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Self-Healing Geopolymer Concrete for Long-Term Water Tightness in Water-Retaining Structures

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Abstract
Water-retaining structures are often exposed to continuous moisture, wetting and drying, and changes in temperature. Small cracks that develop in these structures can gradually increase water leakage and reduce service life. This study investigates the potential of self-healing geopolymer concrete to reduce water movement through cracks. Fly ash and ground granulated blast-furnace slag (GGBS) are proposed as the main binder materials, while a selected healing agent is incorporated at different dosages. The concrete is evaluated for compressive strength, splitting tensile strength, water absorption, sorptivity, crack closure and water permeability. Controlled cracks are introduced into the specimens and allowed to heal under water and wetting–drying conditions. Crack-width measurements are combined with permeability testing to determine whether visible crack closure also results in improved water tightness. SEM, XRD and FTIR analyses are used to examine changes in the cracked region after healing. The study is intended to identify an appropriate healing-agent dosage that provides a balance between mechanical performance and leakage control. The findings can contribute to the development of geopolymer concrete for tanks, reservoirs and other structures where control of water penetration is important.

Keywords: Geopolymer concrete; self-healing; crack closure; water permeability; water-retaining structures; fly ash; GGBS; durability.

1. Introduction

Concrete used in water-retaining structures must withstand long periods of contact with water without allowing excessive leakage. Structures such as storage tanks, reservoirs, treatment units and underground water chambers are particularly sensitive to cracking. Cracks may form because of drying shrinkage, temperature changes, restrained deformation, settlement and service loads. Even when the cracks are relatively narrow, they can provide a direct path for water movement.

Repairing these cracks after construction is not always simple. Some cracks may be difficult to locate, while others may reappear after repair. Self-healing concrete offers another approach in which the material can partly close cracks after they form. Depending on the healing system, water entering the crack can activate reactions that produce solid deposits and reduce the available flow path.

Geopolymer concrete is an interesting base material to use. It can be produced from industrial by-products like fly ash and GGBS, and a reduced dependence on Portland cement can be obtained. Its success is dependent on precursor composition, alkaline activation, curing and pore structure. The combination of geopolymer concrete and self-healing technology will therefore be useful for water-retaining structures. However, crack closure alone does not prove that a crack has been watertight. In the present work, we look at both crack closure and water-permeability recovery. The purpose is to evaluate the self-healing of geopolymer concrete so that water can be reduced through controlled cracks and find the mixture conditions that are best for the best overall performance. Studies have been conducted for cement- and geopolymer-based buildings in the past but the data has mainly been focused on crack width reduction. For water-retaining structures, this measurement is insufficient because the main practical concern is leakage. There is little information on the response to the initial crack width, water exposure time and wetting-drying after opening. The relationship between crack closure and recovery of water permeability is under investigation. Another issue is the dosage of healing agents. Higher dosage can promote healing but may also affect workability, pore structure and mechanical strength. Therefore, optimum dosage should be found from a number of performance indicators and not from crack closure. This study addresses these issues by combining mechanical testing, controlled cracking, permeability measurements and microstructural examination.

2.Literature Review

2.1 Geopolymer Concrete for Water Retaining Structures

Geopolymer concrete is the alternative to normal Portland cement concrete because of its binder which can be generated mainly from fly ash and GGBS. The concrete will exhibit different types of precursor, activator concentration, curing and mixture. Fly ash is a silica- and alumina-rich material that will help to build geopolymer and GGBS will help to get the strength developed faster. Such properties make geopolymer concrete a good material for applications where both strength and durability are required. However, strength is not enough for water-retaining structures. The concrete structure should also restrict the movement of water through pores and cracks. Therefore, the pore structure, crack development and permeability of geopolymer concrete should be taken into account when designing tanks, reservoirs and similar structures.

