JOURNAL OF STRUCTURAL MONITORING AND BUILT ENVIRONMENT
e-ISSN: 2821-3432

Vol. 5 No. 2 (2025) 75-82
https://publisher.uthm.edu.my/ojs/index.php/jsmbe

JSMBE

Role of Nano Materials in Improving Compressive Strength of Bio-Foamed Concrete Bricks: Towards Green Concrete Production

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DOI: https://doi.org/10.30880/jsmbe.2025.05.02.010

Article Info

Received: 14 August 2025
Accepted: 8 December 2025
Available online: 31 December 2025

Keywords

Bio-foamed concrete, nanomaterials, *Bacillus tequilensis*, compressive strength, sustainability, self-healing concrete

Abstract

This study explores the enhancement of compressive strength in bio-foamed concrete through the integration of nanomaterials such as nano rice husk ash (NRHA), nano eggshell powder (NESP), nano coffee grounds (NUCG) as cement replacements, alongside the bacterial agent. By utilizing agricultural and food waste, this research aims to investigate the compressive strength of bio-foamed concrete brick (B-FCB) at 28 days using screening stage method. The nano materials enhanced the compressive strength of the B-FCB. The optimal replacement materials for the maximum compressive strength were 1% NRHA, 1% NUCG, and 5% NESP, combined with *Bacillus tequilensis* at a concentration of 3×10^5 cells/ml. The empirical modelling indicated that *Bacillus tequilensis* and ESP have a significant effect on the compressive strength of B-FCB. Incorporating nanosized agro-industrial wastes into B-FCB improves mechanical performance while reducing the environmental impact of accumulated wastes.

1. Introduction

1.1 The Sustainability Crisis in Concrete Production

Concrete remains indispensable in global infrastructure due to its strength, availability, and versatility. However, the environmental cost of its production, particularly that of cement, poses significant challenges [1]. Cement manufacturing alone is responsible for nearly 8% of global carbon dioxide (CO_2) emissions, making it a leading industrial contributor to climate change. As urbanization accelerates and infrastructure demands continue to expand, the need for sustainable construction materials has become increasingly critical [2]. Addressing these environmental challenges necessitates a fundamental transformation in concrete formulation, particularly through the incorporation of eco-efficient, low-carbon alternatives.

Foamed concrete, a lightweight construction material produced by incorporating stable air bubbles into a cementitious matrix, offers various engineering advantages such as reduced dead load, sound insulation, and fire resistance [3]. Although foamed concrete offers advantages like thermal and sound insulation, it typically suffers from reduced compressive strength, particularly at low densities [4]. The compressive strength of foamed concrete is often compromised by its cellular structure, particularly at lower densities below 1000 kg/m^3 [5] . This trade-off between weight and structural performance limits its application in load-bearing systems [6]. This strength limitation has motivated researchers to explore admixtures that could reinforce the internal matrix without compromising the lightweight nature of the material.

Previous studies have evaluated the benefits of nanomaterials in concrete in various construction applications [7][8] [9]. According to previous studies related to bio foamed concrete, [10] reported that the compressive strength of mortar was maintained when ESP replacement reached up to 10% in a masonry brick. [11] concluded that replacing cement with 5% RHA and sand with 5% ESP with 3×10^5 Bacillus tequilensis significantly improved the compressive strength of B-FCB. Moreover, the performance of these integrated systems has not been optimized statistically. The integration of nanomaterials and microbial healing mechanisms presents a novel, synergistic approach for enhancing the mechanical and environmental performance of lightweight concretes [12].

This research aims to address these limitations by formulating and optimizing a novel bio-foamed concrete mixture incorporating Bacillus tequilensis and NRHA, NESP, and NUCG. A screening stage for the experiment design was used to determine the optimal combinations of ingredients that yield the maximum compressive strength, while SEM and XRD were employed to analyze the nanostructural enhancements. This research was conducted to optimize the compressive strength of B-FCB using nano waste materials, namely UGC, RHA, and ESP. The study contributes to the growing field of green construction materials that is environmentally conscious and structurally effective.

