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Article

Integrated Experimental and Analytical Assessment of Reinforced Geopolymer and Microbial–Mineral SelfHealing Concrete Beams for Strength, Crack Control, Durability, and Service-Life Enhancement

Abhishek Kumar Choubey[1], Dharmendra Singh[2], Vaibhav Mishra[3], Aditya Raj[4], Maaz Allah Khan[5]

[1,2,3,4] Department of Civil Engineering, LNJPIT Chapra, India
[5]Department of Civil Engineering, UIET,BBAU, Lucknow, UP,India (Corresponding Author Email: maazallah@rediffmail.com)

Abstract:

This study presents a comparative experimental and analytical assessment of reinforced concrete (RC) beams manufactured using conventional concrete (CRC), geopolymer concrete (GPC), and microbial–mineral self-healing concrete (SHC). The investigation focuses on flexural response, crack development and closure, stiffness recovery, and implications for durability and service-life performance. The supplied experimental dataset reports first-crack loads of 18.5, 22.3, and 20.1 kN and ultimate loads of 52.0, 61.5, and 55.8 kN for CRC, GPC, and SHC beams, respectively. The corresponding mid-span deflections at ultimate load were 14.8, 12.1, and 13.5 mm. The reported post-healing crack width for the SHC beam was 0.12 mm. The material-property dataset gives compressive strengths of 38.5, 44.8, and 41.2 MPa and elastic moduli of 29.0, 31.5, and 30.2 GPa for CRC, GPC, and SHC, respectively. An analytical framework based on equilibrium, compatibility, modified concrete properties, and a healing-efficiency parameter is used to interpret flexural capacity and serviceability. The results indicate higher reported flexural resistance for GPC and pronounced crack-closure and stiffness-recovery behaviour for SHC. The findings support the potential of combining low-cement/zero-Portland-cement binder technologies with autonomous crack-healing approaches for durable structural concrete; however, long-term durability, statistical repeatability, and the interaction between geopolymer matrices and microbial–mineral healing systems require further structural-scale validation.
Keywords: geopolymer concrete; microbial-induced carbonate precipitation; self-healing concrete; reinforced concrete beam; flexural behaviour; crack closure; stiffness recovery; service life.

1. Introduction

Reinforced concrete remains a dominant structural material because of its strength, availability, and adaptability. Nevertheless, cracking is an inherent feature of reinforced concrete under service and ultimate loading. Cracks can increase pathways for moisture and aggressive agents and may therefore contribute to durability deterioration and reinforcement corrosion. At the same time, reducing dependence on Portland-cement binders has motivated extensive research into geopolymer and alkali-activated materials.
Geopolymer concrete (GPC), commonly produced from aluminosilicate-rich precursors activated by alkaline solutions, has been investigated as a lower-cement or cement-free alternative. Structural research has already demonstrated that reinforced geopolymer beams can exhibit flexural and shear behaviour comparable with conventional Portland-cement concrete beams; therefore, the novelty of the present work should not be framed as the first structural investigation of geopolymer beams. Published reviews document a substantial body of work on reinforced geopolymer members and identify the need for further full-scale and design-oriented

investigations. [1–3]Self-healing concrete provides a complementary approach to durability by promoting autonomous or autogenous sealing of cracks. Microbial systems can induce calcium-carbonate precipitation, while mineral admixtures can contribute to crack filling and matrix densification. Published research has demonstrated microbial crack healing in reinforced concrete and has also investigated microbialinduced carbonate precipitation in geopolymer concrete. [4–6]Against this background, the present study compares conventional RC, reinforced GPC, and microbial–mineral SHC beams using the experimental dataset supplied by the authors. The study evaluates first-crack load, ultimate load, deflection, crack-width reduction, stiffness recovery, and analytical flexural/serviceability behaviour. The specific contribution claimed here is therefore the comparative structural-scale assessment of these performance indicators within one experimental framework, rather than the introduction of geopolymer concrete or microbial self-healing as individually new technologies.The principal objectives are: (i) to compare the flexural response of CRC, GPC, and SHC beams; (ii) to quantify crack closure and stiffness recovery in SHC; (iii) to relate the measured behaviour to analytical flexural and serviceability models; and (iv) to discuss the implications for durability and service-life enhancement.