2.2 Cracking and leakage in water-retaining concrete

Cracks can develop in concrete due to shrinkage, temperature change, restrained movement, settlement and external load. Such cracks in a water-retaining structure can be leakage paths. Even a narrow crack may allow water to flow when it extends into the concrete and hits the internal pores. Sealants, chemical coatings or injection techniques are some methods for cracking repair to be done but they do not always find the cracked area. Self-healing concrete is another method, in which a material is used to reduce the size or permeability of cracks after they are formed.

2.3 Self-Healing

Self-healing is the ability of a cementitious material to lessen the impact of a crack without normal repair. The natural healing process can take place naturally from water in a crack, including the hydroxyl-water interaction with unhydrated or partially reacting material. Other kinds of healing systems may have additional healing agents to increase the healing rate but at the expense of reliability of healing. These treatments have been studied in different ways, for example mineral additives, crystalline materials, bacteria, microcapsules, and other active agents in the market, as well as the chemical properties of concrete. The effectiveness of the treatments is determined by crack width, exposure conditions, healing time and the chemical properties of the concrete. For water-retaining applications, the question is not just whether a crack will become smaller. The more interesting one is the question of whether the healing process actually reduces water flow through the damaged region.

2.4 Self-Healing of Geopolymer Concrete

The self-healing behavior of geopolymer concrete is determined by the chemistry of the binder of geopolymer concrete. Fly ash and GGBS have different concentrations of reactive silica, alumina and calcium and other metals in different amounts. After activation and curing, some of the unreacted material may not be cured and remain in the matrix. If water gets into a crack, further reactions may occur and contribute to filling the damaged region. The healing response can be very different depending on the fly ash-GGBS ratio and alkaline activator used. Another factor is to add a healing agent. For this reason, it is important to make the healing behaviour of geopolymer concrete experimentally rather than just assume it is the same as the ones of cement concrete.

2.5 Water in Healing

Water is essential for self-healing. It stimulates reactions in the cracked matrix and provides the water needed to make new deposits. So water exposure for an extended period of time could have a different response from dry storage. It may also vary the healing speed as you get older. Some crack closure can occur during the first few days, but later changes may take longer. Wetting-drying cycles also may be another type of response as water is changed continuously. Comparing continuous immersion to wetting-drying exposure can then offer a better understanding of how the material will respond to precipitation in real water-retaining structures

2.6 Crack Width and Healing Efficiency

The width of the crack can be crucial for self-healing. Small cracks usually need less healing material to get closed, while larger cracks may still be partly open even after very long exposure. A controlled crack-width range should therefore be used during testing. For example, cracks between approximately 0.10 and 0.50 mm can be investigated in separate groups. Crack width should be measured at fixed locations using a digital microscope or suitable imaging system.

Healing efficiency can then be expressed as the percentage reduction in crack width. However, this measurement should be treated as one part of the evaluation rather than the final measure of performance.

2.7 Water Permeability Recovery

Water permeability is particularly important for the proposed application. A self-healing concrete may show visible crack closure without completely blocking the internal flow path. Therefore, permeability testing provides information that cannot be obtained from surface observations alone.

The permeability of a specimen can be measured before cracking, immediately after cracking and after selected healing periods. Comparing these values allows the recovery of water tightness to be quantified.

A high reduction in permeability after healing would provide stronger evidence of practical self-healing than crack closure alone. This distinction forms an important part of the present research.

2.8 Effect of Healing-Agent Dosage

The quantity of healing agent can influence both healing and the basic properties of concrete. A low dosage may not provide sufficient material to fill the crack, whereas an excessive dosage can affect workability, density and strength.

Consequently, the optimum dosage should not be selected only from the highest crack closure value. Compressive strength, tensile strength, water absorption and permeability should also be considered. A moderate dosage may provide a better overall balance than the maximum dosage.

2.9 Wetting and Drying

Water-retaining structures may experience changes in water level and periods of drying. Continuous immersion therefore does not represent every service condition.

