Effect of *Bacillus megaterium* bacteria on geopolymer concrete as self-healing agent in repairing cracks of bridge structure

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Abstract. Concrete production accounts for up to 10% of total global CO2 emissions, prompting the replacement of cement with environmentally friendly alternatives that have properties equivalent to conventional concrete, such as geopolymer concrete, which consists of a binder (fly ash) combined with an alkali activator (NaOH, Na_2SiO_3), filler or aggregate, water, and other additives. However, geopolymer concrete is not immune to cracking, so its necessary for self-healing technology using microorganisms such as Bacillus Megaterium bacteria which can survive inside concrete. The production of 15x30 cm test specimens began with bacterial inoculation, the crushing of test specimen waste into RCA, and the testing of material physical properties. The research results showed that the compressive strength was 30.35 MPa, while the compressive strength of geopolymer concrete and self-healing geopolymer concrete was 24.17 and 24.21 MPa, respectively. However, geopolymer concrete did not exhibit self-healing due to the 10M alkaline activator solution with a pH > 14. Although the compressive strength may exceed that of ordinary geopolymer concrete, the strong alkaline environment is not a suitable pH for Bacillus Megaterium bacteria.

1 Introduction

In Indonesia, cement consumption increased in 2024 and reached 65 million tons, with domestic consumption reaching around 13.6% or equivalent to 8.84 million tons. Its production results in the release of CO2 emissions proportional to the volume of cement produced [1], a significant carbon footprint accounting for 8-10% of global emissions [2]. Due to the high demand for concrete in construction, there is also a need for raw materials such as natural aggregates. Therefore, efforts are being made to replace cement with more environmentally friendly materials that have equivalent properties to cement. This has led to the development of an innovative green concrete which uses less cement, sand, aggregate, and water, without compromising quality, workability, durability, and performance.

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Geopolymer concrete is cement-free concrete with properties equivalent to conventional concrete. Its composition consists of binding materials (slag, fly ash, truss) combined with alkaline solutions (NaOH, Na_2SiO_3, KOH, K_2SiO_3), filler/aggregate materials (environmentally friendly waste or recyclable materials), and water or other additives [3]. Cement is replaced with fly ash and supplemented with an alkali activator solution that reacts with the silica and alumina content in the fly ash, forming the geopolymer concrete binder. Fly ash can be used as an additive or substitute for up to 70% of the cement. However, the optimal substitution rate for fly ash in this study was 35% of the cement [4]. In previous studies, the addition of shell powder as fine aggregate at a rate of 5% to 30% in this study still falls under waterproof concrete [5]. Based on the research conducted, eggshell powder can be used as a fine aggregate substitute, and concrete waste can be used as a coarse aggregate substitute [6]. The compressive strength of concrete using concrete waste is higher than that of normal concrete, especially after 28 days. This is due to the presence of unhydrated cement residues on the surface of concrete waste aggregate particles, which react with water, thereby increasing the rate of strength development [7]. Thus, recycled concrete can be considered suitable as standard concrete, making it a viable material for concrete innovations [8].

However, the use of geopolymer concrete will inevitably result in cracking. Cracks such as plastic cracks due to sedimentation, thermal cracks triggered by temperature and humidity fluctuations, structural cracks due to external loading, and dry cracks primarily occurring in existing concrete can create pathways for harmful substances to enter the material and gradually deteriorate over time [9]. One innovation that can address this issue is self-healing concrete technology, which uses bacterial spores as healing agents. However, the use of Bacillus Megaterium bacteria in geopolymer concrete has not been extensively studied. The concept of self-healing concrete with bacteria is that when cracks occur, inactive bacterial spores become active [10]. Then, active bacterial cells convert calcium lactate (CaC6H10O6) into calcium carbonate (CaCO3) using oxygen. When the concrete experiences microcracks, the cracks cause the bacteria and calcium lactate present in the concrete mixture to fill and repair the cracks in the concrete [11]. The purpose of this study was to determine the compressive strength of normal concrete, geopolymer concrete, and geopolymer concrete based on Bacillus megaterium bacteria, as well as to determine the effect of Bacillus megaterium bacteria as a self-healing agent on cracks caused by compressive strength testing.

