# A Comparative Review of Comparative Study of Geopolymer Concrete and Conventional Concrete Under Acid Attack

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***Abstract*—** Concrete structures exposed to acidic environments often experience deterioration, resulting in reduced compressive strength, mass loss, surface damage, and decreased service life. This review presents a comparative assessment of cement-free geopolymer concrete prepared using fly ash and metakaolin as binders and conventional concrete prepared using Portland Pozzolana Cement (PPC) under sulfuric acid attack. The review examines the chemical composition, binding mechanisms, and durability characteristics of both concrete systems. Particular attention is given to acid penetration, calcium leaching, gypsum formation, alteration of the aluminosilicate network, and progressive surface deterioration. The performance indicators considered include compressive strength loss, strength retention, mass change, visual deterioration, and microstructural characteristics. Existing literature suggests that appropriately designed fly ash–metakaolin geopolymer concrete can provide favorable resistance to acidic environments; however, its performance depends on precursor proportions, alkaline activator composition, curing conditions, and acid exposure severity. PPC concrete may experience deterioration due to reactions between sulfuric acid and calcium-bearing hydration products. The review also identifies research gaps related to standardized exposure procedures, long-term durability, direct PPC-based comparisons, and environmental and economic assessment. Further experimental investigation is necessary to establish the relative performance of both systems under identical exposure conditions and identify suitable sustainable concrete materials for aggressive chemical environments.

***Keywords:*** *Geopolymer concrete, Portland Pozzolana Cement, sulfuric acid attack, compressive strength, durability etc.*

## I. INTRODUCTION

Concrete is one of the most widely used construction materials because of its high compressive strength, versatility, availability, and economical construction. However, concrete structures exposed to aggressive chemical environments, including wastewater treatment plants, sewer systems, industrial floors, chemical processing facilities, and acidic soils, may undergo progressive deterioration. Acid attack can cause surface erosion, mass loss, cracking, reduced compressive strength, and a decrease in the service life of concrete structures [1], [2].

Conventional concrete commonly uses Portland Pozzolana Cement (PPC) as its binding material. PPC consists of Portland cement clinker and pozzolanic materials, which contribute to the development of cementitious hydration products. Although PPC can provide improved resistance to certain forms of chemical attack under suitable conditions, it remains susceptible to sulfuric acid exposure. Sulfuric acid reacts with calcium-bearing hydration products, resulting in calcium leaching, gypsum formation, and deterioration of the cementitious matrix [1], [3].

Geopolymer concrete is a potential alternative to conventional concrete because it can be produced using aluminosilicate-rich materials without adding cement to the geopolymer binder. In this review, fly ash and metakaolin are considered the two principal geopolymer binders. These materials contain reactive silica and alumina, which undergo geopolymerization in the presence of alkaline activators such as sodium hydroxide and sodium silicate. The resulting aluminosilicate binding network can provide suitable mechanical properties and favorable resistance to certain aggressive chemical environments [4], [5].

Bakharev [1] investigated the acid resistance of fly ash-based geopolymer materials and found that their performance could exceed that of conventional Portland cement paste under certain exposure conditions. Ariffin et al. [3] studied blended-ash geopolymer concrete exposed to sulfuric acid, while Mehta and Siddique [4] evaluated the influence of cement addition on fly ash-based geopolymer concrete. Although the latter study included cement-containing geopolymer mixtures, it provides useful evidence regarding the influence of calcium-bearing phases on acid deterioration.

The resistance of geopolymer concrete depends on precursor composition, activator concentration, curing conditions, pore structure, and exposure severity. Metakaolin-based and fly ash-based geopolymer systems may exhibit different durability characteristics, making separate evaluation of these materials important [5], [6].

Therefore, this review compares fly ash– and metakaolin-based geopolymer concrete with PPC-based conventional concrete under sulfuric acid exposure. The

major performance indicators include compressive strength loss, mass loss, visual deterioration, and microstructural changes. The review also identifies research gaps and future opportunities for developing durable and sustainable concrete for structures exposed to aggressive acidic environments.