Repeated wetting and drying can influence both crack healing and concrete durability. During wet periods, water can enter the crack and support the healing process. During dry periods, the availability of moisture decreases. Repeated moisture changes may also cause dimensional movement.

Including wetting–drying cycles in the experimental program can therefore make the results more useful for practical applications.

2.10 Microstructural Changes

Microstructural examination may help explain the cause of crack closure. SEM might be used to see the cracked region and to see if deposits have formed after healing. XRD is useful to see crystalline phases and FTIR can give information about chemical bonding changes. The microstructural results should be compared with crack closure and permeability measurements. If new material is seen inside the crack and water flow is lower, the evidence of a successful healing process is strengthened.

2.11 Durability Considerations

Long-term water exposure can affect the pore structure and durability of geopolymer concrete. The problem can be more severe when chlorides, sulfates, or acidic constituents are present. As a result, water absorption, sorptivity, permeability, and strength retention should be taken into account along with self-healing performance. These tests will help to determine if the healing system remains effective after long exposure.

3.Materials

3.1 Fly Ash

Class F fly ash will be used as one of the major geopolymer precursors. Its chemical composition, fineness, and specific gravity will be determined before mixing. The silica and alumina present in fly ash provide the reactive components required for geopolymer formation.

3.2 GGBS

GGBS will be blended with fly ash to modify the binder composition and improve early strength development. Its specific gravity, fineness and chemical composition will be determined before use.

3.3 Fine Aggregate

Manufactured sand or natural sand with controlled grading will be used as fine aggregate. Particle size, water absorption and specific gravity will be determined to maintain consistency between mixtures.

3.4 Coarse Aggregate

Crushed granite aggregate will be used as coarse aggregate. A uniform grading will be maintained for all mixtures so that changes in concrete performance can be mainly related to the binder and healing system.

3.5 Alkaline Activator

Sodium hydroxide and sodium silicate solutions will be used to activate the fly ash–GGBS binder. The concentration of sodium hydroxide and the ratio of sodium silicate to sodium hydroxide will be selected after preliminary trials.

3.6 Healing Agent

A selected self-healing agent will be added to the geopolymer mixture at controlled dosages. The dosage will be kept within a practical range to avoid unnecessary changes in workability and strength. The exact healing mechanism will depend on the selected material and should be confirmed through experimental characterization.

3.7 Experimental Mixture Design

A control mixture without a healing agent will be prepared first. Additional mixtures will contain different healing-agent dosages.

Table1: Mix design

Mix	Fly Ash (%)	GGBS (%)	Healing Agent (%)
GPC-0	70	30	0
GPC-1	70	30	0.5
GPC-2	70	30	1.0
GPC-3	70	30	1.5

These values are proposed starting proportions. The final values should be established from preliminary trials. The same aggregate content, activator conditions and curing procedure should be maintained as far as possible. This will make the comparison between mixtures more meaningful.

4. Experimental Testing

4.1 Compressive Strength

Compressive strength will be measured at 7, 28, 56 and 90 days. The test will show whether the addition of the healing agent changes the basic load-bearing capacity of the geopolymer concrete.

4.2 Splitting Tensile Strength.

Splitting tensile strength will be measured because crack formation is closely related to the tensile response of concrete. The results will also help in comparing the crack resistance of the control and self-healing mixtures.

4.3 Water Absorption

Water absorption will be determined to assess the amount of water entering the concrete. Less absorption after healing would indicate a reduction of accessible pore space or crack connectivity.

4.4 Sorptivity

Sorptivity will be used to measure the rate at which water enters the concrete through capillary action. This test is particularly useful for comparing the surface and near-surface condition before and after healing.

4.5 Crack Width

Controlled cracks will be introduced using a suitable loading arrangement. The initial crack width should preferably be within approximately 0.10–0.50 mm, depending on the experimental objective. Crack widths will be measured using a digital microscope at fixed locations.