2. Literature Review

2.1 Reinforced geopolymer concrete

Existing reviews show that reinforced geopolymer concrete members generally exhibit structural behaviour comparable with conventional reinforced concrete. Reported investigations cover flexure, shear, bond, ductility, cracking, and load–deflection response. The literature therefore establishes a strong foundation for structural GPC research, while also identifying the need for additional full-scale investigations and reliable design methodologies. [1–3]

2.2 Microbial self-healing of structural concrete

Microbial self-healing relies on biological mineral precipitation, most commonly calcium carbonate, to reduce crack width and limit transport pathways. Experimental research on reinforced concrete has reported crack healing together with recovery of flexural or mechanical performance, and microbial systems have also been studied in geopolymer matrices. [4–6]

2.3 Research gap addressed in this study

The literature demonstrates that both reinforced GPC and microbial self-healing have been studied separately and, increasingly, in combined material systems. Accordingly, the present study does not claim that the constituent technologies are unexplored. Instead, it addresses the comparative structural-scale evaluation of conventional, geopolymer, and microbial–mineral self-healing beam systems using common flexural-performance indicators. The manuscript further links crack closure and stiffness recovery to a simplified analytical serviceability framework.

3. Materials and Experimental Program

This section must be completed from the laboratory records before submission. The original manuscript did not contain sufficient information to reproduce the experiment.

3.1 Concrete constituents and mix proportions

Conventional concrete was prepared using M35grade, fine aggregate, coarse aggregate, water, admixtures, water-to-binder ratio, and complete mix proportions. The target strength was 410.The geopolymer binder was based on low-calcium fly ash. Sodium hydroxide and sodium silicate were used as alkaline activators. The fly-ash source, chemical composition, NaOH molarity, sodiumsilicate/NaOH ratio, liquid-to-binder ratio, aggregate proportions, activator preparation procedure, mixing sequence, and curing regime must be inserted from the experimental log.The self-healing mixture incorporated Bacillus subtilis as the microbial strain, with porous lightweight aggregate used as the bacterial carrier/immobilization medium. The bacterial concentration was maintained at 1 x 108 CFU/mL. A calcium-based healing admixture was incorporated at a dosage of 2% by mass of the cementitious binder.

3.2 Reinforcement detailing

All beam specimens were reinforced using longitudinal deformed steel bars and transverse stirrups. The original manuscript states that identical reinforcement detailing was used for comparison. The following parameters must be reported: beam width = 150 mm; overall depth = 200 mm; effective depth = 170mm; clear cover = 25mm; effective span = 1000mm; tensile reinforcement = 2-12MM DIA Fe500 bars; compression reinforcement = 2-10 mm dia Fe500 bars; stirrup diameter and spacing = 100mm c/c near supports;150 mm c/c central region steel yield strength = 500MPa. The beam specimen was designed with a width of 150 mm, an overall depth of 200 mm, and an overall length of 1200 mm with an effective span of 1000 mm. A clear concrete cover of 25 mm was provided. The beam was reinforced with 2–12 mm diameter Fe500 deformed steel bars as longitudinal tensile reinforcement and 2–10 mm diameter Fe500 bars as compression reinforcement. 8 mm diameter two-legged Fe500 stirrups were provided at 100 mm c/c near the supports and 150 mm c/c in the central region. The resulting effective depth was approximately 170 mm. The beam was subjected to flexural loading under a four-point bending configuration.

3.3 Specimen matrix and number of replicates

Specimen group	Concrete system	Number of beams	Purpose

CRC	Conventional reinforced concrete	3	Control
GPC	Reinforced geopolymer concrete	3	Flexural comparison
SHC	Microbial–mineral self-healing concrete	3	Crack healing and recovery

Replicate-level results and variability must be reported before submission. Single representative values should not be presented as statistically definitive without the underlying replicate data.

4. Curing, Damage, and Healing Protocol

The geopolymer beams were cured at an ambient temperature of 27 ± 2°C for 28 days, while the self-healing beams were subsequently maintained in a moist environment at 27 ± 2°C and approximately 90% relative humidity to promote microbial activity. The specimens were precracked at 28 days of age. A target crack width of approximately 0.30 mm was adopted for the healing assessment. After pre-cracking, the specimens were exposed to the moist healing environment for 28 days. Crack widths were monitored at 0, 7, 14, 21, and 28 days of healing. For the healing test, the beam was first loaded under displacement control until the target crack width of 0.30 mm was obtained and then unloaded. The first loading cycle was terminated when the target crack width was reached, after which the specimens were subjected to the prescribed healing period before reloading.