2 Methodology

This study used an experimental method, by collecting primary data in laboratory-scale testing with three stages. The initial stage or preparation stage of this research involved inoculating Bacillus Megaterium bacteria at the Bioprocess Laboratory, casting the cylindrical test specimens measuring 15x30 cm at the Stone and Concrete Laboratory, and testing the components of normal concrete and geopolymer concrete and producing test specimens at the Materials Testing Laboratory, Politeknik Negeri Bandung. The research flowchart can be seen in Fig. 1.

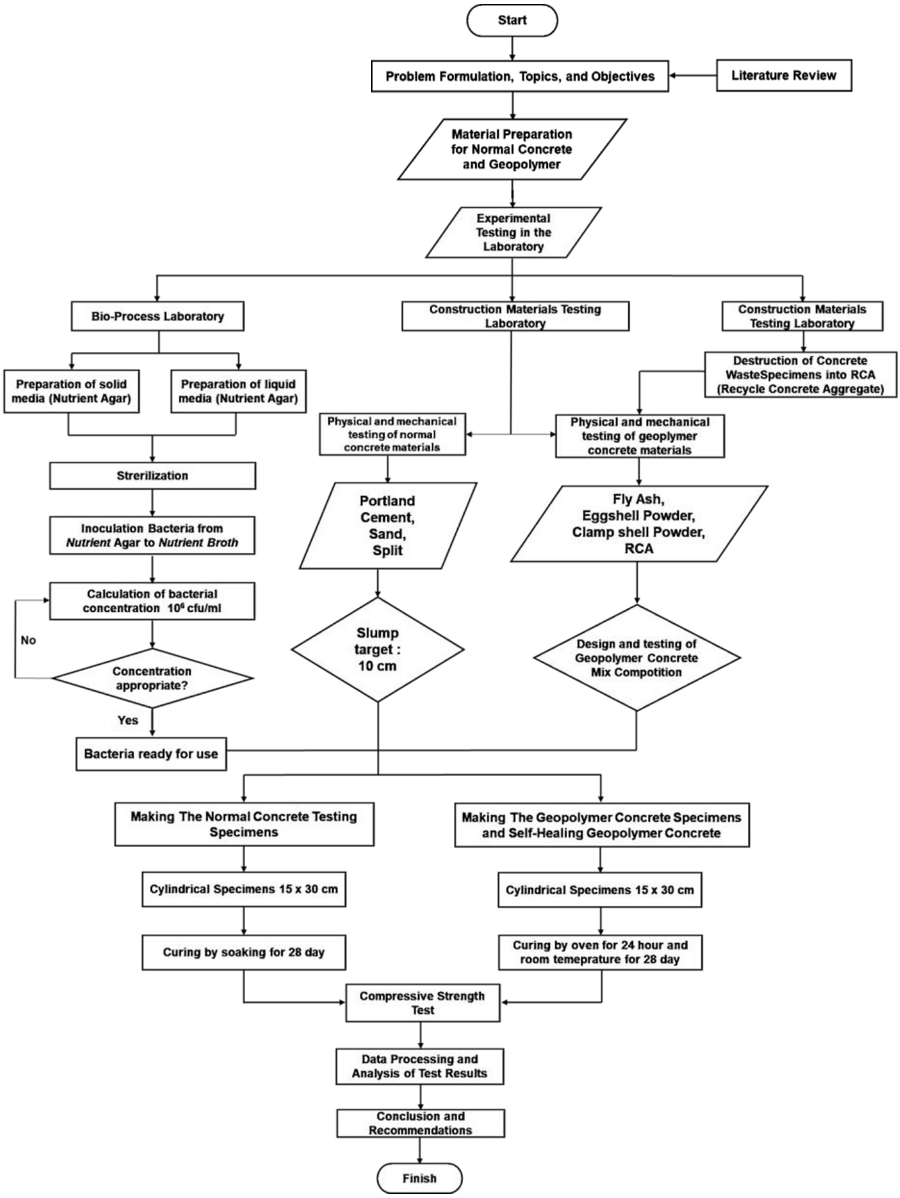

Fig. 1. Research flowchart.