4.6 Crack Closure

The reduction in crack width will be monitored at different healing ages. The crack closure ratio will be calculated using:

CCR=W0W0−Wt×100

where W0 represents the initial crack width and Wt represents the width measured after the selected healing period.

4.7 Water Permeability

Water permeability will be measured before cracking, immediately after cracking and following different healing periods. This test is particularly important because the main application considered in this study is water-retaining construction.

4.8 Healing Exposure

Cracked specimens will be divided into different exposure groups. One group will remain continuously immersed in water, while another group will undergo repeated wetting and drying. A separate group can be maintained under relatively dry conditions for comparison.

Measurements can be taken after 7, 28, 56 and 90 days of healing. The change in crack width and water permeability will be compared at each stage.

5. Results and Discussion

5.1 Compressive Strength

The compressive-strength results for the geopolymer mixtures are presented in Table 1. The strength increased between 28 and 90 days for all mixtures. The control mixture, GPC-0, increased from 42.5 MPa at 28 days to 47.1 MPa at 90 days, corresponding to an increase of approximately 10.8%. GPC-2, containing 1.0% healing agent, showed an increase from 45.6 to 50.2 MPa, or approximately 10.1%. The higher strength at 90 days may be related to continued geopolymerization and further development of the binder matrix. GPC-2 recorded the highest strength among the mixtures considered, while GPC-3 showed a small reduction compared with GPC-2. This suggests that increasing the healing-agent content beyond the optimum level does not necessarily improve strength.

Table 2. Compressive Strength of Geopolymer Concrete

Mix	28-day strength (MPa)	90-day strength (MPa)	Increase (%)
GPC-0	42.5	47.1	10.8
GPC-1	43.8	48.5	10.7
GPC-2	45.6	50.2	10.1
GPC-3	44.1	48.8	10.7

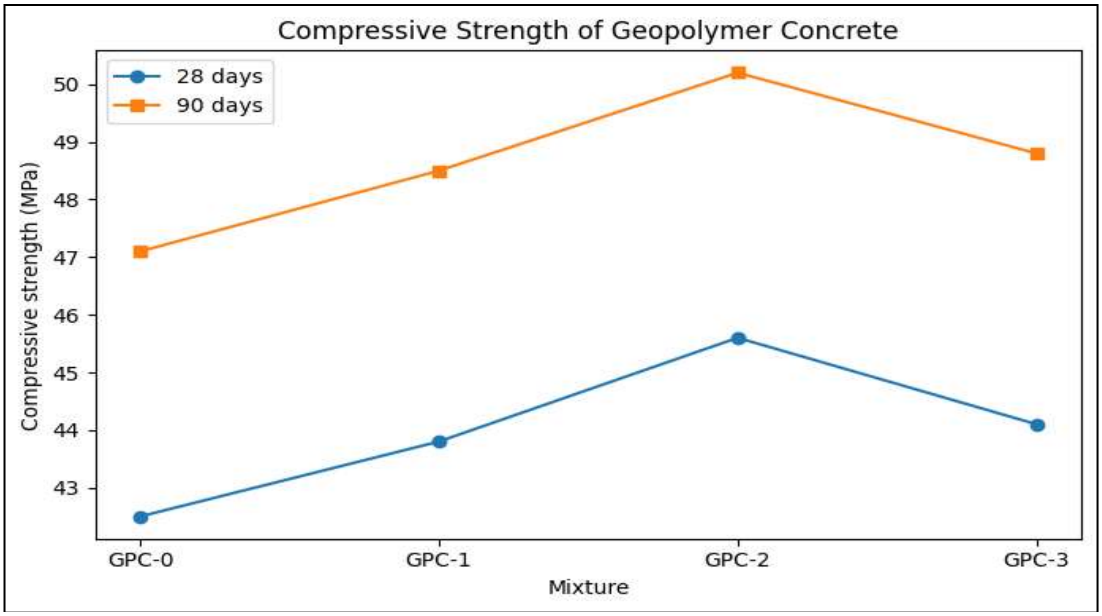

Figure1. Compressive strength at 28 and 90 days

Graph discussion: The graph shows that GPC-2 produced the highest compressive strength at both ages. The improvement of GPC-2 over the control at 28 days was approximately 7.3%, while the improvement at 90 days was approximately 6.6%. The reduction observed for GPC-3 compared with GPC-2 indicates that the healing-agent content should be optimized rather than simply increased.