5. Flexural Testing and Measurements

Four-point bending was used to evaluate using a 100 kN capacity universal testing machine equipped with a calibrated load cell. The beam specimens were tested over an effective span of 1000 mm. Two-point loading was applied symmetrically, producing a constant-moment region of 300 mm and shear spans of 350 mm on either side. The loading rate was maintained at approximately 0.5 kN/min under displacement-controlled loading. Mid-span displacement was measured using a linear variable differential transformer (LVDT) with a measurement range of 50 mm. Crack initiation and propagation were monitored using a digital crack-width microscope with a resolution of approximately 0.01 mm. Crack widths were measured at predetermined locations at the initial cracking stage and after 7, 14, 21 and 28 days of healing. After the healing period, the specimens were reloaded using the same four-point bending configuration and loading protocol.6. Analytical Framework.

6.1 Flexural equilibrium

For a singly reinforced beam under the usual plane-sections-remain-plane assumption, the nominal flexural capacity may be expressed from force equilibrium and moment equilibrium. For a rectangular equivalent stress block:

$C = \alpha_1 f'c\ b\ a$

$T = A_s f_\gamma\ C = T\ a = A_s f_\gamma / (\alpha_1 f'c\ b)$

$M_n = A_s f_\gamma (d - a/2)$

where C is the concrete compression force, T is the tensile reinforcement force, α_1 is the equivalent stress-block coefficient, f'c is compressive strength, b is beam width, a is equivalent stress-block depth, A_s is tensile reinforcement area, f_γ is steel yield strength, d is effective depth, and M_n is nominal flexural capacity. The appropriate code-specific coefficients and strength-reduction provisions must be selected according to the target journal/code framework.

6.2 Material-property substitution for GPC

For GPC, the experimentally measured compressive strength and elastic modulus are used as material inputs rather than assuming conventional concrete properties. The present dataset gives f'c = 44.8 MPa and E = 31.5 GPa for GPC. These values must be accompanied by specimen age and replicate statistics before publication.

6.3 Stiffness recovery

An effective flexural stiffness may be evaluated from the moment–curvature response as: $EI_eff = M / \kappa$

where M is bending moment and κ is curvature. If curvature is not directly measured, an equivalent stiffness index based on the slope of the load–deflection response may be used, but the definition and measurement method must be stated.

The healing efficiency parameter is defined as:

$\eta_h = (w_i - w_h) / w_i$

where w_i is the initial crack width and w_h is the crack width after healing. The percentage healing efficiency is $100\eta_h$.

6.4 Crack-width serviceability

Crack width should be calculated using the selected design-code or mechanics-based expression, with the healing term introduced only if it is experimentally calibrated. The healing factor must not be treated as a universal material constant. Its value should be obtained from the measured crackwidth dataset and reported with uncertainty.

7. Results and Discussion

7.1 Mechanical properties

Material	Compressive strength (MPa)	Elastic modulus (GPa)
Conventional concrete	38.5	29.0
Geopolymer concrete	44.8	31.5
Self-healing concrete	41.2	30.2

The supplied dataset indicates that GPC had the highest reported compressive strength and elastic modulus among the three systems, followed by SHC and conventional concrete. These values are descriptive only until replicate counts and statistical dispersion are supplied.

7.2 Flexural response

Beam type	First-crack load (kN)	Ultimate load (kN)	Deflection at ultimate load (mm)	Reported healed crack width (mm)
CRC	18.5	52.0	14.8	0.42
GPC	22.3	61.5	12.1	0.31
SHC	20.1	55.8	13.5	0.12

Relative to CRC, the reported first-crack load increased by approximately 20.5% for GPC and 8.6% for SHC. The reported ultimate load increased by approximately 18.3% for GPC and 7.3% for SHC. The corresponding deflection at ultimate load decreased by approximately 18.2% for GPC and 8.8% for SHC. These are comparisons of the supplied representative values and should not be interpreted as statistically significant differences without replicate-level analysis.

7.3 Crack-healing behaviour

The reported post-healing crack width for SHC is 0.12 mm. The original manuscript also reports a healing-efficiency range of approximately 0.55–0.75 and states that cracks below 0.4 mm showed healing ratios above 0.70. These statements require the underlying initial crack-width measurements, healing duration, and replicate data to substantiate them.

If the initial crack width was 0.40 mm and the healed width was 0.12 mm, the calculated closure efficiency would be 70%. This example illustrates the calculation only; it must not replace the actual measured initial crack width.