During the implementation phase, which involves the production of normal concrete, geopolymer concrete, and self-healing geopolymer concrete, a trial mix design is first conducted to determine the optimal mixing method and composition for geopolymer concrete based on previous research, such as studies 11 and 12. The binder composition consists of 65% fly ash and 35% alkali activator, with a binder-to-filler ratio of 30%:70. The ratio between coarse and fine aggregate fillers is 40%:30, and the ratio between NaOH solution and Na_2SiO_3 is 1:2.5. The final stage of this study is the analysis of the results from the material testing and concrete strength testing.

3 Result and discussion

3.1 Test results of normal concrete and geopolymer concrete

Material testing is used to determine the quality of materials to be used in the manufacturing process. Tests conducted include sieve analysis, specific gravity, moisture content, and absorption testing on fine aggregates, as well as volume density testing, water absorption, silt content testing, and abrasion testing on coarse aggregates for normal concrete were using standards [12-15]. Material testing of geopolymer concrete, such as fly ash, eggshell powder, shell powder, and RCA are refer to researches of [16-18].

Based on the material testing that has been carried out, the results of material testing for normal concrete can be seen in Tables 1, 2, and 3. Meanwhile, the results for geopolymer concrete can be seen in Tables 4, 5, 6, and 7.

Table 1. Coarse aggregate test results.

Types of Testing	Standard	Result
Sieve analysis	SNI 1969- 2016, ASTM C33-2003	6,67
Bulk specific gravity		2,58
Absorb		2,6 %
Silt content		2,9 %
Solid specific gravity		1,43 gr/cm3
Loose specific gravity		1,23 gr/cm3
Abrasion		19,1 %

Table 2. Fine aggregate test results.

Types of Testing	Standard	Result
Sieve analysis	SNI 1969- 2016, ASTM C136 :2012	5,71
Bulk specific gravity		2,53
Absorb		1,35 %
Organic matter content		2
Silt content		14,4 %
Solid specific gravity		1,67 gr/cm3
Loose specific gravity		1,54 gr/cm3

Table 3. Cement test results.

Types of Testing	Standard	Condition	Result
Specific gravity	ASTM C-311	3 – 3,2	3

Table 4. Clampshell powder test results.

Types of Testing	Standard	Condition	Result
Sieve analysis	Alfuady et al., 2021	1,5 - 3,8	3,3
Absorb		Maks. 4%	0,63
Solid specific gravity		-	0,64
Bulk specific gravity		Min. 2,4	0,74
Water content		1 - 2 %	0,63
Organic matter content		-	2

Table 5. Eggshell powder test results.

Types of Testing	Standard	Condition	Result
Sieve analysis	Karimah et al., 2020	1,5 - 3,8	3,27
Absorb		Maks. 4%	0,53
Solid specific gravity		-	0,66
Bulk specific gravity		Min. 2,4	0,74
Water content		1 - 2 %	1,53
Organic matter content		-	2

Table 6. Recycle concrete aggregate test results.

Types of Testing	Standard	Result
Sieve analysis	Sukri et al., 2025	8,36
Bulk specific gravity		2,61
Absorb		2,5 %
Silt content		0,72 %
Solid specific gravity		1,628 gr/cm3
Loose specific gravity		1,434 gr/cm3
Abrasion		20,84 %

Table 7. Fly ash test results.

Types of Testing	Standard	Condition	Result
Sieve analysis	Prasetia et al., 2019	Maks. 3,4	1,85
Specific gravity		Min. 2,0	2,53
Activity		2	2

From the results of testing these materials, a mix design for normal concrete was obtained from SNI 7656:2012. In the other hand, a mix design for geopolymer concrete based on [19, 20], and trial n error testing results.

Table 8. Mix design of normal concrete for 1 specimen.

Specimen	Composition (Kg)			
	Cement	Coarse Aggregate	Fine Aggregate	Water
Cylindrical 15x30 cm	2,088	5,754	3,582	0,980

Table 9. Mix design of geopolymer concrete for 1 specimen.

Specimen	Composition	Kg
Cylindrical 15x30 cm	Fly Ash	2,54
	Fine Aggregate (Eggshell)	1,65
	Fine Aggregate (Clampshell)	2,16
	Coarse Aggregate (RCA)	5,09
	Water	1,27
	NaOH (10 M)	0,282
	Na_2SiO_3	0,705

Table 10. Mix design of geopolymer concrete with self-healing agent for 1 specimen.