2. Methodology

2.1 Primary Materials of Foamed Concrete Brick Mix

Ordinary Portland Cement (OPC) was used as the primary binder in the mix, meeting the standards outlined by BS 197-1:2000. The sand was tested for grading according to BS 882-1992 to ensure it met the required specifications for concrete mixtures. The particle size distribution of the fine aggregates was verified using a sieve analysis, in which a 1 mm mesh sieve was included to ensure proper control of the particle size range. A synthetic foaming agent was added to the mix to achieve lightweight properties. The agent was diluted with water at a 1:20 ratio and to generate foam with a target density of 65 kg/m^3, following ASTM C796 standard.

2.2 Replacement Materials

Nano rice husk ash (NRHA), nano used coffee grounds (NUCG) and Nano eggshell powder (NESP) have been identified as viable supplementary materials that enhance the compressive strength of concrete through pozzolanic activity, filler effect, and matrix densification. Their particle sizes were refined via grinding and milling to increase their reactivity and strength contribution. The physical properties of nanomaterials are shown in Table 1. The proportions of each material used in the mix varied according to the experimental design. The chemical composition and role of the nano materials are as follows:

- Nano Rice Husk Ash (NRHA): Rich in amorphous silica, this material improves pozzolanic activity and strengthens the cement matrix through secondary C-S-H gel formation [13].
- Nano Used Coffee Grounds (NUCG): High in potassium and has very low ratio of silica, UCG enhances particle packing, though it must be carefully dosed to avoid strength loss due to residual organic matter [14]
- Eggshell Powder (NESP): Composed primarily of calcium oxide, ESP promotes early hydration and supports bacterial-induced calcite formation [9].

Table 1 *Physical properties of nanomaterials*

Material	Source & Processing	Calcination	Ball Milling	Particle Size	Cement Replacement (%)
Used Coffee Ground (UCG)	Collected from cafes/households → cleaned → air-dried	700°C for 5 hours	30 hours	~28 nm	1% – 3%
Rice Husk Ash (RHA)	Rice husks burned in controlled furnace	700°C for 5 hours	30 hours	~28 nm	1% – 5%
Eggshell Powder (ESP)	Discarded eggshells → cleaned and dried	700°C for 5 hours	30 hours	~28 nm	1% – 5%
Bacillus tequilensi	Freeze-dried bacterial culture at −40°C under 0.133 mbar pressure	-	Not applicable	Powder form	3×10^5 – 3×10^7 cells/mL

2.3 Bacteria Preparation

The Bacillus tequilensis bacteria were cultured in a controlled environment. The bacterial solution was prepared in nutrient broth and inoculated at varying concentrations (3×10^5 to 3×10^7 cells/ml), based on effectiveness for self-healing at these concentrations [15]. The bacteria was added to the mix during the final stages of preparation to ensure survival and activity during the curing process.

3. Design of Bio Concrete Mixtures

3.1 Mix Proportions

The design of foamed concrete brick was based on ratio method. The weight of cement to sand was 1:1.35 according to ACI 523.3R and water-to-cement (w/c) ratio of 0.5 [16]. The fresh density of mix was achieved by adjusting the foaming agent to reach a density of 1800 kg/m^3.

The statistical analysis of the factors influencing the compressive strength in B-FCB was evaluated by analyzing the results of 13 runs. A Screening stage for the experimental design was used to evaluate the effects of the variables on the compressive strength. The factors considered were the dosages of nanomaterials and bacteria concentration based on the previous studies. Table 2 presents 13 runs the mix proportions of B-FCB containing nanomaterials. In line with the screening stage, this study considered four variables as input factors: Bacteria (cell/ml), NUCG, NRHA and NESP as cement replacements. The mixtures were developed with various combinations of the three levels for the factors to optimize the compressive strength of B-FCB at 28 days. Analysis of variance (ANOVA) was utilized to assess the adequacy of model predictions and the effect of factors on the compressive strength.