7.4 Reloading response

Load level (kN)	Deflection before healing (mm)	Deflection healing after (mm)	Reduction (%)
15	3.6	2.4	33.3
30	8.9	6.1	31.5
45	13.7	9.8	28.5

The supplied reloading dataset shows lower deflection after healing at each listed load level, indicating a higher apparent stiffness after the healing period. The calculated reductions are approximately 33.3%, 31.5%, and 28.5% at 15, 30, and 45 kN, respectively. A formal stiffnessrecovery index should be calculated from the complete load–deflection curves.

7.5 Durability implications

Reduced crack width can reduce the available transport pathway for moisture and aggressive species; however, crack-width reduction alone does not establish chloride diffusion resistance, carbonation resistance, corrosion protection, or long-term service life. Therefore, the durability discussion is interpreted as an indication of potential rather than direct proof. Direct durability testing—such as water absorption, sorptivity, chloride migration/diffusion, carbonation, or electrochemical corrosion measurements—would strengthen the service-life claims.

8. Comparative Interpretation

The supplied results indicate two distinct performance characteristics. GPC shows the highest reported first-crack and ultimate loads and the lowest reported deflection at ultimate load among the three systems. SHC shows the most pronounced crack-closure behaviour and lower post-healing deflection in the supplied reloading data. Thus, the performance objectives of strength enhancement and autonomous crack control should be considered separately rather than assuming that one concrete system simultaneously maximizes every indicator.

The combined sustainability and durability proposition is technically promising, but a true integrated geopolymer–microbial–mineral system must be experimentally characterized as such. The present manuscript should therefore retain the terminology 'geopolymer concrete' and 'microbial–mineral self-healing concrete' unless the laboratory specimens actually incorporated all constituents in the same matrix.

9. Limitations

The principal limitation of the present manuscript is incomplete reporting of experimental metadata in the supplied source. Specifically, specimen dimensions, replicate numbers, complete mix designs, bacterial identity and dosage, mineral-admixture dosage, curing conditions, loading rate, instrumentation, and statistical dispersion were not provided. In addition, direct durability testing was not reported. These limitations must be explicitly addressed before submission.

The analytical framework is intentionally simplified and should be interpreted as a comparative model rather than a universally validated design equation. The healing-efficiency parameter is material- and exposure-dependent and requires calibration for each healing system.

10. Conclusions

Based on the experimental values supplied in the source manuscript, the following conclusions can be drawn:

1. The reported GPC beam exhibited the highest first-crack load (22.3 kN) and ultimate load (61.5 kN), compared with 18.5 and 52.0 kN for the CRC beam and 20.1 and 55.8 kN for the SHC beam.
2. The reported deflection at ultimate load was 12.1 mm for GPC, 13.5 mm for SHC, and 14.8 mm for CRC, indicating lower deformation at the reported ultimate load for the alternative concrete systems.
3. The SHC system exhibited substantial crack-closure behaviour in the supplied dataset, with a reported post-healing crack width of 0.12 mm. The actual healing efficiency must be calculated from measured pre- and post-healing crack widths for each replicate.
4. The supplied reloading data show lower deflections after healing at 15, 30, and 45 kN, indicating recovery of apparent flexural stiffness. A complete stiffness-recovery index should be derived from the full experimental curves.
5. The reported compressive strengths were 38.5 MPa for CRC, 44.8 MPa for GPC, and 41.2 MPa for SHC. These values indicate that the tested GPC mixture achieved the highest reported compressive strength, but statistical variability must be reported.
6. The results support the potential of geopolymer and microbial–mineral self-healing technologies for improving different aspects of structural concrete performance. Nevertheless, direct durability measurements and long-term structural exposure studies are required before quantitative servicelife extension can be claimed.
7. Future work should investigate an explicitly integrated geopolymer–microbial–mineral system, include multiple replicates and statistical analysis, characterize healing products using appropriate microstructural techniques, and validate the analytical model against independent beam datasets.

11. Data Availability

The complete raw experimental dataset, specimen-level load–deflection records, crack-width measurements, mix-design sheets, curing records, and microscopy data should be deposited in a recognized repository or made available as supplementary material where permitted by the target journal. DOI: 10.33804/IJSRI.2021.01.01.https://doi.org/10.5281/zenodo.18342951.refrence taken from this paper and credit goes to this journal and paper for the data and reference.

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