

The estimation of the cost design of bacteria-based self-healing concrete

Estimativa do custo de produção de concreto auto-regenerativo com adição de bactérias

Estimación del costo de la producción de hormigón auto-regenerativo con la adición de bacterias

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Ana Clara Alves Andrade

ORCID: <https://orcid.org/0000-0001-7281-0852>

Universidade do Estado de Minas Gerais, Brazil

E-mail: ana.alves.andrade@hotmail.com

Ricardo Luiz Perez Teixeira

ORCID: <https://orcid.org/0000-0003-2641-4036>

Universidade Federal de Itajubá, Brazil

E-mail: ricardo.lui@unifei.edu.br

Ladir Antônio da Silva Júnior

ORCID: <https://orcid.org/0000-0002-0193-7060>

Universidade do Estado de Minas Gerais, Brazil

E-mail: ladir@hotmail.com

Haroldo Lhou Hasegawa

ORCID: <https://orcid.org/0000-0003-2986-3910>

Universidade Tecnológica Federal do Paraná, Brazil

E-mail: haroldohasegawa@utfpr.edu.br

Leonardo Lúcio de Araújo Gouveia

ORCID: <https://orcid.org/0000-0001-9387-2112>

Universidade do Estado de Minas Gerais, Brazil

E-mail: leonardo.gouveia.llag@gmail.com

Abstract

This research aims to estimate the design costs of implementing the bioconcrete samples suitable for structural purposes. The bioconcrete samples were produced by adding specific bacteria, *Sporosarcina pasteurii*. The specimens were submitted to tests of resistance to axial compression according to ABNT NBR 5739 under water-curing periods of 7, 14, and 28 days. To the implementation of this research, it was necessary execution of some stages: bibliographic research, and the providing of better visualization of the theme. The initial acquisition of bacteria, then the cultivation of bacteria to incorporate in the concrete. The third stage was laboratory tests to analyze the new concrete and make reports and data tabulation. The early costs results are encouraging further study.

Keywords: Aggregates used in concrete; Bacteria for the regeneration of concrete; Estimative of the design costs of implementing the bioconcrete; Regeneration of concretes.

Resumo

Este trabalho de pesquisa tem como objetivo a estimação dos custos de produção de bioconcreto para fins estruturais. As amostras de bioconcreto foram produzidas pela adição de bactéria específica, *Sporosarcina pasteurii*. Os provectos de bioconcreto produzidos foram submetidos ao ensaio de resistência à compressão axial, de acordo com a ABNT NBR 5739, em períodos de cura com água de 7, 14 e 28 dias. A sequência de execução deste trabalhou se inicia com a pesquisa bibliográfica, seguida da aquisição de bactéria específica e, numa segunda etapa, pelo cultivo dessas bactérias para serem incorporadas no concreto. A terceira etapa corresponde à realização de testes laboratoriais para análise do novo concreto e para verificação das propriedades do novo concreto. Os resultados iniciais de custos de produção obtidos são animadores e impulsionam a continuação do estudo em busca de respostas ainda mais aprofundadas e benéficas ao setor da construção civil.

Palavras-chave: Agregados utilizados em concreto; Bactérias para a regeneração de concreto; Estimativa dos custos de produção de bioconcreto; Regeneração de concreto.

Resumen

Esta pesquisa tiene como objetivo estimar los costos de la producción de bio-hormigón adecuadas para fines estructurales. Las probetas de hormigón de bio-hormigón se produjeron mediante la adición de bacterias específicas, *Sporosarcina pasteurii*. Las probetas fueron sometidos a ensayos de laboratorio de resistencia a la compresión uniaxial según ABNT NBR 5739, con diferentes periodos de curado, 3, 7 y 28 días. Para la implementación de esta investigación, fue necesaria la ejecución de algunas etapas: la investigación bibliográfica, y el suministro de una mejor visualización del tema. La adquisición inicial de bacterias, a continuación, el cultivo de bacterias para

incorporar en el hormigón. La tercera etapa fueron los ensayos de laboratorio para analizar el nuevo hormigón y hacer informes y tabulación de datos. Los resultados iniciales de los costos obtenidos son alentadores y impulsan el desarrollo de nuevos estudios en busca de respuestas aún más profundas y beneficiosas para el sector de la construcción.