Table 2 *Mix proportions of B-FCB containing nanomaterials*

Run No	Density (Kg/m3)	Cement (Kg/m3)	Sand (Kg/m3)	Water (L/m3)	Bacteria (Cell/ml)	NUCG	NRHA	NESP
Control	1800	766.00	1034.00	383	0	0	0	0
1	1800	704.72	982.30	383	3 x 106	3	5	5
2	1800	750.68	1023.66	383	3 x 106	1	1	1
3	1800	712.38	1023.66	383	3 x 107	2	5	1
4	1800	743.02	982.30	383	3 x 105	2	1	5
5	1800	720.04	982.30	383	3 x 107	3	3	5
6	1800	735.36	1023.66	383	3 x 105	1	3	1
7	1800	720.04	1002.98	383	3 x 107	1	5	3
8	1800	735.36	1002.98	383	3 x 105	3	1	3
9	1800	750.68	982.30	383	3 x 107	1	1	5
10	1800	704.72	1023.66	383	3 x 105	3	5	1
11	1800	735.36	1023.66	383	3 x 107	3	1	1
12	1800	720.04	982.30	383	3 x 105	1	5	5
13	1800	727.70	1002.98	383	3 x 106	2	3	3

3.2 Sample Preparation and Curing

Samples were prepared using a mechanical mixer to ensure homogeneous distribution of the materials. After mixing, concrete was poured into standard molds (216 mm x 100 mm x 75 mm) and compacted using hand move shake. The samples were then cured in a controlled environment with a normal temperature for 28 days, which aligns with standard curing protocols for concrete testing.

3.3 Testing Methods

Three foamed concrete brick samples, each measuring 215 × 100 × 65 mm, were prepared for each run to measure the compressive strength at 28 days. The test was conducted according to BS 12390-3:2002 using compression testing machine with 3000 kN capacity. The average compressive strength of three samples was taken for each run. The compressive strength results for 13 runs.

3.4 Statistical Analysis and Optimization

To optimize the mix proportions and ensure that the materials interact effectively, a screening stage was employed. This statistical technique helps model and analyze the relationships between the input variables and the compressive strength. The optimization process helped identify the ideal blend of nanomaterials and bacterial concentration to maximize compressive strength.

4. Results and Discussion

4.1 Compressive Strength Results

The compressive strength results of control and B-FCB and samplesat 28 days are shown in Figure 1. The B-FCB containing NRHA, NGSP and NUCG with *B.tequilensis* improved the compressive strength of foamed concrete bricks. The best-performing mix was Run 12, which included 1% UCG, 5% RHA, 5% ESP, and of 3×10^5 cells/ml of bacterial concentration, achieved a compressive strength of 28.6 MPa at 28 days. This is attributed to hydration acceleration of NEGP, pozzolanic activity of NRHA and pores-filling effect. The addition of RHA enhances the compressive strength of B-FCB by forming dense calcium silicate hydrate (C-S-H) [17]. The bacterial-augmented mix consistently outperformed the control sample across all curing periods, validating the self-healing contribution of *Bacillus tequilensis* [18]. Incorporating *B.tequilensis* in foamed concrete bricks helps in forming $CaCO_3$ which fills the concrete porosity.

Table 3 *Dry density and compressive Strength values of control and B-FCB samples*

Run No	Dry Density (kg/m3)	Compressive strength (Mpa)
Control	1266.56	19.2
1	1275.16	23.8
2	1288.91	24.6
3	1328.27	25.5
4	1273.48	27.5
5	1259.09	21.8
6	1261.30	25.0
7	1283.54	22.9
8	1314.16	24.5
9	1290.56	27.0
10	1255.99	21.0
11	1297.88	20.0
12	1339.41	28.6
13	1365.35	24.9