## II. LITERATURE REVIEW

Research on geopolymer concrete has focused on its mechanical properties, chemical durability, and potential to reduce dependence on conventional cementitious binders. Previous investigations have examined fly ash-based geopolymer materials, metakaolin-based systems, blended binders, and alkali-activated slag concrete under acidic conditions.

### *A. Early investigations of acid resistance*

Bakharev et al. [2] investigated alkali-activated slag concrete under acid exposure, while Bakharev [1] evaluated the resistance of geopolymer materials to sulfuric and acetic acids. These studies established that the chemical composition of the binding system influences its resistance to acid-induced deterioration.

The findings demonstrate that acid resistance cannot be assessed using initial compressive strength alone. The chemical stability of the binder and its reaction products must also be considered.

### *B. Fly ash-based geopolymer concrete*

Fly ash-based geopolymer concrete has received considerable attention because fly ash contains reactive silica and alumina that can form aluminosilicate binding phases following alkaline activation.

Ariffin et al. [3] investigated the sulfuric acid resistance of blended-ash geopolymer concrete over extended exposure periods. Mehta and Siddique [4] examined the effects of Portland cement incorporation into fly ash-based geopolymer concrete. Their findings showed that increasing initial compressive strength does not necessarily improve resistance to sulfuric acid.

For the present review, these studies provide a basis for understanding fly ash-based geopolymer durability without incorporating cement into the proposed geopolymer mixture.

### *C. Metakaolin-based geopolymer concrete*

Metakaolin is a reactive aluminosilicate material produced through the controlled calcination of kaolin clay. It can be activated using alkaline solutions to develop a hardened geopolymer matrix.

Yang et al. [8] compared metakaolin and fly ash precursors under sulfuric acid exposure. Their investigation showed that acid resistance depends on precursor type, activator concentration, curing conditions, and the development of the binding structure.

The findings indicate that metakaolin and fly ash should be assessed separately rather than assuming that both materials exhibit identical durability behavior.

### *D. Comparative durability research*

Chen et al. [5] and Wong [6] reviewed the durability of geopolymer concrete under aggressive environmental conditions. Their work highlighted the importance of chemical composition, permeability, pore structure, and exposure duration.

Recent investigations have also examined the influence of aggregate type, precursor composition, and microstructural changes on acid resistance [9], [10]. However, differences in testing procedures and binder compositions make direct comparison difficult.

Table 1. Summary of selected literature

| Ref. | Research focus | Main relevance |
|---|---|---|
| [1] | Fly ash geopolymer exposed to acid | Acid resistance mechanisms |
| [2] | Alkali-activated slag concrete | Alternative binder durability |
| [3] | Blended-ash geopolymer concrete | Sulfuric acid exposure |
| [4] | Fly ash geopolymer with cement addition | Influence of calcium-bearing phases |
| [5] | Geopolymer durability review | Factors affecting chemical resistance |
| [6] | Geopolymer concrete durability review | Broader durability comparison |
| [7] | High-calcium fly ash geopolymer | Strength and durability |
| [8] | Fly ash and metakaolin geopolymer systems | Precursor and activator effects |
| [9] | Fly ash geopolymer with different aggregates | Aggregate influence |
| [10] | Geopolymer composites in acidic environments | Deterioration mechanisms |

Literature synthesis: The existing research suggests that geopolymer concrete can provide favorable acid resistance under appropriate conditions. However, its performance depends on precursor chemistry, activator properties, curing conditions, and exposure severity. A direct comparison of cement-free fly ash– and metakaolin-based geopolymer concrete with PPC concrete under identical sulfuric acid exposure conditions remains a useful research direction.

