concrete slabs for airport slabs using the finite element (FE) method. The maximum tensile stress increased as the thickness of the slab decreased [18].

In addition to the major attention given to pavement projects and economic growth, the value of pavement projects is very massive, and not only the construction initial cost, but the maintenance cost also needs consideration [13]. The maintenance annual cost was estimated at 2% of the initial construction cost [19]; [20] and the user delay cost according to the closing of the road for maintenance was estimated at 3% for the airport user delay, from reference projects in Egypt. According to the central bank of Egypt's report, a discount rate of 8.75% was estimated [21]. The designed pavement life was 40 years. Walls and Smith [22] suggested an approach for economic evaluation of the construction of a rigid pavement due to the use of a bio-concrete alternative vs. a conventional rigid pavement. Life cycle cost analysis (LCCA) is basically a method based on principles of economic analysis to evaluate the overall long-term economic efficiency of competing alternative investment options [14]. Comparative cost estimates estimate the economic evaluation of the overall long-term economic efficiency. For the construction of rigid pavement, the total life cycle cost of the airport bio-concrete slabs had a reduction of 21% less than the control slab. The bio-concrete pavement strategy had significantly greater cost-effectiveness in the long term than control concrete pavement.

5. CONCLUSION

1) The bacterial consortium presented a promising technique for self-healing civil application.
2) Using a microbial agent in the rigid pavement enhances the ultimate load by 23% more than the control slab. There was also a reduction in the vertical deflection of 29% at the midpoint of the bio-concrete slab compared to the control slab.
3) The bio-concrete pavement considered no maintenance cost for crack repair.
4) The outcome of the economic analysis showed that the initial construction cost of the bio-concrete rigid pavement is greater than the control rigid pavement by 22%. On the basis of the life cycle cost, the bio-concrete airport rigid pavement were less than the control of 21%. So, from an economic perspective, bio-concrete pavement is the ideal alternative pavement to be used.

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