Palabras clave: Agregados utilizados en hormigón; Bacterias para la regeneración de hormigón; Estimación de los costos de proyecto de bio-hormigón; Regeneración de hormigón.

1. Introduction

The construction sector is one of the main responsible for economic and social growth in a country. Attentive to that, researchers all over the world are constantly looking for innovative technologies to apply in this sector (Andre *et al.*, 2021; Andrade *et al.*, 2021; Fernandes *et al.*, 2017; Ferreira *et al.*, 2017). Concrete is one of the most used materials in the world, because of its technical features, properties, economic viability, and formability, making it useful for various purposes, especially in construction as shown by Kadapure (2020). However, concrete has a fragile mechanical behavior. When applied in constructions, concrete suffers tensions that over time damages it in diverse ways, according to Algaifi *et al.* (2018) and Ivanov and Stabnikov (2019). Fissures and disintegration in the concrete are the most common pathologies that can occur due to several factors, such as failures during the performance process, external factors, and excessive fine content, which are catalyzed by aggressive environments. Although, the main coefficient of degradation is directly associated with water action, which, by capillarity, ends up infiltrating the concrete, accelerating its degradation, and causing losses of material and economic resources to manage the problems, as mentioned in Berenguer *et al.* (2016). Therefore, aiming to improve concrete life and to avoid such fissures and cracks, distinct types of additives based on organic material can be used in its material composition. In the last years, research on the utilization of bacteria as an additive to the concrete composition has increased, since these microorganisms allow for the stagnation of cracks, regenerating the concrete, avoiding, or postponing maintenance and bringing economic advantages, as mentioned by Zhang *et al.* (2019). This technique is known as “bioconcrete.”

The first studies that were successful in producing the bioconcrete, which was created using bacteria found in alkaline lakes near volcanoes on the European continent. The production of the concrete from the mixture of bacteria that feeds on calcium lactate, releasing CaCO_3 (calcium carbonate) in the process, brings to concrete the ability to restore fissures.

Therefore, this research of producing bioconcrete is justified by the identification of the bacteria found in Brazil's karstic region that can produce satisfactory results, such as the bacteria *Sporosarcina pasteurii*, in eliminating pathologies in concrete.

2. Theoretical Reference

Due to the constant tension exposure, moves, vibrations, and weather actions, the concrete ends up suffering degradation, which appears in the form of fissures, as mentioned in Ferreira and Jalali (2001). Those fissures could be caused by several factors, whether intrinsic or extrinsic causes. According to de Souza *et al.* (1998) the intrinsic causes are these, in which the structure deteriorating process is inherent, in other words, the ones caused by materials and structural part, during the execution or employment parts, due to human mistake or external actions. The extrinsic causes can be classified with those that occur despite the structure itself, as well as the materials composition, like concrete and steel, or execution errors.

To avoid fissures, the use of additives is increasingly common. The additives are chemical substances added in small portions in mortars or concretes, during the mixing, as reported by Djeison and Seidler (2013). However, the additives do not have the power to prevent the appearance of fissures, but to slow them down. Yet, the Dutch scientist, Henk Jonkers, researched about the regeneration of cracks, incorporating a colony of limestone generating bacteria in the concrete, based on Abreu *et al.* (2016). This research, using a microorganism of the species *Bacillus pseudofirmus* or *Sporosarcina pasteurii*,

which can be found in the highly alkaline lakes near volcanoes, was successful in the process of regeneration of such pathology, as stated by Omoregie *et al.* (2018). These microorganisms can lie dormant for up to two hundred years and start to work when coming in contact with water, producing limestone. The limestone produced can regenerate existing fissures, if it is less than 8 millimeters wide, as mentioned in Nery *et al.* (2019).