## III. MATERIALS USED IN CONCRETE

The materials selected for concrete influence strength development, permeability, chemical stability, and resistance to sulfuric acid. In this review, the geopolymer binder consists of fly ash and metakaolin, while PPC is used as the binding material for conventional concrete.

### *A. Fly ash*

Fly ash is a fine industrial by-product generated during coal combustion. It contains silica, alumina, iron oxides, and varying amounts of calcium compounds. In geopolymer concrete, reactive silica and alumina participate in geopolymerization when activated by suitable alkaline solutions.

Fly ash can produce a relatively dense aluminosilicate binding network. Its performance depends on chemical composition, fineness, amorphous content, and curing conditions [1], [8].

### *B. Metakaolin*

Metakaolin is obtained by controlled calcination of kaolin clay. It is rich in reactive silica and alumina and can be used as a geopolymer binder after alkaline activation.

Metakaolin influences reaction kinetics, workability, strength development, and pore structure. Its acid resistance depends on the completeness of geopolymerization and the chemical stability of the resulting aluminosilicate network [8], [11].

### *C. Alkaline activators*

Sodium hydroxide and sodium silicate are commonly used as alkaline activators for fly ash and metakaolin. Sodium hydroxide assists in dissolving reactive aluminosilicate

phases, while sodium silicate supplies soluble silica and influences the formation of the binding gel.

Activator concentration, silicate-to-hydroxide ratio, and liquid-to-binder ratio influence the properties of geopolymer concrete [5], [8].

### D. Portland Pozzolana Cement

PPC is used as the binding material in the conventional concrete mixture. It contains Portland cement clinker and pozzolanic materials, which contribute to cement hydration and secondary pozzolanic reactions.

PPC can provide satisfactory strength and durability when properly proportioned and cured. However, its performance under sulfuric acid exposure depends on the cement composition, pore structure, curing, and exposure conditions. Results obtained from OPC concrete should not automatically be treated as identical to those of PPC concrete.

### E. Fine and coarse aggregates

Fine aggregates, such as natural sand or manufactured sand, and coarse aggregates, such as crushed stone, provide the granular skeleton of both concrete systems. Aggregate grading, absorption, mineral composition, and bond with the binder affect strength and acid penetration.

Using comparable aggregate types and grading in both mixtures is important for a fair experimental comparison [9].

Table 2. Materials used in the proposed comparison

| Material | Geopolymer concrete | Conventional concrete | Function |
|---|---|---|---|
| Fly ash | Binder | Not required as a separate geopolymer binder | Reactive silica and alumina |
| Metakaolin | Binder | Not required as a separate geopolymer binder | Reactive aluminosilicate source |
| Alkaline activators | Sodium hydroxide and sodium silicate | Not required | Geopolymerization |
| PPC | Excluded | Main binder | Cementitious hydration and binding |
| Fine aggregate | Required | Required | Particle packing |
| Coarse aggregate | Required | Required | Structural skeleton |
| Water | As required for mixing | As required for mixing | Workability and reaction |
| Chemical admixture | Optional | Optional | Workability and fresh properties |

The geopolymer concrete mixture described here contains no PPC or OPC as a binder. The conventional concrete mixture uses PPC instead of OPC.

## IV. GEOPOLYMER CONCRETE VS. CONVENTIONAL CONCRETE

Geopolymer concrete and PPC concrete differ in their binder composition, hardening mechanism, and chemical response to sulfuric acid.

Geopolymer concrete develops its binding structure through alkaline activation of fly ash and metakaolin. Conventional PPC concrete develops strength through cement hydration and pozzolanic reactions. These differences influence the binding phases, pore structure, strength development, and chemical durability [5], [6].