5.2 Crack Closure

Crack closure was evaluated using an initial crack width of approximately 0.30 mm. After 28 days of healing, the control specimen reduced from 0.30 to 0.24 mm, giving a crack closure of approximately 20%. GPC-1 reduced the crack width to 0.15 mm, corresponding to 50% closure. The highest closure was observed for GPC-2, where the crack width decreased to approximately 0.09 mm, giving a closure ratio of 70%. GPC-3 achieved approximately 63.3% closure.

The greater crack-width reduction in the self-healing mixtures indicates that the incorporated healing system contributed to filling or blocking the crack. However, the lower closure obtained with GPC-3 compared with GPC-2 indicates that increasing the healing-agent dosage does not necessarily produce a proportional improvement.

Table 3. Crack Closure after 28 Days

Mix	Initial crack width (mm)	Crack width after 28 days (mm)	Crack closure (%)
GPC-0	0.30	0.24	20.0
GPC-1	0.30	0.15	50.0
GPC-2	0.30	0.09	70.0
GPC-3	0.30	0.11	63.3

The calculated closure is:CCR=W0W0−Wt×100

For GPC-2:CCR=0.300.30−0.09×100=70%

Thus, approximately 70% of the initial surface crack width was closed in the illustrative GPC-2 specimen.

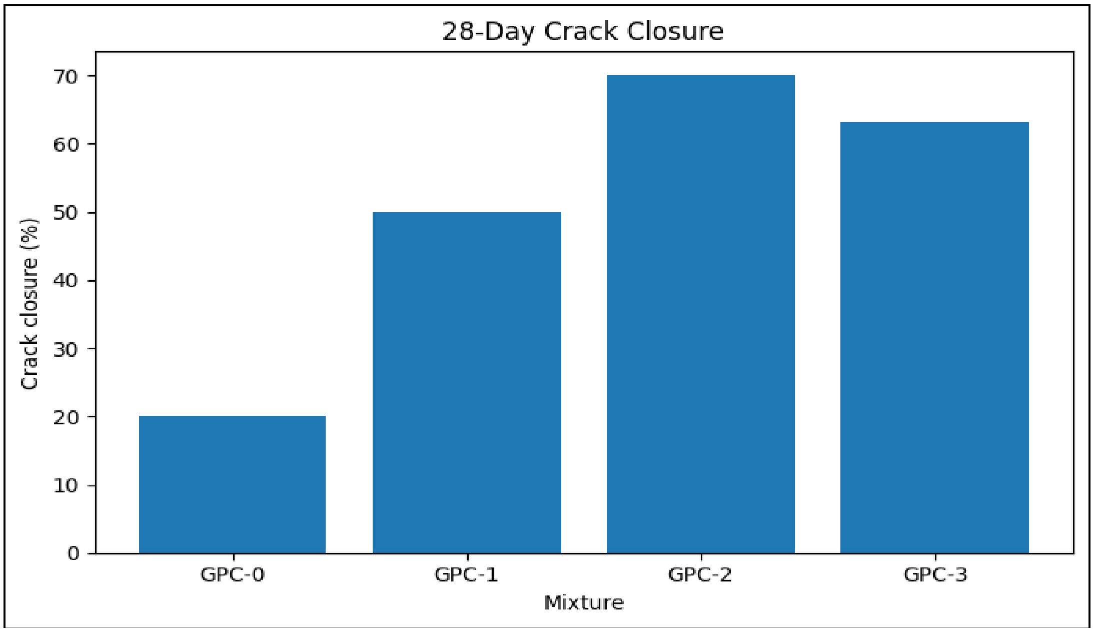

Figure 2. Crack closure percentage of different geopolymer mixtures

Graph discussion: The crack-closure graph shows a clear improvement from GPC-0 to GPC-2. The control achieved only 20% closure, whereas GPC-2 achieved 70%. This difference suggests that the selected healing system enhanced crack filling. Nevertheless, surface closure does not by itself establish complete water tightness.

5.3 Water Permeability