This added microorganism material became known as bioconcrete and self-healing concrete. To keep the bacteria dormant until the pathology occurs, they are encapsulated in small particles of expandable clay with calcium lactate, as reported by Belie (2018). Therefore, when the crack occurs, the capsules are deteriorated, so the bacteria meet water and start to feed on the calcium lactate, producing the limestone and regenerating the fissures, as mentioned earlier on Leite *et al.* (2019a).

3. Methodology

This research is of a quantitative exploratory nature and can provides conditions for engineering students to develop self-learning interpersonal skills, as achieved using the Project Based Learning (Teixeira *et al.*, 2020a; Teixeira *et al.*, 2020b). It followed some steps in this direction, as described Pereira *et al.*, 2018 and others (Estrela, 2018; Severino, 2018; Yin, 2015; Ludke, 2013; Koche, 2011). First, we did the bibliographic research that allowed a better view of the theme and information, in addition to taking the study to the next stages. After that, the bacteria *Sporosarcina pasteurii* was acquired to incorporate in the concrete. The bacteria were cultured as recommended by the supplier provider Fundação André Tosello - Coleção de Culturas Tropical. The third step was the realization of specimens, already including bacteria in the mixture. The mixings of the produced concrete, SAMPLE_I, SAMPLE_II, and SAMPLE_III, are described in Table 1. The next stage was to perform the necessary laboratory tests to verify the properties of the produced bioconcrete. Then, reports and tabulation of the data obtained were made, providing better visualization of the results, as reported by Leite *et al.* (2019a).

The cultured bacteria were introduced in the concrete, in SAMPLE_II and SAMPLE_III, according to Table 1, for the realization of specimens by agreeing with ABNT NBR 7680-1 139 (2015a). The concrete curing of all the Samples happened according to NBR 5738 139 (2015b). In this stage, cylindrical specimens were made by different traits, through the usage of the bacteria *Sporosarcina pasteurii*. All the specimens were evaluated by the axial compression test and permeability test.

Table 1: Probably composition of lime hydrated.

Type of material	SAMPLE_I (kg)	SAMPLE_II (kg)	SAMPLE_III (kg)
Cement	9.73	9.73	1.7
Artificial sand	6.28	6.28	1.1
Natural sand	9.43	9.43	1.65
Clay	3.42	3.42	0.6
Gravel 1	11.8	11.8	2.07
Additive	0.045	0.045	0.008
Water	3.89	3.89	0.68
Calcium lactate	-	0.048	0.0085
Bacteria	-	0.005 g	0.005 g

Source: Adapted from Leite *et al.* (2019b).

The axial compression test was performed according to ABNT NBR 5739 139 (2018), with 7, 14, and 28 days of concrete curing. At least two compression tests made for each type of concrete produced according to Table 1.

The permeability coefficient test was performed according to ABNT NBR 10786 139 (2013). At least two compression tests were made for each type of concrete produced, according to Table 1. These tests were made after 28 days of concrete curing.

4. Results and Discussion

The maintenance and repair costs in concrete structures can easily exceed a value of 40% concerning the cost of execution. As shown in the bibliographic revision, it all starts with the appearance of fissures and water infiltration. Therefore, avoiding this type of pathology can bring significant gains in maintenance and repair.

This condition is reinforced by the studies of Sitter (1983), which proved that the cost of repairing a structure varies depending on a geometric progression based on the stage at which the repair is performed. That is why the sooner a fissure is detected and corrected, the more efficient will be the intervention for the structure, and lower will be the costs.

For this, it is necessary to analyze the source and the ways this pathology manifests. A fissure can be analyzed according to its stability and can be classified as passive, when what caused it has been removed, or active when the cause continues to exist. Repair or maintenance is accomplished according to the classification of the crack type.

Based on the studies cited above, it is possible to note the necessity for repair in concrete structures after the appearance of this type of pathology. It must be quick and effective, trying to avoid reappearing or worsening the current situation, affecting the durability of the construction.

Adding the bacteria to the concrete, the structure maintenance will have its cost reduced in both labor and material work, since the bacteria play the role of repairs, bringing economic and sustainable benefit, and preventing the propagation of these fissures.