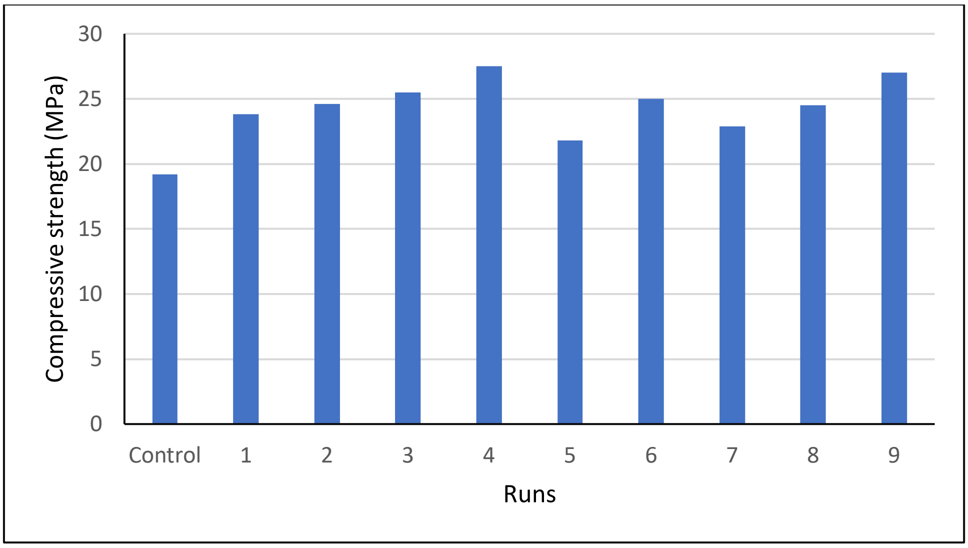

Fig. 1 *Compressive Strength of foam concrete bricks samples*

4.2 ANOVA and Pareto Results

Table 4 displays the effects of B.tequilensis concentration, NUCG, NRHA and NESP on the compressive strength of B-FCB at 28 days. Overall, the model was statistically significant with P-value of 0.028, which is less than 0.05. NUCG was the most significant factor to compressive strength of B-FCB with P-value of 0.002. B.tequilensis and NRHA are an insignificant factors with P-values of 0.112 and 0.742, respectively, which are more than 0.05.

Table 4 *ANOVA analysis of screening stage method of compressive strength of B-FCB*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	53.94	13.48	4.85	0.028
Linear	4	53.94	13.48	4.85	0.028
B	1	8.84	8.84	3.18	0.112
NUCG	1	28.90	28.90	10.40	0.012
NRHA	1	0.324	0.324	0.12	0.742
NESP	1	15.88	15.88	5.71	0.044
Error	8	22.23	2.78		
Total	12	76.17			

The pareto chart illustrates the standardized effects of each input factor on compressive strength as seen Figure 2. It clarifies that NUCG (B) and NESP (D) exceeded the critical t-value threshold of 2.306, indicating that their influence on compressive strength is statistically significant at the 95% confidence level. Bacterial concentration (A) and NRHA (C) also showed slightly lower, contribution to the compressive strength. Interestingly, while the NUCG (B) factor had the highest standardized effect on compressive strength and was statistically significant, it may exhibit a non-linear behavior, potentially reducing effectiveness at higher levels, aligning with previous findings that excessive UCG can negatively affect matrix bonding due to organic residue interference [19].