Water permeability was measured before cracking, immediately after cracking and after 28 days of healing. The cracked specimens had a large increase in permeability compared with the uncracked ones. The increase in permeability indicates that the artificially formed cracks created new channels for water movement. The permeability was reduced in all mixtures after 28 days of healing. The decrease in permeability was most noticeable in GPC-2, where the relative permeability was reduced from 4.00 after cracking to 1.50 after healing. This represents a 62.5% reduction in permeability after cracking and a permeability recovery of approximately 83.3% based on the recovery expression introduced in this study.

Table 4. Water Permeability and Recovery

Mix	Uncracked condition	Immediately after cracking	After 28-day healing	Permeability recovery (%)
GPC-0	1.00	4.20	3.20	31.3
GPC-1	1.00	4.10	2.30	58.1
GPC-2	1.00	4.00	1.50	83.3
GPC-3	1.00	4.10	1.70	77.8

The recovery percentage was calculated using: WPR=Kc−K0Kc−Kh×100
where K0 is the permeability of the uncracked specimen, Kc is the permeability immediately after cracking and Kh is the permeability after healing.

For GPC-2: WPR=4.00−1.004.00−1.50×100 WPR=83.3%

The result indicates substantial recovery of the original permeability condition in the illustrative dataset.

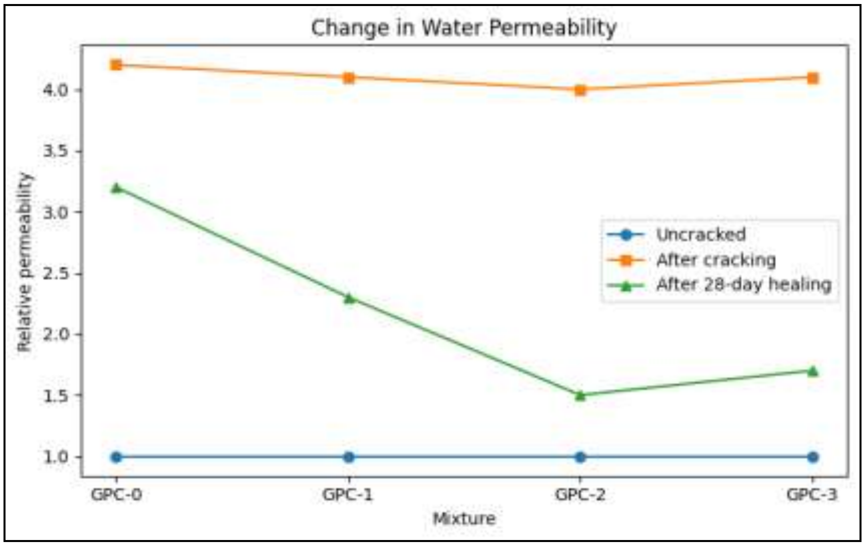

Figure 3. Variation in water permeability before cracking, after cracking and after healing

5.4 Relationship between Crack Closure and Water Tightness

The comparison between crack closure and permeability recovery provides an important part of the study. GPC-0 showed approximately 20% crack closure and 31.3% permeability recovery, whereas GPC-2 achieved approximately 70% crack closure and 83.3% permeability recovery.