4.1 Materials Costs to Produce Specimens

After extensive research on Brazilian organizations that sell the bacterium *Sporosarcina pasteurii*, we found the unit value of USD \$ 112.10. Through the cultivation of the bacteria colonies, we produced the concrete and the specimens. Based on this, the price to produce specimens with the bacteria (SAMPLE_II) or without it (SAMPLE_I) was stipulated.

By Tables 1 and 2, the total production cost per kg of SAMPLE_I and SAMPLE_II specimens can be estimated using the number of materials consumed and their prices. Considering the cost of water consumption as negligible in the calculations, by using Table 2, the cost to produce the amount of 34.428kg of concrete SAMPLE_II is USD \$ 9.55, a ratio of USD \$ 0.28 per kg of SAMPLE_II concrete produced. To estimate the increase of value in SAMPLE_II concrete with the addition of bacteria, it was considered that for 1.0 kg produced, 0.005g of cultivating bacteria will be consumed. The total estimated cost for the bacteria cultivation process, using 0.450kg of bacteria, was around USD \$ 796.00. The total price of bacteria and their culture was around USD \$ 908.10. Since only 0.005g of bacteria were used per kg of SAMPLE_II, the increased cost was approximately USD \$0.01 per kg of SAMPLE_II concrete, ending the cost of production with USD \$ 0.29 per kg. The concrete produced without the bacteria, SAMPLE_I, costs USD 0.16 per kg of concrete produced.

Table 2: Concrete cost production SAMPLE_II.

Material	Unit Price (USD\$/kg)	Quantity (kg)	Amount (USD\$)
Portland Cement CP II-32	0.09	9.73	0.90
Commercial sand	0.03	9.43	0.32
Commercial gravel	0.03	11.8	0.40
Clay	1.39	3.42	4.75
Calcium lactate	66.36	0.048	3.18
Total SAMPLE_II	0.28	34.428	9.55

Source: Authors' data.

Comparing the cost of producing SAMPLE_I with SAMPLE_II, per kg of concrete produced, there is an increase of 81% on the production price. This cost increase could make the use of SAMPLE_II on a large scale unfeasible. However, concrete such as SAMPLE_II can have an impact on reducing maintenance costs for fissures in concrete structures, as well as highly tension regions. These regions can be better treated using self-regenerating concrete with bacteria, such as SAMPLE_II.

4.2 Saturated and Dry Mass

For Table 3, two weighings were performed: one 15:50h and other 16:50h. However, there was no considerable variation in the first numbers acquired, as recorded in the table. After the curing period, the saturated masses of the specimens were checked and were kept in an oven until the value of the masses stabilized. The results are shown in Table 3.

Table 3: Mass ratio.

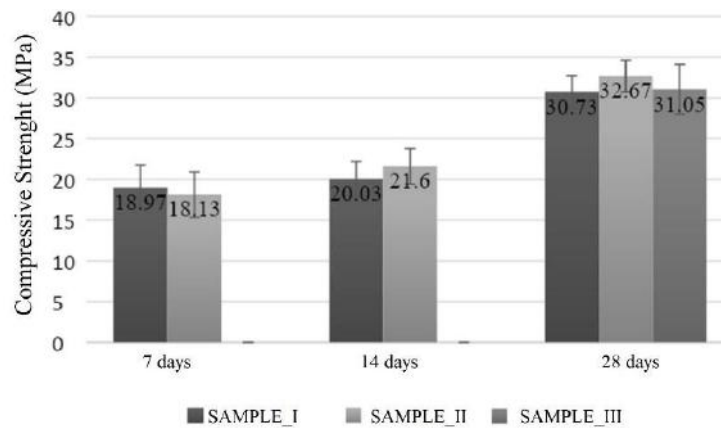
SPECIMENS	SATURATED MASS (KG)	DRY MASS (KG)	VARIATION (%)
SAMPLE_I 1	3.06	2.90	5.52
SAMPLE_I 2	3.20	3.04	5.26
SAMPLE_I 3	3.17	3.03	4.62
SAMPLE_II 1	3.18	3.04	4.60
SAMPLE_II 2	3.29	3.15	4.44
SAMPLE_II 3	3.17	3.02	4.96
SAMPLE_III 1	3.26	3.11	4.82
SAMPLE_III 2	3.23	3.10	4.20

Source: Adapted from Leite *et al.* (2019b).