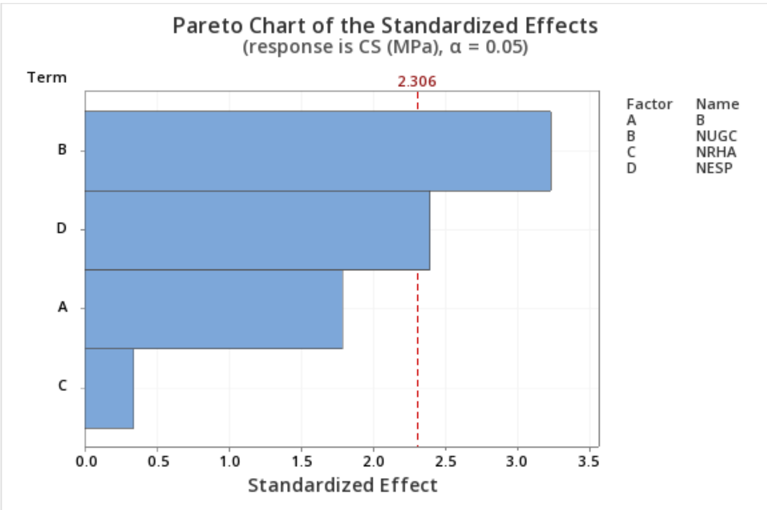

Fig. 2 *Pareto chart of standardized effects*

The normal probability plot of screening stage was conducted to ensure of the accuracy of the empirical model. The accuracy should be 95% and above and the error less than 5%. Figure 3 shows the probability plot of compressive strength for 11 runs, illustrating the distribution and conformity of the data. The data points for the plots of predicted line locates between lower and upper boundaries and align closely with the fitted line, indicating a good fit. The predicted value showed the P-Value of 0.887 which is > 0.05, provides a strong indication of the quality of the response model.

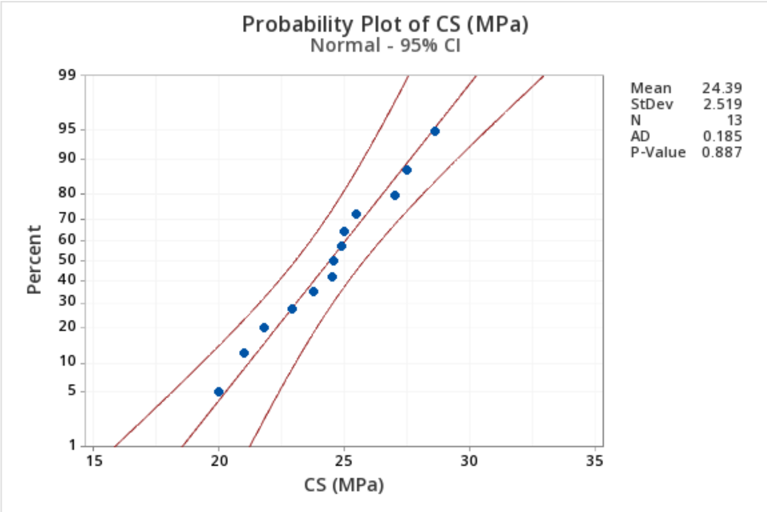

Fig. 3 *Normal probability plots of the compressive strength of B-FCB incorporating RHA and CBA*

As shown in Figure 4, the response plot identified the combinations of variables that yield the maximum compressive strength. The optimum mix which comprises 1% NUCG, 1% NRHA, 5% NESP, and 3×105 cells/ml of bacterial concentration indicates the maximum compressive strength of 28.47 MPa, with a desirability value of 0.98. This high desirability score confirms the model's reliability in predicting optimal results based on factorial input levels.

The mathematical model was developed during the optimization analysis to determine the optimal ratio of the compressive strength. The empirical model was developed for the compressive strength from ANOVA via regression analysis as functions of RHA, CBA and *B.tequilensis* as shown in equation (1).

$$CS\ (MPa) = 31.81 - 0.940\ B - 1.700\ NUGC - 0.090\ NRHA + 0.630\ NESP \quad (1)$$