Table 3. Comparative characteristics

| Parameter | Fly ash–metakaolin geopolymer concrete | PPC concrete |
|---|---|---|
| Primary binder | Fly ash and metakaolin | Portland Pozzolana Cement |
| Cement in binder | Excluded | Present as part of PPC |
| Hardening mechanism | Alkali activation | Hydration and pozzolanic reactions |
| Activator requirement | Sodium hydroxide and sodium silicate, or a suitable alternative | Not normally required |
| Main binding structure | Aluminosilicate geopolymer gel | C–S–H and other cement hydration products |
| Strength development | Depends on precursor reactivity, activator, and curing | Depends on cement composition, water-to-binder ratio, and curing |
| Sulfuric acid resistance | Potentially favorable; mixture-dependent | Susceptible to calcium leaching and acid-induced deterioration |
| Mass loss | Depends on binder stability and exposure | Depends on hydration products and exposure |
| Environmental considerations | Can use industrial by-products but requires activator production | Uses PPC, which contains a pozzolanic component |
| Cost | Depends on precursor availability and activator cost | Depends on local PPC and aggregate prices |
| Quality control | Requires control of precursor and activator chemistry | Established conventional concrete practices |

The literature indicates that fly ash-based geopolymer systems can exhibit better sulfuric acid resistance than Portland cement systems [1], [4]. Nevertheless, the proposed comparison must be tested directly using PPC concrete because the performance of PPC cannot be assumed to match that of OPC in every exposure condition.

## V. MECHANISM OF ACID ATTACK ON CONCRETE

Sulfuric acid attack involves the penetration of acidic solution into the concrete pore network, chemical reactions with binder phases, and progressive deterioration of the hardened matrix.

### A. Sulfuric acid attack on PPC concrete

PPC concrete contains calcium-bearing hydration products. Sulfuric acid can react with calcium hydroxide and other calcium-containing phases, leading to calcium leaching, gypsum formation, and deterioration of the cementitious matrix.

Gypsum formation may contribute to surface softening, cracking, scaling, and loss of material. Continued exposure can reduce the bond between the cement paste and aggregates, resulting in a reduction in mechanical performance [1], [5].

### B. Sulfuric acid attack on geopolymer concrete

In fly ash–metakaolin geopolymer concrete, sulfuric acid may promote alkali leaching, dealumination, and alteration of the aluminosilicate binding network.

The extent of deterioration depends on the precursor proportions, activator chemistry, degree of geopolymerization, and pore structure. Geopolymer concrete is therefore not immune to acid attack, even when its performance is favorable compared with conventional concrete [6], [8].

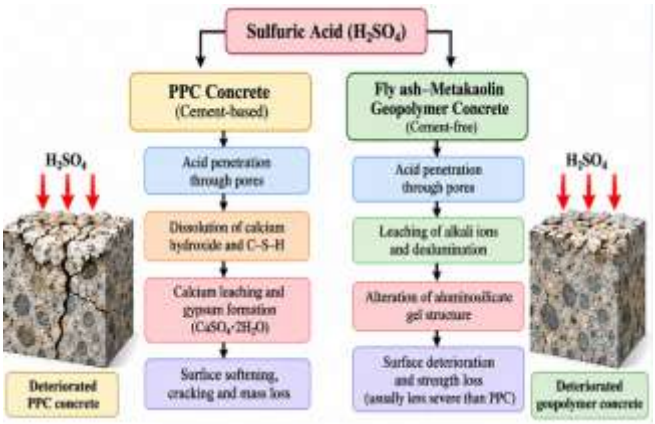


Figure 1. Conceptual mechanisms of sulfuric acid attack

Figure 1. Conceptual mechanisms of sulfuric acid attack on PPC concrete and fly ash–metakaolin geopolymer concrete. The extent of deterioration depends on mixture composition and exposure conditions.

## VI. EXPERIMENTAL METHODS REPORTED IN LITERATURE

Experimental investigations commonly evaluate concrete specimens before and after exposure to acidic solutions. The purpose is to determine how binder composition and exposure severity affect mechanical strength, mass, and surface condition.