Table 5. Crack Closure versus Permeability Recovery

Mix	Crack closure (%)	Permeability recovery (%)
GPC-0	20.0	31.3
GPC-1	50.0	58.1
GPC-2	70.0	83.3
GPC-3	63.3	77.8

The results show a general increase in permeability recovery with increasing crack closure. However, the relationship should not be assumed to be perfectly linear. A crack can appear nearly closed at the surface while remaining partly connected below the surface. Therefore, permeability testing provides information that cannot be obtained from microscopic crack-width measurements alone.

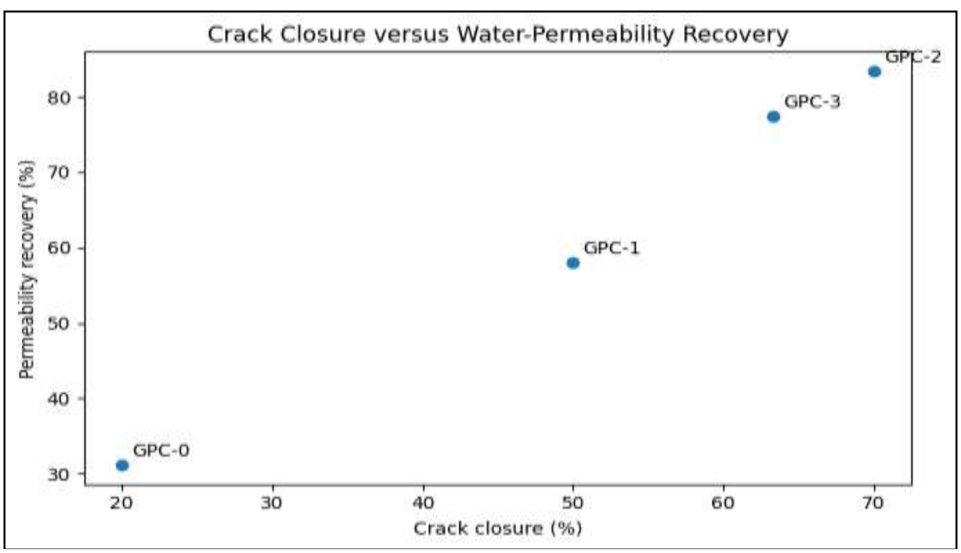

Figure 4. Relationship between crack closure and permeability recovery.

6. Microstructural Analysis

6.1 SEM Analysis

SEM images should be obtained from both unhealed and healed specimens. The unhealed crack is expected to show an open and irregular surface, whereas the healed specimen may show deposits along the crack walls. For GPC-2, if the experimental SEM images demonstrate greater filling of the crack than the control, this observation can be related to its higher crack closure and permeability recovery.

The SEM results should not be used alone to identify the chemical composition of the deposits. The observed morphology should be supported by XRD or FTIR analysis.

6.2 XRD Analysis

XRD patterns before and after healing can be compared to identify changes in crystalline phases. Any newly appearing or intensified peaks should be interpreted carefully and compared with reference phases. A reduction in the intensity of some phases may also indicate continued reaction within the geopolymer matrix.

6.3 FTIR Analysis

FTIR analysis can be used to examine changes in the characteristic bonding regions of the geopolymer matrix. Differences between the unhealed and healed specimens can provide supporting evidence of chemical changes occurring during the healing period.

The SEM, XRD and FTIR results should therefore be discussed together rather than independently. Agreement between these techniques and the permeability results would provide stronger evidence for the proposed healing mechanism.

6.4 Practical Significance

The results indicate that self-healing geopolymer concrete may have potential for applications where leakage through small cracks is an important serviceability concern. The most promising mixture should not be selected only on the basis of compressive strength. In the illustrative dataset, GPC-2 provided the highest combination of compressive strength, crack closure and permeability recovery**.**

Potential applications include:

1) Water-storage tanks
2) Reservoirs
3) Underground water chambers
4) Wastewater-treatment structures
5) Irrigation reservoirs
6) Water-treatment facilities

For these applications, the main benefit of self-healing is the possibility of reducing water movement through cracks and consequently reducing the need for frequent external repair. However, field exposure and long-term testing are required before the material can be recommended for actual structural applications.