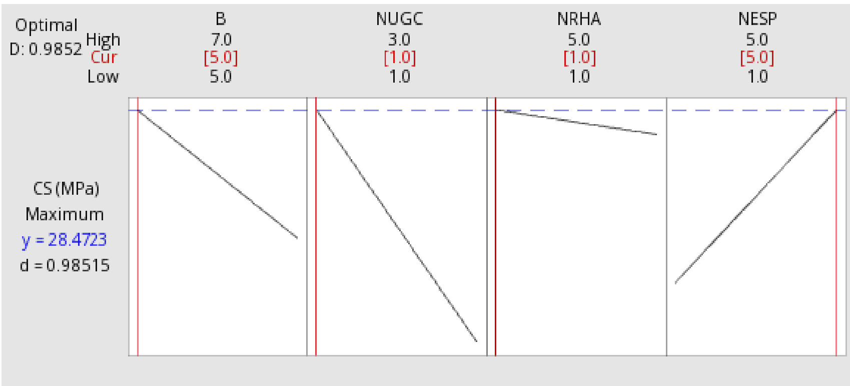

Fig. 4 *Optimizing factors for the compressive strength*

5. Conclusion

This study investigated the combined effects of nano-waste materials and Bacillus tequilensis on the compressive strength of B-FCB, with the broader aim of promoting sustainable bio-foamed concrete. Through the screening stage, the optimal mixture was identified of comprising 1% NUCG, 5% NRHA, 5% NESP, and a bacterial concentration of 3×105 cells/ml. This configuration produced a peak compressive strength of 28.6 MPa, confirming the synergistic interaction of nano-waste and microbial agents in enhancing structural integrity. The use of agro-industrial waste (RHA, ESP, UCG) not only reduces environmental burden but also enhances pozzolanic activity and particle packing. The biological self-healing mechanism provided by Bacillus tequilensis further extends the lifespan and durability of the material, offering a green alternative to conventional concrete.

In conclusion, the integration of nanomaterials and microbial technology into foamed concrete presents a viable and scalable path towards eco-efficient construction practices. The findings underscore the dual benefit of incorporating nano-waste and microbial agents: mechanical enhancement and environmental responsibility. Using agro-waste byproducts like RHA, UCG and ESP helps reduce cement demand, and bacterial self-healing mechanisms extend service life by minimizing crack propagation. The optimized mix can be used for lightweight panels, or insulating walls. The study paves the way for future industrial-scale applications of hybrid nano-bio concrete systems.

Acknowledgement

This research was supported by the MOHE, supported by Universiti Tun Hussien Onn Malaysia (UTHM), Tier 1 grant (Q335), and MDR (VOT No. H486 & H487).

Conflict of Interest

The authors declare that is no conflict of interest regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation

References

[1] M. A. Mansour, M. H. Ismail, M. H. Wan Ibrahim, N. Mokhtar, and A. F. Alshalif, "Optimizing compressive strength of concrete incorporating metakaolin and palm oil fuel ash," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1453, no. 1, 2025, doi: 10.1088/1755-1315/1453/1/012016.

[2] A. Adesina, "Recent advances in the concrete industry to reduce its carbon dioxide emissions," *Environ. Challenges*, vol. 1, no. October, p. 100004, 2020, doi: 10.1016/j.envc.2020.100004.

[3] A. Al-Sibahy and R. Edwards, "Effect of admixtures on the behaviour of lightweight concretes," *Proc. Inst. Civ. Eng. - Struct. Build.*, vol. 171, no. 3, pp. 253–262, Mar. 2018, doi: 10.1680/jstbu.15.00044.

[4] C. Umbach, A. Wetzel, and B. Middendorf, "Durability properties of ultra-high performance lightweight concrete (Uhplc) with expanded glass," *Materials (Basel).*, vol. 14, no. 19, 2021, doi: 10.3390/ma14195817.

[5] R. Kumar, R. Lakhani, and P. Tomar, *A simple novel mix design method and properties assessment of foamed concretes with limestone slurry waste*, vol. 171. Elsevier B.V., 2018.

[6] N. Mokhtar, M. A. Megat Johari, H. A. Tajarudin, A. A. Al-Gheethi, and H. A. Algaifi, "A sustainable enhancement of bio-cement using immobilised Bacillus sphaericus: Optimization, microstructural properties, and techno-economic analysis for a cleaner production of bio-cementitious mortars," *J. Clean. Prod.*, vol. 318, no. July, p. 128470, 2021, doi: 10.1016/j.jclepro.2021.128470.

[7] A. S. Faried, S. A. Mostafa, B. A. Tayeh, and T. A. Tawfik, "Mechanical and durability properties of ultra-high performance concrete incorporated with various nano waste materials under different curing conditions," *J. Build. Eng.*, vol. 43, no. December 2020, p. 102569, 2021, doi: 10.1016/j.jobe.2021.102569.