Specimen	Composition	Kg
Cylindrical 15x30 cm	Fly Ash	2,54
	Fine Aggregate (Eggshell)	1,65
	Fine Aggregate (Clampshell)	2,16
	Coarse Aggregate (RCA)	5,09
	Water	1,27
	NaOH (10 M)	0,282
	Na2SiO3	0,705
	Bacillus Megaterium	0,025
	Calcium Lactate	0,05

3.2 Strength

Compressive strength testing of concrete cylinders refers to SNI 1974:2011. The compressive strength test results can be seen in Table 11.

Table 11. Compressive strength test results.

Code	Period (Day)	Dimension (mm)		Area (mm2)	Weight (gr)	Compressive Strength (MPa)
		D	T			
BK1	28	150	301	17662,50	11682	30,29
BK2		148	298	17194,64	11434	30,13
BK3		150	305	17662,50	11147	30,63
BG-1		150,70	301	17832,47	13104	24,68
BG-2		151	300,70	17898,79	12968	24,36
BG-3		150,80	302	17839,57	13050	22,80
B-SH-G1		150,15	29,90	17697,84	12364	26,16
B-SH-G2		152,25	300	18196,35	11395	22,64
B-SH-G3		151,30	300	17969,98	11967	23,82

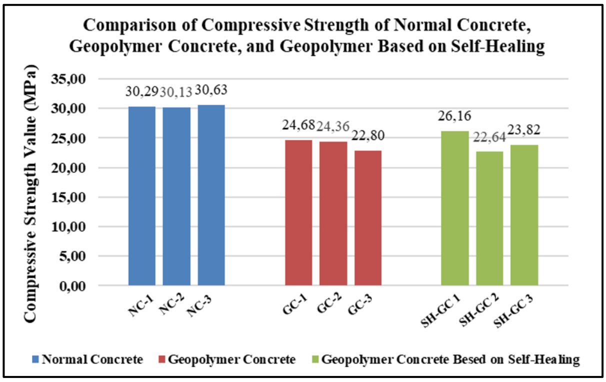

Fig. 2. Comparison of compressive strength of normal concrete, geopolymer concrete, and self-healing based geopolymer concrete

Based on the results of the compressive strength test (Fig. 2), it was found that the average compressive strength of the control concrete was 30.35 MPa, the geopolymer concrete had an average compressive strength of 23.17 MPa, while the self-healing geopolymer concrete had an average compressive strength of 23.21 MPa. Therefore, it can be concluded that the control concrete consistently exhibits the highest compressive strength, the geopolymer concrete and self-healing geopolymer concrete showed compressive strength reductions of approximately 21.1% and 20.2%, respectively, compared to normal concrete.

4 Conclusion

In conclusion, although geopolymer concrete has lower compressive strength than conventional concrete, the addition of Bacillus Megaterium bacteria can improve its performance and has potential for further development. Because it uses waste aggregates such as eggshell and shell powder and concrete test specimen waste, the decrease in compressive strength in geopolymer concrete is likely influenced by the physical and mechanical properties of waste aggregates, which differ from natural aggregates. Waste aggregates generally have higher porosity, less ideal particle shape, and lower bonding strength, so they can only be used as fillers or additives, or combined with alkali activators in geopolymer concrete. The addition of Bacillus megaterium bacteria is expected to increase compressive strength compared to ordinary geopolymer concrete and improve post-compressive microcracks. However, the concrete tested did not exhibit self-healing, but only an increase in compressive strength.

This shows that although conventional concrete is still superior in terms of compressive strength, bacteria-based geopolymer concrete has the potential to be further developed to approach or even exceed the performance of conventional concrete. Therefore, further research is needed on the use of Bacillus Megaterium bacteria in geopolymer concrete to achieve a self-healing mechanism.

The geopolymer concrete did not undergo self-healing due to the alkaline activator solution with a molarity of 10M containing a pH > 14. An alkaline environment with a high pH is not suitable for the life of Bacillus Megaterium bacteria. Therefore, as a recommendation for future improvements, the concentration of the solution and the method of mixing the bacteria need to be reevaluated.