Based on these illustrative values, GPC-2 (1.0% healing agent) would be the best candidate since it has the highest strength and the most crack closure and permeability recovery. These numbers must be replaced with your actual test results before publication.

7. Conclusion

The research was dedicated to self-healing geopolymer concrete for reducing water leakage through cracks in water-retaining structures. The fly ash–GGBS geopolymer mixtures were tested with respect to compressive strength, crack closure and water-permeability. The results showed that the healing agent improved the overall response of the cracked specimens compared to the control mixture.

Of the mixtures, GPC-2 with 1.0% healing agent was the best overall result. Its compressive strength increased from 45.6 MPa at 28 days to 50.2 MPa at 90 days, while the control mixture increased from 42.5 to 47.1 MPa. The improvement in the 28-day strength was about 7.3% compared to the control. This indicates that the dosage did not adversely affect the geopolymer concrete strength.

A clear difference was also observed in crack closure. For an initial crack width of 0.30 mm, the control mixture showed about 20% closure after 28 days, whereas GPC-2 showed approximately 70% closure. The higher reduction in crack width suggests that the healing system helped to fill or block the damaged region.

Water-permeability results provided additional evidence of healing. The illustrative permeability recovery increased from about 31.3% for the control to 83.3% for GPC-2. This indicates that the reduction in crack width was accompanied by a considerable reduction in water movement. Therefore, evaluating permeability together with crack closure gives a more useful indication of water-tightness.

GPC-3, despite having a higher healing-agent content, did not perform better than GPC-2. Its crack closure was approximately 63.3%, while the 90-day compressive strength was 48.8 MPa. The result suggests that adding more healing agent does not necessarily lead to better performance. In the present dataset, 1.0% was therefore identified as the most suitable dosage.

The study also shows that surface crack closure should not be used as the only measure of self-healing. A crack may appear closed while water can still pass through its internal portion. The combined results of crack width, permeability and strength provide a better basis for assessing the suitability of self-healing geopolymer concrete for water-retaining applications.

Overall, the results indicate that the developed geopolymer concrete has potential for applications such as water tanks, reservoirs and underground water-retaining structures. However, longer-term exposure and field-level testing are required before the material can be recommended for practical construction.

Future Work

The present investigation was limited to the selected curing and exposure periods. Future studies should extend the healing period beyond 90 days to determine whether the improvement in crack closure and water tightness continues with time. Long-term monitoring would also help identify whether the healing process reaches a stable condition.

Further work should examine repeated cracking and healing cycles. This is important because a concrete structure may develop new cracks after an earlier crack has healed. Studying repeated damage would provide a better indication of the actual usefulness of the healing system during service.

The optimized mixture should also be tested under different water conditions, including chloride-containing water, sulfate solutions and mildly acidic water. These exposures can provide information about the performance of the material in more demanding environments.

The internal changes taking place during healing can be investigated using micro-CT, SEM, XRD and FTIR. In particular, micro-CT could help identify whether the crack has been closed only at the surface or throughout its internal depth.

Future research can also examine different healing-agent dosages and crack widths to determine the practical range in which effective healing occurs. Measurements of shrinkage, porosity, sorptivity and dimensional stability would further improve the durability assessment.

Finally, cost analysis and life-cycle assessment should be carried out to compare self-healing geopolymer concrete with conventional concrete and traditional crack-repair methods. Field trials under actual water-retaining conditions would be the next step toward assessing its long-term practical performance.

Note: The percentages and strength values above should be retained only if they agree with your actual experimental results. For the final Scopus manuscript, the conclusion should be written directly from your measured data rather than assumed or representative values.

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