[8] S. A. Mostafa *et al.*, "Influence of nanoparticles from waste materials on mechanical properties, durability and microstructure of uhpc," *Materials (Basel).*, vol. 13, no. 20, pp. 1–22, 2020, doi: 10.3390/ma13204530.

[9] H. Hamada, B. Tayeh, F. Yahaya, K. Muthusamy, and A. Al-Attar, "Effects of nano-palm oil fuel ash and nano-eggshell powder on concrete," *Constr. Build. Mater.*, vol. 261, p. 119790, 2020, doi: 10.1016/j.conbuildmat.2020.119790.

[10] P. Murthi and K. Poongodi, "Investigation of the impact of eggshell powder blended mortar on brick masonry compressive strength," *Mater. Today Proc.*, no. xxxx, pp. 2–7, 2023, doi: 10.1016/j.matpr.2023.03.255.

[11] H. A. Y. Al-Shaeer *et al.*, "Innovative development of bio-foam concrete using rice husk ash, eggshell powder, and Bacillus tequilensis: Mechanical, durability, and microstructural performance," *J. Build. Eng.*, vol. 113, no. July, 2025, doi: 10.1016/j.jobe.2025.113934.

[12] M. Sadeghpour and M. Baradaran, "Effect of bacteria on the self-healing ability of fly ash concrete," *Constr. Build. Mater.*, vol. 364, no. April 2022, p. 129956, 2023, doi: 10.1016/j.conbuildmat.2022.129956.

[13] M. F. Adier and D. Silva, "Impact of Incorporating Rice Husk Ash (RHA) into Recycled Concrete Aggregates (RCA) on the Compressive and Flexural Strength of Concrete," *E3S Web of Conferences*, vol. 488. 2024, doi: 10.1051/e3sconf/202448803007.

[14] A. Arulrajah, T.-A. Kua, C. Phetchuay, S. Horpibulsuk, F. Mahghoolpilehrood, and M. M. Disfani, "Spent Coffee Grounds–Fly Ash Geopolymer Used as an Embankment Structural Fill Material," *J. Mater. Civ. Eng.*, vol. 28, no. 5, pp. 1–8, 2016, doi: 10.1061/(asce)mt.1943-5533.0001496.

[15] A. F. Alshalif, J. M. Irwan, N. Othman, A. A. Al-Gheethi, S. Shamsudin, and I. M. Nasser, "Optimisation of carbon dioxide sequestration into bio-foamed concrete bricks pores using Bacillus tequilensis," *J. CO2 Util.*, vol. 44, no. December 2020, p. 101412, 2021, doi: 10.1016/j.jcou.2020.101412.

[16] E. Muthu Kumar and K. Ramamurthy, "Effect of fineness and dosage of aluminium powder on the properties of moist-cured aerated concrete," *Construction and Building Materials*, vol. 95. pp. 486–496, 2015, doi: 10.1016/j.conbuildmat.2015.07.122.

[17] F. Ameri, P. Shoaei, N. Bahrami, M. Vaezi, and T. Ozbakkaloglu, "Optimum rice husk ash content and bacterial concentration in self-compacting concrete," *Constr. Build. Mater.*, vol. 222, pp. 796–813, 2019, doi: 10.1016/j.conbuildmat.2019.06.190.

[18] H. A. Algaifi *et al.*, "Bio-inspired self-healing of concrete cracks using new B. pseudomycoides species," *J. Mater. Res. Technol.*, vol. 12, pp. 967–981, 2021, doi: 10.1016/j.jmrt.2021.03.037.

[19] A. F. Alshalif, Y. M. Azril, J. M. Irwan, A. Mutafi, H. A. Y. Alshaeer, and S. J. S. Hakim, "The use of coffee waste in bio-foamed concrete brick (B-FCB) to reduce the penetration of carbon dioxide (CO 2) into concrete," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1347, no. 1, p. 012080, Jun. 2024, doi: 10.1088/1755-1315/1347/1/012080.