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References

1. M. Setiawati, R. A. S. Martini, R. Nurulita, Variasi molaritas NaOH dan alkali aktivator beton geopolimer. *J. Tek. Sipil* **7**, Palembang (2022).
2. M. R. Olii, A. A. Wahab, I. Ichsan, R. Abdul Djau, S. Nento, Beton hijau menggunakan fly ash sebagai substitusi parsial semen. *Siklus: J. Tek. Sipil* **9**(1), 11–20 (2023).
3. Purwanto, Inovasi beton polimer dan geopolimer sebagai beton ramah lingkungan berbasis green concrete. *J. Tek. Sipil* **10**, Semarang (2021).
4. T. Octaviani, M. Ryanto, Perencanaan campuran beton menggunakan substitusi semen dengan abu terbang. *J. Tek. Sipil* **12**(2), 124–130 (2019).
5. R. Karimah, Y. Rusdianto, D. P. Susanti, Pemanfaatan serbuk kulit kerang sebagai pengganti agregat halus terhadap sifat mekanik beton. *J. Rekayasa Sipil* **6**, Malang (2020).

6. Gunarso, D. Purnamawanti, R. Arbianto, Inovasi eco-friendly self-compacting concrete menggunakan serbuk cangkang telur, serbuk granit, dan limbah beton untuk mengurangi limbah di Indonesia. *J. Tek. Sipil dan Arsit.* **29**(1), 2807–9418 (2024).
7. D. Patah, A. Dasar, Pengaruh limbah beton sebagai pengganti agregat kasar. *J. Tek. Sipil* **10**(2), 158–163 (2022).
8. F. R. Andardi, L. Prasetyo, Pengaruh penggunaan limbah beton sebagai bahan pengganti agregat kasar dan halus berdasarkan grafik Fuller terhadap kuat tekan beton. *Rekayasa Sipil* **11**(1), 1 (2022).
9. E. Tziviloglou, V. Wiktor, H. M. Jonkers, E. Schlangen, Bacteria-based self-healing concrete to increase liquid tightness of cracks. *Constr. Build. Mater.* **122**, 118–125 (2016).
10. L. M. Mauludin, R. Permana, U. Ruslan, A. Zulpanani, L. Fauziah, S. M. Nurhayati, et al., Enhancing performance of high-strength concrete using *Bacillus megaterium* as self-healing agent. *Int. J. GEOMATE* **26**(114), 68–75 (2024).
11. L. Fauziah, S. M. Murhayati, L. M. Mauludin, L. Aisyah, Pengaruh bakteri *Bacillus megaterium* sebagai self-healing agent pada kuat tekan beton mutu tinggi. *RekaRacana: J. Tek. Sipil* **9**(3), 228–239 (2023).
12. Badan Standardisasi Nasional (BSN), *SNI 1969:2016 — Metode uji berat jenis dan penyerapan air agregat kasar*. Jakarta (2016).
13. ASTM International, *ASTM C33-03 — Standard Specification for Concrete Aggregates*. West Conshohocken, PA, USA.
14. ASTM International, *ASTM C136:2012 Metode Uji Untuk Analisis Saringan Agregat Halus Dan Agregat Kasar (ASTM C 136-06, IDT)* (2012)
15. ASTM International, ASTM C-311, *100 Barr Harbor Drive* 1 (2018)
16. F. Alfuady, K. Al Qubro, Analisis cangkang kerang dara sebagai substitusi agregat halus terhadap kuat tekan beton. *J. Deformasi* **8**(2), 192–199 (2023).
17. M. R. A. Syukri, W. Maharani, Y. P. Krisologus, Kuat tekan pada campuran beton dengan bakteri yang diinokulasi dan limbah benda uji. *J. Jalan Jembatan* **42**(1), 1–10 (2025).
18. I. Prasetia, Rusdiyanur, I. T. Wicaksono, M. Syauqi, Karakteristik abu batubara PLTU di Kalimantan. *Proceedings of Seminar Nasional Banjarbaru* (2019).
19. F. Rizal, R. Syahyadi, Z. Jaya, Viabilitas bakteri *Bacillus subtilis* sebagai self-healing agent pada mortar geopolimer. *Prosiding Seminar Nasional Teknik Sipil*, Medan (2020).
20. H. Ashad, M. R. Putra, T. Utina, Studi karakteristik kuat tekan beton geopolimer berbahan dasar fly ash. *J. Tek. Sipil* **30**(3), 379–384 (2023).