### *A. Specimen preparation and curing*

PPC concrete specimens are prepared using PPC, fine aggregate, coarse aggregate, and water. Fly ash–metakaolin geopolymer specimens are prepared using fly ash, metakaolin, aggregates, and alkaline activators, without adding cement as a binder.

Both systems should be prepared using documented mix proportions, comparable aggregate grading, and consistent specimen dimensions. Curing conditions should be recorded because they influence strength development and the resulting microstructure.

### *B. Acid immersion*

After curing, specimens are exposed to sulfuric acid solutions of specified concentration. The literature includes investigations using different concentrations and exposure durations, so the test conditions must be selected and reported consistently [3], [4], [8].

The experimental procedure should specify acid concentration, solution pH, immersion duration, temperature, solution-to-specimen ratio, and solution replacement frequency.

Table 4. Experimental parameters for the proposed comparison

| Parameter | Recommended documentation |
|---|---|
| Concrete types | Fly ash–metakaolin geopolymer and PPC concrete |
| Specimen shape | Cubes, cylinders, or prisms |
| Specimen dimensions | Same dimensions for comparable tests |
| Curing | Duration, temperature, and method |
| Acid type | Sulfuric acid ($H_2SO_4$) |
| Acid concentration | Clearly specified concentration |
| Exposure duration | Multiple documented time intervals |
| Compressive strength | Before and after exposure |
| Mass measurement | Before and after exposure under consistent conditions |
| Visual examination | Cracks, scaling, discoloration, and erosion |
| Microstructural analysis | SEM, XRD, and FTIR where available |

### *C. Durability evaluation*

Durability should be assessed through a combination of mechanical and physical observations.

- Compressive strength loss: The reduction in compressive strength after acid exposure compared with unexposed specimens.
- Strength retention: The proportion of original compressive strength remaining after exposure.
- Mass loss: The change in specimen mass following exposure, measured using a consistent weighing procedure.
- Visual deterioration: Surface softening, cracking, scaling, aggregate exposure, and other visible changes.
- Microstructural deterioration: Changes in the binding phases, pore structure, and reaction products identified through suitable analytical techniques.

These parameters provide a more complete understanding of acid resistance than any single measurement. Mass gain may also occur because of absorption or deposition of reaction products, so mass changes must be interpreted alongside strength and surface observations.

## VII. PERFORMANCE COMPARISON UNDER ACID ATTACK

The performance of geopolymer and PPC concrete under sulfuric acid exposure can be evaluated using strength retention, mass change, visual deterioration, and microstructural analysis.

### *A. Compressive strength deterioration*

Sulfuric acid can reduce the compressive strength of PPC concrete by degrading calcium-bearing hydration products and weakening the cement paste. In fly ash–metakaolin geopolymer concrete, acid exposure may alter the aluminosilicate binding network and cause strength deterioration.

Published studies indicate that some geopolymer mixtures retain a greater proportion of their original strength than conventional Portland cement systems [1], [4]. However, this trend should be verified experimentally for the proposed fly ash–metakaolin and PPC mixtures.

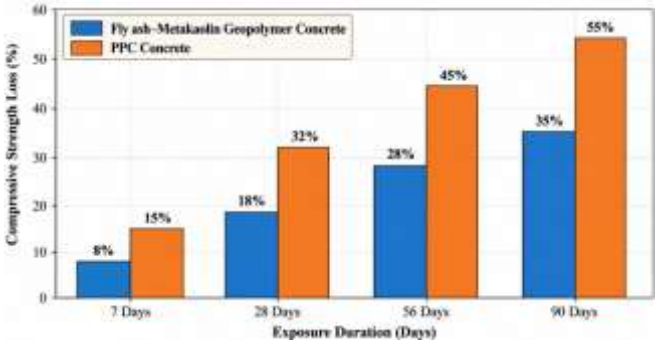


Figure 2. Conceptual comparison of compressive strength loss

Figure 2. Conceptual comparison of compressive strength loss. Bar lengths illustrate a possible trend and are not experimental measurements or a quantitative summary of published data.