4.3 Resistance to Axial Compression

The specimens were submitted to tests of resistance to axial compression according to ABNT NBR 5739 139 (2018) at 7, 14, and 28 days of concrete cure, Figure 1. From the calculation of the average values, it was possible to observe that SAMPLE_I specimens showed an average resistance of 4.63% higher than SAMPLE_II after 7 days. When comparing the resistance for 28 days, however, the SAMPLE_II specimens obtained a value of 7.84% higher than SAMPLE_I (Figure 1). On the 28th day of cure, compression tests were performed with the two SAMPLE_III specimens which presented an average resistance 1,04% higher than the SAMPLE_I and 4.96% lower than the SAMPLE_II, as shown in Figure 1.

Figure 1: Results of the concrete compressive strength test.



Source: Adapted from Leite *et al.* (2019b).

The axial compression strength tests were performed at 28 days with the specimens moistened, Table 4. All the results obtained were higher than the values found in the tests with the dry specimens at 28 days, except SAMPLE_I 2, which presented a 12.24% lower resistance, as shown in Table 4.

Table 4: Compressive strength after humidification.

Specimens	Fck in 28 days (MPa)	Fck in 21 days (MPa)	Variation Fck 21 days/ Fck 28 days (%)
SAMPLE_I (1)	33.50	33.60	+0.30%
SAMPLE_I (2)	29.40	25.80	-12.24%
SAMPLE_I (3)	29.30	30.70	+4.79%
SAMPLE_II (1)	32.00	34.50	+7.81%
SAMPLE_II (2)	33.10	33.80	+2.11%
SAMPLE_II (3)	32.90	33.50	+1.82%
SAMPLE III (1)-	33.20	34.10	+2.71%
SAMPLE III (2)	28.90	31.10	+7.61%

Source: Adapted from Leite *et al.* (2019a).

According to Tables 3 and 4, all the specimens of the concrete produced (SAMPLE_I, SAMPLE_II, and SAMPLE_III) reached the minimum compression strength of 20 MPa after 28 days of concrete curing. This is the minimum requirement for its use in concrete structures established by ABNT NBR 6118 139 (2014).

5. Final Considerations

After the results obtained with the mechanical tests of resistance to axial compression in the specimens, the bacteria presence (in SAMPLE_II and SAMPLE_III) slightly increases the mechanical properties of concrete at 14 and 28 days of curing, when compared to the concrete without bacteria (SAMPLE_I). As the traces used to produce the bioconcrete, all of them produced and evaluated, reached the minimum compression resistance of 20 MPa after 28 days of concrete cure, established by ABNT NBR 6118 139 (2014), for the use of concrete in structural projects.

In terms of production costs, the SAMPLE_II with bacteria, which has better mechanical performance, is about 81% more expensive than SAMPLE_I, specimens without bacteria. This increase in the cost of SAMPLE_II bioconcrete could

prevent its use on a large scale. However, the bioconcrete, like SAM-PLE_II, can have an impact in reducing maintenance costs for concrete structures fissures over time, as well as highly intense stressed regions. These regions can have better use when using self-regenerating concrete, such as SAMPLE_II.

The research has brought encouraging results that encourage the further development of the study, research, and production of bioconcrete, by using bacteria found in national soil, but with similar characteristics to the one already used. Since the concrete is used on a large scale and is essential in all constructions, the use of microorganisms in addition to being a solution for fissures is an ally of sustainability, as it minimizes future repairs.

During this research, it was noticed the lack of research and studies aimed to solve the problem of the production of bioconcrete in Brazil.

For early future bio-based self-healing concrete applications, studies, research, and articles, several critical studies must be addressed to reduce experimental costs, time, and simulate the activity of bacteria in hardened concrete for a long period of time.

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