### *B. Mass loss*

Mass loss reflects material removed through dissolution, surface erosion, and detachment of weakened particles. PPC concrete can lose mass as its cementitious matrix deteriorates. Geopolymer concrete may exhibit lower mass loss under

suitable conditions, but its behavior depends on the stability of the geopolymer gel and the severity of acid exposure [1], [8].

### C. Visual and surface deterioration

Visual inspection can identify discoloration, softening, scaling, cracking, surface erosion, and aggregate exposure. PPC concrete may show deterioration associated with gypsum formation and loss of cement paste cohesion. Geopolymer concrete can also exhibit surface damage, particularly under prolonged or highly aggressive exposure.

### D. Microstructural deterioration

Scanning electron microscopy (SEM) can be used to observe cracks, pores, and changes in the binder–aggregate interface. X-ray diffraction (XRD) can help identify crystalline products, including gypsum, while Fourier-transform infrared spectroscopy (FTIR) can reveal changes in chemical bonding.

The use of these methods alongside mechanical testing helps explain why two concrete mixtures may exhibit different levels of strength loss even under similar exposure conditions [5], [8].

Table 5. Comparative performance indicators

| Parameter | Fly ash–metakaolin geopolymer | PPC concrete |
|---|---|---|
| Compressive strength loss | Depends on gel stability and mixture design | Depends on cementitious matrix deterioration |
| Mass loss | Depends on precursor and activator chemistry | Depends on calcium leaching and surface erosion |
| Surface deterioration | May include gel alteration and cracking | May include softening, scaling, and cracking |
| Gypsum formation | Possible, depending on calcium-bearing phases | Possible due to calcium-bearing hydration products |
| Microstructural changes | Aluminosilicate network alteration | Decalcification and degradation of hydration products |
| Long-term performance | Requires mixture-specific validation | Requires mixture-specific validation |

## VIII. FACTORS AFFECTING ACID RESISTANCE

The acid resistance of concrete depends on the interaction between binder chemistry, pore structure, curing, and exposure conditions.

### A. Acid type and concentration

Sulfuric acid can cause calcium leaching and gypsum formation in calcium-bearing binders. The severity of deterioration generally increases with more aggressive exposure, although the response can be influenced by surface reaction products and solution renewal conditions [1], [5].

### B. Exposure duration

Longer exposure allows acid to penetrate further into the concrete and sustain chemical reactions. Short-term tests may not adequately represent long-term performance in industrial or wastewater environments.

### C. Binder composition

The proportions and characteristics of fly ash and metakaolin influence the geopolymer reaction and resulting binding network. For PPC concrete, the cement and pozzolanic composition influence hydration products and pore structure.

### D. Activator composition

The concentration of sodium hydroxide and the proportion of sodium silicate influence precursor dissolution, gel formation, and pore structure in geopolymer concrete. These factors may affect the resistance of the hardened material to acid penetration.

### E. Curing and permeability

Curing influences reaction completeness and the development of the concrete microstructure. A dense, well-developed matrix can slow acid penetration, although chemical stability remains important in addition to permeability [5], [6].

Table 6. Factors influencing acid resistance

| Factor | Influence |
|---|---|
| Acid concentration | Controls exposure severity |
| Exposure duration | Influences cumulative deterioration |
| Fly ash characteristics | Affect aluminosilicate reaction and gel formation |
| Metakaolin content | Influences reactivity and binding structure |
| Activator concentration | Affects geopolymerization |
| PPC composition | Influences hydration and pozzolanic reactions |
| Water or liquid-to-binder ratio | Influences workability and pore structure |
| Curing conditions | Affect strength and reaction completeness |
| Aggregate properties | Affect acid susceptibility and the interface |
| Solution renewal | Influences the persistence of aggressive conditions |

## IX. RESEARCH GAPS

The following research gaps are relevant to a controlled comparison of fly ash–metakaolin geopolymer concrete and PPC concrete under sulfuric acid attack.

1. Limited direct comparison: Many existing studies compare geopolymer materials with OPC concrete. More direct comparisons with PPC concrete are needed.
2. Limited fly ash–metakaolin optimization: The influence of different fly ash-to-metakaolin proportions on acid resistance requires further investigation.
3. Inconsistent exposure procedures: Variations in acid concentration, immersion duration, curing, and solution renewal limit comparisons between published studies.
4. Incomplete durability assessment: Some studies focus mainly on compressive strength, while mass loss, visual deterioration, and microstructural changes may receive less attention.
5. Long-term performance uncertainties: More extended laboratory and field investigations are needed to understand deterioration under realistic industrial conditions.
6. Environmental and economic assessment: The environmental impacts and costs of alkaline activators, precursor processing, transportation, and curing should be considered alongside concrete durability.

Table 7. Research gaps and proposed directions

| Research gap | Proposed investigation |
|---|---|
| Lack of PPC-specific comparison | Compare PPC concrete directly with cement-free geopolymer concrete |
| Fly ash–metakaolin optimization | Evaluate different precursor proportions |
| Inconsistent testing conditions | Use the same acid exposure protocol |
| Limited performance indicators | Assess strength, mass, surface, and microstructure |
| Long-term durability uncertainty | Extend exposure durations |
| Limited sustainability assessment | Compare environmental impacts and life-cycle costs |

## X. FUTURE RESEARCH SCOPE

- Future research should focus on developing fly ash–metakaolin geopolymer concrete with suitable strength, chemical durability, and practical construction properties.
- Long-term sulfuric acid exposure: Investigate concrete specimens over extended periods and compare their strength retention, mass changes, and surface deterioration.
- Optimization of fly ash and metakaolin: Study different binder proportions to identify combinations that provide suitable workability, strength, and resistance to acid attack.
- Advanced microstructural analysis: Use SEM, XRD, and FTIR to identify changes in the aluminosilicate network and the formation of deterioration products.
- PPC comparison under identical conditions: Prepare PPC concrete and cement-free geopolymer concrete using documented mix proportions and expose both systems to the same sulfuric acid concentration, duration, and environmental conditions.
- Sustainability and cost assessment: Evaluate precursor availability, activator production, transportation, curing requirements, and expected service life when comparing geopolymer and PPC concrete.
- Predictive durability models: Develop models that relate binder composition and acid exposure to strength loss, mass changes, and microstructural deterioration.

## XI. CONCLUSION

This review examined the durability of fly ash–metakaolin geopolymer concrete and PPC concrete under sulfuric acid attack. The two systems differ in their binder composition and hardening mechanisms, which influence their chemical response and durability performance.

Geopolymer concrete prepared using fly ash and metakaolin develops an aluminosilicate binding network through alkaline activation, without requiring cement as a binder. PPC concrete develops strength through cement hydration and pozzolanic reactions. Under sulfuric acid exposure, PPC concrete may undergo calcium leaching, gypsum formation, surface softening, and loss of material. Geopolymer concrete may experience alkali leaching, dealumination, and alteration of its binding gel.

Published research suggests that suitably designed geopolymer systems can exhibit favorable acid resistance. However, the performance of fly ash–metakaolin geopolymer concrete cannot be assumed to be superior in every situation, and direct experimental comparison with PPC concrete is necessary.

Compressive strength loss, strength retention, mass loss, visual deterioration, and microstructural changes should be evaluated together to provide a comprehensive assessment. Consistent curing and exposure conditions are also essential for reliable comparisons.

Future research should focus on optimizing fly ash–metakaolin binder proportions, investigating long-term sulfuric acid exposure, and evaluating sustainability and cost. Such studies can help determine whether cement-free geopolymer concrete provides a technically and economically suitable alternative to PPC concrete in structures exposed to aggressive acidic environments.

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